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# Line × Tester Analysis for Yield, Agronomic and Physiologic Traits under Elevated Plant Density in Maize

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***Authors' contributions***

*This work was carried out in collaboration between all authors. Author AMMA designed the study, wrote the protocol and wrote the first draft of the manuscript. Authors AMMA, RS, MSH and TAE supervised the study and managed the literature searches. Authors AMAM and ASMY managed the experimental process and performed data analyses. All authors read and approved the final manuscript.*

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## ABSTRACT

Knowledge on combining ability and type of gene action of available germplasm would help maize breeder in identifying proper parents and breeding procedure for improving plant density tolerance (PDT). A split plot experiment with three replications was carried out; where plant densities were devoted to main plots, namely low density (LD), medium (MD) and high (HD) density (47600 to 71400 and 95200 plants/ha, respectively) and subplots to genotypes. Both GCA and SCA variances were necessary for the expression of studied traits under all plant densities, but the magnitude of $\delta^2_{SCA}$ was much higher than that of $\delta^2_{GCA}$ for most studied traits, suggesting the predominance of non-additive gene effects in controlling inheritance of the most studied traits under all plant densities. Lines were the highest contributor to the total variation under all densities (HD, MD and LD). For grain yield under increased plant density, the best general combiners were L28, IL51, L21, L17, L14, IL84, IL15 and IL53 and the best test crosses in SCA effects were IL84 × SC10, L21 × Sd7, IL151 × Giza 2, IL51 × Giza 2, IL15 × Sd7 and L17 × Giza2. This germplasm

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could be used in future plant breeding programs for improving maize PDT. Based on the SCA effects of crosses under HD, the three testers successfully classified 15 out of 23 tested inbred lines into three heterotic groups: Five inbreds belong to heterotic group-1, five to heterotic group-2, while the remaining five belong to heterotic group-3; these three groups can maximize heterosis by crossing inbred lines belonging to different heterotic groups/unrelated lines.

*Keywords: Combining ability; gene action; plant density tolerance; heterotic grouping.*

## 1. INTRODUCTION

Egyptian maize hybrids selected under low plant density do not withstand high density and therefore are subject to yield losses when grown under high plant density. Thus, grain yield per land unit area cannot be increased by increasing plant density using the present Egyptian cultivars [1,2,3].

Maximum grain yield per land unit area may be obtained by growing maize hybrids that can withstand high plant density up to 100,000 plants/ha [4]. Average corn grain yield per land unit area in the USA increased dramatically during the second half of the 20$^{th}$ century, due to improvement in crop management practices and greater tolerance of modern hybrids to high plant densities [5,6].

Introducing high density adaptive traits to Egyptian cultivars is important to enable these varieties to produce higher grain yield than present cultivars. Plant density tolerance (PDT) likely involves multiple factors from categories of traits affecting photosynthetic capacity, source–sink relationship, hormonal balance, and plant architecture [7,8,9,10]. Mansfield and Mumm [11] assumed that a combination of traits, likely from diverse categories, may be necessary for expression of PDT. Furthermore, they reported that several types of characteristics related to PDT include photosynthetic capacity, plant architecture, growth response, source–sink relationship, and general stress tolerance.

Combining ability has been defined as the performance of a line in hybrid combinations [12]. Since the final evaluation of inbred lines can be best determined by hybrid performance, it plays a significant role in selecting superior parents for hybrid combinations and in studying the nature of genetic variation [13,14]. Sprague and Tatum [15] reported that GCA and SCA is an indication of genes having mostly additive and non-additive (dominance and epistasis) effects, respectively. Inbred line traits under high plant density stress were more strongly correlated with top cross performance under severe density stress than the line characteristics under low-density conditions [16].

A broad range of biometrical tools is available to breeders for identifying proper parents and crosses, and characterizing genetic control of economically important traits as a guide to decide the appropriate breeding methodology for hybrid breeding. Line x tester analysis proposed by Kempthorne et al. [17] is one of the best biometrical tools to achieve that. Knowledge about combining ability of maize traits in diverse plant density environments is essential for plant breeding programs.

Classifying inbred lines of maize into heterotic groups is the initial step in corn breeding program which would provide maximum exploitation of heterosis. Systematic studies on classifying inbred lines into heterotic groups have been reported [18]. An inbred line that expressed negative SCA effects when crossed to a certain tester implied that the inbred line belongs to the same heterotic group with the tester. On the other hand, if the same line manifests positive SCA effect with the same tester, it is classified into opposite heterotic group.

The objectives of this study were (i) to estimate the general and specific combining ability variances and effects in 69 test crosses between 23 inbreds and three testers for grain yield, important agronomic and physiologic traits related to PDT, (ii) to identify the best inbreds for GCA effects and the best test crosses in SCA effects and (iii) to classify the inbred lines into different heterotic groups for future use in the breeding program for improving PDT.

## 2. MATERIALS AND METHODS

### 2.1 Experimental Site

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 2015 and 2016 seasons.

## 2.2 Genetic Materials

Twenty-three maize inbred lines, of different origins, were chosen by their adaptive traits to high plant density and drought, to be used as females in this study. Seven of them (L14, L17, L18, L20, L21, L28 and L53) were obtained from Agronomy Department, Faculty of Agriculture, Cairo University and 16 inbreds (IL115, IL17, IL24, IL51, IL53, IL80, IL84, IL151, IL171, Sk9, CML67, CML104, Inb174, Inb176, Inb208 and Inb213) were obtained from Agricultural Research Center, Egypt. Three testers of the different genetic base were used as males to make all possible test-crosses with the 23 inbred females, namely the commercial inbred line Sd7, the commercial single cross hybrid SC 10 and the commercial synthetic Giza 2 (open-pollinated variety) in 2015 summer season.

## 2.3 Experimental Design and Treatments

In 2016 season, one field experiment was carried out during the early summer. The experiment was conducted to evaluate 100 genotypes, namely 23 inbred lines, three testers, 69 test crosses and five high-yielding commercial hybrids as checks (the single crosses SC 168, SC 2031, SC 30K9, SC30 N11and the three-way cross TWC 1100). A split-plot design in randomized complete blocks arrangement with three replications was used. The main plots were allotted to three plant densities (low, medium and high) and the sub-plots were devoted to genotypes (100 genotypes each). The inbred lines were separated from other studied material in each block, because of their differences in plant height and vigor. The date of planting was the 20$^{th}$ of May. Sub-plots were single rows 4.0 m long and 0.70 m wide, with hills spaced at a distance of 15 cm for the high density (HD), 20 cm for the medium density (MD) and 25 cm for the low plant density (LD) with two plants hill$^{-1}$ and plants were thinned to one plant hill$^{-1}$ before the first irrigation to achieve the plant densities 95200, 71400 and 47600 plants/ha, respectively. All other agricultural practices were followed according to the recommendations of Agricultural Research Center (ARC), Egypt. Nitrogen fertilization at the rate of 285.6 kg N/ha was added in two equal doses of Urea before the first and second irrigation. Fertilization with calcium superphosphate was performed with soil preparation and before sowing. Weed control was performed chemically with Stomp herbicide (Pendimethalin) before the first irrigation and just after sowing and manually by hoeing twice, the first before the second irrigation and the second before the third irrigation. Irrigation was applied by flooding after three weeks for the second irrigation and every 12 days for subsequent irrigations. Pest control was performed when required by spraying plants with Lannate (Methomyl) 90% (manufactured by DuPont, USA) against corn borers.

## 2.4 Soil Analysis and Meteorological Data

The analysis of the experimental soil, indicated that the soil is clay loam (5.50% coarse sand, 22.80% fine sand, 36.40% silt, and 35.30% clay), the pH (paste extract) is 7.92, the EC is 1.66 dSm$^{-1}$, soil bulk density is 1.2 g cm$^{-3}$, calcium carbonate is 7.7%, the available nutrients in mg kg$^{-1}$were Nitrogen (371.0), Phosphorous (0.4), Potassium (398), DTPA-extractable Zn (4.34), DTPA-extractable Mn (9.08) and DTPA-extractable Fe (10.14). Meteorological variables in the 2016 growing season 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℃, the maximum temperature was 35.7, 35.97, 34.93 and 37.07℃ and relative humidity was 47.0, 53.0, 60.33 and 60.67%, respectively.

## 2.5 Trait Recording

1. **Days to 50% anthesis (DTA):** (Number of days from planting to anthesis of 50% of plants), it was measured on all plants plot$^{-1}$.
2. **Anthesis-silking interval (ASI)** (day): (Number of days between 50% silking and 50% anthesis), it was measured on all plants plot$^{-1}$.
3. **Plant height** (PH) (cm): It was measured on 10 guarded plants plot$^{-1}$ from ground to the point of flag leaf insertion.
4. **Leaf angle** (LANG) ($^{o}$): It was measured as leaf angle between blade and stem for the leaf just above ear using a protractor on 10 guarded plants plot$^{-1}$according to Zadoks *et al*. [19].
5. **Lower stem diameter** (SDL) (mm): It was measured with caliper from 10 guarded plants/plot as the stem diameter above second node; two measurements were taken. The first measurement was used as a base line with the second measurement

recorded after a 90 degree turn of the caliper.

6. **Upper stem diameter** (SDU) (mm): It was measured with caliper from 10 guarded plants/plot as the stem diameter on third internode below flag leaf.
7. **Leaf area to produce 1 g of grain** (LA/1gG) ($cm^2$): It was measured as leaf area per plot /grams of grains per plot.
8. **Penetrated light at the base of top-most ear** (PLE) (%): At 70 days from sowing date light intensity was measured and then penetrated light inside the canopy was calculated for each genotype. The Lux-meter apparatus was used. The light intensity in (lux) was measured at 12 am (noon time) at the top of the plant, and at the base of top-most ear. Penetrated light inside the canopy was measured as a percentage of light penetrated from the top of the plant to the base of top-most ear as follows: PLE =100 (light intensity at the base of top-most ear/light intensity at the top of the plant).
9. **Chlorophyll concentration index** (CCI) (%): It was measured by Chlorophyll Concentration Meter, Model CCM-200, USA as the ratio of transmission at 931 nm to 653 nm through the leaf of top-most ear. It was measured on 5 guarded plants/plot.
10. **Number of ears plant$^{-1}$** (EPP): It was estimated by dividing number of ears plot$^{-1}$ on number of plants plot$^{-1}$.
11. **Number of rows ear$^{-1}$** (RPE): Using 10 random ears plot$^{-1}$ at harvest.
12. **Number of kernels plant$^{-1}$** (KPP): Calculated by multiplying number of ears plant$^{-1}$ by number of rows ear$^{-1}$ by number of kernels row$^{-1}$.
13. **100-Kernel weight** (100KW) (g): Adjusted at 155g water kg$^{-1}$ grain.
14. **Grain yield plant$^{-1}$** (GYPP) (g): It was estimated by dividing the grain yield plot$^{-1}$ (adjusted at 15.5% grain moisture) on number of plants plot$^{-1}$ at harvest.
15. **Grain yield ha$^{-1}$** (GYPH) (ton): It was estimated by adjusting grain yield plot$^{-1}$ at 15.5% grain moisture to grain yield ha$^{-1}$.

## 2.6 Statistical Analyses

Analysis of variance of the split-plot design was performed on the basis of individual plot observation using the MIXED procedure of SAS ® [20]. The data collected from each plant density were subjected to the standard analysis of variance of randomized complete blocks design according to Steel et al. [21] using GENSTAT 10$^{th}$ addition windows software. Data of the test crosses were further subjected to line × tester analysis according to Kempthorne [17]. The sum of squares for $F_1$ hybrids was partitioned into their components, *i.e.* males (testers), females (inbred lines) and females (lines) × males (testers) interaction. The model used to estimate general (GCA) and specific (SCA) combining ability effects of the $X_{ijk}$$^{\underline{th}}$ observation is as follows:

$$X_{ijk} = \mu + g_i + g_j + s_{ij} + e_{ijk}$$

Where: μ = overall population mean. $g_i$ = GCA effect of the $i^{\underline{th}}$ male parent. $g_j$= GCA effect of the $j^{\underline{th}}$ female parent. $s_{ij}$= SCA effect of the ij cross combination. $e_{ijk}$ = the error associated with the $x_{ijk}$ observation. i= number of male parents. j= number of female parents. k= number of replications.

Estimation of GCA effects for females [$\hat{g}_{i(f)}$] was as follows:

$$\hat{g}_{i(f)} = x.f./mr - x../fmr$$

Where: x.f. = total of the $f^{th}$ female parent across all male parents and replications, x..= total of all females across all males and replications, r = number of replications, f = number of females and m = number of males.

Estimation of GCA effects for males [$\hat{g}_{i(m)}$] was as follows:

$$\hat{g}_{i(m)} = x.m. /fr - x../fmr$$

Where: x.m. = total of the $m^{th}$ male parent across all females and replications.

Estimation of SCA effects for crosses [$\hat{s}_{ij(fm)}$] was as follows:

$$\hat{s}_{ij(fm)} = x_{fm.}/r - x_{f..}/mr - x_{.m.} /fr + x../fmr$$

Where: $x_{fm.}$ = total of the $fm^{th}$ single testcross across all replications.

The following standard errors were calculated according to Sharma [22]:

$$SE\ (\hat{g}_i \text{ for female}) = [(f-1)\ M_e / rmf]^{½},$$

$$SE\ (\hat{g}_i \text{ for male}) = [(m-1)\ M_e / rmf]^{½},$$

$$SE\ (\hat{g}_i - \hat{g}_j) \text{ female} = [2M_e / rf]^{½},$$

$$SE\ (\hat{g}_i - \hat{g}_j) \text{ male} = [2M_e / rm]^{½},$$

$$SE\ (S_{ij}) \text{ crosses} = [(f-1)\ (m-1)\ M_e / rmf]^{½},$$

$SE (S_{ij} - S_{kl}) = (2M_e / r)^{½}$

$SE (S_{ij} - S_{ik}) = [(m+1) 2M_e / rm]^{½}$

Where: Me = error variance.

#### 2.6.1 Heterotic grouping

According to Vasal et al. [18], SCA effects for grain yield of the test crosses were used to classify the 23 inbred lines into heterotic groups. An inbred line that expressed negative SCA effects when crossed to a certain tester implied that the inbred line belongs to the same heterotic group with the tester. On the other hand, if the same line manifests positive SCA effect with the same tester, it is classified into opposite heterotic group.

## 3. RESULTS AND DISCUSSION

### 3.1 Analysis of Variance of Line × Tester

Analysis of variance of line × tester according to Kempthorne [17] under low, medium and high density conditions in 2016 season is presented in Table (1). Mean squares due to test crosses and their components, *i.e.* lines, testers and lines × testers were significant (p≤0.05 or p≤0.01) under all plant densities for all studied traits, except DTA for lines under MD and testers under HD, ASI for testers under LD, MD and HD, and EPP for testers under HD. These results indicated significant GCA for lines and testers and SCA for line x tester crosses in most studied traits under LD, MD and HD.

### 3.2 Contribution of Lines, Testers and Lines x Testers to Total Variation

Relative contribution (%) of variances due to lines (L), testers (T) and L x T to total variation for studied traits under low (LD), medium (MD) and high (HD) plant densities is presented in Table (2). Inbred lines (females) were the biggest contributor to the total variation; since they showed the highest percentage of contribution in 23 cases out of total 45 cases (7 traits under HD, 7 traits under MD and 9 traits under LD). It is worthy to note that lines were the highest contributor to the total variation under all densities (HD, MD and LD) for three traits, namely GYPP, GYPH and LANG. It could be concluded that inbred lines used in this study showed big variation for most studied traits under stressed and non-stressed environments.

In the second place comes lines × testers; they showed the highest contributor to total variation in 21 cases out of 45 cases (7 traits under HD, 8 traits under MD and 6 traits under LD). Testers were the highest contributtor to total variation in one case only (SDL under HD).

### 3.3 Combining Ability Variances

Estimates of variances due to general ($δ^2_{GCA}$) and specific ($δ^2_{SCA}$) combining ability calculated according to the line × tester analysis proposed by Kempthorne [17] are presented in Table (3). Significant or highly significant $δ^2_{GCA}$ variances were exhibited for most studied traits under low (LD), medium (MD) and high (HD) density. However, significant or highly significant $δ^2_{SCA}$ variances were exhibited for all studied traits under all plant densities. This indicates that both GCA and SCA variances are necessary the expression of studied traits under low, medium and high plant densities and suggesting that both additive and non-additive gene effects play important roles in controlling the inheritance of these traits under all environments. A similar conclusion was reported by several investigators [23-30]. The magnitude of $δ^2_{SCA}$ is much higher than that of $δ^2_{GCA}$, expressed in the ratio $δ^2_{GCA}/δ^2_{SCA}$, which was less than unity for all studied traits under all plant densities, except for SDL and SDU under all densities, LANG under HD and EPP under LD. This indicates that non-additive genetic variance (dominance and epistasis) is predominating over additive variance in the inheritance of most studied traits, so the breeding method of choice for improving maize plant density tolerance would be heterosis breeding . A similar conclusion was reported by several investigators [1,2,31-35] On the contrary, other investigators [16,27-30,36-39] suggested the existence of a greater portion of additive and additive × additive than non-additive variance in controlling the inheritance of studied traits under elevated plant density environments. Different conclusions reported by various investigators might be due to different genotypes and genotype x environment interaction.

It is observed that $δ^2_{GCA}$ increased by increasing the stress of plant density for all studied traits, except for LANG, SDL, SDU, PL-E, EPP, RPE, KPP, 100-KW and GYPP traits, where the opposite was true. However, $δ^2_{SCA}$ decreased by increasing the stress of plant density for all studied traits, except for LA/1gG, CCI, EPP, RPE, 100KW and GYPH, where the opposite was true.

**Table 1. Analysis of variance of line × tester for studied traits of 69 test crosses partitioned into lines (L), testers (T) and L × T under three plant densities in 2016 season**

| SOV | df | LD | MD | HD | LD | MD | HD | LD | MD | HD |
|---|---|---|---|---|---|---|---|---|---|---|
| | | **Days to 50% anthesis** | | | **Anthesis-silking interval** | | | **Plant height** | | |
| Crosses (C) | 68 | ** | ** | ** | ** | ** | ** | ** | ** | ** |
| Lines (L) | 22 | ** | ns | ** | ** | ** | * | ** | ** | ** |
| Testers (T) | 2 | ** | ** | ns | ns | ns | ns | ** | ** | ** |
| L x T | 44 | ** | ** | ** | ** | ** | * | ** | ** | ** |
| | | **Leaf angle** | | | **Lower stem diameter** | | | **Upper stem diameter** | | |
| Crosses (C) | 68 | ** | ** | ** | ** | ** | ** | ** | ** | ** |
| Lines (L) | 22 | ** | ** | ** | ** | ** | ** | ** | ** | ** |
| Testers (T) | 2 | ** | ** | ** | ** | ** | ** | ** | ** | ** |
| L x T | 44 | ** | ** | ** | ** | ** | ** | ** | ** | ** |
| | | **Leaf area to produce 1 g of grain** | | | **Penetrated light at ear** | | | **Chlorophyll concentration** | | |
| Crosses (C) | 68 | ** | ** | ** | ** | ** | ** | ** | ** | ** |
| Lines (L) | 22 | ** | ** | ** | ** | * | * | ** | ** | ** |
| Testers (T) | 2 | * | * | ** | ** | ** | ** | ** | * | * |
| L x T | 44 | ** | ** | ** | ** | ** | ** | ** | ** | ** |
| | | **Ears per plant** | | | **Rows per ear** | | | **kernels per plant** | | |
| Crosses (C) | 68 | ** | ** | ** | ** | ** | ** | ** | ** | ** |
| Lines (L) | 22 | ** | ** | ** | ** | ** | * | ** | ** | ** |
| Testers (T) | 2 | ** | ** | ns | ** | * | * | ** | ** | ** |
| L x T | 44 | ** | ** | ** | ** | ** | ** | ** | ** | ** |
| | | **100-kernel weight** | | | **Grain yield per plant** | | | **Grain yield per hectare** | | |
| Crosses (C) | 68 | ** | ** | ** | ** | ** | ** | ** | ** | ** |
| Lines (L) | 22 | ** | ** | * | ** | ** | ** | ** | ** | ** |
| Testers (T) | 2 | ** | ** | ** | ** | ** | ** | ** | ** | ** |
| L x T | 44 | ** | ** | ** | ** | ** | ** | ** | ** | ** |

*ns, * and ** indicate non-significant, significant at 0.05 and 0.01 probability levels, respectively.*

**Table 2. Relative contribution (%) of variances due to lines (L), testers (T) and L × T to total variation for studied traits under low (LD), medium (MD) and high (HD) plant densities**

| | LD | MD | HD | LD | MD | HD | LD | MD | HD |
|---|---|---|---|---|---|---|---|---|---|
| | **Days to 50% anthesis** | | | **Anthesis-silking interval** | | | **Plant height** | | |
| Lines (L) | 35.58 | 48.19 | 58.07 | 18.72 | 29.44 | 44.98 | 32.02 | 38.14 | 45.97 |
| Tester (T) | 2.38 | 2.81 | 0.25 | 1.24 | 1.48 | 3.91 | 7.17 | 10.51 | 17.38 |
| L x T | 62.04 | 49.00 | 41.68 | 80.05 | 69.09 | 51.11 | 60.81 | 51.35 | 36.65 |
| | **Leaf angle** | | | **Lower stem diameter** | | | **Upper stem diameter** | | |
| Lines (L) | 49.55 | 56.09 | 58.26 | 48.98 | 48.58 | 33.21 | 42.32 | 51.07 | 51.22 |
| Tester (T) | 18.63 | 17.39 | 17.21 | 29.92 | 33.01 | 40.95 | 40.35 | 39.85 | 38.32 |
| L x T | 31.83 | 26.52 | 24.53 | 21.1 | 18.41 | 25.84 | 17.33 | 9.08 | 10.46 |
| | **Leaf area to produce 1 g of grain** | | | **Penetrated light at ear** | | | **Chlorophyll concentration** | | |
| Lines (L) | 37.75 | 38.17 | 42.76 | 54.2 | 37.83 | 32.08 | 47.36 | 49.68 | 40.36 |
| Tester (T) | 1.23 | 0.84 | 3.67 | 1.21 | 22.99 | 31.76 | 9.14 | 7.00 | 9.38 |
| L x T | 61.02 | 60.99 | 53.56 | 44.59 | 39.19 | 36.17 | 43.5 | 43.32 | 50.26 |
| | **Ears per plant** | | | **Rows per ear** | | | **kernels per plant** | | |
| Lines (L) | 29.7 | 29.15 | 36.83 | 39.13 | 32.69 | 48.11 | 51.79 | 45.17 | 52.09 |
| Tester (T) | 5.86 | 3.24 | 0.68 | 5.3 | 8.43 | 2.86 | 4.35 | 2.45 | 1.36 |
| L x T | 64.43 | 67.64 | 62.41 | 55.56 | 58.88 | 49.02 | 43.87 | 52.39 | 46.55 |
| | **100-kernel weight** | | | **Grain yield per plant** | | | **Grain yield per hectare** | | |
| Lines (L) | 58.1 | 50.6 | 48.2 | 60.85 | 57.95 | 59.61 | 60.9 | 57.98 | 59.6 |
| Tester (T) | 1.54 | 0.68 | 2.51 | 4.26 | 1.84 | 0.59 | 4.25 | 1.84 | 0.6 |
| L x T | 40.37 | 48.72 | 49.29 | 34.89 | 40.2 | 39.8 | 34.85 | 40.18 | 39.8 |

**Table 3. General (GCA) and specific (SCA) combining ability variances estimated from line × tester analysis for studied traits of 69 test crosses**

| Components | LD | MD | HD | LD | MD | HD | LD | MD | HD |
|---|---|---|---|---|---|---|---|---|---|
| | | **Days to 50% anthesis** | | | **Anthesis-silking interval** | | | **Plant height** | |
| $\delta^2_{GCA (F)}$ | 0.08** | 0.37* | 0.70** | -0.06 | -0.01 | 0.05* | 2.40** | 12.63** | 41.07** |
| $\delta^2_{GCA( M)}$ | -0.01 | 0.01** | -0.04 | -0.01 | -0.01 | 0.01 | 9.42** | 11.88** | 33.49** |
| $\delta^2_{GCA (Aver)}$ | 0.05** | 0.22** | 0.39** | -0.04 | -0.01 | 0.03* | 5.28** | 12.32** | 37.96** |
| $\delta^2_{SCA}$ | 1.56** | 0.97** | 1.00** | 0.27** | 0.16** | 0.07* | 74.09** | 55.82** | 39.61** |
| $\delta^2_{GCA}/^2_{SCA}$ | 0.03 | 0.23 | 0.39 | 0.00 | 0.00 | 0.44 | 0.07 | 0.22 | 0.96 |
| | | **Leaf angle** | | | **Lower stem diameter** | | | **Upper stem diameter** | |
| $\delta^2_{GCA (F)}$ | 6.41** | 5.37** | 5.71** | 2.45** | 1.72** | 0.87** | 2.30** | 2.51** | 2.47** |
| $\delta^2_{GCA( M)}$ | 4.69** | 2.91** | 2.87** | 2.65** | 2.02** | 2.45** | 3.88** | 3.05** | 2.91** |
| $\delta^2_{GCA (Aver)}$ | 5.7** | 4.36** | 4.55** | 2.53** | 1.84** | 1.52** | 2.95** | 2.73** | 2.65** |
| $\delta^2_{SCA}$ | 7.25** | 4.44** | 3.87** | 1.47** | 1.07** | 1.26** | 1.44** | 0.64** | 0.71** |
| $\delta^2_{GCA}/^2_{SCA}$ | 0.79 | 0.98 | 1.17 | 1.73 | 1.73 | 1.21 | 2.05 | 4.24 | 3.74 |
| | | **Leaf area to produce 1 g of grain** | | | **Penetrated light at ear** | | | **Chlorophyll concentration index** | |
| $\delta^2_{GCA (F)}$ | 2.71** | 3.14** | 9.85** | 22.5** | 1.26* | 0.38* | 2.72** | 3.80** | 2.90** |
| $\delta^2_{GCA( M)}$ | -0.83 | -1.14 | 1.10** | -0.83 | 2.10** | 1.16** | 1.09** | 0.98* | 1.94* |
| $\delta^2_{GCA (Aver)}$ | 1.26** | 1.39** | 6.26** | 12.9** | 1.6** | 0.7** | 2.05** | 2.64** | 2.51** |
| $\delta^2_{SCA}$ | 29.78** | 34.78** | 45.51** | 37.2** | 3.25** | 1.22** | 5.82** | 8.43** | 13.41** |
| $\delta^2_{GCA}/^2_{SCA}$ | 0.04 | 0.04 | 0.14 | 0.35 | 0.49 | 0.57 | 0.35 | 0.31 | 0.19 |
| | | **Ears per plant** | | | **Rows per ear** | | | **Kernels per plant** | |
| $\delta^2_{GCA (F)}$ | -0.009** | -0.003 | 0.011** | 0.07** | 0.02** | 0.17* | 1206** | 384** | 668** |
| $\delta^2_{GCA( M)}$ | 0.002** | 0.002** | -0.006 | 0.02** | 0.06* | 0.01* | 136.3** | 1.898** | -25.07 |
| $\delta^2_{GCA (Aver)}$ | 0.009** | -0.002 | 0.004** | 0.05** | 0.04** | 0.1** | 766.7** | 227.1** | 383.2** |
| $\delta^2_{SCA}$ | 0.003** | 0.006** | 0.012** | 0.44** | 0.55** | 0.49** | 2295** | 1478** | 1492** |
| $\delta^2_{GCA}/^2_{SCA}$ | 3.21 | 0.00 | 0.34 | 0.11 | 0.07 | 0.21 | 0.33 | 0.15 | 0.26 |
| | | **100-Kernel weight** | | | **Grain yield per plant** | | | **Grain yield per hectare** | |
| $\delta^2_{GCA (F)}$ | 2.17** | 1.77** | 1.79* | 372.3** | 172.8** | 175.1** | 7.59** | 7.95** | 14.29** |
| $\delta^2_{GCA( M)}$ | -0.02 | -0.15 | 0.03** | 32.87** | 0.10** | -7.68 | 0.67** | 0.001** | -0.63* |
| $\delta^2_{GCA (Aver)}$ | 1.27** | 0.98** | 1.07** | 232.9** | 101.84** | 100.02** | 4.75** | 4.69** | 8.16** |
| $\delta^2_{SCA}$ | 3.16** | 4.82** | 5.44** | 401.91 | 263.5** | 250.1** | 8.18** | 12.09** | 20.42** |
| $\delta^2_{GCA}/^2_{SCA}$ | 0.40 | 0.20 | 0.20 | 0.58 | 0.39 | 0.40 | 0.58 | 0.39 | 0.40 |

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

### 3.4 Combining Ability Effects

The best genotypes in both GCA and SCA effects were considered those showing significant positive GCA effects for GYPH, GYPP, EPP, RPE, KPP, I00KW, SDL, SDU, PL-E, CCI, because the high values of these traits are favorable and those showing significant negative GCA effects for DTA, ASI, PH, LANG and LA/1gG, because the low values of these traits are favorable.

#### 3.4.1 GCA effects

For grain yield/ha (Table 4 ), the best inbred lines in GCA effects (descending order), were L28, IL51, L21, L17, L14, IL84, IL15 and IL53, under high plant density, IL51, L28, L14, IL80, L17, IL53, IL15, L21 and IL84 under medium density and IL51, L14, IL53, L17, L28, IL80 and IL151 under low plant density. These lines could be considered good general combiners for GYPH under the respective plant density environment. Therefore, these lines possess additive genes for grain yield and could be used in maize breeding programs for improving PDT.

For testers, the best general combiner for GYPH was Giza 2 under high and medium plant densities and SC10 under low density (Table 4). For other studied traits, the best three inbreds and the worst inbred in GCA effects under low, medium and high density are presented in Table 5. The three best inbreds, identified under high density could be different from those under low-density for most studied traits. Under high-density, the best three inbreds in GCA effects for GYPH and GYPP were L28, IL51 and L21. It is interesting to mention that the inbred L21 was the best inbred line for *per se* performance of GYPH and GYPP under all plant densities. Out of the best inbreds in GCA effects for GYPH and GYPP under HD, L28 and IL51 were also the best inbreds in GCA effects for 100KW, L28, IL51 and L21 for KPP, L28 and IL51 for KPR, IL51 for TBN and L21 for RPE, BR, BL, EPP, TD, TDW and PL-E.

Under high plant density, the best general combiners were IL151 for 6 traits (SDL, SDU, CCI, DTA, LANG and LA/1gG), L14 for 4 traits (SDL, SDU, PL-E, and PH, Inb176) for 4 traits, namely DTA, ASI, PH and LANG, IL80 for 4 traits, namely SDL, SDU, LANG and LA/1gG, IL53 for three characteristics (SDL, SDU and CCI), L17 for two traits (PH and LA/gG), L21 for PL-E, Sk9 for DTA, IL84 for ASI and IL15 for LANG. Miranda and Chaves (1991) concluded that general combining ability could be a good parameter for the selection of the parents to form a useful composite. Inbreds showing the highest significant positive GCA effects for grain yield and its components, SDL, SDU, PL-E and CCI and the lowest significant negative GCA effects for DTA, ASI, PH, LANG and La/1gG traits in the present investigation would be ideal for developing maize composite and/or synthetic varieties of high performance under the high plant density conditions. Moreover, selection may be practiced in such composite or synthetic population to increase gene frequency of the adaptive traits to high plant density and/or to be used as proper sources for isolating better-inbred lines to be used for developing better single or three-way cross hybrids of plant density tolerance.

For testers, the best general combiner under medium and high plant density was Giza 2 cultivar for nine traits, namely GYPH, GYPP, 100-KW, RPE, DTA, ASI, LANG, SDU and LA/1gG and the single cross hybrid SC10 for six characteristics, namely KPP, EPP, PH, SDL, PL-E and CCI.

#### 3.4.2 SCA effects of test crosses

The best three test crosses and the worst testcross in SCA effects under low, medium and high density are presented in Table 6. The three best test crosses, identified under high density were different from those under low-density for the most studied traits.

Out of the best test crosses in SCA effects for GYPH and GYPP under high density, IL84 × SC10, L21 × Sd7, IL151 × Giza2, IL51 × Giza 2 and IL15 × Sd7 were also the best test crosses in SCA effects for 100KW, KPP, RPE, and EPP, *i.e.* for all yield components, IL84 × SC10 for DTA, L21 × Sd7 for PH and IL15 × Sd7 for ASI. The best testcross under high plant density was IL84 x SC10 for DTA, IL17 x Giza2 for ASI, L20 x Giza2 for PH, IL24 x SC10 for LANG, L24 x Giza2 for SDL, IL151 x SC10 and IL53 x Giza2 for SDU, Inb174 x Sd7 for LA/1gG, IL53 x SD7 for PL-E and L18 x Giza2 for CCI. These best crosses in SCA effects could be used in future plant breeding programs for improving plant density tolerance in maize.

For grain yield/ha, the best test cross in SCA effects (Table 7) under elevated plant density was IL84 × SC10 followed by L21 × Sd7, IL151 × Giza2, IL51 × Giza2, IL15 × Sd7, L17 × Giza2, IL24 × SC10, Inb208 × Giza2, L28 × Sd7, L20 × Sd7, L18 × Sd7 and Sk9 × Sd7. It is worthy to mention that the test crosses L21 × Sd7, IL51 × Giza2 and L28 × Sd7 were among the best five test crosses in *per se* performance for GYPH under high plant density.

### 3.5 Heterotic Grouping of Inbred Lines

Twenty-three inbred lines were crossed to three testers: Tester 1 (Sd7), Tester 2 (SC10) and Tester 3 (Giza 2), which were considered belonging to maize heterotic groups 1, 2 and 3, respectively. In heterotic grouping, an inbred line expressed negative SCA effects when crossed to a certain tester implies that both the line and the tester belong to the same heterotic group, while the reverse is true when the SCA effects are positive [18]. Data in Table (7) shows that under HD, five inbred lines belong to heterotic group-1 (L14, IL17, IL51, IL151 and Inb208), five inbreds belong to heterotic group-2 (L18, L20, Sk9, CML104 and Inb176), five inbreds belong to heterotic group-3 (L28, L53, IL15, CML67 and Inb174) and eight inbreds do not belong to anyone of the three groups (L17, L21, IL24, IL53, IL80, IL84, IL171 and Inb213). To maximize genetic diversity and therefore heterosis during hybrid variety development using these inbred lines, one parent should come from one group while the other parent should be from one of the other heterotic groups. In the case of the development of synthetic varieties, inbred lines belonging to the same heterotic group should be used [18]. Likewise, Legesse et al. [40] using population and inbred line testers separated inbred lines into different heterotic groups on the basis of grain yield SCA values. These heterotic groups could serve as sources for developing inbred line and hybrids [18]. Grima et al. [41] reported that based on the SCA effects of crosses, two testers used in their study successfully classified nine out of 25 tested inbred lines into two heterotic groups, A and B: six inbred lines belong to heterotic group A, while the remaining three belong to heterotic group B; these two groups can maximize heterosis by crossing inbred lines belonging to different heterotic groups/unrelated strains. However, in the current study under HD the testers used could not openly discriminate eight inbred lines into distinct heterotic groups. Therefore, further studies should explore the possibility of separating these and other inbred lines into different heterotic groups using the currently used and other more divergent testers.

**Table 4. Estimates of GCA effects for GYPH of the 23 inbreds and 3 testers under low (LD), medium (MD) and high (HD) plant density in 2016 season**

| Inbreds | LD | MD | HD | Inbred | LD | MD | HD |
|---|---|---|---|---|---|---|---|
| L14 | 4.86** | 4.13** | 3.71** | CML67 | -3.41** | -1.50** | -2.91** |
| L17 | 3.86** | 2.11** | 4.62** | CML104 | -3.42** | -3.24** | -3.79** |
| L18 | 1.10 | 1.09** | 0.71 | Inb174 | -2.62** | -2.59** | -3.64** |
| L20 | -2.00** | -2.47** | -3.19** | Inb176 | 0.36 | -1.25** | -2.05** |
| L21 | 0.09 | 1.23** | 6.56** | Inb208 | -4.14** | -5.12** | -5.99** |
| L28 | 3.80** | 7.00** | 11.76** | IL17 | -3.04** | -4.78** | -6.01** |
| L53 | -2.72** | -4.54** | -5.22** | Inb213 | -2.38** | -3.81** | -3.40** |
| IL15 | 0.68 | 1.31** | 2.39** | SE (ĝi) | 0.55 | 0.42 | 0.58 |
| IL24 | 0.22 | -0.18** | -2.71** | SE (ĝi–ĝj) | 0.29 | 0.22 | 0.31 |
| IL51 | 7.81** | 8.35** | 7.89** | Testers | | | |
| IL53 | 4.07** | 1.89** | 2.26** | Sd7 | -1.16** | -0.78** | -0.25 |
| IL80 | 1.46* | 2.16** | 0.25 | SC10 | 0.83** | 0.09 | -0.39 |
| IL84 | 1.24* | 1.20** | 2.75** | Giza 2 | 0.33 | 0.70** | 0.64** |
| IL151 | 0.95 | -0.33 | -1.28* | SE (ĝi) | 0.17 | 0.13 | 0.18 |
| IL171 | -2.88** | -1.23** | -1.05 | SE (ĝi–ĝj) | 0.79 | 0.61 | 0.84 |
| Sk9 | -3.89** | 0.58 | -1.70** | | | | |

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

**Table 5. The 3 best inbreds followed by the worst inbred in GCA effects (ĝ) for all studied traits under low density (LD), medium (MD) and high (HD) plant density**

| LD | | MD | | HD | | LD | | MD | | HD | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Days to 50% anthesis** | | | | | | **Anthesis-silking interval** | | | |
| **L14** | -1.27** | **L28** | -1.35** | **Sk9** | -1.24** | **CML67** | -0.23 | **L53** | -0.34 | **IL17** | -0.37 |
| **IL24** | -1.27** | **Inb176** | -1.46** | **Inb176** | -1.35** | **L20** | -0.34 | **L28** | -0.35 | **IL84** | -0.59** |
| **L28** | -1.61** | **CML67** | -2.01** | **IL151** | -2.13** | **Inb176** | -0.45* | **IL24** | -0.45* | **Inb176** | -0.70** |
| **IL51** | 1.17** | **L17** | 1.43** | **L14** | 1.65** | **CML104** | 0.44* | **Inb208** | 0.66** | **IL171** | 0.63** |
| **SE ($g_i$)** | 0.24 | | 0.23 | | 0.24 | | 0.17 | | 0.19 | | 0.2 |
| **SE (ĝi - ĝj** | 0.12 | | 0.12 | | 0.12 | | 0.09 | | 0.1 | | 0.1 |
| | | **Plant height** | | | | | | **Leaf angle** | | | |
| **CML104** | -8.39 | **Inb176** | -8.52** | **CML104** | -13.25** | **IL15** | -3.65** | **Inb176** | -2.29** | **IL151** | -3.30** |
| **L18** | -9.80* | **CML104** | -9.82** | **L14** | -15.48** | **L21** | -4.65** | **IL15** | -4.85** | **IL15** | -3.60** |
| **IL84** | -18.91** | **L14** | -11.19** | **Inb176** | -15.84** | **IL80** | -7.47** | **IL80** | -6.07** | **IL80** | -5.38** |
| **IL24** | 13.57** | **IL51** | 15.55** | **L18** | 11.93** | **Inb174** | 5.50** | **Inb174** | 6.01** | **Inb174** | 6.44** |
| **SE ($g_i$)** | 4.44 | | 2.66 | | 3.66 | | 0.77 | | 0.42 | | 0.47 |
| **SE (ĝi - ĝj** | 2.32 | | 1.39 | | 1.91 | | 0.4 | | 0.22 | | 0.25 |
| | | **Lower stem diameter** | | | | | | **Upper stem diameter** | | | |
| **IL53** | 3.18** | **IL151** | 2.89** | **IL151** | 2.83** | **IL80** | 3.09** | **IL80** | 3.12** | **IL151** | 2.67** |
| **IL151** | 2.98** | **IL15** | 2.59** | **IL80** | 1.69** | **IL151** | 2.43** | **IL151** | 2.39** | **IL15** | 2.56** |
| **IL15** | 2.94** | **IL53** | 1.95** | **Inb176** | 1.67** | **IL53** | 2.40** | **IL53** | 2.33** | **IL80** | 2.56** |
| **CML67** | -2.97** | **CML67** | -2.15** | **IL17** | -1.79** | **IL171** | -2.41** | **IL24** | -1.92** | **IL17** | -2.15** |
| **SE ($g_i$)** | 0.42 | | 0.21 | | 0.36 | | 0.33 | | 0.17 | | 0.21 |
| **SE (ĝi - ĝj** | 0.22 | | 0.11 | | 0.19 | | 0.17 | | 0.09 | | 0.11 |
| | | **Leaf area to produce 1 g of grain** | | | | | | **Penetrated light at ear** | | | |
| **IL17** | -5.01** | **IL151** | -6.02** | **L17** | -4.97** | **L14** | 19.14** | **L14** | 4.11** | **IL53** | 1.69** |
| **Inb213** | -5.69** | **Inb213** | -6.30** | **IL151** | -7.32** | **L17** | 9.89** | **L21** | 2.69** | **L14** | 1.61** |
| **IL80** | -7.85** | **IL80** | -8.62** | **IL80** | -11.17** | **L21** | 9.78** | **L20** | 2.12** | **L28** | 1.24** |
| **L53** | 8.56** | **L53** | 7.18** | **CML104** | 8.91** | **Sk9** | -7.56** | **IL80** | -2.30** | **IL24** | -1.66** |
| **SE ($g_i$)** | 1.19 | | 0.92 | | 1.13 | 1.78 | | 0.51 | | 0.27 | |
| **SE (ĝi - ĝj** | 0.62 | | 0.48 | | 0.59 | 0.93 | | 0.26 | | 0.14 | |

| LD | | MD | | HD | | LD | | MD | | HD | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Ears per plant** | | | | | | **Rows per ear** | | | |
| **IL80** | 0.08** | **L21** | 0.05** | **Inb213** | 0.02 | **L28** | 0.69** | **IL15** | 1.10** | **IL15** | 1.38** |
| **L18** | 0.06** | **L14** | 0.03** | **L14** | 0.003 | **IL15** | 0.65** | **L28** | 0.95** | **L28** | 1.15** |
| **IL84** | 0.05** | **IL80** | 0.01 | **L17** | 0.003 | **IL80** | 0.61** | **IL53** | 0.58** | **L21** | 0.85** |
| **Inb213** | -0.03* | **Inb213** | -0.01 | **L20** | -0.02** | **CML104** | -0.72** | **Inb213** | -0.74** | **IL151** | -0.80** |
| **SE ($g_i$)** | 0.02 | | 0.01 | | 0 | | 0.13 | | 0.12 | | 0.1 |
| **SE (ĝi - ĝj** | 0.01 | | 0.003 | | 0.002 | | 0.07 | | 0.06 | | 0.05 |
| | | **Kernel per row** | | | | | | **kernels per plant** | | | |
| **IL151** | 4.15** | **IL151** | 3.22** | **L28** | 3.29** | **L14** | 69.5** | **L28** | 64.5** | **L28** | 87.6** |
| **L17** | 2.51** | **IL51** | 3.18** | **IL151** | 2.78** | **IL51** | 66.8** | **IL51** | 53.8** | **L21** | 53.6** |
| **IL51** | 2.11** | **L28** | 2.22** | **IL51** | 2.70** | **IL151** | 64.8** | **IL15** | 33.5** | **IL51** | 46.0** |
| **Inb208** | -3.26** | **Inb208** | -3.97** | **Inb208** | -3.89** | **Inb208** | -79.6** | **Inb208** | -61.2** | **Inb208** | -60.0** |
| **SE ($g_i$)** | 0.44 | | 0.31 | | 0.35 | | 10.77 | | 5.99 | | 6.35 |
| **SE (ĝi - ĝj** | 0.23 | | 0.16 | | 0.18 | | 5.62 | | 3.13 | | 3.31 |
| | | **100-kernel weight** | | | | | | **Grain yield per plant** | | | |
| **IL51** | 5.00** | **IL51** | 4.06** | **L28** | 3.48** | **IL51** | 54.6** | **IL51** | 39.0** | **L28** | 41.2** |
| **L17** | 3.00** | **L14** | 2.76** | **IL51** | 3.08** | **L14** | 34.4** | **L28** | 32.7** | **IL51** | 27.6** |
| **L14** | 1.85** | **L28** | 2.58** | **L14** | 2.77** | **IL53** | 28.4** | **L14** | 19.0** | **L21** | 23.0** |
| **IL171** | -2.47** | **L53** | -3.06** | **L53** | -2.80** | **Inb208** | -29.0** | **Inb208** | -23.9** | **IL17** | -21.0** |
| **SE ($g_i$)** | 0.31 | | 0.19 | | 0.25 | | 3.87 | | 1.94 | | 2.05 |
| **SE (ĝi - ĝj** | 0.16 | | 0.1 | | 0.13 | | 2.02 | | 1.01 | | 1.07 |

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

**Table 6. The best three test crosses followed by the worst one in SCA effects ($\hat{s}_{ij}$) for all studied traits under low (LD), medium (MD) and high (HD) plant density**

| LD | | MD | | HD | | LD | | MD | | HD | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Days to 50% anthesis** | | | | | | **Days to 50% silking** | | | | | |
| IL84×Gz2 | -2.26** | IL15×SC10 | -1.44** | L21×SC10 | -1.42** | L20×Gz2 | -2.19** | IL84×Gz2 | -1.64** | Inb213×Gz2 | -1.40** |
| L20×Gz2 | -2.27** | CML67×Sd7 | -1.72** | Inb208×Gz2 | -1.54** | IL84×Gz2 | -2.52** | Inb213×Gz2 | -2.42** | Inb176×Sd7 | -1.43** |
| CML104×Sd7 | -2.34** | Inb176×Sd7 | -1.94** | IL84×SC10 | -2.20** | IL80×Sd7 | -2.54** | CML67×Sd7 | -2.65** | Inb208×Gz2 | -1.63** |
| L20×SC10 | 2.27** | IL84×Sd7 | 2.17** | IL84×Sd7 | 2.18** | L20×SC10 | 2.95** | CML67×SC10 | 2.18** | L21×Gz2 | 2.04** |
| SE (Sij) | 0.33 | | 0.33 | | 0.33 | | 0.37 | | 0.34 | | 0.34 |
| SE (Sij - Skl) | 0.59 | | 0.58 | | 0.59 | | 0.66 | | 0.59 | | 0.60 |
| SE (Sij - Sik) | 0.68 | | 0.67 | | 0.68 | | 0.77 | | 0.69 | | 0.69 |
| **Anthesis-silking interval** | | | | | | **Plant height** | | | | | |
| Inb213×Gz2 | -0.82** | Inb208×SC10 | -0.69* | IL84×Gz2 | -0.64* | L53×SC10 | -16.90* | IL84×Sd7 | -11.61** | L18×SC10 | -10.65* |
| Inb176×SC10 | -0.88** | CML67×Sd7 | -0.95** | IL15×Sd7 | -0.72* | Inb208×Sd7 | -19.13** | IL151×Gz2 | -11.67** | L21×Sd7 | -15.70** |
| L18×Sd7 | -1.07** | Inb213×Gz2 | -1.36** | IL17×Gz2 | -0.86** | IL84×Sd7 | -28.83** | L20×Gz2 | -12.23** | L20×Gz2 | -22.21** |
| Inb213×Sd7 | 1.37** | CML67×Gz2 | 0.86** | IL84×SC10 | 0.81** | IL84×Gz2 | 27.73** | IL151×Sd7 | 19.31** | IL151×Sd7 | 19.11** |
| SE (Sij) | 0.24 | | 0.26 | | 0.28 | | 6.28 | | 3.77 | | 5.18 |
| SE (Sij - Skl) | 0.43 | | 0.47 | | 0.49 | | 11.12 | | 6.67 | | 9.17 |
| SE (Sij - Sik) | 0.50 | | 0.54 | | 0.57 | | 12.84 | | 7.70 | | 10.59 |
| **Lower stem diameter** | | | | | | **Upper stem diameter** | | | | | |
| IL84×SC10 | 2.65** | IL53×SC10 | 1.78** | IL24×Gz2 | 2.77** | Inb208×SC10 | 2.93** | L28×Sd7 | 1.43** | IL151×SC10 | 1.56** |
| IL24×SC10 | 2.60** | IL24×Gz2 | 1.55** | IL53×SC10 | 2.75** | L17×SC10 | 2.43** | IL24×Gz2 | 1.34** | IL53×Gz2 | 1.56** |
| Inb208×Gz2 | 2.57** | Inb208×SC10 | 1.36** | Inb213×Sd7 | 1.75** | L28×Sd7 | 2.37** | IL84×SC10 | 1.07** | CML104×Gz2 | 1.42** |
| Inb208×Sd7 | -2.68** | IL24×Sd7 | -2.56** | IL53×Sd7 | -2.80** | Inb208×Gz2 | -2.76** | L53×Gz2 | -1.39** | L53×Gz2 | -1.88** |
| SE (Sij) | 0.59 | | 0.3 | | 0.51 | | 0.46 | | 0.24 | | 0.29 |
| SE (Sij - Skl) | 1.05 | | 0.53 | | 0.90 | | 0.82 | | 0.42 | | 0.52 |
| SE (Sij - Sik) | 1.21 | | 0.61 | | 1.04 | | 0.95 | | 0.49 | | 0.60 |
| **Leaf angle** | | | | | | **Leaf area to produce 1 g of grain** | | | | | |
| CML104×Sd7 | -4.11** | IL17×Gz2 | -2.75** | IL84×Gz2 | -3.83** | L14×Gz2 | -7.34** | Inb176×Sd7 | -7.81** | IL51×Gz2 | -10.51** |
| L14×SC10 | -5.70** | Inb208×Sd7 | -2.78** | Sk9×Gz2 | -4.27** | IL84×SC10 | -9.45** | L14×Gz2 | -8.06** | CML67×SC10 | -10.58** |
| Sk9×Gz2 | -6.48** | Sk9×Gz2 | -4.27** | IL24×SC10 | -4.41** | IL80×SC10 | -11.86** | CML104×Sd7 | -8.70** | Inb174×Sd7 | -13.35** |
| IL171×Sd7 | 6.40** | Inb174×SC10 | 3.65** | IL24×Gz2 | 4.39** | L20×SC10 | 10.06** | L20×SC10 | 10.88** | CML67×Gz2 | 15.31** |
| SE (Sij) | 1.08 | | 0.59 | | 0.67 | | 1.68 | | 1.31 | | 1.6 |
| SE (Sij - Skl) | 1.92 | | 1.05 | | 1.18 | | 2.98 | | 2.31 | | 2.84 |
| SE (Sij - Sik) | 2.22 | | 1.21 | | 1.37 | | 3.44 | | 2.67 | | 3.27 |
| **Penetrated light ear** | | | | | | **Penetrated light at bottom** | | | | | |

| LD | | MD | | HD | | LD | | MD | | HD | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| IL171×Sd7 | 21.45** | IL51×SC10 | 3.21** | IL53×Sd7 | 2.16** | CML104×Sd7 | 2.89** | CML104×Sd7 | 1.50** | IL53×SC10 | 1.07** |
| L14×Gz2 | 17.74** | L17×Sd7 | 3.16** | IL17×Gz2 | 1.85** | Inb176×Gz2 | 2.10** | L20×Gz2 | 1.33** | L21×Gz2 | 0.94** |
| L18×SC10 | 9.92** | IL17×Gz2 | 3.10** | IL51×SC10 | 1.75** | IL51×Sd7 | 1.46** | IL84×SC10 | 1.24** | Inb174×Sd7 | 0.76** |
| L14×Sd7 | -13.60** | L20×Gz2 | -4.47** | Inb208×Sd7 | -2.15** | Inb176×Sd7 | -1.94** | L20×SC10 | -1.42** | IL53×Sd7 | -1.05** |
| SE (Sij) | 2.52 | | 0.72 | | 0.39 | | 0.36 | | 0.18 | | 0.17 |
| SE (Sij - Skl) | 4.47 | | 1.27 | | 0.69 | | 0.63 | | 0.33 | | 0.31 |
| SE (Sij - Sik) | 5.16 | | 1.47 | | 0.79 | | 0.73 | | 0.38 | | 0.35 |
| | | **Chlorophyll concentration** | | | | | | **Ears per plant** | | | |
| L21×SC10 | 4.19** | L21×SC10 | 5.73** | L18×Gz2 | 7.26** | L18×SC10 | 0.16** | L21×SC10 | 0.11** | Inb213×SC10 | 0.03** |
| IL51×Gz2 | 3.96** | Inb213×Sd7 | 4.00** | L17×SC10 | 5.60** | L14×SC10 | 0.13** | L14×SC10 | 0.07** | L20×Sd7 | 0.02** |
| L14×SC10 | 3.65** | L14×SC10 | 3.81** | L20×Sd7 | 4.79** | L17×SC10 | 0.11** | IL80×Sd7 | 0.04** | L20×Gz2 | 0.02** |
| L14×Sd7 | -5.25** | L21×Gz2 | -5.75** | L18×SC10 | -7.34** | L18×Gz2 | -0.09** | L21×Gz2 | -0.06** | L20×SC10 | -0.05** |
| SE (Sij) | 0.84 | | 0.5 | | 0.78 | | 0.02 | | 0.01 | | 0.01 |
| SE (Sij - Skl) | 1.49 | | 0.89 | | 1.39 | | 0.04 | | 0.01 | | 0.01 |
| SE (Sij - Sik) | 1.72 | | 1.02 | | 1.60 | | 0.04 | | 0.02 | | 0.01 |
| | | **Rows per ear** | | | | | | **kernels per plant** | | | |
| CML67×Gz2 | 1.33** | L28×Sd7 | 1.63** | Inb208×Gz2 | 1.51** | IL151×Gz2 | 125** | IL84×SC10 | 75.2** | IL84×SC10 | 95.0** |
| Inb213×Sd7 | 1.25** | IL15×SC10 | 1.51** | L28×Sd7 | 1.28** | IL84×SC10 | 75.3** | L28×Sd7 | 70.3** | IL151×Gz2 | 61.0** |
| L28×Sd7 | 1.14** | IL51×Gz2 | 1.15** | IL51×Gz2 | 1.16** | L14×SC10 | 61.5** | L14×SC10 | 60.7** | Inb208×Gz2 | 58.6** |
| IL84×Gz2 | -1.12** | IL15×Gz2 | -1.67** | IL15×Gz2 | -1.62** | IL151×SC10 | -91.3** | L21×Gz2 | -64.6** | IL15×Gz2 | -72.3** |
| SE (Sij) | 0.19 | | 0.17 | | 0.15 | | 15.22 | | 8.47 | | 8.98 |
| SE (Sij - Skl) | 0.34 | | 0.31 | | 0.26 | | 26.96 | | 14.99 | | 15.90 |
| SE (Sij - Sik) | 0.39 | | 0.35 | | 0.30 | | 31.13 | | 17.31 | | 18.36 |
| | | **100-kernel weight** | | | | | | **Grain yield per plant** | | | |
| IL24×SC10 | 3.50** | IL24×SC10 | 4.78** | L28×SC10 | 3.86** | IL151×Gz2 | 39.7** | IL84×SC10 | 31.1** | IL84×SC10 | 39.2** |
| IL151×SC10 | 3.24** | Sk9×Sd7 | 4.50** | IL24×SC10 | 3.73** | IL84×SC10 | 37.3** | IL151×Gz2 | 24.0** | L21×Sd7 | 31.6** |
| Inb208×Gz2 | 3.20** | IL15×Sd7 | 3.71** | Sk9×Sd7 | 3.70** | IL53×SC10 | 35.2** | CML67×Sd7 | 21.8** | IL151×Gz2 | 23.4** |
| Inb208×Sd7 | -3.66** | Sk9×SC10 | -4.08** | Sk9×SC10 | -4.37** | IL151×Sd7 | -31.7** | IL51×Sd7 | -33.0** | IL15×Gz2 | -25.4** |
| SE (Sij) | 0.43 | | 0.27 | | 0.35 | | 5.47 | | 2.74 | | 2.89 |
| SE (Sij - Skl) | 0.77 | | 0.48 | | 0.62 | | 9.68 | | 4.85 | | 5.13 |
| SE (Sij - Sik) | 0.89 | | 0.56 | | 0.71 | | 11.18 | | 5.60 | | 5.92 |

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

**Table 7. Estimates of SCA effects (ŝij) for GYPH of the test crosses under low (LD), medium (MD) and high (HD) plant density and heterotic groups under HD**

| | LD | | | MD | | | HD | | | Heterotic group |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Sd7** | **SC10** | **Giza2** | **Sd7** | **SC10** | **Giza2** | **Sd7** | **SC10** | **Giza2** | |
| L14 | -1.65* | 4.60** | -2.95** | -4.16** | 1.85** | 2.31** | -2.17* | 0.30 | 1.87* | **1** |
| L17 | -2.05* | -0.28 | 2.32** | -0.54 | -1.31* | 1.84** | -2.07** | -3.41** | 5.48** | **--** |
| L18 | 0.25 | 2.27** | -2.52** | 2.45** | -0.70 | -1.74** | 3.87** | -2.36** | -1.52 | **2** |
| L20 | 3.73** | -2.79** | -0.94 | 4.19** | -3.94** | -0.25 | 3.65** | -4.23** | 0.57 | **2** |
| L21 | 1.98* | 0.13 | -2.11** | 2.24** | 0.30 | -2.53** | 9.04** | -5.89** | -3.16** | **--** |
| L28 | 2.21** | -4.31** | 2.10** | 3.97** | 0.81 | -4.77** | 4.62** | 0.72 | -5.34** | **3** |
| L53 | 0.75 | -2.53** | 1.78* | 0.11 | 0.90 | -1.02 | 1.51 | 0.99 | -2.51** | **3** |
| IL15 | 1.84* | 0.27 | -2.11** | 4.12** | 0.64 | -4.76** | 5.91** | 1.34 | -7.26** | **3** |
| IL17 | 1.36 | -0.18 | -1.18 | -1.26* | 0.87 | 0.39 | -1.86* | 0.20 | 1.66* | **1** |
| IL24 | 0.41 | 2.14* | -2.55** | -1.27* | 4.15** | -2.87** | -2.63** | 5.22** | -2.59** | **--** |
| IL51 | -4.08** | -0.35 | 4.42** | -7.07** | 3.43** | 3.63** | -6.34** | 0.15 | 6.19** | **1** |
| IL53 | -0.51 | 5.03** | -4.53** | 1.54* | -1.35* | -0.20 | -0.70 | 0.68 | 0.02 | **--** |
| IL80 | 2.80** | -1.01 | -1.79* | -0.98 | -2.08** | 3.07** | -0.12 | -0.76 | 0.88 | **--** |
| IL84 | -2.65** | 5.34** | -2.69** | -2.80** | 6.66** | -3.86** | -5.92** | 11.20** | -5.28** | **--** |
| IL151 | -4.53** | -1.15 | 5.67** | -5.32** | 0.16 | 5.15** | -6.77** | 0.10 | 6.67** | **1** |
| IL171 | 0.27 | -0.96 | 0.69 | -0.25 | -1.26* | 1.51* | 0.40 | -1.07 | 0.66 | **--** |
| Sk9 | -0.63 | -0.75 | 1.37 | 2.74** | -3.57** | 0.84 | 3.64** | -3.99** | 0.35 | **2** |
| CML67 | 0.97 | -2.16** | 1.19 | 4.68** | -3.56** | -1.12 | 2.64** | -0.82 | -1.82* | **3** |
| CML104 | 0.25 | -1.78* | 1.53 | 0.30 | -3.74** | 3.45** | 0.45 | -2.15* | 1.69* | **2** |
| Inb174 | 2.44** | -0.87 | -1.57* | 1.70** | 0.56 | -2.27** | 0.62 | 1.60 | -2.23** | **3** |
| Inb176 | -0.18 | -1.45 | 1.62* | 1.82** | -1.99** | 0.16 | 0.43 | -2.49** | 2.06* | **2** |
| Inb208 | -4.36** | 1.01 | 3.35** | -4.90** | 1.56* | 3.35** | -7.01** | 2.22** | 4.79** | **1** |
| Inb213 | 1.37 | -0.25 | -1.12 | -1.32* | 1.61** | -0.28 | -1.20 | 2.41** | -1.21 | **--** |
| (Sij) | | 0.78 | | | 0.6 | | | 0.83 | | |
| SE (Sij - Skl) | | 1.38 | | | 1.06 | | | 1.46 | | |
| SE (Sij - Sik) | | 1.59 | | | 1.22 | | | 1.69 | | |

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

## 4. CONCLUSIONS

Line x tester analysis of this study concluded that both additive and non-additive gene effects play important roles in controlling the inheritance of all studied maize traits under all plant densities (LD, MD, and HD). Results suggested the existence of a greater portion of non-additive (dominance) than the additive variance in controlling the inheritance of studied traits under elevated plant density, so the breeding method of choice for improving maize plant density tolerance (PDT) would be heterosis breeding. The best general combiners for GYPH under increased plant density were L28, IL51, L21, L17, L14, IL84, IL15, and IL53. These inbreds would be ideal for developing plant density tolerant composites and/or synthetics, which in turn could be used for isolating higher density tolerant inbreds and hybrids. The best test-crosses in SCA effects for GYPH under increased plant density IL84 × SC10, L21 × Sd7, IL151 × Giza2, IL51 × Giza2, IL15 × Sd7, and L17 × Giza2 constitute a source of valuable genetic material that could be used for future breeding work. In general, the results of this study could be useful for researchers who need to develop high yielding varieties of maize particularly under high plant density in Egypt.

## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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