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PLANT DENSITY TOLERANCE OF 28 EGYPTIAN COMMERCIAL MAIZE (*Zea mays* L.) HYBRIDS AND ITS CORRELATED TRAITS

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ABSTRACT

Growing maize (*Zea mays* L.) at high-plant density using proper genotypes that withstand high density stress is a new approach to maximize its grain productivity. The objectives of the present investigation were to identify the density tolerant and high yielding Egyptian maize hybrids, to estimate the superiority of tolerant (T) to sensitive (S) hybrids and to identify the trait(s) related with the density tolerance capacity. Twenty-eight Egyptian modern commercial maize hybrids were evaluated in Giza, Egypt under four levels of plant density, namely 47,600 plants/ha (D1), 71,400 plants/ha (D2), 95,200 plants/ha (D3) and 119,000 plants/ha (D4) using a split plot design with three replications in two years. The highest density stress tolerance index (STI) under D2, D3 and D4 was exhibited by the hybrids P3444, SC 131, P3433, SC 235 and SC 10. Grain yield/ha (GYPH) of density tolerant (T) hybrids was greater than the sensitive (S) hybrids by 62.37, 74.15, 57.98 and 56.02 %, under plant density conditions of D1, D2, D3 and D4, respectively. Superiority of T in GYPH was associated with superiority in grain yield/plant (GYPP), kernels/plant (KPP), rows/ear, ears/plant, ear leaf area, leaf area index and reduction in leaf angle, leaf area to produce 1g grain (LA/1gG), ear height, thickness of lower and upper stem diameter as compared to S hybrids. The correlation analysis suggested that the secondary traits for high density tolerance in the stressed environments D2, D3 and D4 are high GYPP, high GYPH, high KPP and low LA/1gG and low anthesis-silking interval.

Keywords: Maize; plant density; tolerance; ASI; leaf area; secondary traits.

INTRODUCTION

Productivity of maize (*Zea mays* L.) in Egypt is high, but not as high as in USA and Europe. Egypt ranks the fifth or sixth in productivity after USA, Canada, France, Italy and Germany [1]. Grain yield per land unit area is the product of grain yield per plant and number of plants per unit area [2,3,4]. Countries achieved higher grain yield/ha than Egypt grow maize at high plant density reaching to 100,000 plants/ha [5] coupled with tolerant hybrids to crowding stress. Egypt also can increase the productivity of maize following higher plant density than recommended (50,000 plants/ha) combined with density tolerant hybrids [6]. Modern maize hybrids in North America and Europe are tolerant to high density stress due to reduction in lodging and barreness [7]. Radenovic et al. [8] reported that of maize genotypes having erect leaves are suitable for high density planting as it enhances more light interception. On the other hand, a negative association was reported between anthesis-silking interval (ASI) and yield in high density planting [9]. Moreover, prolific genotypes tended to produce fewer barren plants at higher plant densities than non-prolific ones [10]. Maize genotypes differ in tolerance to high plant density [11,12,13]. Maize grain yield is more affected by variations in plant density than other members of the grass family due to its monoecious floral organization, its low tillering ability, and its short flowering period [14]. At lower plant densities, the differences between older and modern hybrids were smaller, becoming greater as plant density increased [15]. Mansfield and Mumm [16] reported that in US maize germplasm evaluated for plant density tolerance, a subset of traits including leaf angle, upper stem diameter, leaf area required to produce one gram of grain, kernel rows per ear, days to canopy closure, barrenness, kernels/plant, kernel length, leaf number, upper leaf area, stay green, zipper effect, kernels per row, and anthesis-silking interval were associated with grain yield across plant densities ranging from 47,000 to 133,000 plants/ha. Al-Naggar et al. [3,4] reported strong favorable and significant genetic correlations between density tolerance index and each of yield components for inbreds and hybrids and days to anthesis, anthesis-silking interval, plant height, ear height, and leaf angle for hybrids; they considered these traits as secondary traits to plant density tolerance. There is a lack of information in Egypt on utilization of modern high density tolerant maize hybrids to increase crop yield from land unit area. The objectives of the present investigation were: (*i*) to assess plant density tolerance and productivity of 28 Egyptian modern commercial hybrids in order to identify the tolerant and high-yielding ones for future use, (*ii*) to estimate the superiority of tolerant (T) to sensitive (S) hybrids and (*iii*) to identify secondary traits for high plant density tolerance in maize.

MATERIALS AND METHODS

Location and Seasons of Experiment

This study was carried out at the Agricultural Experiment and Research Station of the Faculty of Agriculture, Cairo University, Giza, Egypt (30° 3'N latitude and 31° 13'E longitude with an altitude of 18.6 meters above sea level), in 2019 and 2020 growing seasons.

Genetic materials

In this study, twenty-eight commercial maize hybrids were used (Table 1). They were developed by Agricultural Research Center (ARC), Egypt (11 hybrids) and private national and international companies working in Egypt, namely Corteva Company (7 hybrids), Fine Seeds Company (2 hybrids), Hi-Tec Co. (2 hybrids), and Egaseed Company (6 hybrids).

Experimental Design and Treatments

A split-plot design in randomized complete blocks (RCB) arrangement with three replications was used. The main plots were devoted to four plant densities (D), namely D1 = 47,600 plants/ha (30 x 70 cm), D2 = 71,400 plants/ha (20 x 70 cm), D3 = 95,200 plants/ha (15 x 70 cm) and D4 = 119,000 plants/ha (12 x 70 cm). Sub-plots were assigned to twenty-eight maize hybrids. Each subplot contained two ridges; each ridge was 4.0 m long and 0.70 m wide with an area of 5.6 square meters.

Sowing date was April 29th in the 1st season (2019) and May12th in the 2nd season (2020). Seeds were sown in hills spaced at a distance of 12 cm for the highest plant density (D4), 15 cm for D3, 20 cm for D2 and 30 cm for control (D1) with two plants hill^{-1} and plants were thinned to one plant hill^{-1} before the first irrigation to achieve the plant densities 119,000, 95,200, 71,400 and 47,600.000 plants ha^{1}, respectively. All other agricultural practices were followed according to the recommendations of ARC, Egypt. Nitrogen fertilization at the rate of 285.6 kg N/ha was added in two equal doses of Urea 46% before the first and second irrigation. Fertilization with calcium superphosphate at the rate of 70 kg P_2O_5/ha, was performed with soil preparation and before sowing. Weed control was performed chemically with Stomp Extra 45.5 CS (Pendimethyline) (an herbicide manufactured by BASF, USA) 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. Surface irrigation was applied 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.

Soil analysis

The soil analysis for the experimental site in the two growing seasons was done at the Central Lab for Soil Analysis, Agricultural Research Center, Cairo, Egypt. The analysis of the experimental soil as an average of 2019 and 2020 seasons, 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 2019 and 2020 growing seasons of maize were obtained from Agro-meteorological Station at Giza, Egypt. For May, June, July and August 2019 season, mean temperature was 28.9, 33.5, 32.6 and 32.5°C, maximum temperature was 34.6, 38.6, 38.6 and 37.2°C and relative humidity was 47.0, 53.0, 60.33 and 60.67%, respectively. For the same months 2020 season, mean temperature was 27.87, 29.49, 28.47 and 30.33°C, maximum temperature was 35.7, 35.97, 34.93 and 37.07°C and relative humidity was 38.7, 31.7, 46.3, and 44.3%, respectively.

Data Recorded

1. **Days to 50% anthesis (DTA):** Number of days from planting to anthesis of 50% of plants was measured on all plants plot^{-1}.
2. **Days to 50% silking (DTS):** Number of days from planting to silking of 50% of plants was measured on all plants plot^{-1}.
3. **Anthesis-silking interval (ASI):** Number of days between 50% silking and 50% anthesis was measured on all plants plot^{-1}.
4. **Plant height (PH):** It was measured on 10 guarded plants plot^{-1} from ground to the point of flag leaf insertion.
5. **Ear height (EH):** It was measured on 10 guarded plants plot^{-1} from ground to the base of the top most ear.
6. **Leaf angle (LANG):** 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. [17].
7. **Lower stem diameter (SDL):** 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.
8. **Upper stem diameter (SDU):** It was measured with caliper from 10 guarded plants/plot as the stem diameter on third internode below flag leaf.
9. **Ear leaf area (ELA):** It was measured on the ear leaf from 10 guarded plants/plot, according to Francis et al. [18] as follows: ELA = Leaf length x maximum leaf width x 0.75.
10. **Leaf area index (LAI):** It was calculated by dividing leaf area per plant on the land area occupied per plant (0.21, 0.14, 0.105 and 0.084 m^2 under plant density of 47,600, 71,400, 95,200 and 119,000 plants/ha, respectively).
11. **Leaf area to produce 1 g of grain (LA/1g):** It was measured as leaf area per plot /grams of grains per plot. 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, at the base of top-most ear and at the bottom of the plant (at 20 cm above the soil surface). Penetrated light inside the canopy was measured as a percentage of light penetrated from the top of the plant to either the base of top-most ear or to the bottom of the plant as follows:

12. **Penetrated light at the base of top-most ear (PLE):** It was calculated from 10 guarded plants/plot as follows**:** PLE =100 (light intensity at the base of top-most ear/light intensity at the top of the plant).
13. **Penetrated light at the bottom of the plant (PLB).** It was calculated from 10 guarded plants/plot as follows: PLB =100 (light intensity at the bottom/light intensity at the top of the plant).
14. **Chlorophyll concentration index (CCI)**: It was measured by Chlorophyll Concentration Meter, Model CCM200 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.
15. **Number of ears plant^{-1} (EPP):** It was estimated by dividing number of ears plot^{-1} on number of plants plot^{-1} at harvest.
16. **Number of rows ear^{-1} (RPE):** It was estimated by using 10 random ears plot^{-1} at harvest.
17. **Number of kernels row^{-1} (KPR):** It was estimated by using the same 10 random ears/plot. **18. Number of kernels plant^{-1} (KPP): It was** calculated by multiplying number of ears plant^{-1} by number of rows ear^{-1} by number of kernels row^{-1}.
19. **100-kernel weight (100KW):** It was measured on per plot basis adjusted at 15.5% grain moisture.
20. **Grain yield plant^{-1} (GYPP):** It was estimated by dividing the grain yield plot^{-1} (adjusted at 15.5% grain moisture) on number of plants plot^{-1} at harvest.
21. **Grain yield ha^{-1} (GYPH):** It was estimated by adjusting grain yield plot^{-1} at 15.5% grain moisture to grain yield ha^{-1} (in tons).

Biometrical analyses

Analysis of variance of the split-plot design in randomized complete blocks arrangement was performed on the basis of individual plot observation using the MIXED procedure of SAS ® [19]. The data collected from each season was subjected to the standard analysis of variance of split-plot design. Combined analysis of variance across the two seasons was also performed if the homogeneity test was non-significant. Least significant difference (LSD) was calculated to test significance of differences between means according to Steel et al. [20] using GENSTAT 10th addition windows software. Stress tolerance index (STI) modified from equation suggested by Fageria [21] was used to classify genotypes for tolerance to density stress. The formula used is as follows: STI= (Y1/AY1) X (Y2/AY2), Where, Y1 = grain yield mean of a genotype at non-stress. AY1 = average yield of all genotypes at non-stress. Y2 = grain yield mean of a genotype at stress. AY2 = average yield of all genotypes at stress. Rank correlation coefficients were calculated between STI and each of studied traits under each stressed environment (71,400, 95,200 and 119,000 plants/ha) for studied genotypes according to Steel et al. [20].

RESULTS AND DISCUSSION

Analysis of Variance: Combined analysis of variance of the split-split plot design across two years (Y) for 21 traits of 28 maize hybrids under four plant densities (D) (47,600, 71,400, 95,200 and 119,000 plants/ha) was performed (data not presented). Mean squares due to years were significant ($P \leq 0.01$) for all studied traits, indicating significant effect of climatic conditions on all studied traits. Mean squares due to genotypes were significant ($P\leq 0.01$) for all studied traits, indicating that genotype had an obvious effect on all the 21 studied traits and the presence of genetic-background differences among genotypes for all studied traits across the three plant densities.

Mean squares due to plant density were significant ($P\leq 0.01$) for all studied traits, except for anthesis-silking interval (ASI), indicating that plant density had an obvious effect on all studied traits, except ASI. Mean squares due to genotype × plant density interaction were significant ($P\leq 0.01$) for all studied traits, suggesting that genotypes behaved differently under different plant density conditions for all studied traits and indicating the possibility of selecting genotypes for improved performance under a specific plant density as proposed by several investigators [22,23,24,25,6, 3,4,26,27,28].

Grain Productivity of the Hybrids under Four Plant Densities: Average grain yield/ha (GYPH) was increased as plant density increased (Table 1). GYPH was 8.8 ton/ha under 47,600 plants/ha (D1) and increased to 10.65, 11.80, and 14.29 ton/ha under 71,400 (D2), 95,200 (D3) and 119,000 (D4) plants/ha, respectively. The increase in GYPH from D1 to D4 was recorded for all hybrids, except for SC 131, where GYPH increased to maximum under D3 then decreased under D4, suggesting that optimum density is D4 (119,000 plants/ha) for all studied hybrids, except for SC 131 where its optimum density is D3 (95,200 plants/ha). This result is in conformity with the results reported by Kamara et al. [28]. The highest GYPH (17.73 ton) was achieved by SC 235, followed by P 3444 (16.47 ton) and P 3433 (16.41 ton), all under D4 (119,000 plants/ha), but the lowest GYPH was recorded by TWC 374 (5.67 ton) followed by TWC Nefertiti (5.85 ton) under D1 (47,600 plants/ha). In general, the single crosses group (SC's) had higher GYPH than three-way crosses group (TWC's) under all the four plant densities (Table 1).

Table 1. Mean grain yield/ha in tons of each genotype under plant density of D1 (47,600), D2 (71,400), D3 (95,200) and D4 (119,000) plants/ha across two years

Genotype No.	Genotype designation	D1 (47,600 plants/ha)	D2 (71,400 plants/ha)	D3 (95,200 plants/ha)	D4 (119,000 plants/ha)
1	S C 10	10.93	10.62	12.53	15.74
2	S C 128	8.26	12.32	11.53	15.42
3	S C 131	12.17	12.24	13.16	12.39
4	S C 132	9.08	11.37	12.02	15.39
5	S C 168	9.34	13.54	12.27	14.58
6	S C 178	9.50	12.32	11.79	14.61
7	30 K 8	9.85	10.11	11.57	15.54
8	30 K 9	9.11	9.68	12.51	14.71
9	30 P74	11.02	10.90	12.13	15.94
10	30 N11	6.85	8.44	10.09	14.22
11	P 3433	11.67	14.15	12.14	16.41
12	P 3444	12.15	13.86	13.36	16.47
13	SC 2055	7.72	10.51	12.70	14.48
14	SC 2088	9.58	11.36	11.98	14.49
15	SC-375	7.79	10.11	11.93	13.51
16	SC 77	7.16	8.98	11.21	12.18
17	SC 90	8.88	10.07	14.45	15.20
18	SC 235	9.07	11.64	15.79	17.73
19	TWC 654	5.70	7.37	9.57	11.92
20	P3737	9.59	10.08	11.17	15.41
21	TWC 373	6.20	7.59	8.11	11.24
22	TWC 374	5.67	9.57	10.30	11.55
23	Nefertiti	5.85	8.73	12.70	15.17
24	TWC 321	7.72	11.11	12.42	14.98
25	TWC 324	7.60	12.09	12.60	14.52
26	TWC 360	10.26	9.86	10.02	12.26
27	TWC 368	9.22	11.72	12.02	14.74
28	Giza-2	8.35	7.75	8.45	9.27
	SC's	9.45	11.23	12.4	14.95
	TWC's	7.53	9.79	10.99	13.53
Average		8.8	10.65	11.8	14.29
Max.		12.17 (3)	14.15 (11)	15.79 (18)	17.73 (18)
Min.		5.67 (22)	7.37 (19)	8.11 (21)	9.27 (28)
SC's		9.45	11.23	12.4	14.95
TWC'S		7.53	9.79	10.99	13.53
LSD 0.05		0.71	0.39	0.4	0.41
LSD 0.01		0.94	0.52	0.53	0.54

Each value is followed by genotype No. (in parenthesis). SC's = Single crosses, TWC's = Three-way crosses.

Stress tolerance index of the hybrids under 3 elevated plant densities: Stress tolerance index (STI) values of studied genotypes estimated using the equation suggested by Fageria [21] under the stressed environments 71,400 plants/ha (D2), 95,200 plants/ha (D3) and 119,000 plants/ha (D4) are presented in Table 2. According to our scale, when STI is >1.10, it indicates that genotype is tolerant (T), if STI is < 0.90, it indicates that genotype is sensitive (S) and if STI is between 0.90 and 1.10, it indicates that genotype is moderately tolerant (MT). Based on STI values, the 28 studied Egyptian maize commercial hybrids were grouped into three categories under each stressed environment, namely tolerant (T) (10, 9 and 11 hybrids), moderately tolerant (MT) (10, 11 and 8 hybrids) and sensitive (8, 8 and 9 hybrids) under 71,400 (D2), 95,200 (D3) and 119,000 (D4) plants/ha, respectively. In general, the single crosses were tolerant, but the three-way crosses were moderately tolerant, under the three stressed environments (D2, D3 and D4) (Table 2).

Table 2. Stress tolerance index (STI) of studied genotypes under D1 (47,600), D2 (71,400), D3 (95,200) and D4 (119,000) plants/ha across two years

Genotype	Designation	STI at D2 (71,400 plants/ha)	STI at D3 (95,200 plants/ha)	STI at D4 (119,000 plants/ha)
1	S C 10	1.24 (T)	1.39 (T)	1.35 (T)
2	S C 128	1.10 (MT)	0.98 (MT)	1.04 (MT)
3	S C 131	1.61 (T)	1.63 (T)	1.22 (T)
4	S C 132	1.13 (T)	1.06 (MT)	1.11 (T)
5	S C 168	1.21 (T)	1.13 (T)	1.10 (MT)
6	S C 178	1.17 (T)	1.01 (MT)	1.06 (MT)
7	30 K 8	1.09 (MT)	1.09 (MT)	1.16 (T)
8	30 K 9	0.94 (MT)	1.01 (MT)	1.07(MT)
9	30 P74	1.21 (T)	1.17 (T)	1.34 (T)
10	30 N11	0.65 (S)	0.68 (S)	0.77 (S)
11	P 3433	1.58 (T)	1.32 (T)	1.40 (T)
12	P 3444	1.64 (T)	1.42 (T)	1.44 (T)
13	SC 2055	0.90 (MT)	0.96 (MT)	0.90 (MT)
14	SC 2088	1.22 (T)	1.17 (T)	1.15 (T)
15	SC-375	0.84 (S)	0.85 (S)	0.86 (S)
16	SC 77	0.74 (S)	0.80 (S)	0.73 (S)
17	SC 90	1.07 (MT)	1.21 (T)	1.11 (T)
18	SC 235	1.19 (T)	1.39 (T)	1.29 (T)
19	TWC 654	0.47 (S)	0.54 (S)	0.56 (S)
20	P3737	1.04 (MT)	1.03 (MT)	1.11 (T)
21	TWC 373	0.55 (S)	0.55 (S)	0.60 (S)
22	TWC 374	0.62 (S)	0.59 (S)	0.55 (S)
23	Nefertiti	0.63 (S)	0.79 (S)	0.74 (S)
24	TWC 321	0.92 (MT)	0.90 (MT)	0.96 (MT)
25	TWC 324	0.93 (MT)	0.91 (MT)	0.88 (S)
26	TWC 360	1.02 (MT)	0.95(MT)	0.98 (MT)
27	TWC 368	1.08 (MT)	1.08 (MT)	1.09 (MT)
28	Giza-2	0.78 (S)	0.77 (S)	0.70 (S)
	Number of tolerant (T) genotypes	10	9	11
	Number of moderately (MT) tolerant genotypes	10	11	8
	Number of sensitive (S) genotypes	8	8	9
	SC's	1.134 (T)	1.128 (T)	1.212 (T)
	TWC's	0.989 (MT)	1.001(MT)	1.018 (MT)

T= Tolerant, MT= Moderately tolerant, S= Sensitive

It is observed that seven out of the 28 studied hybrids were tolerant (T) under all the three density stressed environments (D2, D3 and D4), namely the single cross hybrids SC 10, SC 131, 30 P74, P 3433, P 3444, SC 2088 and SC 235. The highest STI under stressed environments was exhibited by the single crosses P3444, SC 131, P3433 (STI ≥1.58) under D2 (71,400 plants/ha), SC 131, P3444, SC 10 and SC 235 (STI ≥1.39) under D3 (95,200 plants/ha) and P3444, P3433 and SC 10 (STI ≥1.35) under D4 (119,000 plants/ha). These five hybrids (P3444, SC 131, P3433, SC 235 and SC 10) were the most tolerant genotypes under the three stressed environments (Table 2); the grain yield/ha of P3444 (No.12), and SC 235 (No.18) were the highest under D3 and D4 stressed environments (Table 1). These genotypes should be recommended to maize breeding programs aiming at improving high plant density tolerance.

Moreover, seven out of the 28 studied hybrids were moderately tolerant (MT) under all the three density stressed environments (D2, D3 and D4), namely SC 128, 30K 9, SC 2055, TWC 321, TWC 360 and TWC 368. The single cross SC 168 was tolerant under D2 and D3 and moderately tolerant under D4. The single cross SC 132 was tolerant under D2 and D4 and moderately tolerant under D3. The single cross SC 90 was moderately tolerant under D2 and tolerant under D3 and D4. The single cross 30K 8 and the 3-way cross P3737 were moderately tolerant under D2 and D3 and tolerant under D4. The TWC 324 was moderately tolerant under D2 and D3 and sensitive under D4.

On the contrary, eight out of the studied 28 hybrids were sensitive (S) under all the three density stressed environments (D2, D3 and D4), namely SC 300N11, SC-375, SC 77, TWC 654, TWC 373, TWC 374, Nefertiti and Giza-2. The most plant density sensitive commercial hybrids were the 3-way crosses TWC-654, TWC 373 and TWC 374 under all stressed environments (Table 2).

Superiority of tolerant (T) to sensitive (S) genotypes: Based on STI, the three most density tolerant (T) hybrids were P3444, P3433 and SC 235 and the three most density sensitive (S) commercial hybrids were TWC-654, TWC 373 and TWC 374 (Table 2). Results averaged for each of the two groups (T and S) of commercial hybrids differing in tolerance to high density indicate that grain yield/ha of high density tolerant (T) was greater than that of the sensitive (S) hybrids by 62.37, 74.15, 57.98 and 56.02 %, under plant density conditions of 47,600, 71,400, 95,200 and 119,000 plants/ha, respectively (Table 3).

Superiority of high-density tolerant (T) over sensitive (S) hybrids in grain yield/ha under elevated plant density was due to their superiority in grain yield/plant (55.76, 63.75, 47.98 and 44.72 %), kernels/plant (13.36, 5.84, 14.21 and 10.15%), rows/ear (4.39, 5.44, 6.36 and 7.29 %), under 47,600, 71,400, 95,200 and 119,000 plants/ha, respectively. Likewise, under elevated plant density, the tolerant hybrids showed 38.98, 42.09, 41.60 and 36.55 % smaller leaf area to produce 1g grain (more efficient), 3.94, 4.00, 1.35 and 2.13 % higher leaf area index, 2.6, 0.66, 1.4, and 0.96% lower ear height under 47,600, 71,400, 95,200 and 119,000 plants/ha, respectively, 0.71, 2.60 and 6.07% thinner upper stem diameter, 1.69, 2,82 and 1,86 % thinner lower stem diameter and 6.97, 7.62 and 11.59% higher ear leaf area, under 71,400, 95,200 and 119,000 plants/ha, respectively and 3.97 and 6.9% narrower leaf angle under the highest densities 95,200 and 119,000 plants/ha, respectively and 2.92 % higher number of ears/plant under the highest density (119,000 plants/ha).

It is observed that the most tolerant hybrids are superior to the most sensitive hybrids in grain yield and its components under the stressed environments (the elevated plant densities (71,400, 95,200 and 119,000 plants/ha) as well as under the non-stressed environment (47,600 plants/ha).

The superiority of modern maize hybrids tolerant to high plant density was attributed to more leaf erectness [8]. Al-Naggar et al. [29] 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. Moreover, Al-Naggar et al. [26] reported that grain yield/ha (GYPH) of density tolerant (T) was greater than the sensitive

(S) inbreds and testcrosses by 100.6 and 89.3%, respectively under high density and that superiority in GYPH was associated with superiority in all yield components, earliness in anthesis, shortening of anthesis-silking interval and plant height, thickness of lower and upper stem diameter, decrease in leaf angle and leaf area to produce 1g grain, increase in penetrated light to ear and in chlorophyll concentration index than the sensitive ones.

Mansfield and Mumm [16] reported that in U. S. maize germplasm evaluated for plant density tolerance, a subset of traits including leaf angle, upper stem diameter, leaf area required to produce one gram of grain, kernel rows per ear, days to canopy closure, barrenness, kernels plant^{-1}, kernel length, leaf number, upper leaf area, stay green, zipper effect, kernels per row, and anthesis-to-silking interval were associated with grain yield across plant densities ranging from 47,000 to 133,000 plants/ha. Similar conclusions have been reported by several investigators [30,10,31,32, 7,9,16,25,26].

Grouping Genotypes:

Based on stress efficiency and responsiveness

Mean grain yield/ha (GYPH) of studied genotypes combined across years under the non-stressed environment (47,600 plants/ha) was plotted against mean GYPH of the same genotypes under elevated density stressed environments, namely 71,400, 95,200 and 119,000 plants/ha (Figs. 1, 2 and 3, respectively). This made it possible to distinguish stress efficient from stress-inefficient genotypes on the basis of above-average and below-average grain yield under the stressed environment, respectively and responsive and non-responsive genotypes on the basis of above-average and below-average grain yield under the non-stressed environment, respectively [33,29, 6,26,34]. According to efficiency under stress (either D2, D3 or D4) and responsiveness to non-stressed environment (D1), studied genotypes were classified into four groups, i.e., stress efficient and responsive (E-R), stress efficient and non-responsive (E-NR), stress non-efficient and responsive (NE-R) and stress non-efficient and non-responsive (NE-NR) based on GYPH.

For the relationship of GYPH between D1 and D2 (Fig. 1), the genotypes No. 11, 12, 5, 6, 18, 9, 14, 4 and 27 in descending order were classified as dense efficient under D2 and responsive genotypes (the 1st group) (E-R). The genotype No. 2, 25 and 24 were classified as dense efficient and non-responsive (the 2nd group) (E-NR). The genotypes No. 1, 26, 7, 20, 17 and 8 were classified as dense inefficient and responsive (the 3rd group) (IE-R). The genotypes No. 19, 21, 28, 10, 23, 16, 22, 15 and 13 were classified as dense inefficient under D2 and non-responsive genotypes (the 4th group) (IE-NR) (Fig. 1).

The first group of genotypes (E-R) had the highest GYPH under both D1 and D2, i.e.; they could be considered as the most density stress efficient under D2 and the most responsive genotypes to D1 in this study. On the contrary, the fourth group of genotypes (IE-NR) had the lowest GYPH under both D1 and D2 and therefore could be considered inefficient and non-responsive (Fig. 1). For the relationship of GYPH between D1 and D3 (Fig. 2), the genotypes No. 18, 17, 12, 3, 1, 8, 11, 9, 5, 4, 27 and 14 were classified as density efficient under D3 and responsive genotypes (the first group) (E-R). Genotypes No. 23, 13, 25, 24 and 15 were classified as density efficient and non-responsive (the 2nd group) (E-NR). The genotypes No. 6, 7, 20 and 26 were classified as density inefficient and responsive (the 3rd group) (IE-R). The genotypes No. 21, 28, 19, 10, 22, 16 and 2 were classified as density inefficient under D3 and non-responsive genotypes (the 4th group) (IE-NR) (Fig. 2). The first group of genotypes (E-R) was the highest GYPH under both D1 and D3, i.e.; they could be considered as the most density stress efficient under D3 and the most responsive genotypes in this study (Fig. 2).

Regarding the relationship of GYPH between D1 and D4 (Fig. 3), the genotypes No. 18, 12, 11, 9, 1, 7, 20, 4, 17, 27, 8, 6, 5 and 14 were classified as density efficient under WS-LN and responsive genotypes (the 1st group) (E-R). Genotypes No. 23, 2, 24, 25 and 13 were classified as density efficient and non-responsive (the 2nd group) (E-NR). The genotypes No. 3 and 26 were classified as density inefficient and responsive (the 3rd group) (IE-R). The genotypes No. 28, 21, 22, 19, 16, 15 and 10 were classified as density inefficient under D4 and non-responsive genotypes (the 4th group) (IE-NR) (Fig. 3). The first group of genotypes (E-R) had the highest GYPH under both D1 and D4, i.e.; they could be considered as the most density stress N efficient under D4 and the most responsive genotypes in this study (Fig. 3).

Based on stress tolerance and grain yield under stress

Mean grain yield/ha (GYPH) of studied genotypes under D2, D3 and D4 stress, was plotted against stress tolerance index (STI) of the same genotypes under D2, D3 and D4, respectively (Figs. 4, 5 and 6), which made it possible to distinguish between four groups, namely tolerant high-yielding, tolerant low-yielding, sensitive high-yielding and sensitive low-yielding according to Sattelmacher et al. [33] and Al-Naggar et al. [6,26]. Under D2 (71,400 plants/ha), the genotypes No 11 followed by No. 12, 5, 3, 6, 2, 27, 18, 14, 4 and 9 were classified as the density tolerant and high yielding genotypes, i.e. they could be considered as the most density (71,400 plants/ha) tolerant and the most responsive genotypes to low density (47,600 plants/ha) in this study (Fig. 4). The genotypes belonging to the group of D2 density tolerant and low yielding under D2 were No. 26, 7, 17, 20 and 8. The genotypes No. 24 and 25 occupied the group of density sensitive and high yielding under D2. The genotypes No 19, 21, 28, 10, 23, 16, 22, 15, 13 and 8 were classified as density stress sensitive and low yielding and therefore could be considered sensitive and low yielding under D2 stress (71,400 plants/ha) (Fig. 4).

Table 3. Superiority (Super %) of the three most tolerant (T) to the three most sensitive (S) genotypes for selected traits under the non-stressed environment D1 (47,600 plants/ha), and the stressed environments D2 (71,400 plants/ha), D3 (95,200 plants/ha) and D4 (119,000 plants/ha), combined across 2019 and 2020 seasons

Genotype	D1	D2	D3	D4	D1	D2	D3	D4
	47,600	71,400	95,200	119,000	47,600	71,400	95,200	119,000
	Leaf angle (°)				Ear height (cm)			
T	45.34	41.65	35.87	32.89	139.67	150.61	156.22	166.17
S	45.21	41.22	37.36	35.09	143.39	151.61	158.44	167.78
Super %	0.29	1.04	-3.97*	-6.29**	-2.60*	-0.66	-1.40*	-0.96
	Upper stem diameter SDU(cm)				Lower stem diameter (cm)			
T	1.98	1.86	1.75	1.60	3.08	2.91	2.75	2.64
S	1.94	1.87	1.80	1.70	3.08	2.96	2.83	2.69
Super %	2.06	-0.71	-2.60*	-6.07*	0.22	-1.69*	-2.82*	-1.86*
	Ear leaf area (cm^2)				Leaf area index			
T	881.33	851.89	807.17	807.59	4.92	5.81	6.98	8.01
S	893.28	796.39	750.03	723.69	4.73	5.59	6.89	7.84
Super %	-1.34	6.97**	7.62**	11.59**	3.94*	4.00*	1.35*	2.13*
	Leaf area to produce 1 g of grain (cm^2)				Number of rows /ear			
T	57.81	46.58	41.28	36.48	15.78	15.11	15.78	16.33
S	94.73	80.43	70.69	57.50	15.11	14.33	14.83	15.22
Super %	-38.98**	-42.09**	-41.60**	-36.55**	4.39*	5.44*	6.36*	7.29*
	Number of ears/plant				Number of kernels/plant			
T	1.41	1.28	1.24	1.29	815.40	680.56	655.57	556.85
S	1.45	1.38	1.33	1.26	719.31	643.02	573.98	505.55
Super %	-2.99	-7.26	-6.78	2.92*	13.36**	5.84*	14.21**	10.15**
	Grain yield /plant (g)				Grain yield /ha (ton)			
T	251.35	234.45	180.82	179.32	10.96	13.22	13.76	16.87
S	161.38	143.18	122.19	123.91	6.75	7.57	8.71	10.81
Super %	55.76**	63.75**	47.98**	44.72**	62.42**	74.59**	58.02**	56.06**

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

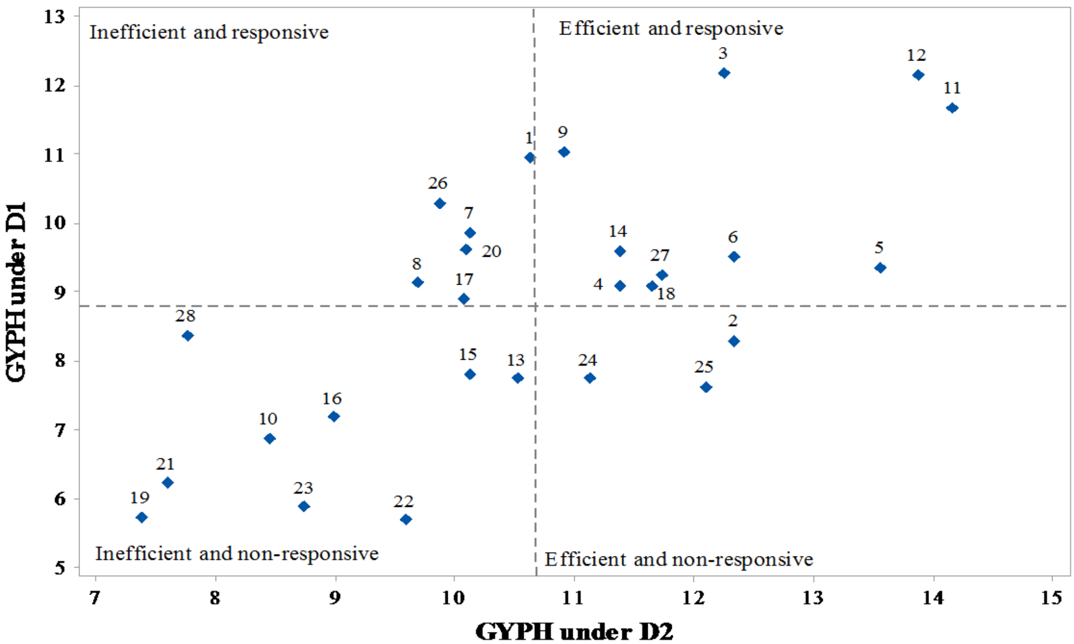

Fig. 1. Relationships between GYPH of 28 maize hybrids under non-stressed environment D1 (47,600 plants/ha) vs density stressed environment D2 (71,400 plants/ha) combined across 2019 and 2020 seasons. Broken lines represent mean of (GYPH), (numbers from 1 to 28 refer to genotype numbers mentioned in Table 1)

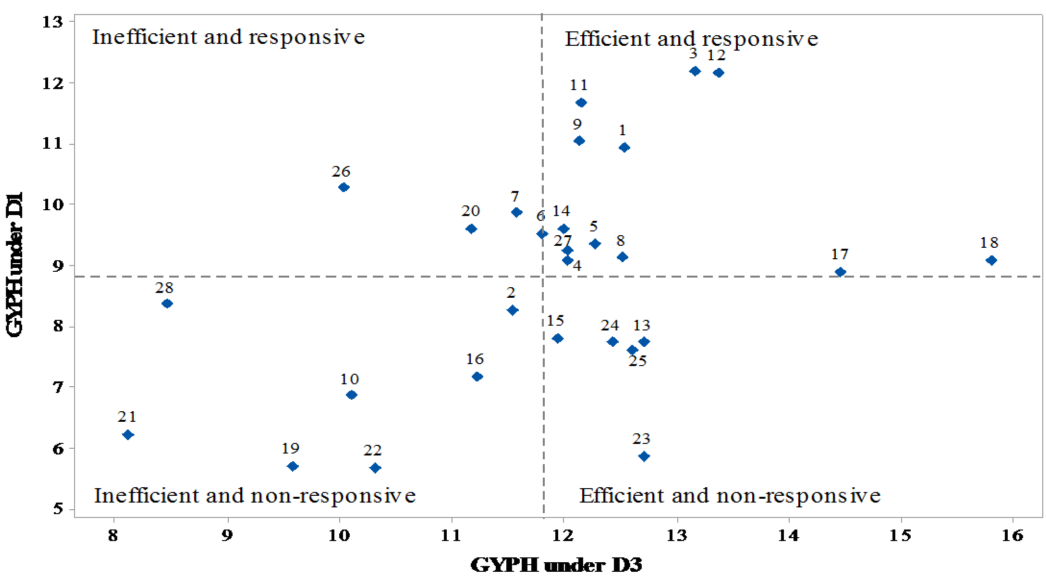

Fig. 2. Relationships between GYPH of 28 maize hybrids under non-stressed environment D1 (47,600 plants/ha) vs density stressed environment D3 (95,200 plants/ha) combined across 2019 and 2020 seasons. Broken lines represent mean of (GYPH), (numbers from 1 to 28 refer to genotype numbers mentioned in Table 1)

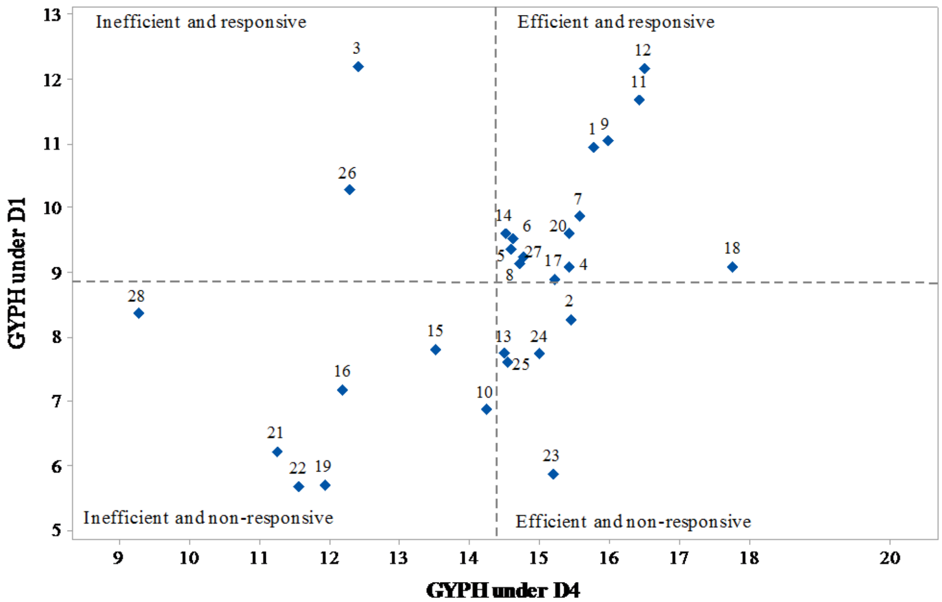

Fig. 3. Relationships between GYPH of 28 maize hybrids under non-stressed environment D1 (47,600 plants/ha) vs density stressed environment D4 (119,000 plants/ha) combined across 2019 and 2020 seasons. Broken lines represent mean of (GYPH), (numbers from 1 to 28 refer to genotype numbers mentioned in Table 1)

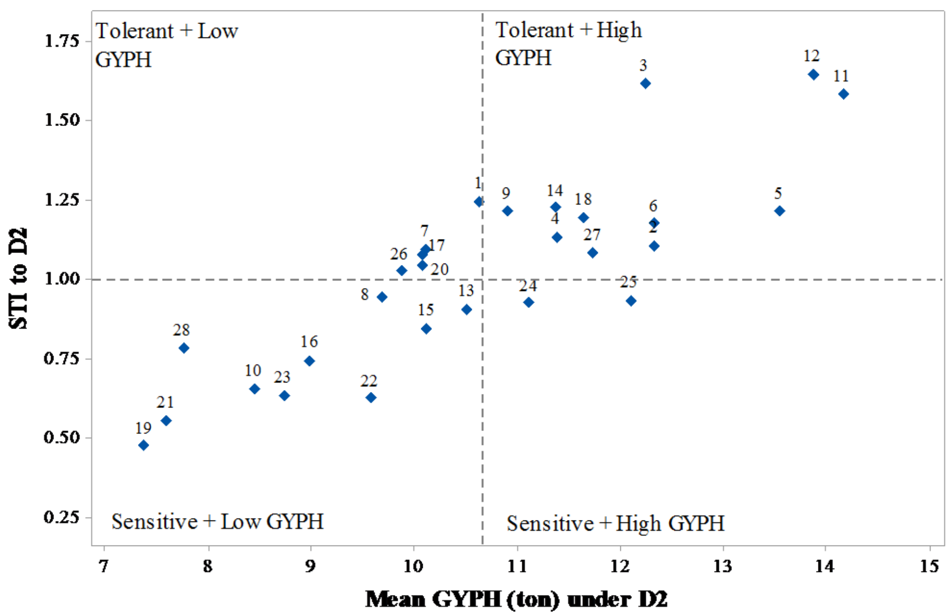

Fig. 4. Relationships between stress tolerance index (STI) of 28 maize genotypes and GYPH under D2 stressed environment (71,400 plants/ha) combined across 2019 and 2020 seasons. Broken lines represent mean of STI's and GYPH, (numbers from 1 to 28 refer to genotype numbers mentioned in Table 1)

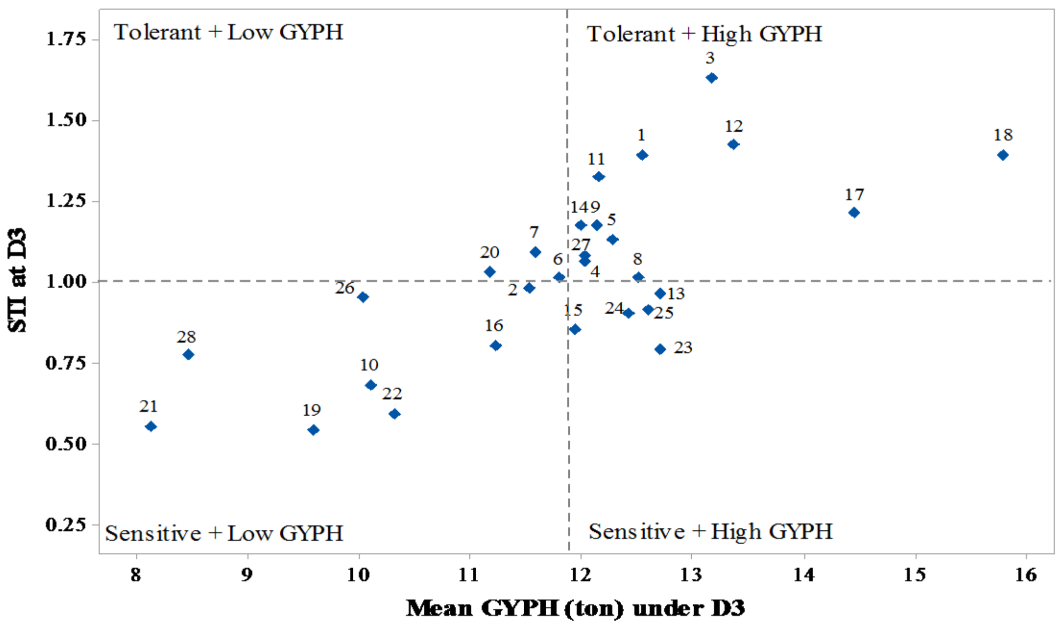

Fig. 5. Relationships between stress tolerance index (STI) of 28 maize genotypes and GYPH under D3 stressed environment (95,200 plants/ha) combined across 2019 and 2020 seasons. Broken lines represent mean of STI's and GYPH, (numbers from 1 to 28 refer to genotype numbers mentioned in Table 1)

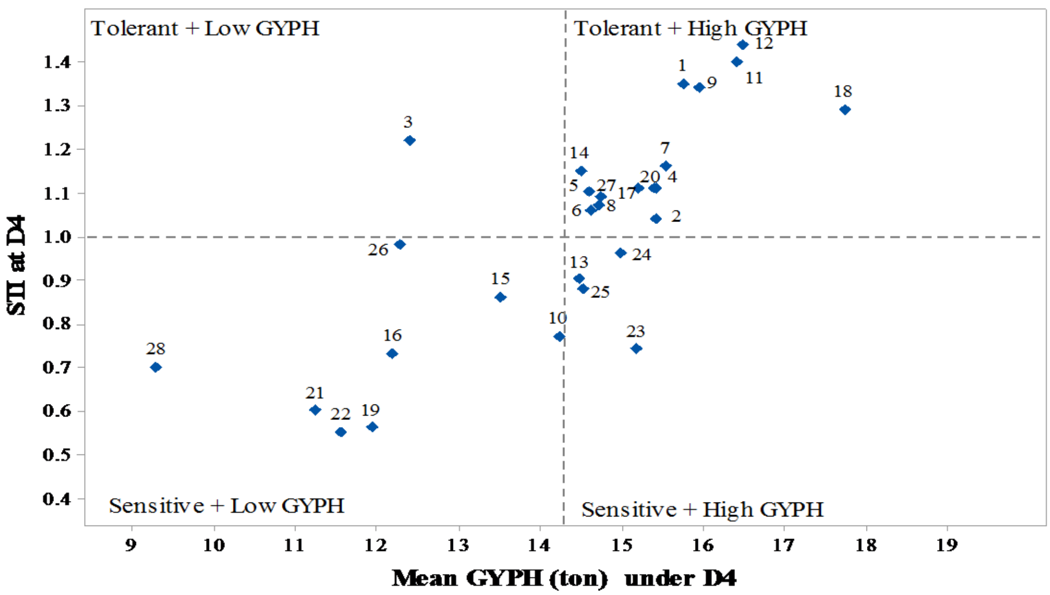

Fig. 6. Relationships between stress tolerance index (STI) of 28 maize genotypes and GYPH under D4 stressed environment (119,000 plants/ha) combined across 2019 and 2020 seasons. Broken lines represent mean of STI's and GYPH, (numbers from 1 to 28 refer to genotype numbers mentioned in Table 1)

Under density stress (95,200 plants/ha) (Fig. 5), the genotype No. 18 followed by 17, 12, 3, 1, 8, 5, 11, 9, 14, 27 and 4 were classified as most density (95,200 plants/ha) tolerant and high yielding in the same environment. On the contrary, genotypes No. 21, 28, 19, 22, 10, 26, 16, and 2 were classified as density (95,200 plants/ha) sensitive and low yielding under the same density (Fig. 5). The genotypes classified as density tolerant and low yielding under D3 (95,200 plants/ha) were No 20, 7 and 6. The genotypes classified as density sensitive and high yielding under D3 (95,200 plants/ha) were No. 23, 25, 13, 24 and 15.

Under D4 stress, i.e. plant density of 119,000 plants/ha (Fig. 6), the genotypes No. 18 followed by 12, 11, 9, 1, 7, 4, 20, 2, 17, 8, 27, 14, 5 and 6 were classified as most density tolerant and high yielding under D4. On the contrary, genotypes No. 28, 21, 22, 19, 16, 15, and 26 were classified as density sensitive and low yielding under D4 (Fig. 6). The genotype No. 3 was classified as tolerant D4 stress and high yielding. The genotypes No. 23, 24, 25. 13 and 10 were classified as sensitive to D4 stress but high or average yielding (Fig. 6).

Summarizing the above-mentioned classifications, it is apparent that under D2 density (71,400 plants/ha), the genotypes No. 11 (P 3433) followed by No. 12 (P3444), No. 3 (SC 131), and No. 5 (SC 168) were the best genotypes that occupied the first group of classifications; they are the most efficient, most density tolerant, the high yielders under D2 stress and non-stress (D1) conditions. Under D3 density (95,200 plants/ha the genotypes No. 18 (SC 235) followed by No. 17 (SC 90), No. 12 (P3444), No. 3 (SC 131), No. 1 (SC 10), No. 11 (P 3433) and No. 9 (30 P74) were the best genotypes that occupied the first group of classifications; they are the most efficient, most density tolerant, the high yielders under D3 stress and non-stress (D1) conditions.

Under the highest density (119,000 plants/ha), the genotypes No. 18 (SC 235) followed by No. 12 (P3444), No. 11 (P 3433), No. 9 (30 P74) and No. 1 (SC 10), and were the best genotypes that occupied the first group of classifications; they are the most efficient, most density (D4) tolerant, the high yielders under D4 stress and non-stress (D1) conditions.

On the contrary, the most sensitive, lowest yielding and non-responsive genotypes in this study were No. 19 (TWC 654), 21 (TWC 373), 28 (Giza-2), 10 (30 N11) and 23 (Nefertiti) under D2 (), No. 21 (TWC 373), 28 (Giza-2), 19 (TWC 654), 10 (30 N11) and 22 (TWC 374) under D3 and No. 28 (Giza-2), 21 (), 22 (TWC 374) and 19 (TWC 654) under D4.

Screening criteria for density tolerance: One approach to increasing the efficiency of selection in a stressed environment relies on the use of correlated secondary traits [35]. Correlations between density tolerance index (STI) and studied traits may be of value in determining useful selection criteria for high plant density tolerance. Estimates of rank correlation coefficients (r) between STI and studied traits across all genotypes, under the three stressed environments D2, D3 and D4 across two years are given in Table 4.

Stress tolerance index had a strong significant ($P \leq 0.01$) and positive correlation coefficient with grain yield/plant (0.87, 0.76 and 0.73) and grain yield/ha (0.86, 0.73 and 0.76) under the stressed environments D2 (71,400 plants/ha), D3 (95,200 plants/ha) and D4 (119,000 plants/ha), respectively, moderate significant ($P \leq 0.05$) and positive correlation coefficient with KPP (0.26 and 0.27) under the stressed environments D3 (95,200 plants/ha) and D4 (119,000 plants/ha), respectively and KPR (0.31) under the stressed environments D3 (95,200 plants/ha). This indicates that grain yield is the best indicator of density stress tolerance under all stressed environments.

On the contrary, STI had a strong significant ($P \leq 0.01$) and negative correlation coefficient with leaf area to produce 1g grain (photosynthetic efficiency) (-0.77, -0.69 and -0.60), and moderate significant ($P \leq$ 0,05) and negative correlation coefficient with ASI (-0.21, -0.41 and -0.37) under the three stressed environments D2 (71,400 plants/ha), D3 (95,200 plants/ha) and D4 (119,000 plants/ha), respectively.

Table 4. Rank correlation coefficients between stress tolerance index (STI) and studied traits under D2 (71,400 plants/ha), D3 (95,200 plants/ha) and D4 (119,000 plants/ha) across two years

Trait	D2	D3	D4
Days to anthesis (DTA)	0.21	0.23	0.08
Days to silking (DTS)	0.09	0.02	-0.08
Anthesis-silking interval (ASI)	-0.21*	-0.41*	-0.37*
Chlorophyll conc. index CCI (%)	-0.01	-0.11	-0.07
Leaf angle (LANG)	-0.12	-0.23	-0.20
Plant height (PH)	-0.02	-0.15	-0.02
Ear height (EH)	-0.16	-0.13	-0.14
Lower stem diameter (SDL)	-0.15	-0.24	-0.10
Upper stem diameter (SDU)	-0.20	-0.08	-0.31
Ear leaf area (ELA)	-0.01	0.13	0.26
Leaf area to produce 1 g of grain (LA/1g)	-0.77**	-0.69**	-0.60**
Leaf area index (LAI)	-0.06	0.01	-0.15
Rows/ear (RPE)	0.07	0.02	0.18
Kernels/row (KPR)	0.08	0.31*	0.17
Ears/plant (EPP)	0.20	0.04	0.19
Kernels/plant (KPP)	0.07	0.26*	0.27*
100-Kernel weight (100KW)	0.09	0.16	0.20
Grain yield/plant (GYPP)	0.87**	0.76**	0.73**
Grain yield/ha (GYPH)	0.86**	0.73**	0.76**

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

The correlation analysis presented in Table 4 suggests that the selection criteria of high density tolerance represented in the three stressed environments are high GYPP, high GYPH, high number of kernels/plant and low leaf area to produce 1g grain, low ASI. These traits could be considered as selection criteria for high density tolerance in maize if they proved high heritability and high predicted genetic advance from selection. This conclusion is in accordance with other investigators [36,29,3,4,26,16]. It is well known that the best indicators of plant tolerance to density stress are high grain yield, low anthesis-silk interval (ASI), and low leaf area to produce 1g grain [16,3,4,26].

CONCLUSIONS

The study suggested that the optimum plant density is 119,000 plants/ha for all studied Egyptian commercial hybrids, except for SC 131 which showed an optimum density of 95,200 plants/ha. The study concluded that the five hybrids P3444, SC 131, P3433, SC 235 and SC 10 were the most tolerant genotypes under the three stressed environments; the grain yield/ha (GYPH) of P3444, and SC 235 were the highest under the two highest stressed environments. These genotypes would be recommended to maize breeding programs aiming at improving high plant density tolerance. Superiority of density tolerant (T) hybrids in GYPH was associated with superiority in grain yield/plant (GYPP), kernels/plant, rows/ear, ears/plant, ear leaf area, leaf area index and reduction in leaf angle, leaf area to produce 1g grain, ear height, thickness of lower and upper stem diameter as compared to sensitive (S) hybrids. The study concluded that high GYPP, high GYPH, high number of kernels/plant and low leaf area to produce 1g grain, low anthesis-silking interval could be considered as selection criteria for high density tolerance in maize.

DISCLAIMER

The products used for this research are commonly and predominantly use products in our area of research and country. There is absolutely no conflict of interest between the authors and producers of the products because we do not intend to use these products as an avenue for any litigation but for the advancement of knowledge. Also, the research was not funded by the producing company rather it was funded by personal efforts of the authors.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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