Original Research Article

Combining Ability and Heterosis of Quality Protein Maize Hybrids for Yield, Qualitative and Quantitative Traits under Heat stress in Different Environments

Abstract

Heat stress (HS) have evidently become major yield reducing factors for maize (*Zea mays* L.) in tropical and sub-tropical regions. The variances for GCA and SCA of variance were found significant for most of the characters. However, relative magnitude of variances indicated both additive and non-additive gene action for the expression of these traits were more prominent for all the characters studied. GCA and SCA effects both showed significant interaction with environment for all the traits. Parents NBPGR-36548 (P_4), VL-153237 (P_5) and BHU QPM-2 (P_2) were found to be good general combiners for grain yield per plant, chlorophyll content, oil content and starch content. Indicating that they could be good parental lines in hybridization programs. The range of heterosis expressed by different crosses was from 0.71 % (P_2 X P_6) to 45.11 % (P_5 X P_6) in E_1, from 0.42 % (P_1 X P_7) to 5.69 % (P_1 X P_8) in E_2 and 18.92% (P_4 X P_8) in E_3. The better performing five crosses P_5 X P_7, P_5 X P_6, P_4 X P_8, P_5 X P_9 and P_4 X P_5. Crosses between good x average, average x average and good x good shows greater economic heterosis and exhibited high SCA effects for yield under HS. These best hybrids didn't show any symptoms of leaf firing, tassel blast, root lodging and no severe loss of yield in the present investigation. These crosses also need to be evaluated further multilocation in large scale.

Key words

Quality Protein Maize, Heat tolerance, Combining ability, Heterosis and Gene action.

Introduction

Breeding for heat tolerance in Quality Protein Maize is one of the economically viable and sustainable ways of reducing yield losses caused by heat stress in QPM maize. Research on QPM has been ongoing for several decades. Opaque-2 (*o2*) is a natural recessive mutation in the transcriptional activator conditioning negative expression of zein protein (Tripathy, S. K., *et al.,* 2017). However, the lower yields of QPM versus non-QPM varieties, as well as the susceptibility of QPM varieties to stresses, such as ear rot, heat stress, resulting in less tryptophan and lysine produced per unit area of land have been the focus of researchers over a number of years.

However, crop suffering from heat stress and drought stress maize varieties that produced the highest metabolites are not usually high yielding varieties. This directly impacts on children suffering from malnutrition so, to overcome this issue Quality Protein Maize is the best source of food which surplus your daily needs for the reason that QPM maize has more amount of lysine and tryptophan content which eventually fulfil the total protein content to humankind. As per the FAO recommendations total intake for children should be 6.6 % lysine and 1.7% tryptophan whereas for adults 1.6% lysine and 0.5% tryptophan. Since, Quality Protein Maize has the accountability to at benchmark which contain 4.1% lysine and 1% tryptophan which is more higher than normal maize which accounts 2.7% of lysine and 0.6 % of tryptophan.

Increasing the climatic temperature around the globe makes the earth surface hotter, this makes plant kingdom thrive to survive and it mainly effects plant growth and development particularly in tropical and subtropical countries. Among abiotic stresses, high temperature stress is a major factor disrupting plants performance (Wahid *et al.*, 2007). Above optimum temperature (37.3^{0}C) affects maize morphological, physiological, biochemical and molecular traits, which ultimately leads to poor growth and yields. On the other hand increase the air temperature in field conditions usually induce higher vapour pressure deficit, enhancing the demand for soil water and effect of water deficit (Mittler 2008), which in turn can rise canopy temperature.\

QPM genotypes can produce yields as high as the non-QPM varieties. OPVs and synthetics yield ranged from 2-7.3 t/ha in QPM as compare 4 t/ha and above in Non-QPM (Pixley, K. V 2003). In hybrids QPM yields 3-13.9 t/ha whereas, Non-QPM yields around 5t/ha and above (Prasanna, B. M *et al.*, 2001; Pixley, K. V 2003; Bello *et al.*, 2012; Bisen, P. *et al.*, 2017.). In India, during the 2019-2020 cropping seasons, 9.7 million ha of land was covered with maize with national average productivity of 2.9 tonnes/ha and production of 28.6 million tonnes is still far below the world average 5.1 tons/ha **(Department of Agriculture Co-operation, 2020)**. Whereas in Uttar Pradesh, it occupies an area 0.73 million hectares with an average productivity of 1.67 tonnes/ha and production of 1.23 million tonnes. **(The International Plant Nutrition Institute (IPNI), Regional Profiles-India, 2018).**

The exploitation of heterosis in maize (*Zea mays* L.) can be accomplished through the development and identification of high *per se* performance vigorous parental lines and their subsequent evaluation for combining ability in cross combinations to identify the hybrids with high heterotic effects (Abdel-Moneam *et al.,* 2014). A diallel is simple to manipulate in maize and supplies important information about the studied populations for various genetic parameters (Vacaro *et al.,* 2002). Exploitation of heterosis is considered to be one of the outstanding achievements of maize breeding. In India, very less emphasis was given for exploitation of heterosis particularly for quality traits like high oil and starch content in maize grains. The variability for selection and the expected genetic advance is in the population of singe cross is largest. The whole of the additive, dominance and epistatic components of genetic variation is available for exploitation in single crosses. Single cross hybrids exhibit 40 to 53 percent superiority over open pollinated varieties, while three way crosses and double crosses exhibit 26 to 33 per cent and 20 to 26 percent superiority over open pollinated varieties (OPV's) respectively (Vasal *et al.,* 1995). The phenomenon of heterosis has been exploited extensively in crop breeding, leading to significant increase in yield.

Combining ability investigations of parental generations need to be conducted under appropriately stressed selection environments for the successful selection of suitable parents that can be used in hybridization programs (Hallauer and Miranda. 1988). Combining ability is defined as the capacity of an inbred line to transmit any of its superior traits to its offspring (Sprague and Tatum 1942). Successful estimation of combining abilities involves various steps such as parental selection for crossing, performing crosses using a definite mating design, evaluation and interpretation of data. The study of the effects of combining ability, both general combining ability (GCA) and specific combining ability (SCA), are important indicators of potential value for assessing inbred lines in hybrid combinations as a step to develop hybrid varieties in maize (Abdel-moneam *et al.,* 2014). Cayhen (2003) mentioned that the information about parents, genetic structure and their combining ability, are one of the most important criteria for identifying high yielding hybrids. Heterosis and combining ability are the prerequisites for formulating hybrid breeding programme. Parents with good GCA effects and *per se* performance can be crossed to develop high yielding hybrids that can be released for cultivation. The ratio of SCA and GCA is a good indicator for the predominance of non-additive effect in the expression of quantitative characters if it is found greater than one (Dodia and Joshi, 2003). The evaluation of crosses among inbred lines is an important step towards the development of hybrid varieties in maize. The diallel analysis provides information on the type of gene action and general combining ability and specific combining ability (SCA) of genotypes (Silva *et al.*, 2010, Moterle *et al.*, 2011).

Therefore, the present study was undertaken to study the combining ability among the parental lines and heterosis among the newly generated cross combinations using 10 x 10 half diallel mating design.

Materials and methods

The trial was conducted in three sites at Central Research Farm, SHUATS at an altitude of 98m above sea level. These sites are located 100 mts away from each other, all the locations has sub-tropical climate with extremes of summer and winter. During winter season especially in month of December and January, temperature drops down to as low as 1-2^0 C, while during summer the temperature reaches up to 48^0C. The average precipitation is around 983 mm annually with maximum concentration during July to September with a few occasional showers and drizzles in winter too.

Quality protein inbred lines (Table 1) obtained from different research centres in India, were used to generate single cross hybrids. Total of 45 F_1s obtained using diallel fashion with non-reciprocals.

Table 1. Name, origin and heat stress status of parental lines.

Inbred line	Name	Origin	Heat tolerance status
P_1	BHU-QPM-8	B	HT
P_2	BHU-QPM-2	B	HT
P_3	NBPGR-33000	N	HS
P_4	NBPGR-36548	N	HT
P_5	VL-153237	C	HT
P_6	IC-53826	N	HT
P_7	IC-381506	N	HT
P_8	IC-1306641	N	HT
P_9	BHU-N3	B	HT
P_{10}	BHU-B73-BC2	B	HS

B = BHU, Varanasi; N = NBPGR, New Delhi; C = CIMMYT, R/o Hyderabad;
HT = Heat Tolerance; HS = Heat susceptible.

Firstly, 10 inbred lines which were selected are crossed in all possible ways without reciprocals to produce 45 F_1s (Table 2).

Table 2. List of hybrids produced by crossing in a 10 x 10 diallel fashion excluding reciprocals.

F/M	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	P_{10}
P_1	-	P_1 x p_2	P_1 x P_3	P_1 x P_4	P_1 x P_5	P_1 x P_6	P_1 x P_7	P_1x P_8	P_1 x P_9	P_1 x P_{10}
P_2	-	-	P2 x P_3	P_2 x P_4	P_2 x P_5	P_2 x P_6	P_2 x P_7	P_2x P_8	P_2 x P_9	P_2 x P_{10}
P_3	-	-	-	P_3 x P_4	P_3 x P_5	P_3 x P_6	P_3 x P_7	P_3x P_8	P_3 x P_9	P_3 x P_{10}
P_4	-	-	-	-	P_4 x P_5	P_4 x P_6	P_4 x P_7	P_4x P_8	P_4 x P_9	P_4 x P_{10}
P_5	-	-	-	-	-	P_5 x P_6	P_5 x P_7	P_5x P_8	P_5 x P_9	P_5 x P_{10}
P_6	-	-	-	-	-	-	P_6 x P_7	P_6x P_8	P_6 x P_9	P_6 x P_{10}
P_7	-	-	-	-	-	-	-	P_7x P_8	P_7 x P_9	P_7 x P_{10}
P_8	-	-	-	-	-	-	-	-	P_8 x P_9	P_8 x P_{10}
P_9	-	-	-	-	-	-	-	-	-	P_9 x P_{10}
P_{10}	-	-	-	-	-	-	-	-	-	-

Data Collection

Data on quantitative, qualitative and other important agronomic traits were collected on plot and individual plant basis. Data collected on plot basis were for days to 50% tasselling, days to 50% silking, anthesis silking interval. Data on individual plant basis were taken for plant height, cob height, tassel length, seed index (100 seed weight), seed yield, days to maturity, harvest index, chlorophyll content, canopy temperature deficit, leaf area index, starch content and oil content. Total of fourteen parameters were taken in this research.

Experimental design and trial management

The study was carried out in three research sites representative different places in CRF, SHUATS. In kharif 2019 screening and evaluation of 160 diverse parental inbred lines used and among them selection of 10 vigorous and productive parental inbred lines based on *per se* performance for grain yield, quantitative and qualitative traits were undertaken. In Rabi-2019-2020 crossing program was under taken as per Diallel mating design given by Griffing, (1956) (Model I, Method II) to generate 45 F_1 hybrids. In kharif 2020 multi-environment evaluation of F_1 hybrids + Parents + Check at three different dates of sowing with different environments *viz.*, (1^{st}, 15^{th} and 31^{st} July, 2020) in Randomized Block Design with three replications for assessing their stability. Data were recorded for quantitative and qualitative traits. Plot sizes for the progenies and parental lines were one row, 4.0 - 5.0 m long, with 0.75 m inter-row spacing and 0.25 m intra- row spacing. All agronomic practices like fertilisation and weeding were followed according to recommendations for maize cropping at each site. In all the 3 environments.

Statistical analysis

The statistical analysis was done by using replication mean values based on the recorded data. The different statistical procedures followed were Analysis of variance, Estimation of Heterosis, Heterobeltiosis and Economic heterosis, Combining ability analysis and Stability Analysis. The data obtained for each character in F_1's and parents were analyzed for each statistical procedure given by **Panse and Sukhatme (1967)**, 'F' test and 'I' test were worked out by the analysis of variance to test the significance. It was carried out according to the procedure of RBD analysis for each character as per methodology of **Fisher and Yates (1938)**.

$$Y_{ij} = M + B_i + T_i + E_{ij}$$

Where,

M = General effect

B= Block effect

T_i= Treatment effect

E_{ij}= Error component

Heterosis expressed as percent deviation from the mid parent. In the present experiment heterosis was estimated for 5-6 hybrids for the 19 characters studied, suggested by **Turner (1953)**

$$\text{Heterosis (ha)} \ (\%) = F1 - MP|MP \ x \ 100$$

$$(\boldsymbol{F1 - MP}) = \sqrt{(\frac{\boldsymbol{2MSe}}{\boldsymbol{r}})}$$

$$Heterobeltiosis\ (hb)\% = \frac{(F1-BP)}{BP} \text{ X } 100$$

$$\text{Standard heterosis (hc) (\%)} = \frac{[(\mathbf{F_1} - \mathbf{BC})]}{\mathbf{BC}} \times \mathbf{100}$$

The combining ability analysis was computed on data obtained for parents and F_1s only by using diallel mating design (Model-I Method-II), (Griffings, 1956). $X_{ij} = \mu + g_i + g_j + S_{ij} + 1/rk + \Sigma e i_{jk}$ where, μ = population mean, g_i = general combining ability of i_{th} variety, g_j = general combining ability of j_{th} variety, S_{ij} = specific combining ability of ij_{th} cross, ei_{jk} = environmental component pertaining to ijk_{th} observation, i and j = male and female parents responsible for producing ij_{th} hybrid, r = number of replications

General and specific combining ability effects were calculated as follows: gi. = 1/(p+2) $\{X_i + X_{ii} -(2/p)\ X\}$ and $S_{ij} = X_{ii}-1(p+2)\ (X_i + X_{ii} + X_j + X_{jj}) + 2/\{(p+1)\ (p+2)\}\ X$. Where, g_i =Estimation of general combining ability (gca) effect of i^{th} parent and S^{ij} = Estimation of specific combining ability (sca) effect of the hybrid between ¡th and jth parent. Where, Sg = Sum of squares due to gca, Ss = Sum of squares due to sca, X_{ij} = Values of cross between i^{th} and j^{th} parent, Xi = Total of i^{th} (row) array in diallel table (summed over), X. = Grand total of 'P' parents/ lines and P(P-1)/2 progenies of diallel table and, X_{ij}= Parental value of the i^{th} parent.

Results

Analysis of variance

Under HS conditions, Analysis of variance (Table 1) indicated that the mean sum of squares due to genotypes were significant for all the characters studied. The variances due to general combining ability (gca) and specific combining ability (sca) were highly significant for all the characters studied, indicating the importance of both additive and non-additive gene actions in the expression of most of the quality traits in maize. The dominance variance has greater influence in the inheritance of the trait as it was evident from the ratio of additive to dominance variance which was below unity (VA/VD<1). Similar findings were also reported by Ram *et al.,* (2018), Gideon *et al.,* (2017) and Ravi *et al.,* (2021). High estimates of sca variances for grain yield, chlorophyll content, canopy temperature deficit, starch content and oil content and the ratio of *gca* and *sca* variance was less than unity (σ2g/ σ2s<1) indicated the preponderance of non- additive gene action for its expression and inheritance of the above characters. Similar results in maize have been reported by Naggar *et al.,* (2014), Iiyas *et al.,* (2020), Bhusal *et al.,* (2020) and Bekele and Rao (2021).

Table 3. Analysis of variance for different quantitative traits in maize

Source of variation	Df	Env	Days to 50% tasseling	Days to 50% silking	ASI	Plant height	Cob height	Tassel length	LAI	Chlorophyll Content	CTD	Seed Index	Grain yield/ plant	Days to maturity	Oil content	Starch content
Replicate	2	E_1	42.62	44.92	0.65	2442.61	736.86	14.49	2.69	148.54	12.91	5.65	20665.98	0.55	0.05	1.32
		E_2	0.01	0.46	0.44	687.12	310.13	19.74	3.01	125.94	94.81	1.06	1733.81	0.99	0.01	003
		E_3	0.92	5.31	0.12	104.33	79.23	12.48	2.16	112.18	33.85	5.70	40.28	0.84	0.00	0.02
Treatments	54	E_1	9.12	9.36	0.28	853.37	414.37	89.16	0.60	42.62	1.64	15.29	2165.46	26.28	1.25	59.65
		E_2	8.42	7.19	0.24	1955.13	765.89	92.33	0.47	43.11	1.17	8.38	877.93	14.30	1.07	65.51
		E_3	26.73	25.89	0.36	657.38	306.53	57.33	0.41	36.52	1.13	13.22	356.23	21.17	1.08	65.34
Parents	9	E_1	4.67	5.86	0.83	410.88	231.51	68.66	0.61	90.52	1.31	17.23	588.75	31.50	0.53	15.39
		E_2	24.40	25.72	0.09	411.88	230.52	47.89	0.67	90.36	2.13	13.01	687.24	23.44	0.45	19.09
		E_3	19.43	12.09	0.03	409.88	230.90	106.73	0.65	89.30	2.10	15.68	688.20	23.40	0.44	17.51
Hybrids	44	E_1	9.32	9.30	0.18	397.97	235.87	39.46	0.26	30.66	1.74	9.04	2120.54	25.60	1.30	69.40
		E_2	3.37	2.73	0.26	1363.18	587.96	45.56	0.19	31.17	6.76	7.61	935.37	12.37	1.12	75.84
		E_3	4.99	5.75	0.40	608.69	243.87	43.75	0.18	25.37	0.37	13.00	168.73	10.04	1.14	76.18
Parent vs hybrids	1	E_1	40.07	43.39	0.01	24873.18	9913.87	2460.57	15.69	139.50	0.01	273.22	18332.02	9.50	5.60	28.89
		E_2	86.55	75.33	0.49	41899.23	12404.10	2550.00	11.16	142.92	1.74	0.42	67.07	17.05	4.39	28.87
		E_3	1048.90	1035.86	1.42	5018.52	3739.18	210.13	7.76	42.70	25.69	0.63	5627.40	490.52	4.28	18.96
Error	108	E_1	2.97	2.99	0.19	189.72	736.86	15.48	0.27	37.36	1.49	2.73	1466.44	0.93	0.02	0.82
		E_2	1.91	1.52	0.27	238.77	141.24	21.74	0.20	25.03	1.00	1.90	598.49	1.64	6.00	0.09
		E_3	2.22	3.82	0.24	96.51	63.13	10.22	0.17	24.66	0.68	2.43	146.66	2.22	0.01	0.02

Under optimum conditions, the mean sum of squares for GCA was significant for all traits except chlorophyll content and canopy temperature deficit (Table 4). Significant SCA effects were observed for most of the traits except for chlorophyll content.

Table 4. Magnitude of genetic variance for different maize traits.

Source of variation	Days to 50% tasseling	Days to 50% silking	ASI	Plant height	Cob height	Tassel length	LAI	Chloro phyll Content	CTD	Seed Index	Grain yield/ plant	Days to maturity	Oil content	Starch content
σ^2 g	7.64***	8.19**	0.17*	262.83**	215.23**	10.61*	0.11	11.94	0.33	5.56***	928.50	9.38***	0.46**	22.70**
σ^2 s	2.11***	2.11**	0.08	288.78**	122.70**	33.54**	0.22***	14.66	0.59	5.00***	68.48	8.64***	0.41**	19.32**
GCA/SCA	0.49	0.54	0.50	0.07	0.17	0.02	0.01	-0.02	-0.15	0.09	0.19	0.09	0.09	0.10
VA (σ^2 A)	1.10	1.20	0.02	33.27	29.67	0.91	0.00	-0.09	-0.03	0.78	73.28	1.51	0.08	3.74
VD (σ^2 D)	1.12	1.11	0.02	225.54	85.51	2.38	0.13	2.21	0.09	4.09	191.67	8.33	0.40	19.05
VA/VD (σ^2 A/ σ^2 D)	0.98	1.00	1.00	0.15	0.34	0.03	0.03	-0.04	-0.30	0.19	0.38	0.18	0.19	6.20

Significant levels: * = <.05, ** = <.01 & *** = <.001
ASI= Anthesis silking interval; LAI= leaf area index; CTD= canopy temperature deficit.

General combining ability analysis:

Estimates of GCA effects different characters were either positive or negative. Mostly, parental lines which has positive GCA are recommended as good general coming ability traits and negative GCA are suitable for some characters. Under Heat stress condition P_2, P_4 and P_5 are good general combiners for seed yield per plant and seed index (Table 5), indicating parental lines P_1, P_4, P_5, P_6, P_7, P_8 and P_2 were heat tolerant (Table 1). Parental lines with negative GCA effects P_3, P_7 and P_{10} were noted as poor inbred lines selected as parental material and among all this parental lines P_{10} found susceptible for HS.

Table 5: General combining ability (GCA) effects for different characters in maize

Parents	code	Days to 50% tasseling	Days to 50% silking	ASI	Days to maturity	Plant height	Cob height	Tassel length	Chlor- -ophyll Content	CTD	LAI	Seed index	Grain yield/ plant	Starch content	Oil content
BHU- QPM-8	P_1	1.16 ***	1.12 ***	0.01	0.54 **	6.29 **	6.52 ***	-0.22	-1.64	0.08	0.01	0.92 ***	5.41	0.71 ***	-0.24 ***
BHU QPM-2	P_2	0.083	-0.13	-0.12	1.03 ***	9.52 ***	7.69 ***	-1.14 *	-1.93 *	-0.17	0.06	0.64 **	2.31	2.77 ***	0.18 ***-
NBPGR-33000	P_3	-0.06	0.05	0.10	-0.76 ***	5.73*	-1.47	-0.02	1.07	0.24	-0.17 *	1.01 ***	0.82	1.24 ***	0.01 *
NBPGR-36548	P_4	0.71 **	0.65 *	-0.05	-0.56 ***	-2.46	-3.08	0.84	-0.62	0.02	-0.08	-0.63 *	7.88	-0.38 **	0.04
VL-153237	P_5	0.29	0.27	-0.03	-0.90 ***	3.69	0.65	1.01	0.76	-0.10	0.14	-0.28	14.40 *	-0.11	0.30 ***
IC-53826	P_6	0.15	0.05	-0.11	0.73 ***	-11.90 ***	-5.88 **	-2.92 ***	0.02	-0.10	-0.08	-1.00 ***	8.39	1.09***	-0.25 ***
IC-381506	P_7	-0.64 *	-0.76 **	-0.08	-0.01	1.74	2.88	0.68	1.57	0.20	0.02	-0.06	1.91	-2.04 ***	0.01
IC-1306641	P_8	1.05 ***	1.01 ***	-0.05	1.68 ***	6.85 **	5.64 **	-0.07	0.30	0.28	0.02	-0.01	-3.53	0.73 ***	0.02
BHU-N3	P_9	0.57 *	0.87 **	0.30 ***	-0.17	1.68	1.67	-0.83	-1.13	0.09	0.05	-0.61 *	-2.90	0.89 ***	0.18***
BHU-B73-BC2	P_{10}	-0.56 *	-0.59 *	-0.05	0.29	-0.56 *	-0.59 *	-0.05	-0.35	-0.09	0.02	0.03	-6.89	0.63 ***	-0.23 ***

Under HS conditions, positive GCA effect values of chlorophyll content were desirable. Positive GCA depicts the plants ability to maintain chlorophyll content, which would enable such plants to photosynthesize when other plants were senescing. Parental lines P_5, P_6, P_7 and P_3 were good combiners for chlorophyll content. However, P_1, P_2, P_4, P_8 and P_{10} were not combine well for this character.

Negative GCA effects were desirable for days to 50% tasselling, days to 50% silking and anthesis silking interval since it demonstrated the ability of the plant to flower early under stressed conditions. Parental lines P_7 and P_{10} had negative GCA effects for 50% tasselling, days to 50% silking and Anthesis silking interval. P_3, P_7 and P_{10} shows negative GCA only for days to 50% tasselling and P_2, P_7 and P_{10} shows negative GCA only for days to 50% silking and P_2, P_4, P_5, P_6, P_7 and P_8 shows negative GCA only for anthesis silking interval hence these parental lines are desirable for shortening the anthesis silking interval in the breeding programs. Plants showing positive GCA indicates late flowering and eventually probes to heat stress. Late maturing parental lines are not desirable since yield is greatly reduced under heat-stressed condition. Negative anthesis siliking interval were desirable since it implies good synchronization of anthesis and silking. Negative GCA for canopy temperature deficit and plant height are well suitable for HS conditions. Negative GCA effects for canopy temperature deficit implied that CTD was not elevated under HS conditions. Parental lines P_2, P_4, P_5 and P_{10} were good combiners for canopy temperature deficit while P_1, P_3, P_7, P_8 and P_9 were poor combiners. Plants which shows negative GCA for plant height are implied good combiners hence, short plant height are well suitable because they are less prone to lodging. Short plants shown by negative GCA effects are desirable. parental lines P_4, P_6 and P_{10} are good parental lines for plant height, whereas, P_1, P_2, P_3 and P_8 are poor parental lines.

Under HS conditions parental lines P_1, P_2, P_3, P_4, P_5, and P_6 shows best combing ability for grain yield per plant while, parental lines P_8, P_9 and P_{10} are poor combiners (Table 5). All parental lines except P_1, P_2 and P_3 were good combiners for seed index. All parental lines except P_4, P_5 and P_7 were poor combiners for starch content. Parental lines P_1, P_6 and P_{10} are poor combiners for oil content whereas, P_2, P_3, P_4, P_5 and P_6 are good combiners and shows good oil content these inbred are well suitable for oil content. Combining ability effects for the rest of the traits under HS conditions are shown in Table 5

Based on the general combing ability results different parental lines under HS condition no parental line showed good combiners for all the traits hence, parental line P_7 showed good general combining ability for all the characters except seed index and starch content under HS condition.

Specific combining ability

Significant SCA effects observed for most of the characters under Heat-stress. Under HS no significant effects were observed for chlorophyll content, canopy temperature deficit and ear height. Negative and positive SCA effect values were recorded under HS and in three different environments. Depending on the character, cross combinations with high positive SCA values denoted as the best specific combiners for that particular character while which show negative SCA effects are described as poor combiners. Positive SCA values for the starch content, oil content, grain yield, tassel length and seed index were desirable. As such, QPM hybrids exhibiting high positive SCA values for these traits were considered as good specific combiners while those exhibiting negative SCA values were shown as poor combiners for SCA.

Under HS 26 F_1s combined well for grain yield in E_1, 24 F_1s combined well in E_2. whereas, only 12 F_1s are combined well for grain yield per plant in $E_{3.}$ Hence E_1 shows great specific combing ability than the both environments. Cross combinations $P_{1\ x}\ P_{10}$ E_1 (21.32), E_2 (29.68*), E_3 (12.99*); $P_{3\ X}\ P_5$ (15.85), (0.74), (5.86); $P_{3\ X}\ P_7$ (17.18), (8.26), (7.15) and $P_{5\ X}\ P_7$ (46.63*), (22.80), (6.14) combined well for grain yield (Table 6), recording total grain yield of 165.65, 211.60, 196.40 and 255.87 q/ha (Table 8). These hybrids performed better than the check HQPM-5 (172.22 q/ha). Hybrid P_1 x P_9 with grain yield (100.48 q/ha) was the worst specific combiner for the grain yield under HS condition. It is noted that this F_1s are derived from the crosses made by the best parents which are suitable for HS (Table 1). The average yield loss for all the 45 F_1s was 15 % as compare to check.

Precisely 61 % of the F_1s had positive SCA effects for the oil content hybrids P_3 X P_8 E_1 (1.17***), E_2 (1.17**) and E_3 (1.10**); and P4 X P5 (1.32**), (1.25**), (1.26**) were the best cross combinations for this character while, hybrid P_5 X P_8 (-0.99), (-0.83), (-0.82) with the highest negative SCA value, was the worst cross combination. In consider to starch content, P7 X P8 (9.19), (9.24), (8.48) and P1 X P8 (7.50), (8.75), (9.05) recorded the highest positive SCA effects and these cross combinations were good for starch content. While P2 X P10 (-4.51), (-5.37), (-4.99) was the worst cross combination for this character. Negative SCA effects for days to 50% tasselling, days to 50% silking, anthesis-silking interval and days to maturity were desired. Negative SCA effects for anthesis silking interval demonstrated that flowering synchronization was good while negative days to 50% tasselling and days to 50% silking demonstrated early flowering of F_1s. while negative SCA of days to maturity is good because of early harvesting of crop and it is must necessary for HS condition. Hybrids were top five early flowering in all the environments P_1 X P_3, P_1 X P_4, P_4 X P_6, P_5 X P_9 and P_5 X P_{10}. Among them E1 hybrid P_3 X P_6 (-2.67**), (-3.01**), (-0.071) is good for early flowering since it shows good negative SCA for days to50% tasselling, days to 50% silking and anthesis-silking interval. Only 30 % of the F_1s are good combiners for anthesis-silking interval.

Table 6. Specific combining ability (SCA) effects for different characters in maize over three environments

S.NO	Hybrids	Env.	Days to 50% tasselling	Days to 50% Silking	ASI	Plant height	Ear height	Tassel length`	LAI	Chlorophyll content	CTD	Seed index	Seed yield per plant	Days to maturity	oil content (%)	Starch content (%)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(8)	(9)	(10)	(12)	
1	P_1 X P_2	E_1	0.629	0.399	-0.265	1.558	-2.404	1.52	-0.007	1.4	1.753 **	0.801	3.642	-1.409 **	-0.674 ***	2.488 ***
		E_2	-0.753	-0.639	0.068	-7.344	3.688	2.136	0.736 **	1.923	0.368	0.219	-1.167	-0.293	-0.602 ***	3.037 ***
		E_3	-0.404	-0.487	-0.169	-7.763	-10.855*	5.495 **	0.727 **	0.813	0.46	0.072	-2.748	1.798 *	-0.566 ***	1.690 ***
2.	P_1 X P_3	E_1	0.712	0.677	-0.098	10.149	2.933	-5.049 *	-0.041	-2.184	-1.213	-0.667	-2.067	-0.742	0.122	-0.072
		E_2	-0.28	-0.444	-0.237	10.184	-7.257	-1.223	0.408	-2.615	0.004	1.387	12.985	0.568	0.148 ***	0.497 **
		E_3	-0.543	-0.904	-0.169	2.32	-7.466	0.856	0.443	-3.472	-0.171	0.568	-2.123	1.687 *	0.187 ***	0.41
3.	P_1 X P_4	E_1	-0.732	-0.795	-0.126	12.061	5.655	0.705	0.262	1.331	1.267	3.416***	-11.792	1.730 **	0.856 ***	2.071 ***
		E_2	-0.947	-0.972	-0.098	16.173	9.695	7.519 **	0.451	-0.654	-0.641	0.949	8.428	0.152	0.383 ***	1.997 ***
		E_3	-0.947	-0.972	-0.098	16.173	9.695	7.519 **	0.451	-0.654	-0.641	-0.528	-6.143	0.659	0.367 ***	1.553 ***
4.	P_1X P_5	E_1	-0.205	0.649	0.513 *	-3.846	-4.487	1.987	-0.108	-1.274	-0.702	0.996	-44.082 *	-3.270 ***	-0.740 ***	-0.426
		E_2	-0.641	-0.333	0.235	0.684	-3.916	-2.731	-0.03	-1.339	0.654	0.917	3.798	-1.265	-0.732 ***	1.010 ***
		E_3	0.707	0.79	-0.003	1.459	4.43	-4.977 **	-0.015	-1.866	0.06	1.795 *	-3.579	-1.23	-0.773 ***	0.851 **
5.	P_1 X P_6	E_1	0.101	0.371	0.179	11.681	8.594	4.725 *	-0.252	-0.643	-0.027	1.964 *	-2.27	-4.576 ***	0.11	5.376 ***
		E_2	-0.169	-0.111	-0.015	14.823	12.149	5.241 *	-0.172	0.469	0.19	-0.998	-18.98	-4.210 ***	0.118 ***	5.693 ***
		E_3	1.874 *	1.679	-0.086	4.292	8.773 *	2.023	-0.048	0.475	-0.038	-0.272	-7.279	-2.174 **	0.044 *	5.718 ***
6.	P_1 X P_7	E_1	0.629	-0.045	-0.098	4.353	13.700 *	3.242	0.068	4.175	0.12	-0.654	-13.696	-4.826 ***	0.157 *	-4.377 ***
		E_2	-0.336	-1.083	-0.182	0.862	-3.638	7.463 **	-0.056	3.052	-0.505	-0.639	17.747	-4.571 ***	0.191 ***	-5.107 ***
		E_3	2.290 **	2.652 *	0.192	6.665	7.292	-3.338	-0.186	3.23	-0.155	-0.253	-4.438	-2.230 **	0.202 ***	-5.215 ***
7.	P_1 X P_8	E_1	0.934	1.177	0.207	12.799	7.897	4.782 *	0.616 *	1.298	-0.558	-1.486	18.694	0.813	-0.258 ***	7.506 ***
		E_2	1.109	1.278	0.096	46.928***	27.219***	5.602 *	0.001	0.367	-0.656	-1.600 *	26.887 *	2.679 ***	-0.158 ***	8.751 ***
		E_3	1.235	1.374	0.053	14.592 **	6.621	2.217	0.065	0.189	-0.082	-1.423	-2.725	3.465 ***	-0.202 ***	9.054 ***
8.	P_1 X P_9	E_1	1.407	0.982	-0.154	12.169	14.327 *	3.516	0.503	-0.487	-0.908	-3.023**	3.07	2.008 ***	-0.117	-3.961 ***
		E_2	1.164	1.194	0.263	2.417	4.72	3.352	0.11	0.396	-0.137	-1.406	-54.05***	1.985 **	0.008	-5.649 ***
		E_3	2.596 **	1.957	-0.169	10.442	3.038	1.051	0.084	0.481	-0.079	-1.686 *	-15.783 *	1.659 *	0.023	-5.230 ***
9.	P_1 X P_{10}	E_1	-0.455	-0.212	0.207	27.296***	20.218***	13.131 ***	0.576 *	-0.864	0.234	1.945 *	21.322	3.535 ***	-0.242 **	-6.441 ***
		E_2	0.581	0.556	-0.098	36.517***	40.426***	-3.37	0.005	0.582	0.318	0.802	29.686 *	1.763 *	-0.298 ***	-7.512 ***
		E_3	1.179	1.235	-0.03	-18.874***	-4.006	1.412	-0.032	0.892	-0.196	-0.614	12.992 *	1.104	-0.315 ***	-7.110 ***
10.	P_2 X P_3	E_1	1.184	1.01	-0.182	16.987 *	11.575 *	2.155	0.987 ***	4.858	-0.711	-1.12	3.069	-1.854 ***	0.862 ***	7.891 ***
		E_2	1.497 *	0.972	-0.487	12.928	12.851 *	7.074 **	0.511 *	3.181	-0.562	-1.012	25.415	0.346	0.745 ***	8.395 ***
		E_3	0.735	0.513	-0.03	-7.158	-6.442	5.856 **	0.508 *	2.518	-0.094	0.903	-2.025	3.187 ***	0.765 ***	9.065 ***
11.	P_2 X P_4	E_1	-1.927 *	-1.795	0.124	-5.232	6.096	-0.111	0.554 *	-0.417	-0.13	0.89	-15.674	2.619 ***	-0.707 ***	-2.437 ***
		E_2	-1.169	-0.889	0.318	19.250 *	-5.532	3.916	-0.023	0.196	-0.241	0.35	-21.942	1.596 *	-0.516 ***	-1.342 ***
		E_3	1.04	0.929	-0.197	23.026 ***	16.203***	2.273	-0.016	0.337	-0.743	0.073	-19.361**	1.159	-0.499 ***	-1.899 ***
12.	P_2X P_5	E_1	-0.732	-0.351	0.429	-4.012	-8.979	0.943	0.083	1.122	-0.533	1.11	-35.33	-0.381	0.680 ***	-2.206 ***
		E_2	-1.197	-1.25	-0.015	-10.572	-9.809	-4.667	0.036	1.981	0.221	-0.835	-14.506	0.513	0.762 ***	-2.818 ***
		E_3	0.985	0.874	-0.197	1.981	2.454	3.356	-0.244	1.764	-0.176	-1.824 *	-16.314 *	-0.063	0.805 ***	-2.584 ***
13.	P_2 X P_6	E_1	0.573	0.371	-0.237	5.615	7.106	4.359 *	0.05	3.697	-0.358	-2.002 *	2.215	-0.354	-0.400 ***	-2.994 ***
		E_2	-0.725	-0.361	0.402	5.901	14.590 *	0.638	0.041	3.756	-0.876	-1.897 *	-4.7	0.902	-0.298 ***	-2.358 ***
		E_3	0.152	0.096	0.053	3.815	0.13	4.356 *	-0.027	4.018	-0.293	-4.13***	-7.404	0.992	-0.234 ***	-2.720 ***
14.	P_2 X P_7	E_1	-1.899 *	-2.045 *	-0.182	9.676	7.188	4.095	0.12	-5.915	0.256	0.793	15.123	-0.937	0.853 ***	-2.438 ***
		E_2	-1.891 *	-1.333 *	0.235	22.606 **	9.803	2.194	0.273	-7.352 **	-0.005	-0.372	-22.423	-0.126	0.751 ***	-3.399 ***
		E_3	1.235	1.068	-0.336	-9.146	0.316	5.995 ***	0.225	-6.936 *	-0.241	-1.875 *	-2.616	-0.396	0.737 ***	-2.677 ***
15.	P_2 X P_8	E_1	-0.927	-0.823	0.124	21.646 **	8.386	4.642 *	0.308	0.134	-1.088	1.437	12.379	1.035 *	1.189 ***	-2.417 ***
		E_2	-1.114	-0.972	0.179	17.673 *	3.993	7.333 **	0.106	1.137	-0.123	1.035	-4.65	0.79	0.829 ***	-1.997 ***
		E_3	1.179	1.79	0.525 *	6.781	-5.689	-3.783 *	0.143	1.135	-0.488	-0.741	-1.277	-0.369	0.787 ***	-1.748 ***

16.	P_2 X P_9	E_1	0.879	1.316	0.429	10.449	5.625	-0.258	0.065	-3.754	1.295	0.404	-4.185	0.563	-0.810 ***	-1.059 *
		E_2	-0.391	-0.056	0.346	14.162	6.827	6.749 **	0.386	-3.294	0.029	-1.572 *	11.208	1.429 *	-0.855 ***	-2.084 ***
		E_3	2.207 **	2.04	0.303	-7.035	-0.605	0.051	0.403	-2.979	-0.011	-2.051 *	6.099	0.492	-0.836 ***	-1.975 ***
17.	P_2 X P_{10}	E_1	0.684	0.455	-0.21	5.876	4.04	4.281 *	0.045	2.709	0.803	1.925 *	-7.96	1.758 **	-0.472 ***	-4.154 ***
		E_2	0.359	0.306	-0.015	14.595	3.866	3.694	-0.016	2.799	0.318	1.670 *	2.373	1.207	-0.377 ***	-5.377 ***
		E_3	1.790 *	2.652 *	0.775 **	-20.685 ***	-3.982	-7.255 ***	0.023	2.245	-0.155	1.720 *	-10.149	1.937 *	-0.450 ***	-4.995 ***
18.	P_3 X P_4	E_1	2.157 *	2.149 *	-0.043	14.483	9.1	2.17	-0.116	1.026	-0.23	2.168 *	-30.049	3.952 ***	-0.088	-1.293 *
		E_2	-1.364	-1.028	0.346	-13.555	-6.143	1.858	-0.067	0.484	-0.571	-0.389	-12.89	2.457 ***	0.007	-2.081 ***
		E_3	2.568 **	2.179 *	-0.197	8.442	-6.074	-0.366	0.027	0.355	-0.541	0.396	-5.94	3.715 ***	0.027	-3.108 ***
19.	P_3X P_5	E_1	0.684	0.593	-0.071	-7.54	-1.442	4.288 *	0.51	0.674	0.334	-1.759	15.852	4.619 ***	-0.594 ***	-2.070 ***
		E_2	-1.058	-1.056	0.013	25.956 **	4.58	4.608	0.492 *	1.436	0.324	-1.268	0.747	1.04	-0.665 ***	-3.014 ***
		E_3	3.513 ***	3.457**	0.136	4.731	4.176	-1.949	0.479 *	1.022	0.36	-1.791 *	5.86	0.826	-0.686 ***	-3.677 ***
20.	P_3 X P_6	E_1	-2.677 **	-3.018**	-0.071	-4.58	-4.557	4.967 *	0.21	2.449	0.776	3.51***	23.077	3.980 ***	0.202 **	6.916 ***
		E_2	-2.919 ***	-2.833***	0.096	11.428	2.978	1.247	-0.097	2.577	-0.073	4.03***	-2.748	1.763 *	0.172 ***	7.079 ***
		E_3	0.013	3.346 **	0.386	3.231	3.852	-0.616	-0.08	3.189	-0.435	0.962	-2.326	0.881	0.165 ***	7.023 ***
21.	P_3 X P_7	E_1	0.184	0.566	0.318	3.791	-2.828	4.876 *	0.33	-1.81	0.289	0.018	17.118	-0.604	-0.371 ***	-2.845 ***
		E_2	-0.419	-0.806	-0.404	34.801 ***	19.858 **	1.802	-0.164	-0.987	-0.702	-0.437	8.262	1.402 *	-0.399 ***	-2.869 ***
		E_3	3.429 ***	2.985 **	-0.336	-10.063	-6.629	0.023	-0.145	-0.735	-0.642	-3.51***	7.155	2.492 **	-0.401 ***	-2.453 ***
22.	P_3 X P_8	E_1	-2.177 *	-1.879 *	0.29	14.511	3.857	1.533	-0.149	-2.084	0.145	-0.265	24.897	2.035 ***	1.172 ***	-4.431 ***
		E_2	-1.641 *	-1.111	0.54	27.867 **	24.382 ***	2.274	0.262	-1.354	-0.787	0.202	23.102	-1.015	1.179 ***	-4.280 ***
		E_3	0.707	0.374	-0.141	1.531	-1.967	-1.088	-0.014	-1.043	-0.836	6.22***	8.971	-1.48	1.109 ***	-5.727 ***
23.	P_3 X P_9	E_1	-2.705 **	-2.740 **	-0.071	14.294	5.829	3.817	0.295	-0.885	-0.272	-0.168	27.92	-2.104 ***	-0.244 **	-3.552 ***
		E_2	0.747	0.806	0.04	17.356 *	2.549	2.691	0.335	-0.543	-0.535	-1.17	-14.507	-2.043 **	-0.199 ***	-3.547 ***
		E_3	1.402	1.29	0.636 *	-24.285 ***	-6.216	-0.588	0.175	-0.301	-0.499	-0.555	-6.18	-1.952 *	-0.143 ***	-2.628 ***
24.	P_3 X P_{10}	E_1	-1.899 *	-1.934 *	-0.043	0.901	4.147	6.212 **	-0.219	1.134	0.703	0.94	-1.968	-3.576 ***	0.174 *	0.682
		E_2	0.164	0.5	0.346	-7.877	-6.412	-1.698	0.067	1.43	0.154	-0.596	-7.108	-2.265 **	0.163 ***	1.123 ***
		E_3	1.652 *	1.235	-0.225	-5.935	8.073	0.773	0.099	0.303	0.04	-1.317	-0.038	0.492	0.145 ***	1.516 ***
25.	P_4X P_5	E_1	-0.427	-0.545	-0.098	17.508 *	-2.097	4.275 *	0.163	-3.337	0.948	1.891 *	28.263	-1.576 **	1.323 ***	-3.897 ***
		E_2	-1.725 *	-1.583 *	0.152	19.945 *	6.865	2.449	0.201	-2.42	0.112	0.761	-6.078	-1.376 *	1.251 ***	-4.401 ***
		E_3	0.485	0.54	-0.03	-20.085 ***	-8.845 *	-5.199 **	0.158	-3.192	-0.003	1.042	-1.182	0.798	1.251 ***	-4.328 ***
26.	P_4 X P_6	E_1	0.545	0.843	0.568 *	-5.866	-3.992	3.261	0.126	0.541	0.023	-0.797	2.744	-1.215 *	-0.271 ***	5.775 ***
		E_2	-0.586	-0.694	-0.098	3.417	7.263	3.088	0.276	-0.195	0.548	-0.433	-15.339	-1.654 *	-0.206 ***	7.042 ***
		E_3	-0.682	-0.904	-0.114	-12.585 *	-6.836	-0.199	0.229	-0.498	0.226	2.335 **	-9.409	-1.146	-0.189 ***	6.653 ***
27.	P_4 X P_7	E_1	1.073	1.093	-0.043	-1.704	5.003	2.417	0.313	1.292	1.337 *	2.255 *	13.319	0.202	-0.107	1.271 *
		E_2	0.247	0.667	0.402	12.789	1.476	-2.356	0.338	2.794	-0.273	2.65***	-0.462	-0.015	-0.037	1.298 ***
		E_3	0.402	1.402	0.831 **	-17.880 **	-8.983 *	-4.561 *	0.274	3.001	-0.071	2.258 **	-8.548	1.465	-0.107 ***	1.796 ***
28.	P_4 X P_8	E_1	0.045	-0.018	-0.071	6.952	1.511	1.04	0.294	3.075	0.126	2.519 **	44.898 *	-0.159	-0.618 ***	-3.855 ***
		E_2	0.025	-0.306	-0.321	8.523	2.666	4.116	0.085	2.893	0.068	1.198	6.478	1.568 *	-0.546 ***	-2.497 ***
		E_3	0.013	-0.21	-0.308	-10.619 *	-5.654	-1.338	0.112	2.842	-0.289	1.458	7.685	2.826 ***	-0.528 ***	-3.265 ***
29.	P_4 X P_9	E_1	-0.482	-0.545	-0.098	14.656	6.35	-3.379	0.325	6.056	-1.258	-0.447	39.481	1.702 **	0.929 ***	5.938 ***
		E_2	0.081	-0.056	-0.154	19.345 *	6.167	3.199	0.401	6.138 *	-0.713	-1.608 *	6.435	2.207 **	0.910 ***	4.069 ***
		E_3	1.707 *	1.04	-0.197	-5.102	1.096	0.162	0.388	5.678 *	-0.766	1.215	-12.039	2.020 *	0.927 ***	4.651 ***
30.	P_4 X P_{10}	E_1	0.99	0.927	-0.071	-16.851 *	-8.618	-9.253 ***	-0.442	2.806	-1.316 *	-1.587	14.893	0.563	-0.249 **	1.362 **
		E_2	0.164	-0.028	-0.182	-9.555	13.873 *	-3.189	-0.214	3.608	0.209	1.233	12.667	2.318 **	-0.359 ***	0.813 ***
		E_3	2.290 **	2.318 *	-0.058	-21.752 ***	-15.615***	-2.477	-0.255	3.185	0.067	0.886	7.403	1.798 *	-0.355 ***	0.678 **
31.	P_5 X P_6	E_1	0.073	-0.045	-0.126	1.445	9.399	-2.811	-0.004	3.279	-0.347	-0.641	40.698	2.785 ***	-0.353 ***	1.825 ***
		E_2	-1.28	-1.389 *	-0.098	13.595	4.986	2.505	-0.092	3.54	-0.557	-1.852 *	20.264	1.263	-0.381 ***	1.499 ***
		E_3	2.596 **	2.374 *	-0.114	-19.963 ***	-16.585 ***	-5.116 **	0.204	3.822	-0.236	1.605	-7.755	1.965 *	-0.415 ***	1.941 ***
32.	P_5 X P_7	E_1	0.268	0.205	-0.071	8.173	-2.628	-3.985	0.283	-0.886	-0.033	-0.976	46.633 *	0.535	0.667 ***	-0.688
		E_2	0.553	0.306	-0.265	3.634	9.199	-0.273	0.168	-0.044	0.048	-0.26	22.808	1.568 *	0.698 ***	-0.235
		E_3	-0.321	-0.321	-0.169	-16.591 **	-12.400 **	3.523 *	0.15	0.318	-0.49	-1.106	6.149	-0.091	0.733 ***	-0.275
33.	P_5 X P_8	E_1	-1.427	-1.24	0.235	6.329	4.236	0.938	0.031	-3.543	0.189	2.132 *	18.292	1.174 *	-0.997 ***	-5.318 ***

		E_2	-1.669 *	-2.000 **	-0.321	11.034	14.056 *	-2.134	0.184	-3.505	-0.27	0.312	11.848	1.485 *	-0.838 ***	-4.770 ***
		E_3	0.957	1.402	0.359	-6.33	-17.737 ***	4.078 *	0.187	-3.11	-0.251	-2.27**	3.882	2.270 **	-0.831 ***	-5.630 ***
34.	P_5 X P_9	E_1	-1.288	-1.768	-0.46	11.232	9.408	1.889	0.291	-5.585	-0.127	-0.085	28.271	-2.631 ***	0.547 ***	5.754 ***
		E_2	0.386	0.583	0.179	16.856 *	7.89	2.283	0.124	-8.410 **	0.582	0.706	11.205	-0.876	0.435 ***	5.166 ***
		E_3	1.318	0.985	0.136	4.52	-4.32	0.912	0.107	-6.685 *	0.379	-1.682 *	13.258 *	1.131	0.440 ***	5.643 ***
35.	P_5 X P_{10}	E_1	-0.482	-0.629	-0.098	4.143	-1.427	2.881	-0.206	3.788	-0.686	14.923	1.230 *	-0.024	4.472 ***	-0.553
		E_2	0.803	0.611	-0.182	-11.377	-7.071	4.894	-0.191	2.059	0.138	-2.48**	-24.93	0.568	0.780 ***	4.766 ***
		E_3	1.568	1.596	-0.058	8.537	3.303	3.606 *	-0.24	0.516	0.335	-0.111	-9.567	2.576 **	0.779 ***	4.873 ***
36.	P_6 X P_7	E_1	-1.427	-1.073	0.263	3.05	5.39	2.867	0.523	4.738	-0.624	-0.397	-8.589	-3.770 ***	0.223 **	-0.513
		E_2	-0.641	-0.806	-0.182	-11.894	1.264	-1.967	0.292	4.541	-0.116	-1.088	11.347	-2.043 **	0.215 ***	-0.062
		E_3	0.846	-0.432	-0.253	-0.091	-6.057	-4.144 *	0.263	0.989	0.392	1.854 *	-8.164	-1.035	0.177 ***	-0.122
37.	P_6 X P_8	E_1	2.212 *	2.149 *	-0.098	-1.411	3.931	1.464	0.384	-2.689	0.998	1.017	-16	-7.465 ***	0.249 **	-6.326 ***
		E_2	0.47	0.222	-0.237	-25.827 **	-18.546 **	-2.828	0.092	-2.047	-0.334	-4.31***	-15.48	-5.793 ***	0.206 ***	-5.907 ***
		E_3	1.457	1.29	-0.058	-8.163	-2.061	8.412 ***	-0.222	-2.513	-0.316	-4.61***	-9.135	-3.674 ***	0.193 ***	-6.356 ***
38.	P_6 X P_9	E_1	0.684	0.288	-0.46	-0.031	3.337	0.961	0.008	5.613	0.814	2.694 **	-5.81	4.396 ***	0.313 ***	-2.564 ***
		E_2	0.859	0.806	-0.071	-13.005	-2.379	-4.078	0.228	5.921 *	0.785	1.945 *	6.344	2.513 ***	0.139 ***	-3.967 ***
		E_3	0.818	0.54	0.386	-7.98	-1.644	0.912	0.207	4.909	0.134	-0.023	-5.012	3.520 ***	0.168 ***	-3.217 ***
39.	P_6 X P_{10}	E_1	-1.51	-1.24	0.235	3.153	4.205	-3.307	0.117	5.339	-0.044	-1.039	1.062	1.924 ***	0.354 ***	4.324 ***
		E_2	-0.725	-0.5	0.235	0.095	-5.006	0.533	-0.08	4.421	0.74	3.32***	-1.447	2.624 ***	0.370 ***	3.753 ***
		E_3	2.068 *	2.152 *	0.192	0.37	-2.354	1.939	-0.129	4.863	0.081	2.316 **	-5.904	2.631 **	0.413 ***	3.860 ***
40.	P_7 X P_8	E_1	-0.927	-0.934	-0.043	8.251	7.226	1.223	-0.223	-0.671	-0.488	0.325	-4.825	4.619 ***	0.273 ***	9.194 ***
		E_2	-1.697 *	-1.083	0.596 *	-26.455 **	-8.333	-1.939	0.014	-0.911	0.838	2.176 **	-23.237	0.846	0.328 ***	9.242 ***
		E_3	-1.793 *	-0.737	0.886 **	1.876	2.124	1.717	0.066	-1.41	-0.353	2.410 **	-5.28	1.27	0.308 ***	8.481 ***
41.	P_7 X P_9	E_1	0.212	-0.129	-0.404	-3.593	0.399	0.344	0.121	-4.449	-0.772	2.559 **	10.044	-1.187 *	-0.543 ***	-2.874 ***
		E_2	-0.641	-0.833	-0.237	0.034	3.835	2.811	0.294	-4.813	-0.743	1.237	15.521	-1.515 *	-0.672 ***	-3.265 ***
		E_3	1.568	0.846	-0.336	10.726 *	-3.792	1.884	0.306	-5.135	-0.373	0.967	7.325	-0.202	-0.654 ***	-3.163 ***
42.	P_7 X P_{10}	E_1	-2.316 *	-1.990 *	0.29	1.081	-1.526	0.126	-0.186	-0.306	-0.263	1.043	-4.231	3.341 ***	0.281 ***	3.017 ***
		E_2	-0.225	-0.139	0.068	-1.199	-0.126	3.088	0.012	-1.34	-0.655	0.245	-9.947	1.929 **	0.285 ***	2.915 ***
		E_3	1.152	1.457	0.136	7.409	4.164	4.578 **	-0.004	-0.644	-0.083	1.438	-1.796	1.576	0.321 ***	2.750 ***
43.	P_8 X P_9	E_1	0.184	-0.24	-0.432	12.72	-0.473	4.861 *	0.129	0.857	-0.616	2.000 *	-40.023	1.452 **	0.272 ***	5.540 ***
		E_2	0.136	-0.139	-0.293	19.434 *	11.025	3.949	0.194	0.1	-0.362	-0.524	11.394	-0.265	0.285 ***	5.417 ***
		E_3	1.513	1.235	0.192	-14.346 **	-9.129 *	1.773	0.19	-0.083	-0.487	0.3	2.828	0.826	0.248 ***	5.686 ***
44.	P_8 X P_{10}	E_1	-0.677	-0.768	-0.071	-0.143	0.335	-1.664	-0.268	2.853	0.826	2.481 **	-4.575	-0.687	0.387 ***	4.684 ***
		E_2	-1.114	-1.111	0.013	5.201	-13.936 *	5.227 *	0.052	2.003	-0.873	-0.716	-9.907	0.179	0.096 **	-0.746 ***
		E_3	1.096	0.846	-0.336	5.337	-0.507	-1.199	0.08	1.804	-0.464	-1.295	-3.98	1.604 *	0.320 ***	4.713 ***
45	P_9 X P_{10}	E_1	-0.205	-0.295	-0.098	6.274	2.887	1.24	-0.061	-4.955	0.242	2.734 **	-15.172	-4.159 ***	-0.266 ***	-4.000 ***
		E_2	2.609 ***	2.806 ***	0.179	-10.311	-5.435	0.311	-0.458	-2.216	-0.754	-0.955	-6.916	-3.515 ***	0.146 ***	4.600 ***
		E_3	2.457 **	1.763	-0.225	10.854 *	-4.756	1.967	-0.473 *	-2.604	-1.017 *	2.195 *	-7.271	-2.202 **	-0.038 *	-1.308 ***
	Sij <> 0 at 95%	E_1	1.849	1.853	0.462	14.763	11.322	4.217	0.552	6.551	1.308	1.771	41.044	1.033	0.146	0.969
	Sij--Sik at 95%		2.718	2.724	0.678	21.701	16.642	6.199	0.811	9.63	1.923	2.604	60.332	1.518	0.215	1.425
	Sij--Skl at 95%		2.591	2.597	0.647	20.691	15.868	5.91	0.774	9.182	1.834	2.483	57.525	1.447	0.205	1.359
	Sij <> 0 at 95%	E_2	1.483	1.322	0.557	16.562	12.738	4.998	0.477	5.363	1.071	1.476	26.221	1.374	0.067	0.324
	Sij--Sik at 95%		2.179	1.944	0.818	24.345	18.724	7.346	0.701	7.883	1.574	2.169	38.543	2.019	0.099	0.476
	Sij--Skl at 95%		2.078	1.853	0.78	23.212	17.852	7.004	0.668	7.516	1.501	2.068	36.749	1.925	0.094	0.454
	Sij <> 0 at 95%	E_3	1.598	2.094	0.524	10.529	8.516	3.426	0.448	5.322	0.884	1.671	12.98	1.597	0.036	0.5
	Sij--Sik at 95%		2.349	3.077	0.77	15.477	12.518	5.035	0.658	7.824	1.299	2.456	19.08	2.347	0.052	0.735
	Sij--Skl at 95%		2.24	2.934	0.734	14.757	11.936	4.801	0.628	7.46	1.239	2.342	18.192	2.238	0.05	0.7

Table 7. Best and worst cross combinations for grin yield under HS condition.

High yielding hybrids				Low-yielding hybrids			
Hybrid	Grain yield (q/ha)			Hybrid	Grain yield (q/ha)		
Env	E_1	E_2	E_3		E_1	E_2	E_3
P_3 x P_6	153.57	101.13	83.67	P_8 x P_9	74.81	107.03	91.25
P_4 x P_9	165.73	109.87	84.33	P_1 x P_5	75.17	113.57	83.30
P_5 x P_6	184.77	126.30	79.27	P_2 x P_5	96.70	92.17	75.41
P_5 x P_7	184.23	127.73	95.02	P_3 x P_4	99.93	95.23	88.50
P_5 x P_{10}	161.05	109.23	101.83	P_8 x P_{10}	106.27	85.47	84.33

Under the HS conditions, the best cross combinations for the seed index were P_3 x P_8 (6.22***), P_3 x P_6 (4.03**), P_1 x P_4 (3.41***). Single cross hybrids P_4 x P_9 (6.05), (6.13*), (5.67); P_6 x P_9 (5.61), (5.92*), (4.90); P_6 x P_8 (4.73), (4.51), (0.98) combined well for chlorophyll content in all E_1, E_2 and E_3 environments. On the other hand hybrids P_2 x P_6 (-4.13), P_3 x P_7 (-3.51), P_6 x P_8 (-4.61) were the worst three combinations for seed index among them third environment effects more than other two whereas P_5 x P_9 (-5.58), (-8.41), (-6.68); P_1 x P_6 (-5.91), (-7.35), (-6.93), P_4 x P_5 (-3.33), (-2.42), (-3.19), were the worst three combiners for chlorophyll content.

Heterosis

The range of standard / economic heterosis expressed by the F_1 hybrids over the National check (HQPM-5) for different quantitative traits along with number of hybrids in desirable direction. For maturity traits (days to 50 % tasselling, days to 50 % silking and ASI) hybrid P_1 x P_6, P_1 x P_7, P_2 x P_3, P_3 x P_4, P_3 x P_7, P_4 x P_6, P_4 x P_8 recorded significant heterosis in desirable negative direction in E_1 and E_2 which was found to be earliest over all the three environments over check HQPM-5, however, P_4 x P_8 was significant heterosis in negative direction and early. Similarly, for plant growth parameters (plant height and ear height, tassel length) among them P_1 x P_6, P_1 x P_7, P_2 X P_4 showed heterosis in positive direction and P_1 x P_8 and P_1 x P_{10} showed significant heterosis in positive direction over the best check HQPM-5 in E_1 and E_2 environments however, E_3 environment showed negative significant it indicates low plant in that environment as compare to the E_1 and E_2 environments over the best check HQPM-5 and out of them the hybrids P_1 X P_8 (225.00 cm) in E_1, P_1 x P_{10} (186.76 cm) in E_2 and P_1 x P_7 (145.10 cm) in E_3. Hence, P_1 as a female parent is best suitable for plant height moreover, for ear height hybrid P_1 x P_{10} has more cob height in both the E_1 and E_2 environments (97.32 cm and 120.67 cm) over the best check HQPM-5 (73.60). Nevertheless, E_3 has very low cob height 64.67 cm P_1 x P_6 these were identified as the best genotypes in all three environments. Whereas, the range of heterosis was low for canopy temperature. For leaf area index deficit trait there were reasonably good number of hybrids which recorded significant heterosis over all the three environments. While for chlorophyll content there were least number of hybrids which recorded significant heterosis over check. Similarly, over check, HQPM-5 a total of 12 hybrids recorded significant standard heterosis in desirable positive direction in leaf area index. These results were in line with the findings of Mohammed and Yousif (2020) and karim *et al.,* (2018). The highest grain yield was recorded in the hybrid P_5 x P_7 (188.41 q/ha) and this hybrid differed significantly over the best check for seed index, cob length, plant height and starch content. For majority of the top five hybrids the higher grain yield was manifested through seed index. Similarly, P_3 x P_8 had higher test weight and P_1 x P_8 higher cob height as compared to the best check for the respective traits. For seed yield and all of the top five hybrids were statistically on par with the best check. E_1 and E_2 shows the best standard heterosis in all the parameters as compared to E_3 environment.

Discussion

The progress of most crop improvement programs vigorously relies on the limit of the hereditary material to convey desired traits unto its progeny. Combining ability studies involve determining the average breeding value gca of germplasm used as well as the genetic value due to the interaction between these specific genes in a cross combination (SCA). Variances due to SCA and GCA were estimated for assessing the gene action influencing inheritance of different characteristics studied under HS conditions. Hence results shown significant differences traits studied under HS conditions. Results showed significant differences for GCA and SCA effects thus implying the presence of adequate additive variation and dominance variance, respectively. General combining ability defined as the average performance of the genotype in a series of hybrid combinations and is a measure of additive gene effect. While specific combining ability refers to the performance of the genotype in a specific cross in relation to the formal and is a measure of non-additive gene effect (Sharief *et al.,* 2009). Combining ability in maize grain yield has been studied exclusively and the findings have been extensively used in maize breeding programs (Shimelis *et al.,* 2019). Under HS, GCA effects were more important in determining most traits non- additive variances were higher than additive variances similar observations were reported by (Richard, O. A. *et al.,* 2021). Preponderance of additive effects is observed when the GCA:SCA ratio is greater than one while preponderance of dominance effects is observed when the ratio is less than one.

Dominance or epistatic genetic effects mostly influenced maize grain yield under HS. The results obtained in this investigation are partially in accordance with Hallauer and Miranda (1988), who emphasised that dominance effects for the traits showing strong expression of heterosis phenomenon are often more important than additive ones. From the breeders' point of view, having dominance as the major type of gene action for the most important traits suggests that selection for these traits would be quite difficult and a long-term process. Pfunde 2016 observed that inheritance of grain yield among white QPM inbred lines was mostly influenced by non-additive gene action under HS. Since SCA effects were predominant in determining yield under HS conditions, the breeding strategy to improve this trait under these stresses must consist of inbreeding followed by cross-breeding to generate superior hybrids Awata, L.A *et al.,* 2018. Genetic effects governing maize grain yield and other yield attributing traits under heat stress condition is still sparse as far as we could possibly know. Principally, outcome from this research showed gene action governing grain yield and other traits were shown non additive in variance since the ratio among gca and sca is less than 1 for almost all the characters. This prioritize the need for heat-stress breeding for the improvement of maize yields under sub-tropical regions.

According to the GCA values obtained in this study, inbred lines P_4 and P_5 were observed as good general combiners for grain yield, under HS and for oil content P_2, P_4, P_5, P_7 and P_9 were the best combiners, whereas, P_1, P_3, P_6, P_8, P_9 and P_{10} were the good combiners for starch content since they exhibited high GCA values. Two of these inbred lines P_3 and P_{10} were heat-susceptible rest all parental lines (Table 1) are heat tolerant for HS conditions. This may suggest that heat tolerance at the early stages was not synonymous with tolerance to HS during vegetative and grain formation stages in this study. This could be further supported by the fact that the lowest yielding F_1 ($P_{1\ X}$ P_9) was derived from a cross between two inbred lines that were classified to be heat tolerant at the early and later stages too. Most of these inbred lines were able to transfer their high yielding potential to their F_1s. The highest yielding F_1 (P_5 X P_6: 2.56 t/ha) came from two lines that were generally good combiners for yield under HS condition. However, in some cases, high starch was observed in cross combinations involving (P4 X P5: 5.80 %) under heat stressed conditions. Similar observations were reported by Nyasha and Charles 2020 and Tulu *et al.,* 2018. Such observations demonstrate the importance of non-additive gene effects in influencing yield potential.

Conclusions

Based on the results, grain yield was significantly influenced by non-additive gene action under heat-stress condition. The breeding strategy to improve yield under heat-stress condition must consist of inbreeding followed by cross-breeding to generate superior hybrids. Single cross hybrids $P_5 \times P_7$, $P_5 \times P_6$, $P_4 \times P_8$ and $P_4 \times P_5$ exhibited high SCA effects for grain yield under the stressed environment. These hybrids were therefore the highest yielders under heat stress condition. As such, these hybrids can be recommended for further evaluation, such as in intermediate variety trials. They can also be used as parents when generating three-way and four-way hybrids in breeding programs. On the other hand, inbred lines (NBPGR-36548) P_4 and (VL-153237) P_5 exhibited high GCA effects for grain yield under HS condition. It was found that significant SCA estimates involving at least one of parent with high GCA is desirable in the resent study. Further, these experimental hybrids depicted positive significant economic heterosis (Hc), and positive significant *sca* effects for grain yield and quality traitsand thus can be very useful source materials in hybridization programs.

References

Abuali, A. I., Abdelmulla, A. A., Khalafalla, M. M., Idris, A. E. and Osman, A. M. (2012). Combining Ability and Heterosis for Yield and Yield Components in Maize (*Zea mays* L.). *Australian Journal of Basic and Applied Sciences,* **6** (10): 36-41.

Anusheela, V., John, J. and Muthiah, A. (2013). Heterosis in Quality Protein Maize. *International Journal of Scientific Research,* **2**(11):15-16.

Awata, L. A. O., Ifie, B., Tongoona, P., Danquah, E., Marchelo, P. W. (2018). Common Mating Designs in Agricultural Research and Their Reliability in Estimation of Genetic Parameters. *Journal of agriculture and veterinary sciences,* **11**(1):16-36.

Abdel, M., Sultan, M. S., Salama, S. M. G. and Oraby, A. M. (2014). Evaluation of Combining Ability and Heterosis for Yield and its Components Traits of Five Maize Inbreds under Normal and Stress Nitrogen Fertilization. *Asian Journal of Crop Science,* **6**(2):142-149.

Aggarwal, P. K. (2008). Global climate change and Indian agriculture: impacts, adaptation and mitigation. *Indian Journal of Agricultural Sciences*, **78** (10): 911-919.

Amiruzzaman, M., Islam, M. A., Hasan, L., Kadir, M. and Rohman, M. M. (2013). Heterosis and combining ability in a diallel among elite inbred lines of maize (*Zea mays* L.) *Emirates Journal of Food and Agriculture,* **25**(2): 132-13.

Apraku, B. B., Annor, B., Oyekunle, M., Akinwale, R. O., Fakorede, M. A. B., Talabi, O., Akaogu, I. C., Fasanmade, Y. and Melaku, G. (2015). Grouping of early maturing quality protein maize inbreds based on SNP markers and combining ability under multiple environments, *Field crop research,* **183** (15):169-175.

Bhusal, T. N. and Lal, G. M. (2020). Heterosis, Combining Ability and Their Inter-Relationship for Morphological and Quality Traits in Yellow Maize (*Zea mays* L.) Single-Crosses Across Environments. *AGRIVITA Journal of Agricultural Science*. **42**(1): 174–190.

Bello, O. B., Ganiyu, O. T., Wahab, M. K. A., Azeez, M. A., Abdulmaliq, S. Y., Ige, S. A., Mahmood, J., Oluleye, F., Afolabi, M. S. (2012). Yield and disease reactions of quality protein maize varieties in the Southern Guinea Savanna agro-ecology of Nigeria. *International Journal of Agriculture Forestry,* **2**(1): 203–209.

Bisen, P., Dadheech, A., Namrata, N. O., Meena, R. K. (2017). Exploitation of heterosis in single hybrids of quality protein maize (*Zea mays* L.) for yield and quality traits. *International Journal of Bio-Resources Stress Management,* **8**(1): 12–19.

Beruk, H., Hussein, M. and Azmach. G. (2021). Standard heterosis in quality protein maize hybrids. *Journal of innovative agriculture,* **8**(3): 25-29.

Basser, P., Marker, S. and Patil, K. S. (2021). Combining ability analysis of early maturing Quality Protein Maize (*Zea mays* L) lines and heterosis of their F_1 hybrids. *International Journal of Current Microbiology and Applied Sciences,* **10**(02): 2065-2075.

Gideon, S., Marker, S. and Ramteke, P. W. (2017). Gene Action and Combining ability analysis for Grain yield and Quality parameters in Sub-tropical Maize (*Zea mays* L.). *Vegetos an International Journal of Plant Research*, **30**(Special): 2229-4473.

Griffing, B. (1956). Concept of general and specific combining ability in relation to diallel crossing system. *Australian Journal of Biological Science*, **9**(1): 463-493.

Hallauer, A. R., Miranda, J. B. (1988). *Quantitative Genetics in Maize Breeding*, 2nd ed, Iowa State University Press. Ames, IA, USA; pp. 86–89.

Karim, A. M. M. S., Shahin, A., Akhi, A. H., Talukder, M. Z. A. (2018). Combining ability and heterosis study in maize inbreds throughout diallel mating design. *Bangladesh Journal of Agricultural Research*, **43**(4): 599.

Liliane, N. T., Charles, S. M., Eddy, L. M., Ngonkeu, N. W. and Vernon, G. (2017). Breeding for Quality Protein Maize (QPM) Varieties: A Review. *Agronomy***,** **7**(4): 80.

Maqbool, M. A., Beshir, A. R. and Khokha, E. S.(2021). Quality protein maize (QPM): Importance, genetics, timeline of different events, breeding strategies and varietal adoption. *Plant Breeding*, **140**(3): 375-339.

Nyasha, E. C. and Charles, S. M. (2020). Combining Ability of Quality Protein Maize Inbred Lines for Yield and Morpho-Agronomic Traits under Optimum as Well as Combined Drought and Heat-Stressed Conditions. *Agronomy*, **10**(2): 184-196.

Prasanna, B. M., Vasal, S. K., Kassahun, B., Singh, N. N. (2001). Quality protein maize. *Current Science*, **81**(1): 1308–1319.

Pixley, K. V. (2003). The Development and Promotion of Quality Protein Maize in Sub-Saharan Africa, Progress Report, CIMMYT: Harare, Zimbabwe, 65p.

Rajesh, V., Kumar, S. S., Reddy, V. N. and Sankar, A. S. (2018). Combining Ability and Genetic Action Studies for Yield and Its Related Traits in Maize (*Zea mays* L.). *International Journal of Current Microbiology and Applied Science*, **18**(7): 2645–2652.

Rajasekhar, D., Naveen, K. L., Pramod, K. P and Devyani, S. (2022). Analysis of Morphological Variation, Grouping and Path Coefficient Studies in a Set of Maize Inbred Lines Local to North East Hill Region of India. *International Journal of Plant & Soil Science,* **34**(17): 105-113.

Srinivasa, Y. R., Krishnan, V., Vengadessan, V., Paramasivam, K. and Narayanan, A. L. (2018). Heterosis analysis for grain yield traits in Maize (*Zea mays* L.). *Electronic Journal of Plant Breeding,* **9**(2) : 518-527.

Singh, D. and Jagadev, P. N. (2021). Combining Ability in Diallel Crosses of Quality Protein Maize Inbreds. *International Journal of Current Microbiology and Applied Science,* **10**(04): 894-899.

Tajwar, I. and Chakraborty, M. (2018). Combining ability and heterosis for grain yield and its components in maize inbreds over environments (*Zea mays* L.). *African journal of agriculture research,* **8**(25): 3276-3280.

Vasal, S. K., Srinivasan, G., Shivaji, P., Gonzalez, F. C., Crossa, J. and Beck, D. L. (1993). Heterosis and Combining Ability of CIMMYT's Quality Protein Maize Germplasm: I. Lowland Tropical. *Crop Breeding, Genetics & Cytology,* **33**(1): 46-55.

Yousuf, M. and Saleem, M. (2020). Estimates of Heritability for Some Quantitative Characters in Maize. *International Journal of Agriculture and Biology,* **04**(1):103-104.