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Optimum Plant Density for Maximizing Yield of Six Inbreds and their F1 Crosses of Maize (*Zea mays* L.)

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Authors' contributions

This work was carried out in collaboration between all authors. Author AMMA-N designed the study, wrote the protocol and the first draft of the manuscript. Authors RS and MMMA managed the literature searches and discussed the conclusion. Author THA-K managed the analyses of the study. All authors read and approved the final manuscript.

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ABSTRACT

One of the reasons Egypt do not achieve very high maize crop yield is that cultivars used commercially are bred and grown under low plant density (ca 20,000 plants/ fed; one fed= 4200 m^2). Therefore, the objective of the present study was to identify maize genotypes of tolerance to high plant density in order to enhance grain productivity from unit area. Six inbred lines of maize differing in adaptive traits to high plant density were crossed in a diallel fashion. Higher plant densities (30,000 and 40,000 plants/fed) caused a significant increase in grain yield/fed (GYPF) compared with the low-density (20,000 plants/fed) by 5.7 and 6.3% for inbreds and 14.0 and 27.6% for F_1 crosses, respectively. The inbreds L17, L18 and L53 proved to be tolerant (T), while the L29, L54 and L55 inbreds were sensitive (S) to high density. The T×T group of crosses exhibited better performance in most studied traits than T×S and S×S groups of crosses under the three plant densities. The cross L17 × L54 came in the 1st rank under all plant densities for both grain yield/plant and grain yield/fed; this cross gave 42.7 ard/fed (ca. 14 ton/ha) [one ard (ardab) = 140 kg] under the high plant density (40,000 plants/fed) and showed a significant superiority of 28.6% over the best check cultivar in this study (SC 2066) under this density. The crosses L17 × L18, L29 × L55, L53 × L54 and L53 × L55 came in the 2nd, 3rd, 4th and 5th ranks, for grain yield/fed under all plant densities. Grain yield/fed of all studied genotypes showed a quadratic response of increase to

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the increase in densities from low to high levels, except L29, L54 and L55 inbreds, which showed a quadratic response of decrease. Optimum plant density in this study differed from genotype to genotype and was the lowest (20,000 plants/fed) for the three inbreds L29, L54 and L55, but was the medium one (30,000 plants/fed) for the inbred L53 and the two crosses L17 × L29 and L54 × L55 and was the highest density (40,000 plants/fed) for the inbreds L17 and L18 and the rest of F_1 crosses.

Keywords: Zea mays; high-density tolerance; regression; adaptive traits; crop yield.

1. INTRODUCTION

One of the potential methods to maximize total production of maize grains in Egypt is to raise productivity/land unit area and thus upgrade our global rank in average productivity, especially with the irrigation system used in Egypt and good weather and soil conditions that suit maize compared to other regions in the world. Grain yield/land unit area is the product of grain yield/plant and number of plants/unit area [1].

Trying to grow hybrid cultivars released by National Maize Breeding Program (NMBP) at high plant densities causes a drastic reduction in grain yield/plant and consequent reduction in grain yield/unit area. The reason is probably due to the fact that these cultivars are not tolerant to high plant densities, due to their tallness, one-eared, decumbent leaf and large-size type plants. On the contrary, 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 [2]. Radenovic et al. [3] pointed out that maize genotypes with erect leaves are very desirable for increasing the population density due to better light interception.

To increase maize grain yield/unit area in Egypt, breeding programs should be directed towards the development of inbreds and hybrids that are characterized with adaptive traits to high plant density tolerance. Although high plant density results in interplant competition (especially for light, water and nutrients), which affects vegetative and reproductive growth of maize [4,5], 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. Therefore, the objectives of present study were: (i) attempting to develop tolerant maize genotypes to high plant density and of high responsiveness to the improved environments, (ii) studying the effects of elevating plant density on traits of inbreds and hybrids under investigation, (iii) determining the optimum plant density for maximizing the grain yield/unit area of studied genotypes and (iv) recognizing the maize traits of strong associations with grain yield under 3 studied plant densities.

2. MATERIALS AND METHODS

This study was carried out in 2011, 2012 and 2013 years at the Agricultural Experiment and Research Station of the Faculty of Agriculture, Cairo University, Giza, Egypt, located at 30° 02' N latitude, 31° 13' E longitude and altitude of 22.50 m. Six maize (*Zea mays* L.) inbred lines in the 6th selfed generation (Table 1), showing clear differences in performance and general combining ability for grain yield/feddan (fed) and prolificacy under high plant density were chosen as parents of diallel crosses. In 2011 season, all possible diallel crosses (except reciprocals) were made among the six parents, and seeds of the 15 direct F_1 crosses were obtained.

Two field evaluation experiments were carried out in 2012 and 2013 years; the date of sowing was 5th of April and 1st of May, respectively. Each experiment included 15 F_1 crosses, their 6 parents and 5 check cultivars, *viz.,* SC 10 (white grains), SC 128 (white grains) and SC 173 (yellow grains) obtained from the Agricultural Research Center (ARC) and SC 2055 (yellow grains) and SC 2066 (yellow grains) obtained from Hi-Tech Company-Egypt. Evaluation in each season was carried out under three plant densities, *viz.*, high- (HD), medium- (MD) and low- (LD) plant density (40,000, 30,000 and 20,000 plant/fed, respectively). A split plot design was used in the experiment assigning plant density in the main plot and genotypes in the sub-plot. Each experimental plot size was 4m long and 0.7 m width. Seeds were sown in hills at 15, 20 and 30 cm apart. Before 1st irrigation, thinning was done keeping one plant/hill to achieve the three plant densities. The soil of the experimental site was clay loam. All other agricultural practices were followed according to the recommendations of ARC, Egypt. Fertilization was performed with Calcium Super Phosphate 15.5% with a rate of 30 kg P_2O_5/fed at soil preparation and before sowing, and Urea 46% with a rate of 120 kg N/fed splitted into two equal doses; 1st dose before 1st irrigation and 2nd dose before 2nd irrigation. Weed control was performed chemically by adding Stomp herbicide before 1st irrigation and just after sowing and manually by hoeing twice; the 1st before the 2nd irrigation and the 2nd before the 3rd irrigation. Irrigation was performed by flooding after 3 weeks for the 2nd irrigation and each 12 days for the next irrigations. Pest control was performed when required *via* spraying plants with Lannate 90% against corn borers.

Data were collected on days to 50% silking (DTS), anthesis-silking interval (ASI), plant height (PH), ear position (EP), percent of barren stalks (BS), leaf angle (LANG) and chlorophyll concentration index (CCI) measured by Chlorophyll Concentration Meter, Model CCM 200 as the ratio of transmission at 931 nm to 653 nm through the leaf of top-most ear (http://www.apogeeinstruments.co.uk/apogee-instruments-chlorophyll-content-meter-technical-information/). At 50 and 80 days of sowing, light intensity was measured and then penetrated light inside the canopy was calculated for each genotype, by using Lux-meter apparatus. The light intensity in lux was measured at 12 am (noon) at the top of the plant and at the base of top-most ear. Penetrated light, at 50 (PL-M50) and 80 days (PL-M80) after sowing, 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:

$$\text{Penetrated light \%} = 100 \times \frac{\text{Light intensity at the base of top} - \text{most ear}}{\text{Light intensity at the top of the plant}}$$

At harvest, number of ears per plant (EPP), number of kernels per plant (KPP), 100-kernel weight (100-KW), grain yield/plant (GYPP), grain yield/feddan (GYPF), total above ground dry matter plant^{-1} (TDM) and harvest index (HI) were measured.

2.1 Biometrical Analysis

Combined analysis of variance of the split plot design across the two years was performed if the homogeneity of variance test was non-significant. LSD values were calculated to test the significance of differences between means according to Snedecor and Cochran [6]. Grouping of genotypes based on tolerance and responsiveness was performed according to Sattelmacher et al. [7] and Worku et al. [8]. For each genotype or group of genotypes, regression function was performed for plant density effects by Microsoft Office Excel 2010 computer software. Genetic correlation coefficients were calculated between grain yield (/plant and /feddan) and other studied traits under each plant density according to Singh and Chaudhary [9] using the following formula: $\mathbf{r_g = \delta^2_{gxy} / (\delta^2_{gx} \cdot \delta^2_{gy})^{1/2}}$, where: $\boldsymbol{\delta^2_{gxy}}$ = the genotypic covariance between traits, X and Y and $\boldsymbol{\delta^2_{gx}}$ and $\boldsymbol{\delta^2_{gy}}$ = the genotypic variance of the two traits, X and Y, respectively.

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)	rolificacy	Productivity under high density	Barren stalks % under high density	Plant height
L17-Y	SC 30N11	Pion. Int. Co.	Prolific	High	Low	Short
L18-Y	SC 30N11	Pion. Int. Co.	Prolific	High	Low	Short
L53-W	SC 30K8	Pion. Int. Co.	Prolific	High	Low	Short
L29-Y	Pop 59	ARC-Thailand	Non prolific	Low	High	Tall
L54-W	SC 30K8	Pion. Int. Co.	Non prolific	Low	High	Tall
L55-W	SC 30K8	Pion. Int. Co.	Non prolific	Low	High	Tall

ARC = agricultural research center, pion. int. Co. = pioneer international company in egypt, SC = single cross, W = white grains and Y = yellow grains

3. RESULTS AND DISCUSSION

3.1 Analysis of Variance

Combined analysis of variance across years (Y) of the split plot design for the 26 studied genotypes (G) of maize (6 inbreds +15 F_1's + 5 check commercial single-cross hybrids) under three plant densities (D) is presented in Table 2.

Mean squares due to years were significant ($P \leq 0.01$) for all studied traits, except for ASI, plant height, EPP and 100-KW, indicating significant effect of climatic conditions on most studied traits. Mean squares due to plant densities and genotypes were significant ($P \leq 0.01$) for all studied characters, indicating that each of the two factors in this study, *i.e.,* plant density or genotype has an obvious effect on all studied traits. Mean squares due to the 1st order interaction, *i.e.,* D×Y, G×Y and G×D were significant ($P \leq 0.01$) for all studied traits, except for DTS, ASI and BS for D×Y, DTS, ASI, BS, EPP, KPP and HI for G×Y. Mean squares due to the 2nd order interaction G×D×Y were insignificant for all studied traits, except for PH, EP, LANG, PL-M50 and PL-M80, KPP and GYPP, which were significant, indicating that the rank of maize genotypes differ from one density to another and from one year to another and the possibility of selection for improved performance under a specific plant density as proposed by Kamara et al. [10] and Al-Naggar et al. [11]

Table 2. Significance of mean squares in the analysis of variance of the split plot design for studied maize genotypes under three plant densities (D) combined across two years

SOV	**df**	**Significance of mean squares**					
		DTS	**ASI**	**PH**	**EP**	**BS**	**LANG**
Years (Y)	1	**	ns	ns	**	**	**
Densities (D)	2	**	**	**	**	**	**
D×Y	2	ns	ns	**	**	ns	**
Error	8	1.28	0.005	64.1	29.6	0.01	1.6
Genotypes (G)	25	**	**	**	**	**	**
G×Y	25	ns	ns	**	**	ns	**
G×D	50	**	**	**	**	**	**
G×D×Y	50	ns	ns	**	**	ns	**
Error	300	1.26	0.0006	54.1	23.5	0.002	0.6
		CCI	**PL-M50**	**PL-M80**	**EPP**	**KPP**	**100-KW**
Years (Y)	1	**	**	**	ns	**	ns
Densities (D)	2	**	**	**	**	**	**
D×Y	2	**	**	**	**	**	**
Error	8	11.4	24.2	4.6	0.01	28090.1	2.8
Genotypes (G)	25	**	**	**	**	**	**
G×Y	25	**	**	**	ns	ns	**
G×D	50	**	**	**	**	**	**
G×D×Y	50	ns	**	**	ns	*	ns
Error	300	6.5	4.3	2.2	0.007	3228.5	1.5
		GYPP	**GYPF**	**TDM**	**HI**		
Years (Y)	1	**	**	**	**		
Densities (D)	2	**	**	**	**		
D×Y	2	**	**	**	**		
Error	8	252.4	6.9	175.5	7.5		
Genotypes (G)	25	**	**	**	**		
G×Y	25	**	**	**	ns		
G×D	50	**	**	**	**		
G×D×Y	50	**	ns	ns	ns		
Error	300	27.1	0.8	23.3	1.4		

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

3.2 Effect of Plant Density

Mean grain yield/plant was significantly ($P \leq 0.01$) reduced due to elevating the plant density from 20,000 (recommended density) to 30,000 and 40,000 plants/fed, by 42.5 and 36.0% for inbreds and 32.5 and 32.5% for F_1 crosses, respectively (Table 3). This reduction was associated with significant reductions in all yield components, namely EPP (9.1 and 18.2% for parents and 8.3 and 25.0% for F_1 crosses), KPP (16.5 and 31.5% for parents and 19.1% and 35.5% for F_1´s) and 100-KW (9.0 and 17.2% for parents and 4.1 and 13.2% for F_1 crosses) at plant density of 30,000 and 40,000 plants/fed, respectively as compared with 20,000 plants/fed, indicating the importance of number of kernels and number of ears/plant as indicators of tolerance to high-density. This conclusion is confirmed by Al-Naggar et al. [11], Vega et al. [12] and Sangoi et al. [13]. The reduction in number of kernels/plant was 1.8 and 2.7 fold greater than reduction in 100-kernel weight under high plant density (40,000 plants/fed) for inbreds and hybrids, respectively, which is consistent with previous investigators on high-density stress in maize [11,14,15]. Elevating plant density from 20,000 to 30,000 and 40,000 plants/fed also resulted in significant reductions of TDM (13.7 and 22.0% for parents' and 14.4 and 22.1% for crosses), HI (13.1 and 19.2% for parents' and 10.8 and 14.4% for crosses), LANG (5.6 and 8.6% for parents' and 10.8 and 13.5% for crosses), CCI (18.5 and 16.2% for parents' and 11.0 and 23.0% for crosses), PL-M50 (13.0 and 25.3% for parents' and 18.9 and 32.9% for crosses), PL-M80 (10.2 and 22.0% for parents' and 16.7 and 30.7% for crosses) and DTS (1.2 and 3.0% for parents' and 2.7 and 4.4% for crosses) at density of 30,000 and 40,000 plants/fed, respectively.

The reductions in TDM, HI, CCI, PL-M50, PL-M80 and yield components are expected and may be attributed to the increase in competition between plants at higher densities for light, nutrients and water [16,17,18]. A small but significant reduction in leaf angle (erectness) and DTS (earliness) is the result of increasing of plant density in this study, which is consistent with Hashemi and Herbert [19], Tokatlis and Koutroubas [20] and Al-Naggar et al. [21]. Differences in conclusions regarding the effects of high density on LANG and DTS may be attributed to the differences in the genetic background of the plant materials and/or climatic conditions prevailing throughout the growing seasons of different studies.

On the contrary, higher plant densities (30,000 and 40,000 plants/fed) caused significant increases in grain yield/fed (GYPF) compared with the low-density by 5.7 and 6.3% for inbreds and 14.0 and 27.6% for F_1 crosses, respectively (Table 3). The increase in GYPF due to increasing plant density for F_1´s was 2.46 and 4.38 fold greater than the increase for inbred parents under 30,000 and 40,000 plants/fed, respectively, indicating that heterozygotes (F_1 crosses) are more adapted to high plant density than homozygotes (inbreds) in maize. This conclusion was also confirmed by previous researchers [17,22, 23,24].

In contrast, Monneveux et al. [25] reported that inbred lines yielded more than open-pollinated varieties and hybrids under high population density, probably because of lower vigor and lower competition between plants. Moreover, high density caused a significant increase in ASI by 0.6 and 1.6 days (18.8 and 50.0%) in parents and 0.2 and 0.7 days (12.5 and 29.2%) in crosses, PH by 4.5 and 12.3 cm (2.4 , 6.5%) for parents and 5.6 and 22.1 cm (2.6 and 10.2%) for crosses, EP by 9.9 and 20.3% for parents and 5.2 and 11.0% for crosses, and BS by 36.3 and 50.7 for parents and 16.1 and 35.7 for crosses under 30,000 and 40,000 plants/fed, respectively.

In general, the increase of ASI due to high plant density, in this study was less than that reported by other investigators. Bolanos and Edmeades [26] reported that ASI increase due to elevating plant density ranged from 4 to 10 days. Tokatlis and Koutroubas [20] reported that the time gap between pollen shedding and silking increased from 0 to 9 days by increasing plant density from 5-20 plant m^{-2}. Delayed silking and ASI period as symptoms of interplant competition were demonstrated by a variety of studies [27,28]. These two traits (DTS and long ASI) are also considered as indicators of barrenness or high-density intolerance [24,26,28,29,30].

Several workers showed that the separation of reproductive organs in maize may also account for its sensitivity to stress at flowering [31,32,33]. Delayed silking under conditions of drought or high-density is related to less assimilates being partitioned to the growing ears around anthesis, which results in lower ear growth rates,

Table 3. Means of studied traits under 20,000 (low-D), 30,000 (medium-D) and 40,000 (high-D) plants/fed and relative change (%) compared to the low-D combined across two seasons

Traits	Parameters	Parents			Crosses		
		Low-D	Medium-D	High-D	Low-D	Medium-D	High-D
DTS (day)	Mean	72.5	71.6	70.3	70.3	68.4	67.2
	Change	-	-1.2**	-3.0**	-	-2.7**	-4.4**
ASI (day)	Mean	3.2	3.8	4.8	2.4	2.7	3.1
	Change	-	18.8**	50.0**	-	12.5**	29.2**
PH (cm)	Mean	190.0	194.5	202.3	216.6	222.2	238.7
	Change	-	2.4**	6.5**	-	2.6**	10.2**
EP (%)	Mean	42.4	46.6	51.0	46.4	48.8	51.5
	Change	-	9.9**	20.3**	-	5.2**	11.0**
BS (%)	Mean	14.6	19.9	22.0	5.6	6.5	7.6
	Change	-	36.3**	50.7**	-	16.1**	35.7**
LANG (o)	Mean	30.4	28.7	27.8	34.2	30.5	29.6
	Change	-	-5.6**	-8.6**	-	-10.8**	-13.5**
CCI (%)	Mean	47.6	38.8	39.9	53.4	47.5	41.1
	Change	-	-18.5**	-16.2**	-	-11.0**	-23.0**
PL-M50 (%)	Mean	15.4	13.4	11.5	14.3	11.6	9.6
	Change	-	-13.0**	-25.3**	-	-18.9**	-32.9**
PL-M80 (%)	Mean	12.7	11.4	9.9	11.4	9.5	7.9
	Change	-	-10.2**	-22.0**	-	-16.7**	-30.7**
EPP	Mean	1.1	1.0	0.9	1.2	1.1	0.9
	Change	-	-9.1*	-18.2*	-	-8.3*	-25.0*
KPP	Mean	643.3	537.2	442.2	753.8	609.5	486.5
	Change	-	-16.5**	-31.3**	-	-19.1**	-35.5**
100-KW (g)	Mean	34.3	31.2	28.4	34.2	32.8	29.7
	Change	-	-9.0**	-17.2**	-	-4.1**	-13.2**
GYPP (g)	Mean	132.1	99.7	84.5	181.1	138.5	122.2
	Change	-	-24.5**	-36.0**	-	-23.5**	-32.5**
GYPF (ard)♀	Mean	17.5	18.5	18.6	24.3	27.7	31.0
	Change	-	5.7*	6.3*	-	14.0**	27.6**
TDM (g)	Mean	275.4	237.6	214.7	336.5	287.9	262.1
	Change	-	-13.7**	-22.0**	-	-14.4**	-22.1**
HI (%)	Mean	39.6	34.4	32.0	44.4	39.6	38.0
	Change	-	-13.1**	-19.2**	-	-10.8**	-14.4**

*D = density, * and ** significant at 0.05 and 0.01 probability levels, respectively, change (%) = 100 × [(high-D or medium-D) – (low-D)]/(low-D) and ♀ 1 ard = 140 kg of grains*

increased ear abortion, and more barren plants [31]. When assimilate supply is limited under stress, it is usually preferentially distributed to the stem and tassel at the expense of ear nutrition, leading to poor pollination and partial or complete failure of grain set. This practically occurs with all kinds of stress, including drought, low soil N and P, excess moisture, low soil pH, iron deficiency and high population density [25,34]. Considerable evidence indicates that maize plants exposed to any of these stresses have reduced ears/plant and kernels/plant [17,29,31].

Elongation of plant stalks and increase of ear position exhibited in this study due to elevating the plant densities could be attributed to lower light level and greater competition among plants for light. This conclusion was confirmed by other investigators [25,35,36,37].

3.3 Genotype × Plant Density Interaction

Means of GYPP and GYPF of each inbred, F_1 cross and check cultivar under different plant densities (low, medium and high) across two seasons are presented in Table 4. For inbred parents, the highest grain yield/plant was shown by the L53 inbred while the lowest one was shown by L55 inbred under all plant densities. The three inbreds L17, L18 and L53 were higher yielders than the three inbreds L29, L54 and L55 under all densities. These inbred lines were chosen for the present investigation from a previous study [11], based on their contrast tolerance and/or sensitivity to high plant density, where L17, L18, and L53 were considered tolerant and L29, L54 and L55 were sensitive. The present results assure their diversity in high density tolerance and confirm their reaction to high density stress reported by Al-Naggar et al. [11].

The optimum plant density, that gives the highest grain yield/fed, was the medium one (30,000 plants/fed) for L53, the lowest one (20,000 plants/fed) for L29, L54 and L55 and the highest one (40,000 plants/fed) for L17 and L18.

The cross L17 × L54 (tolerant × sensitive) came in 1st rank under all plant densities for both grain yield/plant and grain yield/fed (Table 4). This cross gave grain yield of 42.7 ard/fed under the highest plant density (40,000 plants/fed) and showed a significant superiority of 28.6% over the best check cultivar (SC 2066) in this study.

Superiority of this cross over the well-known Egyptian commercial variety SC 10 reached 31.0% under the 40,000 plants/fed density. This cross is therefore considered the most tolerant cross in the present experiment and also the most responsive to medium and low density environments. The crosses L17 × L18, L29 × L55, L53 × L54 and L53 × L55 came in the 2nd, 3rd, 4th and 5th ranks, for grain yield/fed under all plant densities. The first four crosses showed about the same rank under all densities and could also be considered tolerant to high densities and responsive to the non-stressed environment. Superiority in GYPF of these crosses (L17 × L18, L29 × L55, L53 × L54 and L53 × L55) under 40,000 plants/fed density was 16.7, 11.45, 9.34 and 8.43%, respectively over the best check SC 2066 and 18.70, 13.50, 11.35 and 10.43%, respectively over the most popular Egyptian commercial hybrid SC 10.

Table 4. Means of grain yield/plant (GYPP) and grain yield/feddan (GYPF) of inbreds, crosses and check cultivars under low-, medium- and high-density (D) (20, 30 and 40 thousand plants/fed, respectively) combined across two seasons

Genotypes (G)	**GYPP (g)**			**GYPF (ard)**		
	Low-D	**Medium-D**	**High-D**	**Low-D**	**Medium-D**	**High-D**
			Inbreds			
L17	156.1	112.1	95.9	21.0	22.4	24.3
L18	150.2	113.2	101.1	20.2	22.6	25.7
L53	157.9	130.7	101.5	21.2	26.2	25.7
L29	105.7	80.1	67.5	13.7	12.9	11.4
L54	117.9	86.7	73.8	15.3	14.4	12.8
L55	104.5	75.6	67.0	13.6	12.7	11.5
			Crosses			
L17XL18	204.9	163.0	147.1	27.4	32.2	38.7
L17XL53	168.4	128.2	112.4	22.7	25.7	27.8
L17XL29	155.4	123.3	97.8	20.7	24.8	24.1
L17XL54	237.3	177.3	165.7	31.7	35.4	42.7
L17XL55	156.1	116.7	97.9	20.9	23.4	24.5
L18XL53	188.3	140.9	124.3	25.4	28.3	30.9
L18XL29	159.8	129.0	112.1	21.3	25.9	27.9
L18XL54	180.3	113.6	103.4	24.3	22.8	26.1
L18XL55	182.7	141.2	131.7	24.4	28.3	33.3
L53XL29	178.6	136.7	120.2	24.1	27.4	30.1
L53XL54	198.1	152.6	138.5	26.5	30.0	36.3
L53XL55	175.2	148.9	139.1	23.4	29.8	36.0
L29XL54	160.1	115.6	100.0	21.6	23.2	24.8
L29XL55	221.5	167.5	145.7	29.6	33.4	37.0
L54XL55	150.2	122.7	96.8	20.0	24.6	24.2
			Checks			
SC 128	177.5	141.6	120.3	23.7	28.3	30.5
SC 173	189.2	150.3	121.8	25.3	30.1	31.0
SC 10	207.7	161.2	128.2	28.0	32.3	32.6
SC 2055	176.9	143.7	119.4	23.9	28.8	30.2
SC 2066	219.8	159.8	133.1	29.6	32.0	33.2
LSD 0.05	G = 1.96, D = 2.14, G×D = 3.40			G = 0.34, D = 0.35, G×D = 0.60		

ard = 140 kg of grains

For all crosses and checks, the optimum density for obtaining the highest grain yield/fed was the highest one (40,000 plants/fed), except for the two crosses L17 × L29 and L54 × L55 and the check SC 10, where the optimum density was the medium one (30,000 plants/fed). Consequently, the optimum density that results in the highest grain yield/unit area should be identified for each genotype, separately. This density differed in the present study from one inbred to another and from one F_1 hybrid to another. The optimum population density was lowest (20,000 plant/fed) for the inbreds L29, L54 and L55, the medium one (30,000 plant/fed) for the inbred L53 and for the F_1 crosses L17 × L29 and L54 × L55 and the check SC 10 and the highest density (40,000 plant/fed) for the rest of inbreds, F_1 crosses and checks. The optimum plant density for maize was previously studied by several investigators. They found that the ideal plant population density for a cultivar depends on several factors in each location and on the availability of suitable environmental resources [13,15]. The best check under density of 40,000 plants/fed was the SC 2066 (an imported cultivar that was bred for tolerance to high plant densities). Its plant type is suitable for this purpose, such as short type, prolificacy, erect leaves and flowering synchronization. The superior hybrids developed in the present investigation under high plant density stress may also possess one or more of these adaptive traits.

3.4 Superiority of Tolerant (T) Over Sensitive (S) Genotypes

To describe the differences between T and S inbreds and hybrids, data of the selected characters were averaged for the two groups of inbreds and hybrids differing in tolerance in grain yield/fed under high density (Table 5). The higher absolute GYPF and higher ratio of GYPF under high plant density to yield under low plant density were considered as indices of tolerance to high plant density. Based on these indices, the high-density tolerant inbred lines were L17, L18 and L53 and the high-density sensitive inbred lines were L29, L54 and L55. Moreover, the three F_1 crosses L17 × L18, L17 × L54 and L29 × L55 were considered the most tolerant to high density, while the crosses L17 × L29, L54 × L55 and L17 × L55 could be considered as the most high-density sensitive crosses.

Data averaged for each of the two groups (T and S) of inbreds and crosses differing in tolerance to high density indicate that grain yield/feddan of the T group was greater than that of S inbreds and crosses by 112.0 and 36.1%, respectively under high density (40,000 plant/fed) conditions. Superiority of high-density T over S inbreds in GYPF under high density was due to their superiority in GYPP (43.4%), EPP (20.5%), KPP (51.1%), 100-KW (17.0%) and HI (18.9%), *i.e.,* in all studied yield traits. Likewise, under high plant density, the tolerant inbreds showed 29.4% less barren stalk, 15.0% shorter plant height, 14.7% shorter ASI and 5.2% more penetrated light (PL-M50) than sensitive inbreds (Table 5).

Superiority of T over S hybrids in GYPF under high density was due to their superiority in GYPP (31.5%), EPP (5.6%), KPP (17.8%), HI (10.4%), PL-M50 (4.6%), BS (-31.4%) and ASI (-23.4) than sensitive F_1 crosses (Table 5). The superiority of modern maize hybrids tolerant to high plant density was also attributed to

Table 5. Superiority (%) in some selected characters of the three most tolerant (T) to high plant density over the three most sensitive (S) inbreds and crosses grown under high-density (40,000 plants/fed) combined across two seasons

Trait	Inbreds			Crosses		
	T	S	% Superiority	T	S	% Superiority
GYPF (ard) ♀	25.2	11.9	112.0	39.1	28.8	36.1
GYPP (g)	99.5	69.4	43.4	150.6	114.5	31.5
EPP	0.94	0.78	20.5	0.95	0.90	5.6
KPP	532.3	352.2	51.1	558.8	474.5	17.8
100-KW (g)	30.6	26.1	17.0	28.7	29.3	-1.8
HI (%)	34.8	29.3	18.9	41.5	37.6	10.4
BS (%)	18.2	25.7	-29.4	7.2	10.5	-31.4
PL-M50 (%)	11.8	11.2	5.2	10.1	9.7	4.6
PH (cm)	185.9	218.7	-15.0	231.7	233.6	-0.8
ASI (day)	4.4	5.1	-14.7	2.7	3.5	-23.4

% Superiority = 100 × [(T – S)/S] and ♀ 1 ard = 140 kg of grains

decreased barrenness [38], more leaf erectness [3], synchronization of 50% anthesis with 50% silking [31] and increased prolificacy, *i.e.,* more ears plant^{-1} [39].

A shortened ASI is considered as an indication of a higher flow of assimilates to the developing ears during the early reproductive stage under conditions of high density stress [40]. High plant density-tolerant genotypes possess shorter ASI than sensitive ones [34,41]. Al-Naggar et al. [11] also reported that under high plant density, the tolerant testcrosses showed 314.4% more GYPP, 115.0% more KPP, 48.4% heavier 100-KW, 42.9 more EPP, 98.2% less BS and 63.3 % shorter ASI than sensitive testcrosses.

3.5 Differential Response of T×T, T×S and S×S Crosses

Mean performance of traits were averaged across the three groups of F_1 crosses, *viz.,* T×T, T×S and S×S groups based on grain yield/feddan of their parental lines under stress and non-stress conditions, *i.e.,* parental tolerance to high plant density stress and presented in Table 6. Number of crosses was 3, 9 and 3 for the T×T, T×S and S×S groups, respectively. In general, T×T crosses had favorable (higher) values for grain yield and its attributes and lower (favorable values for DTS, ASI, BS and LANG) than S×S and T×S crosses under high plant density. In general, high density T×T group of crosses exhibited better values in most studied traits than high density T×S and S×S groups of crosses (Table 6).

Superiority of high density T×T crosses over other groups of crosses was more pronounced under high density (40,000 plants/fed) than under medium density (30,000 plants/fed) and low density (20,000 plants/fed). Grain yield/fed (32.5 ard) of high-density tolerant T×T was significantly greater than that of S×S (28.7 ard) and T×S (31.2 ard) by 13.24 and 4.17%, respectively under high plant density conditions.

Superiority of high-density T×T over S×S and T×S crosses in GYPF was associated with their superiority in grain yield/plant by 13.8 and 5 g, KPP (83.4 and 83.2 grain), TDM (21.9 and 9.4 g) and HI (1.3 and 0.5%), respectively. The high T×T crosses were earlier in DTS by 4.5 and 3.2 days, shorter in ASI (1.2 and 0.5 day), shorter in PH (9 and 7 cm), lower in BS (2.8 and 4.4%) and narrower in LANG (0.8 and 1.8%), than high density S×S and T×S crosses, respectively under high-density conditions (40,000 plants/fed) (Table 6).

3.6 Grouping F_1 Hybrids Based on Tolerance and Responsiveness

Mean grain yield/plant or /feddan across seasons of studied hybrids under high-D was plotted against same trait of the same hybrids under low-D (Figs. 1 and 2) where numbers from 1 to 15 refer to F_1 hybrids as follows: 1 = L17×L18, 2 = L17×L53, 3 = L17×L29, 4 = L17×L54, 5 = L17×L55, 6 = L18×L53, 7 = L18×L29, 8 = L18×L54, 9 = L18×L55, 10 = L53×L29, 11 = L53×L54, 12 = L53×L55, 13 = L29×L54, 14 = L29×L55 and 15 = L54×L55, which made it possible to distinguish between efficient (E) and

Table 6. Trait differences averaged across two seasons for T×T, T×S and S×S groups of F_1 crosses under three plant densities

Trait	T × T			T × S			S × S		
	LD	MD	HD	LD	MD	HD	LD	MD	HD
DTS (days)	68.7	66.5	64.3	70.8	68.8	67.5	70.5	69.1	68.8
ASI (days)	2.4	2.3	2.4	2.3	2.8	3.3	2.6	2.6	3.6
PH (cm)	217.6	223.3	232.9	215.1	221.1	239.7	220.1	224.3	241.8
BS (%)	3.8	4.3	4.4	5.9	6.9	8.8	6.5	7.2	7.2
LANG (^{o})	31.6	27.4	28.4	35.3	31.5	30.2	33.6	30.4	29.2
EPP	1.2	1.1	1.0	1.2	1.1	0.9	1.2	1.1	0.9
KPP	801.3	661.4	553.1	741.8	599.1	469.9	742.1	588.6	469.7
100-KW (g)	35.8	34.1	30.5	33.8	32.0	29.4	34.1	34.0	29.6
GYPP (g)	187.2	144.1	127.9	180.4	137.7	122.9	177.3	135.3	114.1
GYPF (ard) ♀	25.2	28.7	32.5	24.2	27.5	31.2	23.8	27.1	28.7
TDM (g)	349.1	299.2	272.1	334.7	286.2	262.7	329.2	281.8	250.2
HI (%)	44.6	40.1	38.6	44.4	39.5	38.1	44.5	39.5	37.3

T = tolerant, S = sensitive, LD = low-density (20,000 plants/fed), MD = medium- density (30,000 plants/fed) and HD = high-density (40,000 plants/fed) and ♀ 1 ard = 140 kg of grains inefficient (I) hybrids on the basis of above-average and below-average grain yield under high-D, respectively, and responsive (R) and non-responsive (NR) hybrids on the basis of above-average and below-average grain yield under low-D, respectively [7,8]. According to tolerance to high-density and responsiveness to low-density, studied hybrids were classified into three groups based on GYPP, *i.e.,* density efficient and responsive, density inefficient and non-responsive and density efficient and non-responsive (Fig. 1). The hybrids No. 4 (L17 × L54), No.14 (L29 × L55), No. 1 (L17 × L18). No. 11 (L53 × L54), No. 9 (L18 × L55) and No. 6 (L18 × L53) had the highest GYPP under both high-density and low-density, and thus could be considered as the most high density efficient (tolerant) and the most responsive crosses to low-density in the present study, based on grain yield/plant.

On the contrary, the F_1 hybrids No. 15 (L45 × L55), No. 3 (L17 × L29), No. 5 (L17 × L55), No. 13 (L29 × L54), No. 8 (L18 × L54), No. 7 (L18 × L29), No. 2 (L17 × L53) and No. 10 (L53 × L29) had the lowest GYPP under both low- and high-densities and therefore could be considered density inefficient and non-responsive (Fig. 1). Only hybrid No. 12 (L53 × L55) was classified as density-efficient and non-responsive genotype based on GYPP.

Classification of the studied hybrids based on GYPF for their tolerance to high density and responsiveness to low-D (Fig. 2) grouped them in four groups, *i.e.,* density efficient (tolerant) and responsive (the four hybrids Nos. 4, 1, 14 and 11), density efficient and non-responsive (the two hybrids Nos. 12 and 9), density inefficient and responsive (only the hybrid No. 6) and density inefficient and non-responsive (the 8 hybrids Nos. 15, 3, 13, 5, 7, 8, 2 and 10).

3.7 Identifying Optimum Density

Data were reanalyzed to evaluate GYPF responses of inbreds and hybrids under varying levels of density. For each genotype or group of genotypes, a quadratic regression function was performed for plant density effects. The regression functions were used to distinguish which density provides optimum value for each genotype (or group of genotypes).

The relationship between plant densities and GYPF of the inbreds across years (Fig. 3) clearly shows that the inbred L53 showed a quadratic response to elevated plant density, with an optimum GYPF at plant density of 30,000 plants/fed. The two inbreds L18 and L17 showed near linear response to N levels,

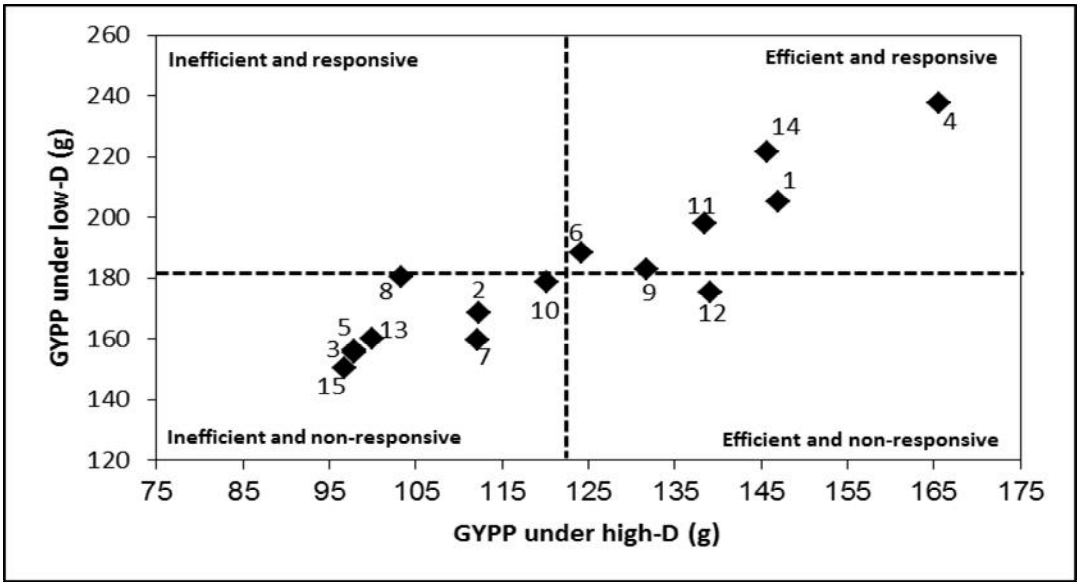

Fig. 1. Relationships between grain yields/plant (GYPP) of 15 F_1 maize hybrids under high- and low-D combined across two seasons. broken lines represent mean of GYPP (numbers from 1 to 15 refer to F_1 hybrids)

with an optimum GYPF at the highest plant density in our experiment (40,000 plants/fed). By contrast, the three inbreds L54, L29 and L55 showed a negative slope in GYPF due to increasing plant density, with optimum GYPF at the lowest plant density in this experiment (20,000 plants/fed). The relationship between plant density and GYPF of the studied groups of F_1 crosses across seasons is illustrated in Fig. 4. In general, all the 15 F_1 crosses showed near linear regression due to increasing plant density, with an optimum density of 40,000 plants/fed. The most responsive crosses to elevated plant density belong to the ER and ENR groups, while the IR and INR groups were of less response.

In this context, Shapiro and Wortmann [42] reported that the maize grain yield typically exhibits a quadratic response to plant density with a near-linear increase across a range of low densities, a gradually decreasing rate yield increase relative to density increase and finally a yield plateau at some relatively high plant density.

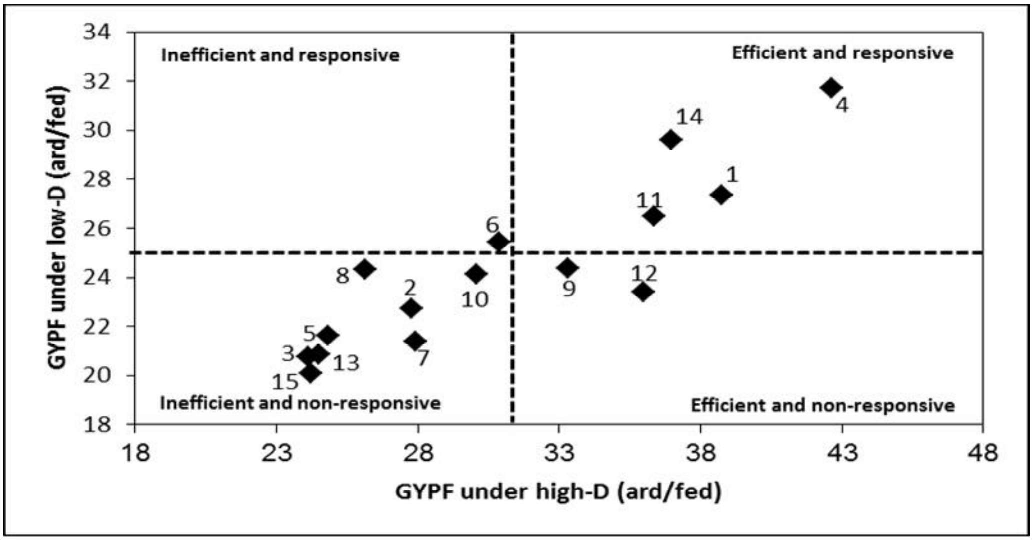

Fig. 2. Relationships between grain yields/feddan (GYPF) of 15 F_1 maize hybrids under high- and low-D combined across two seasons. broken lines represent mean of GYPF (numbers from 1 to 15 refer to F_1 hybrids)

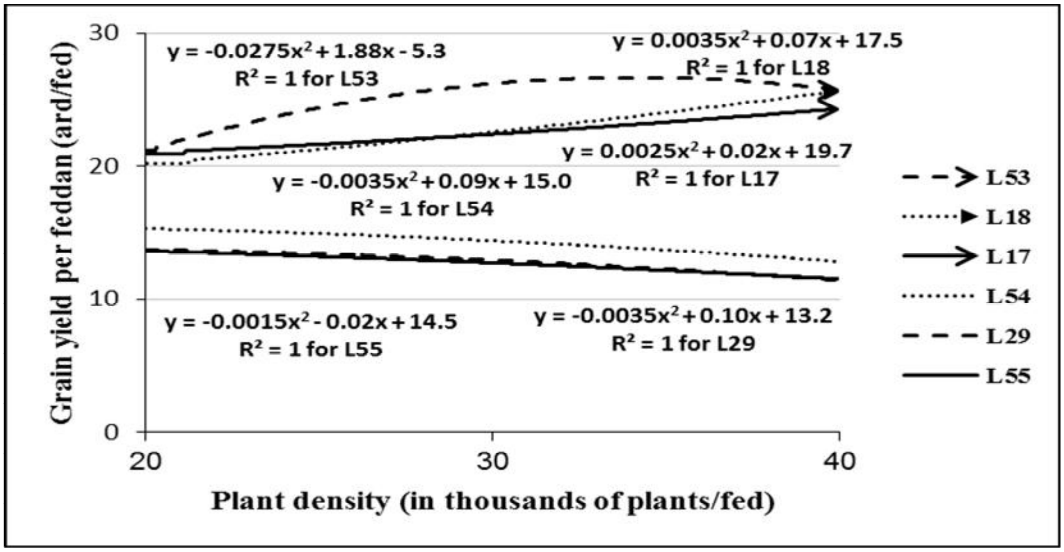

Fig. 3. Relationship between GYPF of inbreds and plant density across two seasons

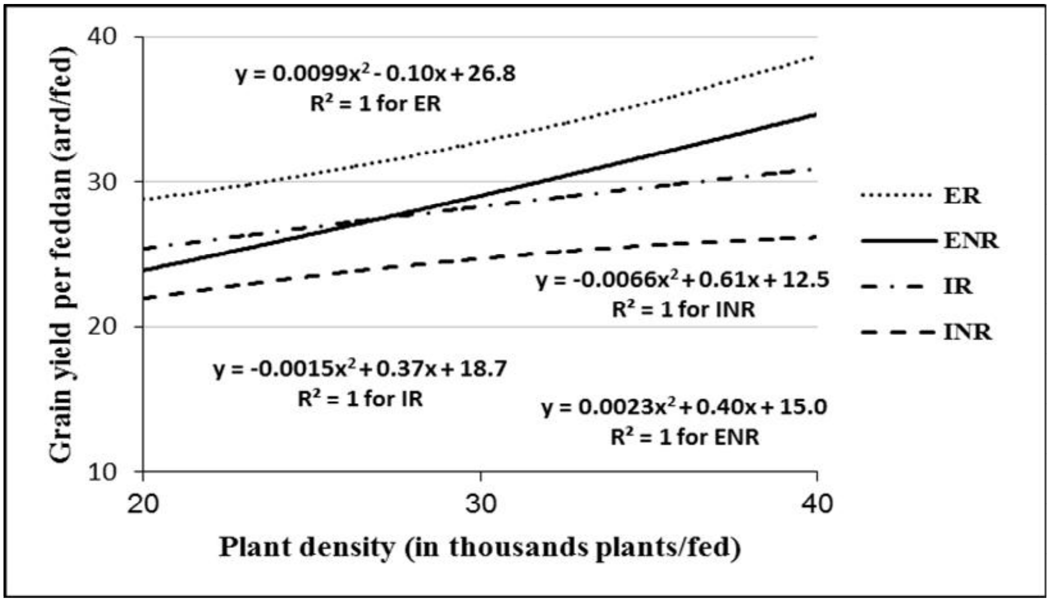

Fig. 4. Relationship between GYPF of four groups of F_1 crosses, namely, four efficient and responsive (ER), two efficient and non-responsive (ENR), one inefficient and responsive (IR) and eight inefficient and non-responsive (INR) crosses and plant density across two seasons

3.8 Trait Interrelationships

Estimates of genetic correlation coefficients between each of GYPP and GYPF and other studied traits across two seasons under the three studied plant densities were calculated across all inbred lines and across all F_1 crosses and presented in Table 7. Grain yield/plant of inbreds showed perfect positive genetic association with grain yield/feddan (r_g = ca. 1.00) under the 3 plant densities; this explains why the estimates of genetic correlation coefficients between GYPP and other traits are very close to those between GYPF and the same traits. In general, grain yield (either per plant or per feddan) of inbreds showed very strong positive correlation with TDM and HI traits under the three plant densities. Significant and negative genetic correlation coefficients were observed between grain yield/fed and each of BS under all plant densities (r_g ranged between -0.79** under low-D (20,000 plants/fed) and -0.99** under high-D (40,000 plants/fed)) and ASI in all plant densities (r_g ranged from -0.65** under high-D to -0.85 under low-D). Less barren stalks and short ASI could, therefore, be used as important selection criteria of inbreds for high grain yield/unit area under different plant densities, especially if heritability of BS and ASI is high. Similar conclusions were reported by Al-Naggar et al. [24], Banziger and Lafitte [29], Gebre [30], Miller et al. [39] and Edmeades et al. [40]. Grain yield of inbreds also showed a significant and positive genetic correlation with each of PL-M50, EPP, KPP and 100-KW (under all plant densities) and PL-M80 under low-D. The strong relationship between grain yield and number of kernels/plant (the product of EPP × rows/ear × kernels/row) is in harmony with other reports [14,24]).

Significant and positive (r_g) values were detected between GYPF or GYPP of inbreds and ear position under low- and high-D. This indicates that inbreds of higher ear position are high yielding than inbreds of lower ear position under low- and high-D. This could be due to more light penetration to the ear leaf of the higher than that for lower ear position. Low but significant and negative (r_g) values were detected between GYPF or GYPP of inbreds and plant height under high-D, indicating that shorter inbreds are of high yielding, especially under high plant density conditions.

This conclusion is in agreement with others [13,43]. On the contrary, Al-Naggar et al. [21] and Carena and Cross [37] reported that taller inbreds are higher yielding than shorter inbreds under both low and high densities.

Table 7. Genetic correlation coefficients between GYPP or GYPF and other studied traits for parental inbred lines and their F_1 crosses under low-D, medium-D and high-D (20, 30 and 40 thousand plants/fed, respectively) combined across two years

Trait	Inbreds			Crosses		
	Low-D	Medium-D	High-D	Low-D	Medium-D	High-D
			Grain yield/plant (GYPP)			
DTS	-0.08	-0.11	0.45*	0.13	-0.17	0.16
ASI	-0.84**	-0.75**	-0.65**	-0.79**	-0.80**	-0.62**
PH	-0.16	0.24	-0.44*	-0.07	-0.02	0.18
EP	0.74**	0.16	0.54*	-0.52**	-0.36*	-0.39*
BS	-0.83**	-0.89**	-0.96**	-0.70**	-0.87**	-0.28
LANG	0.45*	0.41*	0.35	-0.43*	-0.22	-0.53**
PL-M50	0.31*	0.71**	0.59*	0.70**	0.59**	0.76**
PL-M80	-0.28	-0.17	0.25	0.64**	0.50**	0.70**
EPP	0.78**	0.63**	0.58*	0.18	0.31	0.04
KPP	0.57*	0.65**	0.75**	0.46**	0.67**	0.46**
100-KW	0.94**	0.73**	0.70**	0.77**	0.62**	-0.10
GYPF	1.00**	1.00**	1.00**	1.00**	1.00**	1.00**
TDM	0.94**	0.94**	0.94**	0.96**	0.96**	0.97**
HI	0.94**	0.95**	0.94**	0.93**	0.96**	0.97**
			Grain yield/feddan (GYPF)			
DTS	-0.08	-0. 17	0.39*	0.13	-0.17	0.16
ASI	-0.79**	-0.82**	-0.71**	-0.80**	-0.81**	-0.64**
PH	-0.19	0.18	-0.49*	-0.07	-0.02	0.18
EP	0.72**	0.17	0.55*	-0.52**	-0.35*	-0.39*
BS	-0.79**	-0.93**	-0.99**	-0.72**	-0.87**	-0.26
LANG	0.45*	0.42*	0.35*	-0.42*	-0.22	-0.54**
PL-M50	0.81**	0.71**	0.60*	0.69**	0.59**	0.76**
PL-M80	-0.31*	-0.10	0.25	0.63**	0.50**	0.68**
EPP	0.75**	0.69**	0.56*	0.19	0.32*	0.03
KPP	0.55*	0.69**	0.73**	0.46**	0.68**	0.46**
100-KW	0.91**	0.72**	0.69**	0.77**	0.62**	-0.10
GYPP	1.00**	1.00**	1.00**	1.00**	1.00**	1.00**
TDM	0.93**	0.93**	0.93**	0.96**	0.96**	0.97**
HI	0.95**	0.97**	0.96**	0.93**	0.96**	0.96**

*D = density and *and ** indicate that r_g estimate exceeds once and twice its standard error, respectively*

Grain yield/feddan of crosses showed a perfect positive genetic association with grain yield/plant and very strong positive correlations with TDM and HI traits under the three plant densities. Estimates of genetic correlation coefficients between GYPF and other studied traits were very close in magnitude and sign to those between GYPP and the same other traits (Table 7). Grain yield/plant or /feddan of crosses also showed significant and positive genetic correlation coefficients with 100-KW (under low- and medium-D), KPP (under all three plant densities), EPP (under medium-D), PL-M50 and PL-M80 (under all plant densities).

On the contrary, GYPF or GYPP of crosses showed significant and negative genetic correlations with ASI (under all plant densities) and BS (under low- and medium-D) and with LANG (under low- and high-D), but with less magnitude (Table 7). This indicates the importance of ASI, BS and LANG to tolerance to high density. These results are in agreement with those reported by other investigators [21,33,44,45].

4. CONCLUSIONS

1. The present investigation showed that the cross L17 × L54, gave 42.7 ard/fed (ca. 14 ton/ha) or a 28.6% significant superiority over the best check cultivar SC 2066 in this study, when grown under high plant density (40,000 plant/fed = ca. 100,000 plant/ha) without any additional resources and, thus, increasing the benefit to our society from the limited area allocated to maize in the summer season. The crosses

L17 × L18, L29 × L55, L53 × L54 and L53 × L55 came in 2nd, 3rd, 4th and 5th ranks, for grain yield/fed under all plant densities. Superiority in GYPF of these crosses under density of 40,000 plants/fed was 16.7, 11.45, 9.34 and 8.43% over the best check SC 2066, in the same order.

2. Stress tolerant genotypes are characterized by more grain yield/plant, more ears/plant, high harvest index, high total dry matter, narrow leaf angle, short anthesis-silking interval, less barren stalks, less plant height and lower ear position than sensitive genotypes. Identification of high population density tolerance-traits would help to plan indirect selection and marker assisted selection for yield under stress.
3. Optimum plant density in this study differed from genotype to genotype and was lowest (20,000 plants/fed) for the three inbreds L29, L54 and L55, but was the medium one (30,000 plants/fed) for the inbred L53 and the two crosses L17 × L29 and L54 × L55 and was the highest density (40,000 plants/fed) for the inbreds L17 and L18 and the rest of F1 crosses.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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