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Mean Performance, Heterobeltiosis and Combining Ability of Corn (*Zea mays* L.) Agronomic and Yield Traits under Elevated Plant Density

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Authors' contributions

This work was carried out in collaboration between all authors. Author AMMAN designed the study, wrote the protocol and wrote the first draft of the manuscript. Authors MMMA and MAA managed the literature searches. Author ASMY managed the experimental process and performed data analysis. All authors read and approved the final manuscript.

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ABSTRACT

The objective of this study was to assess performance, heterosis and combining ability parameters and their interrelationships in six maize inbreds and their 15 diallel F_1 crosses under different plant densities (D). Three experiments were carried out in each season of 2013 and 2014, using RCBD with three replicates. The experiment consisted of three treatments, *i.e.* low-D, medium-D or high-D (47,600, 71,400 and 95,200 plants/ha, respectively). A greater portion of additive than non-additive variance across seasons was observed for leaf angle (LANG), ears/plant (EPP), Kernels/row (KPP) and rows/ear (RPE) under all environments. Similar results were observed for 100-kernel weight (100 KW) under low and high plant densities, and barren stalks (BS) and days to anthesis (DTA) under low plant density. The rest of traits exhibited greater preponderance of non-additive variance. For grain yield/plant (GYPP), the best inbred in general combining ability (GCA) effects was L53 followed by L20 and Sk5 and the best cross for specific combining ability (SCA) effects was Sk5 × L18 followed by L20 × L53 and L28 × Sd7 under the three environments. Out of 12 traits, the

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highest performing inbred lines were those that displayed the highest GCA and *vice versa* for nine traits and the highest performing crosses were the highest specific combiners and *vice versa* for all 12 traits under all plant densities. For anthesis silking interval (ASI), plant height (PH), ear height (EH) and BS under all environments, DTA and LANG (except low-D) and EPP under low-D, the mean performance of a cross could be used as an indicator of its useful heterosis. For LANG, EPP, RPE, kernels/row (KPR), KPP, 100 KW (except high-D), BS (except low-D) and ASI (except medium-D), the useful heterosis of a cross could be used as an indicator of its SCA effects under the corresponding environments.

Keywords: Heterosis; population density; GCA; SCA; rank correlations.

1. INTRODUCTION

Egypt produces about 5.8 million tons of maize grain per year cultivated in approximately 0.75 million hectares [1]. Maize in Egypt is used primarily for human food, animal feed and ranks second to wheat in land under cereal cultivation. Despite the increasing grain yield of maize in Egypt due to the use of single and three-way cross hybrids under high inputs and low plant density, there is a lack of information on utilization of high density tolerant maize hybrids to increase crop yield from unit area. One of the potential methods to maximize total production of maize in Egypt is through raising productivity per unit area. Grain yield per unit area is the product of grain yield per plant and number of plants per unit area [2,3]. Maximum yield per unit area may be obtained by growing maize hybrids that can withstand high plant density up to 100,000 plants ha^{-1} [2-4].

Modern maize hybrids in developed countries are characterized with high yielding ability from unit area under high plant densities, due to their morphological and phenological adaptability traits, such as early silking, short anthesis silking interval (ASI), less barren stalks and prolificacy [5-9]. Radenovic et al. [6] and Al-Naggar et al. [8,9] pointed out that maize genotypes with erect leaves are very desirable for increasing the population density due to better light interception. Although high plant density results in interplant competition (especially for light, water and nutrients), which affects vegetative and reproductive growth of maize [10,11], the use of high-density tolerant hybrids would overcome the negative impacts of such competition and lead to maximizing maize productivity from the same unit area.

Heterosis is the genetic expression of the superiority of a hybrid in relation to its parents [12]. This phenomenon manifests in increased size, or other parameters resulting from the increase in heterozygosity in the F_1 generation of crosses between inbred lines [13,14] and is associated with stress tolerance [15]. In general, based on parents used, two major types of estimation of heterosis are reported in literature: (1) Mid-parent or average heterosis, which is the increased vigor of the F_1 over the mean of two parents. (2) High-parent or better parent heterosis, which is the increased vigor of the F_1 over the better parent [15,16]. The term heterobeltiosis has been suggested to describe the increased performance of the hybrid over the better parent [17-19]. Duvick [13] and Betran et al. [20] reported extremely high expression of heterosis under severe abiotic stress because of the poor performance of inbred lines under these conditions.

Combining ability has been defined as the performance of a line in hybrid combinations [21]. Since the final evaluation of inbred lines can be best determined by hybrid performance, it plays an important role in selecting superior parents for hybrid combinations and in studying the nature of genetic variation [13,22]. Sprague and Tatum [23] introduced the concepts of general (GCA) and specific (SCA) combining ability. For random individuals, the authors reported that GCA is associated with additive effects of the genes, while SCA is related to dominance and epistatic effects (non-additive effects) of the genes. In general, diallel analysis has been used primarily to estimate general and specific combining ability effects from crosses of fixed lines [22,24]. Investigators reported more proportional and significant GCA effects for yield, days to silk and plant height in different groups of broad based CIMMYT maize populations and pools across locations [25-27]. On the other hand, Singh and Asnani [28] concluded that both GCA (additive) and SCA (non-additive) effects play an important role in the inheritance of yield and its components. Shewangizaw et al. [29] also reported significant GCA and SCA for most traits, but predominance of non-additive genetic

Table 1. Designation, origin and most important traits of 6 inbred lines (L) used for making diallel crosses of this study

Entry designation	Origin	Institution (country)	Prolificacy	Grain yield under high density	Leaf angle
L20-Y	SC 30N11	Pion. Int.Co.	Prolific	High	Erect
L53-W	SC 30K8	Pion. Int.Co.	Prolific	High	Erect
Sk 5-W	Teplacinco - 5	ARC-Egypt	Prolific	High	Erect
L18-Y	SC 30N11	Pion. Int.Co.	Prolific	Low	Wide
L28-Y	Pop 59	ARC-Thailand	Non-Prolific	Low	Wide
Sd 7-W	A.E.D.	ARC-Egypt	Non-Prolific	Low	Erect

ARC = Agricultural Research Center, Pion. Int. Co. = Pioneer International Company in Egypt, SC = Single cross, A.E.D. = American Early Dent; an old open-pollinated variety, W = White grains and Y = Yellow grains

variance in the case of yield. Dass et al. [30] reported that estimates of combining abilities across environments have indicated that both GCA and SCA for most characters interacted with environmental change, but GCA was found to be more sensitive to environmental change than SCA. Inbred line traits under high plant density stress were more strongly correlated with top-cross performance under severe density stress than line traits under low density conditions [31]. The objectives of this study were to assess the following for diverse inbred lines in high density tolerance and their crosses under elevated plant density: (i) mean performance, heterosis and combining ability effects of the studied agronomic and yield traits under elevated plant density and (iii) correlations among inbred and hybrid per se performance, general and specific combining ability and heterosis.

2. MATERIALS AND METHODS

This study was carried out at the Agricultural Experiment and Research Station of the Faculty of Agriculture, Cairo University, Giza, Egypt (30° 02'N latitude and 31° 13'E longitude with an altitude of 22.50 meters above sea level), in 2012, 2013 and 2014 seasons.

2.1 Plant Material

Six S_8 (8^{th} selfed generation) maize (*Zea mays* L.) inbred lines showing clear differences in performance and general combining ability for grain yield under high plant density, were chosen as parents for diallel crosses in this study. The selection was based on the results of previous experiments [31].

2.2 Producing F_1 Diallel Crosses

In 2012 season, all possible diallel crosses (except reciprocals) were made among the six parents, so seeds of 15 direct F_1 crosses were obtained. The seeds of the six parents were also increased by selfing in the same season (2012) to obtain enough seeds for comparative evaluation trials.

2.3 Evaluation of Parents and F_1`s

Three field experiments were carried out in each of 2013 and 2014 seasons at the Agricultural Experiment and Research Station of the Faculty of Agriculture, Cairo University, Giza. Each experiment included 21 genotypes (15 F_1 crosses and their 6 parents). The first experiment was done under low plant density (low-D); 47,600 plants/ha, the second experiment was done under medium plant density (medium-D); 71,400 plants/ha and the third experiment under high plant density (high-D); 95,200 plants/ha. A randomized complete blocks design with three replications was used in each experiment.

Each experimental plot consisted of one ridge of 4 m long and 0.7 m width, *i.e.* the experimental plot area was 2.8 m^2. Seeds were sown in hills at 15, 20 and 30 cm apart, thereafter (before the 1^{st} irrigation) were thinned to one plant/hill to achieve a plant density of 47,600, 71,400 and 95,200 plants/ha, for the first, second and third experiment, respectively. Sowing date of the three experiments was on May 5 and May 8 in 2013 and 2014 seasons, respectively. The soil of the experimental site was clayey loam. All other agricultural practices were followed according to the recommendations of ARC, Egypt. The analysis of the experimental soil, as an average of the two growing seasons 2013 and 2014, indicated that the soil is clay loam (4.00% coarse sand, 30.90% fine sand, 31.20% silt, and 33.90% clay), the pH (paste extract) is 7.73, the EC is 1.91 dSm-1, soil bulk density is 1.2 g cm-3, calcium carbonate is 3.47%, organic matter is 2.09%, the available nutrient in mg kg-1 are Nitrogen (34.20), Phosphorous (8.86), Potassium

(242), hot water extractable B (0.49), DTPA - extractable Zn (0.52), DTPA - extractable Mn (0.75) and DTPA - extractable Fe (3.17). Meteorological variables in the 2013 and 2014 growing seasons of maize were obtained from Agro-meteorological Station at Giza, Egypt. For May, June, July and August, mean temperature was 27.87, 29.49, 28.47 and 30.33°C, maximum temperature was 35.7, 35.97, 34.93 and 37.07°C and relative humidity was 47.0, 53.0, 60.33 and 60.67%, respectively, in 2013 season. In 2014 season, mean temperature was 26.1, 28.5, 29.1 and 29.9°C, maximum temperature was 38.8, 35.2, 35.6 and 36.4°C and relative humidity was 32.8, 35.2, 35.6 and 36.4%, respectively. Precipitation was nil in all months of maize growing season for both seasons.

2.4 Data Collection

1. Days to 50% anthesis (DTA)
2. Anthesis-silking interval (ASI)
3. Plant height (PH)
4. Ear height (EH)
5. Barren stalks (BS)
6. Leaf angle (LANG)
7. Ears per plant (EPP)
8. Rows per ear (RPE)
9. Kernels per row (KPR)
10. Kernels per plant (KPP)
11. 100-kernel weight (100-KW)
12. Grain yield/plant (GYPP)

2.5 Biometrical and Genetic Analyses

Analysis of variance of the RCBD was performed on the basis of individual plot observation using GENSTAT 10th addition windows software. Combined analysis of variance across the two seasons was also performed if the homogeneity test was non-significant. Least significant differences (LSD) values were calculated to separate the means according to Steel et al. [32]. Diallel crosses were analyzed to obtain general (GCA) and specific (SCA) combining ability variances and effects for studied traits according to Griffing [33] Model I (fixed effect) Method 2.

Heterobeltiosis was calculated as a percentage of F_1 relative to the better-parent (BP) values as follows: Heterobeltiosis (%) = $100[(\overline{F}_1-\overline{BP})/\overline{BP}]$ Where: $\overline{F}_1$= mean of an F_1 cross and $\overline{BP}$= mean of the better parent of this cross. The significance of heterobeltiosis was determined as the least significant differences (LSD) at 0.05 and 0.01 levels of probability according to Steel et al. [32] using the following formula: LSD $_{0.05}$ = $t_{0.05}(edf)\ x\ SE$, LSD $_{0.01}$ = $t_{0.01}(edf)\ x\ SE$, Where: *edf* = the error degrees of freedom, SE= the standard error, SE for heterobeltiosis $=(2MS_e/r)^{1/2}$ Where: $t_{0.05}$ and $t_{0.01}$ are the tabulated values of '*t*' for the error degrees of freedom at 0.05 and 0.01 levels of probability, respectively. MS_e: The mean squares of the experimental error from the analysis of variance Table. *r*: Number of replications.

Rank correlation coefficients were calculated between *per se* performance of inbred lines and their GCA effects; between *per se* performance of F_1 crosses and their SCA effects and between SCA effects and heterobeltiosis of F_1 crosses for studied traits under WW and WS conditions by using SPSS 17 computer software and the significance of the rank correlation coefficient was tested according to Steel et al. [32]. The correlation coefficient (r_s) was estimated for each pair of any two parameters as follows: $r_s = 1 - (6\sum d_i^2)/(n^3-n)$, Where, d_i is the difference between the ranks of the ith genotype for any two parameters, n is the number of pairs of data. The hypothesis Ho: $r_s = 0$ was tested by the r-test with (n-2) degrees of freedom.

3. RESULTS AND DISCUSSION

3.1 Analysis of Variance

Combined analysis of variance across two seasons for 12 traits of 21 maize genotypes for each of the three experiments (plant densities (D); *i.e.,* low-D, medium-D, high-D), is presented in Table 2. Mean squares due to parents and F_1 crosses under all environments (densities) were highly significant for all studied traits, except ASI under low-D and high-D, indicating the significance of differences among studied parents and among F_1 diallel crosses in the majority of cases. Genotypic variation under elevated plant density has been reported by several investigators [3,18,34-37].

Mean squares due to parents *vs.* F_1 crosses were highly significant for all studied traits under all environments, except for ASI under low-D, high-D, BS under low-D, EPP under high-D suggesting the presence of significant heterosis for most studied cases. Mean squares due to the interactions parents × years (P×Y) and crosses × years (F_1×Y) were significant or highly significant for 20 and 27 out of 36 cases, respectively. Mean squares due to parents *vs.* crosses × years were significant or highly significant in 15 out of 36 cases, indicating that heterosis differ from season to season in these cases. It is observed that among genotypes components under all environments (36 cases), the largest contributor to total variance was parents vs. F_1's (heterosis) variance for 21 cases, followed by F_1 crosses (12 cases) and parents (3 cases; Table 2).

3.2 Mean Performance

Mean grain yield/plant was significantly ($P \leq 0.01$) reduced due to elevating plant density from 47,600 to 71,400 and 95,200 plants/ha, by 25.77 and 39.54% for inbreds and 17.99 and 28.20% for F_1 crosses, respectively (Table 3). This reduction was associated with reductions in all yield components, namely EPP (6.40 and 13.14% for parents and 10.13 and 13.59% for crosses), KPP (16.88 and 30.64% for parents and 16.99 and 25.47% for crosses) and 100-KW (9.79 and 17.46% for parents and 5.82 and 11.72% for crosses) at plant density of 71,400 and 95,200 plants/ha, respectively as compared with 47,600 plants/ha, indicating that the reduction in number of kernels is the main cause of reduction in GYPP due to high density stress and the GYPP and yield component reduction due to high plant density stress is more pronounced in the inbred lines than F_1 crosses. This means that crosses are more tolerant to high plant density stress than inbred lines, which might be due to the hybrid vigor (heterosis) and that heterozygotes are more adapted to stress conditions than homozygotes.

Elevation of plant density from the low density to medium and high density also resulted in significant reductions of LANG (6.68 and 6.26% for parents and 1.69 and 2.08% for crosses, respectively). Moreover, higher plant density (71,400 and 95,200 plants/ha) caused a significant decrease in grain yield/plant (GYPP) compared with the low-density by 25.8 and 39.6% for inbreds and 18.0 and 28.2% for F_1 crosses, respectively. The decrease in GYPP due to increasing plant density for inbreds was 1.43 and 1.40 fold greater than the decrease for F_1 crosses under 71,400 and 95,200 plants/ha, respectively. This conclusion was also confirmed by Monneveux et al. [38] who reported that reduction in yield of lines was less than open-pollinated varieties and hybrids under high plant population density, probably because of lower vigor and lower competition between plants. An opposite conclusion was reported by Has et al. [39] and Al-Naggar et al. [3,18]. Differences in conclusions regarding the effects of high density may be attributed to the differences in the genetic background of the plant materials and/or climatic conditions prevailing through the growing seasons of different studies.

Moreover, high density (95,200 plants/ha) caused a significant increase in plant height (PH) by 4.85 and 4.38%, ear height (EP) by 21.98 and 8.73%, anthesis-silking interval (ASI) by 10.31 and 28.23%) and barren stalks (BS) by 18.40 and 28.5% for parents and crosses, respectively as compared with low plant density (47,600 plants/ha). Days to anthesis (DTA) showed a slight and significant decrease (2.86%) for inbreds and a slight and significant increase (2.01%) for hybrids, due to elevating plant density to 71,400 and 95,200 plants/ha.

In general, GYPP of three inbreds, *viz.* L53, L20 and Sk5 was higher than that of the three other inbreds (L18, L28 and Sd7) under all the three environments. The highest GYPP of all inbreds was achieved under low density because of the less competition between plants. The highest GYPP of the F_1 crosses was also obtained at low-D. The highest GYPP in this experiment (277.36 g) was obtained from the cross L20 × L53 under low-density environment followed by the crosses L53 × Sk5 (245.53 g) and L53 × Sd7 (240.96 g) under the same environmental conditions. These crosses could therefore be considered responsive to this good environment. The highest GYPP under the most severe stress in this experiment (high density) was obtained by the same crosses (161.05 g, 136.96 g and 132.46 g, respectively). These crosses were considered tolerant to high-density stress and responsive to the good environment. It is clear that L53, Sk5 and L20 might be considered as source of tolerance and responsiveness in these crosses.

3.3 Heterobeltiosis

Estimates of better parent heterosis (heterobeltiosis) across all F_1 crosses, maximum values and number of crosses showing significant favorable heterobeltiosis for all studied traits under the three environments (3 plant densities) across 2011 and 2012 years are presented in Table 4. Favorable heterobeltiosis in the studied crosses was considered negative for DTA, ASI, PH, EH, LANG and BS and positive for the remaining studied traits under all plant densities. In general, the highest average significant and positive (favorable) heterobeltiosis was shown by grain yield/plant 151.79, 176.63

and 191.31% under low, medium and high density, respectively. The traits PH, EH, BS, LANG, EPP and RPE under all environments showed on average unfavorable heterobeltiosis. However, some crosses showed significant favorable heterobeltiosis in these cases.

The reason for getting the highest average heterobeltiosis estimates under high density environment could be attributed to the large reduction in grain yield/plant and its components of the parental inbreds compared to that of F_1 crosses due to severe stress of high plant density existed in this environment (Table 4). These results are in agreement with those of Weidong and Tollenaar [40], who reported that increasing plant density from 4 to 12 plants m^{-2} resulted in increased heterosis for grain yield of maize. In general, maize hybrids typically yield two to three times as much as their parental inbred lines. However, since a cross of two extremely low yielding lines can give a hybrid with high heterosis, a superior hybrid is not necessarily associated with high heterosis [13]. This author suggested that a cross of two high yielding inbreds might exhibit less heterosis but nevertheless produce a high yielding hybrid. Besides, a hybrid is superior not only due to heterosis but also due to other heritable factors that are not influenced by heterosis.

On the contrary, the non-stressed environment (low-D) showed the lowest average favorable heterobeltiosis for all yield traits. The largest significant favorable heterobeltiosis for GYPP in this study (455.28%) was shown by the cross (L18 × Sd7) under medium density environment (Table 5). This cross showed also the highest significant and favorable heterobeltiosis for the yield components KPR (53.09%), 100 KW (39.66%) and KPP (54.79%). Under the most stressed environment (high-D), the cross (L28 x Sd7), followed by (L18 × Sd7) and (L18 x L28) showed the highest heterobeltiosis (404.32, 352.04 and 303.74%, respectively) and could therefore be recommended as good genetic material under high plant density conditions for maize breeding programs.

Table 2. Combined analysis of variance across two years for studied traits of 6 parents (P) and 15 F_1 crosses (F) and their interactions with years (Y) three plant density

SOV	df	%Sum of squares								
		Low-D	Med-D	High-D	Low-D	Med-D	High-D	Low-D	Med-D	High-D
			DTA			ASI			PH	
P	5	7.84**	8.17**	14.57**	2.5	8.85*	2.44	13.22**	6.42**	20.39**
F_1	14	3.95*	4.87*	7.17**	14.83	29.08**	9.51	21.97**	9.90**	15.79**
P vs F_1	1	29.35**	28.77**	19.95**	2.42	2.53*	2.21	58.93**	71.74**	58.03**
P × Y	5	7.58**	2.74*	2.79*	1.61	5.64*	7.97	0.26	0.47*	0.09
F_1 × Y	14	1.97	3.78	4.95**	15.00*	14.67**	13.19	0.41*	0.29	0.44
P vs F_1 × Y	1	0.27	0.22	0.09	2.18	0.01	0.11	0.07	0.23*	0.03
			EH			BS			LANG	
P	5	15.48**	15.94**	33.49**	9.11*	20.55**	14.02**	19.35**	24.74**	19.89**
F_1	14	25.23**	17.57**	18.15**	17.60**	19.02**	14.84**	50.17**	42.71**	33.36**
P vs F_1	1	50.17**	54.43**	34.31**	0.04	9.71**	9.65**	6.12**	3.52**	4.37**
P × Y	5	0.46	0.58	2.55**	9.11*	1.35	6.82*	2.65**	3.93**	3.50**
F_1 × Y	14	1.77**	1.19**	3.69**	19.56**	9.84**	6.64	10.12**	4.89*	13.16**
P vs F_1 × Y	1	0.02	0.43**	0.04	0.33	0.86	2.51*	0.40*	0.19	0.99*
			EPP			RPE			KPR	
P	5	17.23**	18.95**	17.93**	28.95**	29.18**	24.81**	5.85**	12.20**	13.61**
F_1	14	27.41**	26.08**	20.44**	28.54**	27.01**	27.93**	10.66**	13.80**	12.49**
P vs F_1	1	3.82**	5.97**	0.66	7.44**	4.13**	4.15**	65.45**	58.66**	57.73**
P × Y	5	2.07	3.36	5.57*	3.73**	0.16	1.2	1.64*	1.24**	0.85
F_1 × Y	14	7.97*	3.86*	4.04	4.68*	3.98	6.26*	1.84**	2.29**	1.16*
P vs F_1 × Y	1	2.81*	0.83*	10.38**	0.09	0.34	0.01	0.90**	0.15	0.01
			KPP			100-KW			GYPP	
P	5	9.69**	8.35**	7.07**	11.75**	22.80**	18.87**	5.50**	6.07**	3.53**
F_1	14	6.63**	18.17**	13.53**	16.33**	12.05**	9.73**	9.66**	12.07**	10.52**
P vs F_1	1	59.24**	46.18**	52.05**	45.48**	46.16**	32.91**	75.18**	71.22**	71.13**
P × Y	5	0.74	0.37	0.98	4.11**	4.20**	4.54	0.37**	0.26**	0.20*
F_1 × Y	14	5.21**	4.14**	1.54	4.20**	5.39**	10.60**	1.91**	1.88**	1.22**
P vs F_1 × Y	1	0.001*	0.00*	0.54	2.09**	0.72**	0.16	0.01	0.38**	0.55**

**and ** indicate significant at 0.05 and 0.01 probability levels, respectively*

Table 3. Means of studied agronomic and yield traits of each inbred and hybrid under three plant densities across two seasons

Genotypes	DTA			ASI			PH			EH		
	Low-D	Mid-D	High-D	Low-D	Mid-D	High-D	Low-D	Mid-D	High-D	Low-D	Mid-D	High-D
							Parents (P)					
L20	59.67	62.67	62.58	2.33	3.42	4.67	194.2	201.2	212.7	72.3	75.8	91.5
L53	63.33	64.67	65.75	2.83	3.58	5.17	233.7	206.8	250.3	99.3	92.6	128.0
Sk5	61.00	63.17	65.67	2.67	3.83	4.83	174.7	194.2	201.7	72.3	94.8	87.9
L18	64.58	66.00	67.50	2.67	4.33	4.67	178.3	177.3	186.7	66.3	69.7	86.7
L28	60.00	60.83	63.50	2.67	3.67	4.50	182.8	186.2	166.5	56.7	58.5	64.8
Sd7	64.08	66.00	67.17	3.00	3.33	4.33	202.3	215.2	204.7	87.8	92.7	95.7
Average P	62.11	63.89	65.36	2.69	3.69	4.69	194.3	196.8	203.8	75.8	80.7	92.4
							Crosses (F_1)					
L20 X L53	58.00	59.17	60.67	2.00	2.83	3.83	216.0	227.2	227.0	78.2	90.0	91.2
L20 XSK5	59.00	60.83	62.00	2.33	3.17	4.33	243.3	247.3	255.2	105.1	109.6	112.4
L20 X L18	60.00	61.00	62.00	2.00	3.00	4.17	247.2	251.7	258.5	110.7	113.1	119.1
L20 X L28	59.00	60.00	61.50	2.50	3.50	4.00	240.2	243.3	252.5	104.4	109.8	114.3
L20 X Sd7	59.17	60.58	62.00	2.83	2.92	3.58	242.2	247.7	253.5	107.3	111.4	116.5
L 53 X Sk5	59.00	60.00	61.00	2.00	2.67	3.83	224.0	235.0	238.3	93.8	101.7	106.2
L53 X L18	60.50	61.50	62.67	2.00	3.42	4.33	267.0	257.0	271.8	117.3	121.9	122.7
L53 X L28	59.00	60.00	61.50	2.00	3.00	4.00	238.0	239.3	247.8	99.5	105.7	110.3
L53 X Sd7	59.00	60.00	61.25	2.00	3.00	4.00	234.0	237.3	245.5	96.7	104.3	109.2
Sk5 X L18	59.00	60.00	61.50	2.08	3.08	4.00	238.7	241.8	250.2	103.1	107.9	112.3
Sk5 X L28	59.75	60.92	62.00	2.25	2.92	4.00	245.2	250.0	255.3	109.1	112.4	118.2
Sk5 X Sd7	60.00	61.33	62.50	2.17	3.17	4.17	255.2	255.2	266.5	113.8	118.5	121.0
L18 X L28	61.50	63.17	64.67	2.67	2.83	3.83	273.0	268.0	280.7	125.3	126.0	131.6
L18 X Sd7	60.00	61.17	62.17	2.00	3.00	4.33	251.2	252.8	263.0	113.1	115.1	120.2
L28 X Sd7	59.83	61.00	62.17	2.17	2.50	3.83	247.3	248.7	257.0	105.8	112.1	116.4
Average F_1	59.52	60.71	61.97	2.20	3.00	4.02	244.2	246.8	254.9	105.5	110.6	114.8
LSD_{05}	0.34	0.36	0.38	0.25	0.28	0.35	5.4	3.5	3.7	1.8	2.0	2.1
	LANG			**EPP**			**RPE**			**KPR**		
							Parents (P)					
L20	23.33	23.33	23.00	1.34	1.30	1.17	15.3	15.0	14.7	37.4	36.3	35.8
L53	23.83	20.67	22.17	1.39	1.27	1.16	16.0	15.4	14.8	42.4	38.6	36.5
Sk5	19.67	18.33	20.67	1.25	1.16	1.06	14.2	13.9	13.6	33.7	30.6	28.5

L18	31.33	27.67	28.17	1.15	1.03	0.98	12.9	11.8	11.4	29.1	27.3	21.6
L28	35.00	32.33	30.33	1.09	1.12	1.02	12.6	12.8	12.0	28.2	28.1	24.8
Sd7	26.50	26.67	25.33	1.18	1.05	1.04	13.3	12.4	12.3	30.9	25.7	25.6
Average P	26.61	24.83	24.94	1.23	1.16	1.07	14.0	13.6	13.1	33.6	31.1	28.8
							Crosses (F_1)					
L20 X L53	20.17	20.17	22.33	1.47	1.26	1.20	16.6	16.3	15.8	54.0	52.3	50.5
L20 XSK5	28.33	27.33	28.17	1.29	1.11	1.07	14.8	14.3	13.8	46.5	44.5	42.2
L20 X L18	29.83	30.17	28.50	1.20	1.05	1.03	14.2	13.6	13.1	44.6	42.5	41.0
L20 X L28	27.50	27.50	26.50	1.23	1.12	1.09	14.9	14.2	13.7	45.7	44.1	42.5
L20 X Sd7	28.33	28.67	27.17	1.21	1.12	1.06	14.8	14.0	13.6	45.5	43.8	41.9
L 53 X Sk5	24.67	22.83	24.00	1.32	1.20	1.12	15.8	15.3	14.6	48.5	46.1	44.9
L53 X L18	32.33	31.67	31.00	1.13	1.04	1.00	13.8	13.1	12.9	42.5	40.4	39.1
L53 X L28	25.83	25.50	25.83	1.29	1.15	1.11	15.0	14.6	14.1	46.9	45.1	43.2
L53 X Sd7	25.33	24.17	25.00	1.30	1.17	1.11	15.4	14.9	14.4	47.7	45.7	43.9
Sk5 X L18	27.00	26.50	26.33	1.26	1.13	1.10	14.9	14.3	14.0	46.3	44.7	43.0
Sk5 X L28	29.50	29.00	27.50	1.20	1.10	1.04	14.5	13.7	13.3	45.1	43.0	41.6
Sk5 X Sd7	31.00	30.83	30.00	1.18	1.05	1.00	13.8	13.3	13.0	43.4	41.2	40.0
L18 X L28	35.17	34.50	35.33	1.08	1.00	1.00	12.4	12.1	11.7	40.6	37.5	35.8
L18 X Sd7	30.33	30.67	29.00	1.19	1.05	1.01	13.9	13.5	13.1	43.8	41.7	40.4
L28 X Sd7	28.50	27.17	28.33	1.20	1.12	1.08	14.4	14.1	13.6	46.0	43.8	43.1
Average F_1	28.26	27.78	27.67	1.24	1.11	1.07	14.6	14.1	13.6	45.8	43.8	42.2
LSD_{05}	0.69	0.76	0.74	0.05	0.04	0.03	0.3	0.3	0.3	0.9	0.8	0.8
		KPP			**100-KW**			**GYPP**				
							Parents (P)					
L20	681.1	578.4	492.0	34.09	31.25	28.96	106.58	92.85	71.48			
L53	755.1	580.9	508.1	35.41	30.99	29.76	132.05	93.69	71.70			
Sk5	575.1	495.6	415.1	31.69	28.75	26.35	77.56	64.94	52.97			
L18	492.1	418.6	282.0	26.35	23.12	18.74	46.69	27.23	20.07			
L28	458.1	447.6	354.6	25.55	25.76	22.95	44.37	35.38	30.45			
Sd7	524.6	376.7	366.3	28.09	23.59	22.78	55.10	29.14	32.87			
Average P	581.0	483.0	403.0	30.20	27.24	24.92	77.06	57.20	46.59			
							Crosses (F_1)					
L20 X L53	1001.4	868.2	767.6	40.60	36.94	35.20	277.4	238.2	191.6			
L20 XSK5	851.2	682.4	621.2	35.75	32.76	31.05	221.7	182.3	153.1			
L20 X L18	800.6	660.8	586.5	35.43	33.58	31.05	219.2	193.8	178.1			

L20 X L28	829.1	689.4	626.5	36.31	34.55	32.31	232.8	186.5	156.3
L20 X Sd7	818.5	682.1	614.8	35.92	34.35	32.09	226.7	182.4	159.9
L 53 X Sk5	903.1	764.5	677.7	38.08	36.12	33.75	245.5	224.5	184.7
L53 X L18	743.2	616.7	554.8	33.91	31.71	29.72	197.5	147.7	138.3
L53 X L28	862.1	722.7	657.6	37.23	35.07	32.98	237.5	168.9	165.7
L53 X Sd7	885.4	736.5	667.4	37.63	35.42	33.50	241.0	219.1	182.0
Sk5 X L18	844.8	707.1	638.4	36.74	34.75	32.66	234.8	197.0	165.1
Sk5 X L28	806.2	671.3	597.5	35.57	34.01	31.66	223.2	201.3	167.1
Sk5 X Sd7	773.0	640.1	567.1	34.56	32.53	30.35	207.2	157.6	145.2
L18 X L28	668.0	499.1	456.9	31.78	29.89	27.73	171.1	124.4	122.9
L18 X Sd7	777.9	647.9	575.6	34.84	32.94	30.66	213.3	161.8	148.6
L28 X Sd7	811.3	684.5	614.2	36.28	34.51	32.55	227.6	183.5	165.8
Average F_1	825.1	684.9	614.9	36.04	33.94	31.82	225.1	184.6	161.6
LSD_{05}	38.3	28.5	26.1	0.76	0.65	0.55	4.7	3.8	3.4

Table 4. Estimates of average (Aver) and maximum (Max) heterobeltiosis and number (No.) of crosses showing significant favorable heterobeltiosis for studied traits under three plant densities across two seasons

Parameter	Low-D	Med-D	High-D	Low-D	Med-D	High-D	Low-D	Med-D	High-D
		DTA			**ASI**			**PH**	
Aver.	-2.07	-3.02	-3.37	-13.63	-13.73	-11.09	34.75	31.67	37.55
Max.	2.5	3.84	1.84	21.43	2.44	0.00	53.08	51.2	68.57
Min.	-6.84	-7.32	-7.44	-29.41	-25.58	-20.69	11.24	12.92	6.74
No.	9	13	11	5	1	1	0	0	0
		EH			**BS**			**LANG**	
Average	61.92	59.02	45.73	15.23	1.15	12.19	23.51	29.82	22.47
Max	121.05	115.53	103.02	111.3	101.77	123.39	57.63	68.18	45.16
Min	8.11	9.86	-0.41	-33.48	-54.44	-43.91	-13.57	-2.42	0.75
No.	0	0	0	0	2	0	1	0	0
		EPP			**RPE**			**KPR**	
Average	-5.07	-8.84	-4.18	-1.59	-2.17	-2.32	25.57	29.38	32.18
Max	6.25	0.66	4.08	8.27	10.49	10.45	48.82	55.88	68.15
Min	-18.35	-18.71	-13.64	-13.57	-14.65	-12.77	0.39	4.62	7.11
No.	1	0	0	4	3	3	14	15	15
		KPP			**100-KW**			**GYPP**	
Average	28.44	28.95	36.01	10.73	15.96	16.56	151.79	176.63	191.31
Max	54.65	54.79	67.67	29.15	39.66	41.87	313.14	455.28	404.32
Min	-1.58	6.16	9.2	-4.24	2.33	-0.14	49.55	57.64	92.96
No.	14	15	15	11	14	14	15	15	15

For days to anthesis, six crosses (L18 x Sd7, L53 x Sd7, L53 x Sk5, Sk5 x L18, Sk5 x Sd7 and L20 x L53) showed favorable, but slight and significant heterobeltiosis estimates under all the three environments. Two crosses (L53 x L28 and L53 x Sd7) exhibited significant favorable BS heterobeltiosis estimates under low-D environment (-51.63 and -54.44%, respectively).

Regarding anthesis-silking interval(ASI), significant and negative (favorable) heterobeltiosis estimates were shown by some crosses such as L53 x Sk5 under low, medium and high-D (-25.00, 25.58 and 20.69%, respectively) and L53 x L18 (-25.00%), L53 x L28 (-25.00%), L53 x Sd7 (-29.41%) and L18 x Sd7 (-25.00%) under low-D environment. In this respect, Bolanos and Edmeades [41] reported that short anthesis-silking interval (ASI) in hybrids and subsequently better pollination should not be discarded as an explanation of heterosis in grain number. Days required to tasseling along with other maturity traits are commonly used by plant breeders as basis of determining maturity of maize. Anthesis-silking interval revealed the time span or heat units required between anthesis to pollination. It is a trait used mostly in screening genotypes for tolerance to stresses especially for drought, and high plant density resistance [42].

3.4 Combining Ability Variances

Estimates of variances due to general (GCA) and specific (SCA) combining ability of the diallel crosses of maize for combined data across two seasons under three environments (plant densities) are presented in Table 6. Mean squares due to GCA and SCA were significant ($P \leq 0.01$ or 0.05) for most studied cases (51 out of 72 cases), suggesting that both additive and non-additive gene effects play important roles in controlling the inheritance of most studied traits under all environments. A similar conclusion was reported by Mason and Zuber [43], Khalil and Khattab [44] and Al-Naggar et al. [7,8,9].

In the present study under all environments, the magnitude of GCA mean squares was higher than that of SCA mean squares (the ratio of GCA/SCA mean squares was higher than unity) for four traits (LANG, EPP, KPP and RPE) under all environments, 100 KW under low and high-D, BS and DTA under low-D, suggesting the existence of a greater portion of additive and additive x additive than non-additive variance in controlling the inheritance of these traits under respective environments (16 out of 36 cases). These results are in agreement with those reported by Subandi and Compton [45], Khalil and Khattab [44], El-Shouny et al. [46], Sultan et al. [47] and Al-Naggar et al. [8,9,36,37].

Table 5. Estimates of heterobeltiosis (%) for selected traits of diallel F_1 crosses under three plant densities across 2013 and 2014 seasons

Cross	Low-D	Med-D	High-D	Low-D	Med-D	High-D	Low-D	Med-D	High-D
		DTA			**ASI**			**BS**	
L20 X L53	-2.79**	-5.59**	-3.06**	-14.29	-17.07	-17.86	-33.48	-50.90	-43.91
L20 XSK5	-1.12	-2.93**	-0.93	0.00	-7.32	-7.14	13.91	6.49	14.86
L20 X L18	0.56	-2.66**	-0.93	-14.29	-12.2	-10.71	12.40	28.36	26.92
L20 X L28	-1.12	-1.37**	-1.73*	7.14	2.44	-11.11	28.02	-27.45	-22.68
L20 X Sd7	-0.84	-3.32**	-0.93	21.43	-12.5	-17.31	6.15	-10.87	-25.63
L 53 X Sk5	-3.28**	-5.01**	-7.11**	-25.00*	-25.58*	-20.69*	-10.37	-36.08	-19.64
L53 X L18	-4.47**	-4.90**	-4.69**	-25.00*	-4.65	-7.14	-8.76	65.17	62.90
L53 X L28	-1.67*	-1.37**	-3.15**	-25.00*	-16.28	-11.11	16.84	-51.63*	0.72
L53 X Sd7	-6.84**	-7.22**	-6.84**	-29.41*	-10	-7.69	-5.56	-54.44*	-4.90
Sk5 X L18	-3.28**	-5.01**	-6.35**	-21.88	-19.57	-14.29	-0.48	-20.63	3.30
Sk5 X L28	-0.42	0.14	-2.36*	-15.63	-20.45	-11.11	37.64	4.13	8.39
Sk5 X Sd7	-1.64*	-2.90**	-4.82**	-18.75	-5.00	-3.85	16.79	40.93	36.17
L18 X L28	2.50**	3.84**	1.84	0.00	-22.73	-14.81	111.30**	101.77*	123.39**
L18 X Sd7	-6.37**	-7.32**	-7.44**	-25.00*	-10.00	0.00	14.42	41.87	35.91
L28 X Sd7	-0.28	0.27	-2.10*	-18.75	-25.00	-11.54	29.64	-19.51	-12.92
		EPP			**RPE**			**KPR**	
L20 X L53	6.25**	-2.75	2.72	3.83*	5.92**	7.06**	27.51**	35.67**	38.27**
L20 XSK5	-4.26*	-14.43**	-8.72**	-3.05	-5.03**	-6.19**	24.50**	22.52**	18.00**
L20 X L18	-10.69**	-18.71**	-12.03**	-7.04**	-9.25**	-10.61**	19.25**	17.02**	14.57**
L20 X L28	-8.83**	-13.58**	-6.47**	-2.61	-5.70**	-6.22**	22.37**	21.60**	18.81**
L20 X Sd7	-10.00**	-14.05**	-8.94**	-3.07	-6.66**	-6.97**	21.72**	20.57**	17.13**
L 53 X Sk5	-5.18*	-5.49**	-3.03	-1.04	-0.58	-1.28	14.42**	19.51**	23.04**
L53 X L18	-18.35**	-18.36**	-13.64**	-13.57**	-14.65**	-12.77**	0.39	4.62**	7.11*
L53 X L28	-6.92**	-9.98**	-4.52*	-6.05**	-5.19**	-4.96**	10.79**	16.99**	18.24**
L53 X Sd7	-6.42**	-7.66**	-3.80	-3.83*	-3.25	-2.70	12.50**	18.55**	20.19**
Sk5 X L18	0.55	-2.66	4.08	4.68**	2.80	2.93	37.19**	46.12**	50.82**
Sk5 X L28	-4.00	-5.08**	-1.97	1.87	-1.20	-1.96	33.81**	40.65**	46.12**
Sk5 X Sd7	-5.21*	-9.77**	-5.46*	-3.04	-4.15*	-4.33*	28.69**	34.70**	40.41**
L18 X L28	-6.05*	-10.38**	-2.03	-3.68	-5.31**	-3.14	39.75**	33.28**	44.25**
L18 X Sd7	1.37	-0.30	-2.71	4.51*	9.15**	5.95**	41.79**	53.09**	57.66**
L28 X Sd7	1.65	0.66	3.87	8.27**	10.49**	10.45**	48.82**	55.88**	68.15**
		KPP			**100-KW**			**GYPP**	
L20 X L53	32.62**	49.46**	51.09**	14.66**	18.22**	18.30**	110.04**	154.23**	167.17**
L20 XSK5	24.97**	17.99**	26.25**	4.88	4.84**	7.22**	107.99**	96.33**	114.13**
L20 X L18	17.55**	14.26**	19.20**	3.93	7.46**	7.22**	105.63**	108.68**	149.12**
L20 X L28	21.72**	19.20**	27.33**	6.51*	10.57**	11.56**	118.39**	100.89**	118.60**
L20 X Sd7	20.17**	17.94**	24.95**	5.36*	9.91**	10.83**	112.69**	96.48**	123.68**
L 53 X Sk5	19.61**	31.61**	33.39**	7.54**	16.57**	13.40**	85.93**	139.64**	157.64**
L53 X L18	-1.58	6.16*	9.20**	-4.24	2.33	-0.14	49.55**	57.64**	92.96**
L53 X L28	14.17**	24.40**	29.43**	5.14*	13.16**	10.82**	79.87**	80.27**	131.11**
L53 X Sd7	17.27**	26.78**	31.36**	6.26*	14.29**	12.57**	82.47**	133.89**	153.78**
Sk5 X L18	46.89**	42.68**	53.80**	15.93**	20.87**	23.94**	202.76**	203.37**	211.68**
Sk5 X L28	40.17**	35.46**	43.94*	12.24**	18.32**	20.16**	187.76**	209.98**	215.49**
Sk5 X Sd7	34.41**	29.17**	36.62**	9.05**	13.16**	15.16**	167.16**	142.63**	174.13**
L18 X L28	35.73**	11.49**	28.84**	20.58**	16.03**	20.84**	266.42**	251.59**	303.74**
L18 X Sd7	48.28**	54.79**	57.14**	24.03**	39.66**	34.58**	287.11**	455.28**	352.04**
L28 X Sd7	54.65**	52.92**	67.67**	29.15**	33.97**	41.87**	313.14**	418.62**	404.32**

**and ** indicate significant at 0.05 and 0.01 probability levels, respectively*

On the contrary, the magnitude of SCA was higher than GCA mean squares (the GCA/SCA ratio was less than unity) for the rest of cases (20 out of 36 cases), the most importantly are 5 traits, namely ASI, PH, EH, KPR and GYPP under all the studied environments, indicating a greater portion of non-additive than additive variance in controlling the inheritance of these traits under respective environments. A similar conclusion was reported by Mostafa et al. [48], Nawar et al. [49], Ahsan et al. [50] and Singh and Shahi [51].

Results in Table 6 indicate that mean squares due to the SCA × year and GCA x year interactions were highly significant for 10 traits, namely DTA, PH, EH, BS, LANG, RPE, KPR, KPP, 100 KW and GYPP, under all studied environments, indicating that additive and non-additive variances for these traits under the three studied environments were affected by years.

The mean squares due to GCA × year was higher than those due to SCA × year in 25 out of 36 cases, indicating that GCA (additive) variance is more affected by years than SCA (non-additive) variance for these cases. On the contrary, the mean squares due to SCA × year was higher than GCA × year in the rest of cases, suggesting that SCA (non-additive variance) is more affected by years than GCA for such cases.

3.5 GCA Effects of Inbred Parents

Estimates of general combining ability (GCA) effects of parental inbreds for studied traits under the three environments (3 plant densities) across two seasons are presented in Table 7. The best parental inbreds were those showing negative and significant GCA effects for DTA, ASI, PH, EH, BS and LANG and those of positive and significant GCA effects for EPP, RPE, KPR, KPP, 100-KW and GYPP traits. For GYPP, the best inbred in GCA effects was L53 in all environments followed by L20 and Sk5. These best general combiners for grain yield were also the best ones in *per se* performance under the respective environments (Table 3). On the contrary, the inbred lines L18, L28 and Sd7 were the worst in GCA effects for GYPP and the worst in *per se* performance for the same traits under the three environments. Superiority of the inbreds L53, L20 and Sk5 in GCA effects for GYPP was associated with their superiority in GCA effects for most studied traits (Table 7).

Inbreds L53 and L20 were the best general combiners under all environments for the eight traits PH, EH, BS, LANG, RPE, KPR, KPP and 100 KW. These inbreds under the 3 environments were also the best general combiners for low DTA*, i.e.* the best in producing good hybrid combinations for earliness under the respective environments. The inbred L53 was also the best general combiner for short ASI under low-D environment. Inbred Sk5 was also the best general combiner under low and high-D for PH, under medium-D for EH and BS, under low-D for RPE and under low-D and medium-D for KPP. For more ears/plant (EPP), the inbred L53 under all environments was the best general combiners.

In previous studies [31,34-37], the inbred lines L53, L20 and Sk5 were also the best general combiners for GYPP and GYPF under high and low plant densities, so we confirm these results. Previous studies proved that positive GCA effects for EPP and kernels/plant and negative GCA effects for DTA, BS, and LANG traits are a good indicator of high density and/or drought stress tolerance [20,52].

3.6 SCA Effects of F_1 Crosses

Estimates of specific combining ability effects (SCA) of F_1 dialled crosses for studied traits under the six environments are presented in Table 8. The best crosses in SCA effects were considered those exhibiting significant negative SCA effects for DTA, DTS, ASI, PH, EH, LANG and BS and the worst ones were those showing significant positive SCA effects for the rest of studied traits. For GYPP, the largest positive (favorable) and significant SCA effects were recorded by the cross Sk5 × L18 followed by L20 × L53 and L28 × Sd7 under the 3 environments. The above crosses may be recommended for maize breeding programs for the improvement of tolerance to high plant density [53-55].

For RPE, KPR, KPP and 100 KW, the largest positive and significant SCA effects were exhibited by the cross (Sk5 × L18) followed by L20 x L53, L28 x Sd7 and L18 x Sd7 under all the three environments. For EPP, the highest positive, but not significant SCA effects were exhibited by the crosses Sk5 x L18 and L20 x L53 under all environments. Regarding BS, the lowest negative and significant SCA effects were shown by the crosses Sk5 × L18, L20 x L53, L18 x Sd7 and L28 x Sd7 under the 3 environments. For PH and EH, the lowest negative (favorable) and significant SCA effects were recorded by the crosses Sk5 × L18, L18 x Sd7, L20 x L53 and L28 x Sd7 under all environments. For days to 50% anthesis, the lowest negative (favorable) and significant SCA effects were shown by the cross Sk5 × L18 under all environments, L18 × Sd7 under medium and high-D. It is worthy to note that for the studied traits, most of the best crosses in SCA effects for a given trait included at least one of the best parental inbred lines in GCA effects for the same trait. The same conclusion was reported previously by some investigators [3,31,43,46,47].

Table 6. Mean squares due to general (GCA) and specific (SCA) combining ability and their interactions with years (Y) for studied characters under three plant density across 2013 and 2014 seasons

Parameter	Low-D	Med-D	High-D	Low-D	Med-D	High-D	Low-D	Med-D	High-D
		DTA			**ASI**			**PH**	
GCA	23.90*	18.73*	19.41	0.23	0.62	0.42	976.55	375.2*	929.20
SCA	16.77**	24.38**	25.71**	0.85	1.24**	1.08*	6058**	5112**	6697**
GCA/SCA	1.43	0.77	0.75	0.27	0.50	0.39	0.16	0.07	0.14
GCA×Y	2.72**	1.90**	6.68**	0.66**	0.56	0.73*	577.80**	61.1**	418.8**
SCA×Y	1.37**	2.32**	1.57**	0.37**	0.34	0.37	323.73**	208.2**	251.1**
GCA×Y/SCA×Y	1.98	0.82	4.27	1.76	1.64	1.99	1.78	0.29	1.67
		EH			**BS**			**LANG**	
GCA	455.50	545.3*	621.30	25.05*	61.80	124.90	263.1*	250.1*	157.39**
SCA	2520**	2218**	1942**	21.33**	83.00	127.20	50.8*	58.80	41.70
GCA/SCA	0.20	0.25	0.32	1.17	0.74	0.98	5.20	4.30	3.77
GCA×Y	280.3**	113.59**	268.3**	4.27	16.60	252.5**	46.3**	33.8**	13.63**
SCA×Y	126.9**	135.00**	94.9**	5.32	45.1*	72.0**	18.0**	33.0**	22.80**
GCA×Y/SCA×Y	2.20	0.33	2.83	0.80	0.37	3.51	2.60	1.02	0.60
		EPP			**RPE**			**KPR**	
GCA	0.17**	0.12**	0.06**	21.40*	23.05*	21.39**	259.57**	257.2*	306.05**
SCA	0.02	0.02	0.01	2.35	2.53	2.28	279.75**	303.9**	338.09**
GCA/SCA	9.27	7.40	6.47	9.09	9.12	9.39	0.93	0.85	0.91
GCA×Y	0.01	0.01	0.00	2.28**	2.76**	1.89**	23.47**	41.2**	19.43**
SCA×Y	0.02	0.01	0.01	1.20**	1.22**	1.06**	17.02**	15.4**	18.76**
GCA×Y/SCA×Y	0.75	1.02	0.48	1.89	2.27	1.78	1.38	2.67	1.04
		KPP			**100-KW**			**GYPP**	
GCA	139470**	97058*	94731**	130.19**	89.19*	121.22**	12189**	12513*	5180*
SCA	114543**	86904**	86824**	71.88**	91.04**	95.11**	39215**	30650**	23841**
GCA/SCA	1.22	1.12	1.09	1.81	0.98	1.27	0.30	0.41	0.22
GCA×Y	10640**	14627**	5906**	9.47**	12.85**	11.53**	1067**	1241**	590.3**
SCA×Y	9869**	7218**	7938**	6.05**	6.39**	4.11**	797.8**	1581.4**	689.0**
GCA×Y/SCA×Y	1.08	2.03	0.74	1.57	2.01	2.81	1.30	0.78	0.86

**and ** indicate significant at 0.05 and 0.01 probability levels, respectively*

Table 7. Estimates of general combining ability (GCA) effects of parents for studied characters under three plant density across 2013 and 2014 seasons

Parent	Low-D	Med-D	High-D	Low-D	Med-D	High-D	Low-D	Med-D	High-D
		DTA			**ASI**			**PH**	
L20	-0.61**	-0.44**	-0.49**	0.17	-0.07	0.11	-7.99**	-4.59**	-4.24**
L53	-0.52**	-0.80**	-0.72**	-0.25**	-0.02	-0.02	-10.44**	-6.50**	-9.57**
Sk5	-0.21	-0.19	-0.12	-0.04	-0.01	0.00	-3.61**	-1.38	-1.19
L18	0.85**	0.87**	0.82**	-0.06	0.01	0.08	14.06**	7.71**	9.31**
L28	0.38**	0.58**	0.38**	0.15	-0.07	-0.06	5.72**	2.79**	3.81**
Sd7	0.10	-0.01	0.13	0.04	0.17	-0.10	2.26**	1.96**	1.89**
SE g_i-g_j	0.24	0.17	0.19	0.19	0.20	0.26	1.00	1.07	0.95
		EH			**BS**			**LANG**	
L20	-5.52**	-5.16**	-4.81**	-0.89*	-1.35**	-1.61**	-1.78**	-1.53**	-1.26**
L53	-10.57**	-7.74**	-7.42**	-1.72**	-3.57**	-2.92**	-3.24**	-3.53**	-3.64**
Sk5	-0.70	-1.76**	-0.74	-0.12	-0.57**	-0.70	-0.20	-0.65*	-0.60**
L18	10.42**	8.55**	7.71**	1.80**	3.80**	3.45**	3.35**	3.64**	3.65**
L28	4.12**	3.80**	3.21**	1.02*	1.64**	0.93*	1.31**	1.39**	1.19**
Sd7	2.25**	2.31**	2.05**	-0.09	0.05	0.84*	0.56*	0.68*	0.65**
SE g_i-g_j	0.87	0.72	0.73	0.64	0.33	0.62	0.42	0.41	0.35
		EPP			**RPE**			**KPR**	
L20	0.05	0.05	0.03	0.57**	0.43**	0.48**	1.83**	1.85**	2.09**
L53	0.08*	0.11*	0.07**	0.86**	0.85**	0.95**	2.65**	2.47**	2.72**
Sk5	0.02	0.02	0.01	0.19*	0.06	0.12	0.18	0.11	0.15
L18	-0.08*	-0.10*	-0.07**	-0.96**	-0.94**	-0.95**	-2.81**	-2.93**	-3.03**
L28	-0.05	-0.04	-0.02	-0.46**	-0.27**	-0.45**	-1.16**	-0.97**	-1.30**
Sd7	-0.03	-0.03	-0.01	-0.20*	-0.14	-0.15	-0.69**	-0.53**	-0.64*
SE g_i-g_j	0.50	0.71	0.71	0.12	0.14	0.14	0.35	0.22	0.45
		KPP			**100-KW**			**GYPP**	
L20	43.89**	48.56**	39.63**	0.95**	0.98**	0.62**	13.05**	17.64**	15.05**
L53	67.50**	78.48**	71.03**	1.81**	1.83**	1.39**	18.35**	20.21**	18.86**
Sk5	13.27*	23.14**	10.25	0.12	0.11	0.12	1.74	1.43	9.93**
L18	-72.71**	-89.77**	-73.22**	-1.88**	-2.22**	-1.71**	-22.40**	-22.47**	-24.59**
L28	-37.17**	-41.08**	-39.36**	-0.76**	-0.61**	-0.42**	-8.31**	-12.73**	-14.60**
Sd7	-14.78*	-19.32**	-8.33	-0.24	-0.09	0.01	-2.42	-4.07*	-4.65
SE g_i-g_j	9.64	8.75	9.35	0.31	0.16	0.19	3.08	3.00	3.99

**and ** indicate significant at 0.05 and 0.01 probability levels, respectively*

In this study, it could be concluded that the F_1 cross Sk5 x L18 is superior to other crosses in SCA effects for grain yield and all of its components as well as in earliness, short plants, lower ear height, barren stalks, and leaf angle under stressed and non-stressed environments, *i.e.* all adaptive traits to high density tolerance. The crosses L20 x L53, L18 x Sd7 and L28 x Sd7 follow the cross Sk5 x L18 in superiority for such traits. These crosses could be offered to plant breeding programs for improving tolerance to high plant density tolerance at flowering.

3.7 Correlations among Performance, GCA and SCA Effects and Heterosis

Rank correlation coefficients calculated between mean performance of inbred parents ($\bar{x}_p$) and their GCA effects, between mean performance of F_1's ($\bar{x}_c$) and their SCA effects and heterobeltiosis and between SCA effects and heterobeltiosis, for studied characters are presented in Table 9. Out of 12 studied traits, significant (P≤ 0.05 or 0.01) correlations between $\bar{x}_p$ and GCA effects existed for 9 traits, namely PH, EH, LANG, EPP, RPE, KPR, KPP, 100 KW and GYPP. Such significant correlations between ($\bar{x}_p$) and their GCA effects in this investigation representing 75.0% of all studied cases suggest the validity of this concept in the majority of studied traits, especially yield, yield components, plant and ear heights and leaf angle under all environments. These results indicate that the highest performing inbred lines are also the highest general combiners and *vice versa* for the previously mentioned traits and therefore, the mean performance of a given parent for these traits under all studied environments is an indication of its general combining ability. This conclusion was previously reported by Meseka et al. [56] and Al-Naggar et al. [3, 34] in maize and Le Gouis et al. [57], Yildirim et al. [58] and Al-Naggar et al. [59] in wheat.

Table 8. Estimates of specific combining ability (SCA) effects for studied characters under three plant densities across 2013 and 2014 seasons

Cross	Low-D	Med-D	High-D	Low-D	Med-D	High-D	Low-D	Med-D	High-D
		DTA			**ASI**			**PH**	
L20 × L53	-0.39	-0.38*	-0.33	-0.12	-0.07	-0.25	-9.72**	-4.38**	-5.85**
L20 ×SK5	0.30	0.35	0.74**	0.01	0.26	0.06	10.77**	4.32**	5.94**
L20 × L18	0.23	-0.05	-0.04	-0.31	-0.18	-0.19	-3.06*	-0.93	-0.23
L20 × L28	-0.29	-0.25	-0.60**	-0.01	0.05	0.46	-1.72	-0.51	-3.06*
L20 × Sd7	0.15	0.33	0.23	0.43	-0.07	-0.08	3.73**	1.49	3.19*
L 53 × Sk5	0.21	-0.13	0.13	0.09	0.22	-0.31	-6.10**	-0.59	-1.06
L53 × L18	0.65**	0.81**	0.69**	0.11	0.13	0.35	19.23**	9.66**	10.44**
L53 × L28	-0.37	-0.07	-0.37	-0.10	-0.23	0.09	-1.43	-2.26	-1.73
L53 × Sd7	-0.10	-0.23	-0.12	0.01	-0.05	0.13	-1.98	-2.42*	-1.81
Sk5 × L18	-1.16**	-0.80**	-1.41**	-0.01	-0.27	0.00	-15.93**	-10.47**	-13.10**
Sk5 × L28	0.07	0.00	-0.06	-0.05	-0.24	-0.02	-1.10	-1.05	0.56
Sk5 × Sd7	0.59*	0.58**	0.61**	-0.04	0.03	0.27	12.36**	7.78**	7.65**
L18 × L28	0.75**	0.52**	1.25**	0.38	0.32	-0.19	9.07**	6.20**	8.07**
L18 × Sd7	-0.48	-0.48**	-0.50**	-0.18	0.00	0.02	-9.31**	-4.47**	-5.19**
L28 × Sd7	-0.16	-0.19	-0.22	-0.22	0.09	-0.33	-4.81**	-2.38*	-3.85**
SE $S_{ij} - S_{ik}$	0.42	0.30	0.32	0.32	0.35	0.46	1.73	1.86	1.65
SE $S_{ij} - S_{kl}$	0.35	0.24	0.26	0.26	0.28	0.37	1.41	1.52	1.35
		EH			**BS**			**LANG**	
L20 × L53	-11.29**	-7.23**	-8.43**	-1.24	-2.38**	-0.56	-3.08**	-1.87**	-2.71**
L20 ×SK5	5.79**	3.96**	4.51**	1.54*	2.30**	2.68**	2.05**	1.26*	1.42**
L20 × L18	0.21	-0.64	-0.41	-0.53	-0.98*	-0.48	0.01	-0.04	0.00
L20 × L28	0.28	0.35	0.81	-0.56	-0.61	-1.79*	-0.28	-0.45	-0.21
L20 × Sd7	5.01**	3.56**	3.53**	0.79	1.67**	0.15	1.30*	1.09*	1.50**
L 53 × Sk5	-0.45	-0.91	-0.74	0.31	-0.67	-0.39	-0.16	-0.57	-0.71
L53 × L18	11.88**	10.58**	10.95**	0.95	3.33**	4.26**	3.97**	3.80**	3.87**
L53 × L28	0.41	-0.75	-0.77	-0.57	-0.24	-1.49*	-0.49	-0.45	0.17
L53 × Sd7	-0.56	-1.69	-1.01	0.55	-0.04	-1.82*	-0.24	-0.91*	-0.62
Sk5 × L18	-12.21**	-9.57**	-9.67**	-2.27**	-4.69**	-5.94**	-4.41**	-4.24**	-4.33**
Sk5 × L28	0.13	-0.62	-0.68	-0.61	-0.24	-0.11	0.14	0.51	0.63
Sk5 × Sd7	6.74**	7.14**	6.59**	1.02	3.29**	3.77**	2.38**	3.05**	3.00**
L18 × L28	5.25**	4.83**	4.43**	2.97**	4.18**	3.82**	2.26**	2.05**	1.88**
L18 × Sd7	-5.13**	-5.20**	-5.30**	-1.12	-1.84**	-1.67*	-1.83**	-1.58**	-1.42**
L28 × Sd7	-6.07**	-3.82**	-3.80**	-1.23	-3.09**	-0.44	-1.62**	-1.66**	-2.46**
SE $S_{ij} - S_{ik}$	1.50	1.25	1.27	1.12	0.57	1.07	0.73	0.70	0.60
SE $S_{ij} - S_{kl}$	1.22	1.02	1.03	0.91	0.47	0.88	0.60	0.57	0.49
		EPP			**RPE**			**KPR**	
L20 × L53	0.10	0.10	0.06	0.53**	0.80**	0.79**	3.74**	3.41**	3.77**
L20 ×SK5	-0.02	-0.03	-0.03	-0.54**	-0.47*	-0.43*	-1.29**	-1.82**	-1.54*
L20 × L18	-0.01	-0.01	-0.01	-0.01	0.06	0.01	-0.26	-0.02	-0.36
L20 × L28	-0.02	-0.02	0.00	0.18	-0.08	0.04	-0.74	-0.21	-0.42
L20 × Sd7	-0.05	-0.04	-0.01	-0.16	-0.31*	-0.40*	-1.46**	-1.35**	-1.45*
L 53 × Sk5	-0.02	0.01	0.02	0.14	0.07	0.15	-0.16	-0.27	-0.52
L53 × L18	-0.11	-0.13	-0.07	-0.72**	-0.94**	-0.95**	-3.11**	-3.27**	-3.10**
L53 × L28	0.02	0.00	-0.02	-0.02	0.01	0.00	-0.36	0.12	-0.04
L53 × Sd7	0.01	0.02	0.01	0.08	0.07	0.01	-0.11	0.02	-0.11
Sk5 × L18	0.09	0.11	0.08	1.05**	1.05**	1.03**	3.08**	3.95**	3.78**
Sk5 × L28	0.00	-0.01	0.00	0.16	0.09	-0.02	0.29	0.25	0.38
Sk5 × Sd7	-0.04	-0.08	-0.06	-0.80**	-0.74**	-0.73**	-1.92**	-2.09**	-2.09**
L18 × L28	-0.03	-0.02	-0.02	-0.76**	-0.59**	-0.62**	-1.19*	-2.11**	-1.94**
L18 × Sd7	0.06	0.06	0.02	0.44**	0.42*	0.53**	1.48**	1.46**	1.62**
L28 × Sd7	0.03	0.05	0.04	0.44**	0.57**	0.60**	2.00**	1.97**	2.03**
SE $S_{ij} - S_{ik}$	0.87	1.22	1.22	0.21	0.24	0.24	0.61	0.39	0.77
SE $S_{ij} - S_{kl}$	0.71	1.00	1.00	0.17	0.20	0.20	0.50	0.32	0.63
		KPP			**100-KW**			**GYPP**	
L20 × L53	64.97**	53.97**	72.66**	1.80**	1.69**	1.00**	20.88**	30.32**	19.69**
L20 ×SK5	-31.02*	-34.54**	-52.37**	-1.36**	-1.93**	-1.91**	-18.21**	-26.79**	-27.29**
L20 × L18	4.40	1.92	9.54	0.31	0.60**	0.73**	3.43	12.38**	18.70**
L20 × L28	-2.72	7.60	4.26	0.08	0.33	0.41*	2.93	-7.74*	1.48

L20 × Sd7	-35.63**	-28.94*	-34.10**	-0.83*	-0.68**	-0.22	-9.03*	-8.17*	-12.57*
L 53 × Sk5	-2.68	11.18	-1.66	0.11	0.49*	0.68**	0.34	6.80*	11.12*
L53 × L18	-76.70**	-87.28**	-66.01**	-2.07**	-2.24**	-1.91**	-23.56**	-33.38**	-31.18**
L53 × L28	6.73	4.73	6.11	0.14	0.04	0.16	2.40	-10.39*	-19.96**
L53 × Sd7	7.67	17.41	-11.10	0.02	0.01	0.08	-0.06	6.65*	20.32**
Sk5 × L18	79.19**	95.19**	85.16**	2.45**	3.02**	2.40**	30.40**	30.18**	27.08**
Sk5 × L28	5.01	6.69	15.54	0.16	0.38*	0.38	4.67	14.00**	21.39**
Sk5 × Sd7	-50.51**	-78.52**	-46.68**	-1.36**	-1.97**	-1.54**	-17.21**	-24.19**	-32.30**
L18 × L28	-47.19**	-59.45**	-73.23**	-1.62**	-2.38**	-1.92**	-23.29**	-15.37**	-21.03**
L18 × Sd7	40.30**	49.62**	44.54**	0.93*	1.00**	0.70**	13.02**	6.20	6.43
L28 × Sd7	38.18**	40.44**	47.33**	1.24**	1.64**	0.98**	13.28**	19.50**	18.12**
SE $S_{ij} – S_{ik}$	16.70	15.15	16.20	0.53	0.27	0.32	5.34	5.20	6.91
SE $S_{ij} – S_{kl}$	13.64	12.37	13.23	0.44	0.22	0.26	4.36	4.24	5.64

**and ** indicate significant at 0.05 and 0.01 probability levels, respectively*

Table 9. Rank correlation coefficients among mean performance of inbreds ($\bar{x}_p$) and their GCA effects and between mean performance of F_1's ($\bar{x}_c$) and their SCA effects and between heterosis(H) and each of $\bar{x}_c$ and SCA effects three plant density across two seasons

Parameter	Low-D	Med-D	High-D	Low-D	Med-D	High-D	Low-D	Med-D	High-D
		DTA			ASI			PH	
$\bar{x}_p$ *vs.* GCA	0.43	0.01	0.42	-0.49	-0.21	0.29	-0.61*	-0.63*	-0.85**
$\bar{x}_c$ *vs.* SCA	0.60**	0.63**	0.66**	0.74**	-0.04	0.51*	0.65**	0.61**	0.61**
$\bar{x}_c$ *vs.* H	0.35	0.57*	0.51*	0.92**	0.89**	0.81**	0.73**	0.78**	0.81**
SCA *vs.* H	0.37	0.36	0.46	0.56*	0.04	0.56*	0.22	0.36	0.26
	EH			BS			LANG		
$\bar{x}_p$ *vs.* GCA	-0.67*	-0.54	-0.68*	-0.16	-0.37	-0.26	0.66*	0.68*	0.73*
$\bar{x}_c$ *vs.* SCA	0.60**	0.64**	0.57*	0.66**	0.63**	0.63**	0.62**	0.59*	0.58*
$\bar{x}_c$ *vs.* H	0.79**	0.76**	0.78**	0.87**	0.96**	0.94**	0.36	0.50*	0.51*
SCA *vs.* H	0.28	0.43	0.18	0.49	0.61**	0.58*	0.63**	0.55*	0.58*
	EPP			RPE			KPR		
$\bar{x}_p$ *vs.* GCA	0.94**	0.90**	0.92**	0.94**	0.94**	0.96**	0.93**	0.88*	0.99**
$\bar{x}_c$ *vs.* SCA	0.59*	0.54*	0.66**	0.55*	0.57*	0.58*	0.61**	0.62**	0.64**
$\bar{x}_c$ *vs.* H	0.52*	0.39	0.49	0.26	0.36	0.37	-0.13	0.01	-0.02
SCA *vs.* H	0.89**	0.77**	0.80**	0.72**	0.78**	0.78**	0.55*	0.63**	0.60**
	KPP			100-KW			GYPP		
$\bar{x}_p$ *vs.* GCA	0.93**	0.84*	0.98**	0.92**	0.85*	0.95**	0.91*	0.94**	0.97**
$\bar{x}_c$ *vs.* SCA	0.57*	0.58*	0.60**	0.64**	0.71**	0.67**	0.67**	0.68**	0.71**
$\bar{x}_c$ *vs.* H	-0.07	0.48	0.27	-0.05	0.15	0.07	-0.36	-0.16	-0.20
SCA *vs.* H	0.59*	0.76**	0.76**	0.52*	0.58*	0.47	0.27	0.42	0.32

**and ** indicate significant at 0.05 and 0.01 probability levels, respectively*

For F_1 crosses, rank All correlations between $\bar{x}_p$ and GCA effects in the present study, were positive for all traits, except for PH, EH and ASI, where the correlations were negative. The traits which did not show any correlation between $\bar{x}_p$ and GCA effects under all the three environments were DTA, ASI and BS. In general, the environment high-D (the most stressed environment) showed the highest in magnitude correlations between $\bar{x}_p$ and GCA effects for most studied traits. The strongest correlation (highest in magnitude) between $\bar{x}_p$ and GCA effects was shown by GYPP, RPE, KPR, KPP, EPP and 100-KW traits, *i.e.* yield and all yield components.

correlation coefficients calculated between their mean performance ($\bar{x}_c$) and their SCA effects (Table 9) showed that for all studied traits, significant (P≤ 0.05 or 0.01) correlations existed under the three densities, except ASI under medium-D only. Such significant correlations between ($\bar{x}_c$) and SCA effects in this investigation representing 97.0% of all studied cases suggest the validity of this concept in all studied traits and environments, except ASI under medium-D. All correlations between ($\bar{x}_c$) and SCA effects in the present study, were positive for all traits. These results indicate that the highest performing crosses are also the highest specific combiners and *vice versa* for the studied traits and therefore, the mean performance of a given cross for these traits under the respective environment is an indication of its specific combining ability. This conclusion was previously reported by Srdic et al. [60] and Al-Naggar et al. [3]. In general, the high density environment (the most stressed) showed the strongest correlation between ($\bar{x}_c$) and SCA effects for GYPP, KPP, KPR, RPE and EPP traits, *i.e.* grain yield and its components. This conclusion was also reported by Le Gouis et al. [57] and Yildirim et al. [58] under stress conditions.

Significant correlations between mean performance of crosses ($\bar{x}_c$) and heterobeltiosis (Table 9) were exhibited only in 17 out of 36 cases (47.22%), namely ASI, PH, EH and BS under all environments, DTA (except low-D), LANG (except low-D), EPP under low-D. For these density adaptive traits, the mean performance of a cross could be used as an indicator of its useful heterosis under the corresponding environments. The traits KPR, KPP and GYPP; *i.e.* yield traits did not exhibit any correlation between $\bar{x}_c$ and heterobeltiosis under all (three) environments and therefore, SCA effects of crosses could not be expected from their *per se* performance for such yield traits.

Significant correlations between crosses SCA effects and heterobeltiosis (Table 9) were exhibited only in 21 out of 36 cases (58.33%) under all environments, namely LANG, EPP, RPE, KPR, KPP, 100 KW (except high-D), BS (except low-D) and ASI (except medium-D). For these density adaptive traits, the useful heterosis of a cross could be used as an indicator of its SCA effects under the corresponding environments. The traits DTA, PH, EH and GYPP did not exhibit any correlation between SCA effects and heterobeltiosis under all (three) environments and therefore, SCA effects of crosses could not be expected from their heterobeltiosis values in such cases.

4. CONCLUSIONS

The present study identified three inbreds (L53, L20 and Sk5) and three F_1 crosses (L20 x L53, L53 x Sk5 and L53 x Sd7) of good performance under high plant density. These crosses are considered tolerant to elevated density stress and responsive to the good environment. It is clear that L53, Sk5 and L20 might be considered as source of tolerance and responsiveness in these crosses. Results concluded that under the highest plant density, the traits leaf angle (LANG), ears/plant (EPP), kernels/row (KPP) and rows/ear (RPE),100-kernel weight (100 KW) are controlled mainly by additive genes and therefore selection would be effective in improving these traits, but the opposite was true for the rest of traits including GYPP, *i.e.* they are controlled mainly by non-additive genes (dominance and epistasis) and therefore heterosis breeding is the best choice for improving such traits under these stress conditions. For grain yield/plant (GYPP), the best inbred in GCA effects was L53 followed by L20 and Sk5 and the best cross for SCA effects was Sk5 × L18 followed by L20 × L53 and L28 × Sd7 under the three environments. Correlation analysis concluded that for grain yield under high plant density, the mean performance of a given parent could be considered an indication of its general combining ability and the mean performance of a given cross could be considered an indication of its specific combining ability, but the mean performance of a given cross could not be considered an indication of its heterobeltiosis and the heterobeltiosis of a given cross could not be used as indication of its SCA effects. These results are true also under low and medium plant densities, and may help maize breeder in quick prediction of GCA and SCA effects of his parents and F_1 crosses, respectively.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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