Indian J. Genet. Plant Breed., (2022) 82(2): 153-160
ISSN: 0975-6906
doi: 10.31742/IJGPB.82.2.3
www.isgpg.org

RESEARCH ARTICLE

Productivity-based assessment of tolerance to high plant density stress in tropical maize (*Zea mays* L.) inbred lines and their single cross hybrids

Aditi Sarkar, Surinder Sandhu*, Lalit Pal, Ashutosh Kushwah and Mahesh Kumar

Abstract

High density planting (HDP) has been used extensively to achieve high productivity in temperate maize and the same can be exploited in tropical/subtropical maize. Based on two years field evaluation of tropical maize inbred lines under different planting regimes, this study led to identification of high plant density stress tolerant (at 30 percent higher plant population than cultural practice) high yielding maize inbreds. Leaf angle of first leaf above ear, anthesis-silking interval, cob length, and 1000 kernel weight were found directly affecting grain yield under HDP. Specific cross combinations exhibiting higher grain yield under HDP (approx. 15-20 percent), than normal planting practices, were identified. This is the first report on systematic development and evaluation of parental lines under high plant population and to generate high plant density stress tolerant hybrids in tropical maize.

Keywords: Combining ability, high density planting, high plant density stress, maize, productivity per unit area

Introduction

Maize has the highest potential for grain yield among all other crops of the grass family. Though the introduction of single-cross hybrids led to an improvement in maize yields significantly, genetic gains are still low particularly under marginal environments in the developing world (Chakradhar et al. 2017). Globally, the USA is the highest producer of maize followed by China, Brazil, the European Union, Ukraine, Argentina, India and Mexico (Anonymous 2019). In the USA, since the 1930s, the drastic increase in maize grain yield per unit land area has been attributed to an increase in plant density per unit area. Many studies have suggested that yield potential has not been changed in terms of yield/plant rather stress tolerance in plants has been increased for obtaining high yield potential under a wider range of environmental conditions (Tokatlidis and Koutroubas 2004). Sumalini et al. (2020) conducted genotype-by environment interaction study of homozygous inbreds and heterozygous hybrids and reported that hybrids have better yield stability due to heterozygosity as compared to homozygous inbred lines.

Understanding the traits which makes the plant the best suited to a higher plant population is of critical importance for the improvement of maize productivity through high-density planting. The small and compact plant architecture is important in providing tolerance to maize plants at high densities and to reduce lodging (Sangoi and Salvador 1998). The traits of ideal plant architecture suited for increasing plant density includes lodging resistance, reduced angle of leaf, reduced anthesis to silking interval and smaller architecture of tassel (Leivar et al. 2012). Lower height of plant and ear and a strong stem can reduce lodging and is favorable for high-density planting. Shorter hybrids perform well than longer ones under a higher plant population due to increased shading at a higher population which in turn results in stem elongation. Upright leaf allows the plant to intercept light more efficiently in all its canopy

Department of Plant Breeding and Genetics, Punjab Agricultural University, Ludhiana 141 004, Punjab, India

Corresponding Author: Surinder Sandhu, Department of Plant Breeding and Genetics, Punjab Agricultural University, Ludhiana 141 004, Punjab, India, E-Mail: surindersandhu@pau.edu

How to cite this article: Sarkar A., Sandhu S., Pal L., Kushwah A. and Kumar M. 2022. Productivity based assessment of tolerance to high plant density stress in tropical maize (*Zea mays* L.) inbred lines and their single cross hybrids. Indian J. Genet. Plant Breed., **82**(2): 153-160.

Source of support: Nil

Conflict of interest: None.

Received: Dec. 2021 **Revised:** March 2022 **Accepted:** April 2022

thus increasing the photosynthetic efficiency. The small and less leafy plant reduces the level of competition over the other plants (Sangoi and Salvador 1998). Smaller tassel size decreases the effect of apical dominance on the ear and competition between ear and tassel for assimilate partition is decreased. Light interception is also reduced by relatively smaller tassels and improves grain production efficiency at higher plant populations (Doebley et al. 1997). Sass and Loeffel (1959) had implied that the primary cause of barrenness is the lengthening of anthesis to the silking interval. Therefore, a shorter anthesis-silking interval is one of major attributes for proper seed setting.

High-density planting has its limitations as well. Planting at high density increases interplant competition for resources and negatively affects final yield. This might be due to apical dominance, barrenness, reduced number of ears per plant and reduced kernel per ear (Sangoi and Salvador 1998). Earlier studies in this domain indicated that high plant density stress reduced the ability of plants to use soil N prominently during the post-silking period (Yan et al. 2017). The increased incidence of lodging and biotic stresses has also been indicated. Despite all the constraints, it is expected that high density apposite inbred lines would generate high-density responsive hybrids. (Al-Naggar et al. 2016) emphasized that hybrids developed under low plant population do not perform well under higher plant population. The present study was aimed at the identification of efficient inbred lines, with key variants which may facilitate to cope up high plant density stress *viz*., altered plant height, leaf angle, ear placement, and ear and kernel traits. Hybrids were generated from a selected set of inbreds and evaluated for their yield and component traits under two planting regimes- normal density planting (recommended) and high-density planting and reported.

Materials and methods

The study was undertaken at Punjab Agricultural University (PAU), Ludhiana. A selected set of 45 inbred lines (Table 1), were planted in alpha lattice design with two replications

Table 1. Name, pedigree, and source institution of 45 inbred lines

S. No.	Lines	Pedigree
1	LM5	Tux Pool C2-5-1-1-2-2-2-3-1 -1-1-1---f
2	LM6	MS Pool C2 IC2-5-1-2-1-1-2-1-1 -1-1 -f
3	LM11	Suwan 1-26-1-1-1-1-1-1-1-1-1-f
4	LM13	JCY 3-7-1-1-1--f
5	LM14	CA 00 310-1-1-1-1-1-*f*
6	LM17	Partap 69-2-1-2-1-1-1-1-1-1-1…f
7	LM25	DK999-1-1-1-1-2-3-*f*
8	CML451	Pool 25 [(NPH28-1*G25) * NPH28]-1-2-1-1-3-1-B*6
9	PML5	(MS C2 IC2-3-2…x MBR plot 102-6-1) #-4-1-2-1-1-1-1-1-1-1-1-*f*
10	PML10	(MS C2 IC2-20-2x Pop28 MBR)-16-1-2-1-6-1-1-1-1-1-1-1-1-1-1-*f*
11	PML34	(Tux C2. B 73 x Tux C2-10.x CM 123)-3-1…x Tux C2 IC3-35-1 #-2-1-1-1-1-1-1-1-1-1-*f*
12	PML46	(Tux 162. Tux C2 IC2-5-1…)-4-1-1-1-4-(OP)-1-1-1-1-1-1-1-1-1-1- *f*
13	PML51	(Tux 162.LM 5-6-1 x Sw1 155086-4-3)#-1-1-2-1-1-1-1-1-1-1-1-1-1- *f*
14	PML81	TAMNET E19-b-b-1-1-1-1-1-1-1-1- *f*
15	PML97	Pioneer Hyb LEP Long Ear -27-2-1-1-1-3-1-1-1-1-1-1-1-1-2-1-1-f/ LM13- #-1- *f*
16	PML112	PAC 985 Pacific-f / LM 13 - # -1-2-1-1-*f*
17	PML115	DK 999 EC 468659-b-1-1-1-4-1-1-1- *f*
18	PML166	(CL 03618 x CML 287)-b-1-1-1-1-1-1-1-1-1-1-1- *f*
19	PML207	DMR 201 P102 E2-1-B-1-f / LM 13-#-1-2-1-1----*f*
20	PML226	HS-2785-1-1-(1)-2-2-1-1--- *f*
21	PML243	HS-2785-5-1-(2)-4-#-1-1-1-1- *f*
22	PML368	LM 13 Selection N/G -4-1-1-1-1- *f*
23	PML387	[{Tux 162xLM 5-6-1....x LM 5.Pop 24-4-4..}x LM 13]BC 2-1- 3-#-1- *f*
24	PML420	E37-1-1-1-1-1-1--- *f*
25	PML494	EC 619112-1----- *f*
26	PML898	30B07-#-1-1-1-1- *f*
27	PML1124	FMH 405-B #-1-1-1-1- *f*
28	PML1149	S 6217-1-1-2-3-1-----*f*
29	PML1170	16/LM13C// LM13C/3/LM13C # ……. *f*
30	PML1173	95/LM13C//LM13C/3/LM13C #........*f*
31	PML1228	JCY 31-1-2- ---*f*
32	PML1230	SW 93-D-313-23 Pop 49-2-3-1—*f*
33	PML 1242	WNC DMR 10R YFWS 8464/LM14—2-3-1-1-1----*f*
34	PML 1245	((P-3396-B x LM 13) x LM 13)-1-1-2- *f*
35	PML 1247	((P-3396-B x LM 14) x LM 14)-1-1---- *f*
36	PML 1248	((P-3396-B x LM 17) x LM 17)-1-1----- *f*
37	PML 1250	(G25C18MH5201/P1/P2/G25C18MH520)-B-8-2-b-b-b-b-1-1-1-1--2-1- *f*
38	PML 1266	JCY 11-2-1-1-1----- *f*
39	PML1267	CIMMYT heat tolerant selection -1-2-1-1----*f*
40	PML 1268	CIMMYT heat tolerant selection -1-2-1-1----*f*
41	PML 1269	CIMMYT heat tolerant selection 3-2-1-1----*f*
42	PML1270	CIMMYT heat tolerant selection #-1-2-4-1----*f*
43	PML1271	CIMMYT heat tolerant selection -1-2-1-1----*f*
44	PML1272	CIMMYT heat tolerant selection -1-2-1-1----*f*
45	PML1273	CIMMYT heat tolerant selection 5-2-1-1----*f*

All the inbred lines source institution is Punjab Agricultural University, Ludhiana except CML451, which was sourced from CIMMYT in two environments: normal density planting (NDP) comprising 33,333 plants/acre (at a recommended row to row and plant to plant spacing of 60 cm and 20 cm, respectively) and high-density planting (HDP) comprising 44,444 plants/acre (at row to row and plant to plant spacing of 60 cm and 15 cm, respectively). One acre corresponds to 4000 sq meters. The experiment was conducted across two years (2019 and 2020). Observations were recorded on morphological traits, grain yield and its component traits. Out of 45 inbred lines, 27 were used as parental lines. The selection of 27 inbreds was done based on their plant architectural traits viz., narrow leaf angle, moderate plant height, reduced anthesis silking interval (ASI) under HDP and high seed yield potential. Based on reproductive synchronization and pre-determined heterotic grouping, 32 hybrids were generated. The set of 32 hybrids along with two checks were evaluated in randomized block design under NDP and HDP comprising two replications in each. The checks used in this experiment were PMH 1 (released by Punjab Agricultural University (PAU) for high grain yield under irrigated conditions in Punjab state in 2005 and for north-western plains of India in 2007) and PMH 11 (released by PAU for commercial cultivation in Punjab state in 2019). In India, no cultivar has been recommended for HDP, so the common set of checks used in NDP were also used under HDP. Data for grain yield of hybrids was recorded.

Based on five randomly taken plants of each genotype of each replication, plant height (PH; in cm) was determined on standing crop by measuring from the soil surface to the base of the tassel (excluding tassel length); leaf angle (LA; in degree) was measured as the angle between the midrib of the leaf with the main axis of growth using a digital inclinometer, tassel branch number (TBN) was recorded by manually counting the number of primary branches on the tassel. 1000 kernel weight (TKW; in gram) was recorded by counting 1000 kernels manually and weighed with a digital weighing balance. Based on whole plot observation, days to 50% anthesis (DTA) was recorded when at least half of the plants in a plot extruded the first anther (pollen shedding). Similarly, days to 50% silking (DTS) was recorded when the first silk was visible on at least half the plants in the plot. Anthesis silking interval was derived by taking the absolute value of the difference between DTA and DTS. Yield per plot (Y/plot; in Kg) was recorded in terms of ear weight per plot (also called field weight per plot) immediately after crop harvest. Ear weight per plot was converted into grain yield after accounting for grain moisture content (to be recorded in the field) and shelling percentage. Statistical analysis of phenotypic data was conducted using SAS software (SAS 2011). Combined analysis of variance was performed following a test of homogeneity of variances.

Results

Effect of planting densities (environment), on agronomic performance of maize inbred lines

Table 2 summarizes the results from the combined analysis of variance for agronomic traits. Highly significant differences were observed among the main effects of genotypes for all the test traits. Similarly, highly significant differences were observed among the effects of genotypes by environment for all the traits except leaf angle of first leaf above ear (LAA).

Significant differences were noted in the overall means of the traits PH, EPH, ASI, and GY. The mean plant height under NDP was 132.62 cm with an increment of 3.89% under HDP (137.79 cm). CML451 was the shortest genotype under both NDP and HDP with a PH of 61.25 and 65.75 cm, respectively. The tallest genotype was PML226 (169.25 cm) under NDP and PML1269 (177.20 cm) under HDP. EPH ranged from 0.54 to 0.73 under NDP and 0.50 to 0.68 under HDP with PML97, PML115 with the lowest and highest value, respectively under both planting regimes. Mean value of ASI showed an increment of one day under HDP as compared to NDP. The genotype PML1273 was recorded with the highest value of ASI under both NDP (6 days) and HDP (7 days).

The distribution of variability in the traits PH, ASI and GY has been represented through box plots (Fig. 1) and genotypes differ in their specific response to these traits. PH

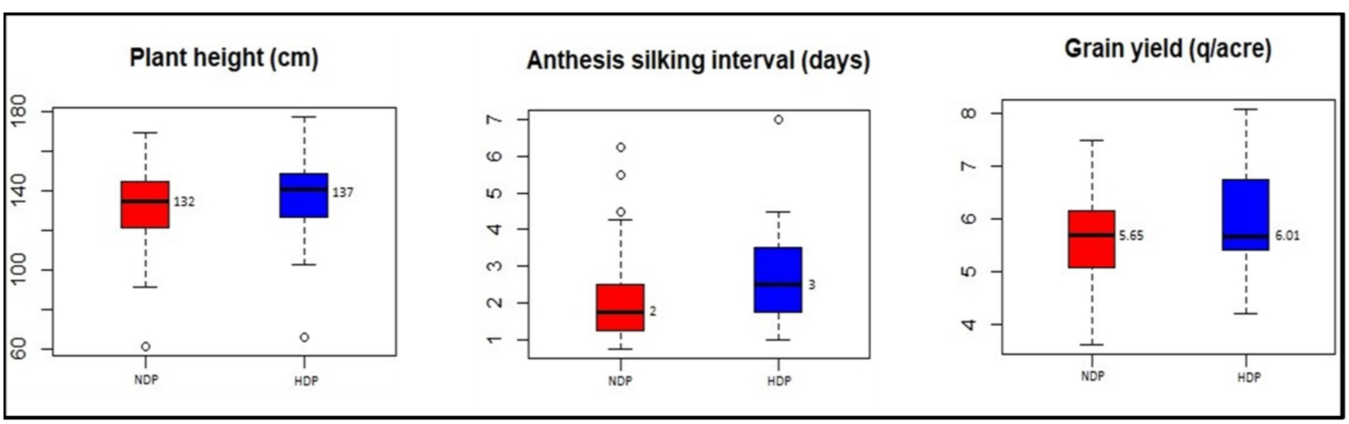

Fig. 1. Distribution of plant height, anthesis silking interval, and grain yield among inbred lines under normal (NDP) and high-density planting (HDP). The ends of the whiskers extending from the box indicate the range of minimum and maximum values.

Table 2. Mean squares and significant tests after combined analysis of variance for 11 phenotypic traits of 45 maize inbred lines evaluated across two years and two planting densities (environments)

Source	df	Traits										
		Plant height	Ear to plant height ratio	Leaf angle of first leaf above ear	Leaf angle of first leaf below ear	Tassel branch number	Anthesis silking interval	Cob length	Cob girth	Kernel row number	1000 kernel weight	Grain yield
Environment	1	2406.64**	0.10**	12.10	1.60	0.12	22.00**	0.61	0.47**	0.26	139.38**	13.86**
Year	1	24.13**	0.01	5.55	3.21	5.40*	1.00	0.02	9.17**	0.30	0.47	1.72
Genotypes	44	2560.74**	0.04**	554.82**	173.67**	87.33**	11.04**	52.24**	0.97**	7.03**	1553.35**	5.53**
Year × Genotypes	44	1.31	0.01	1.50	18.80**	0.01	0.35	0.21	0.26**	0.30	0.50	0.08
Environment × Genotypes	44	177.07**	0.01**	6.80	60.45**	10.88**	1.23**	7.09**	0.22**	2.46**	25.54**	0.70**
Environment × Year	1	97.34**	0.01	0.04	3.21	2.30	0.47	0.01	0.27*	3.33	0.04	0.18
Environment × Year × Genotypes	44	1.50	0.01	0.37	45.04**	0.01	0.40	0.19	0.16**	0.40	0.04	0.07

** significant at 1%, * significant at 5%

was normally distributed under NDP with a slightly negative skewness under HDP. Distribution was positively skewed for ASI under both NDP and HDP. For GY, distribution was positively skewed under HDP thereby depicting only some selective inbred lines exhibiting higher GY than population mean.

Average value of GY increased by 6.37% under HDP as compared to NDP. Under HDP, out of 45 genotypes, 13 genotypes were identified in which GY increased by more than 10% as compared to NDP *viz*., LM6, LM25, PML10, PML34, PML46, PML51, PML81, PML112, PML226, PML368, PML494, PML898, PML1242, and PML1271. Amongst these, in the genotypes PML34, PML46, PML51, PML81, PML494, and PML1242, GY was lower under NDP<5 q/acre. This observation generated valuable information that inbred lines which cannot be used as seed parents under NDP, showed their suitability under HDP, hence widening the pool of seed parents for breeding programs.

The lines which showed tolerance to high plant density stress along with high grain yield potential are recommended for use as female parents for hybrid seed production under high plant density stress conditions. Based on productivity under both NDP and HDP, LM6, LM25, PML112, PML 368, and PML898 were selected as good performers in which yield performance was higher (> 6 q/acre) under NDP and a significant increment of 11.32%, 12.27%, 22.85%, 17.46%, and 10.70%, respectively was observed under HDP. Tolerance to HDP and improved resource use efficiency were the chief parameters in these lines, which contributed to improved productivity. Critical analysis of these lines revealed that these harbor suitable traits imparting tolerance to high plant density stress.

Correlation and path coefficient analysis of maize inbred lines under NDP and HDP

It was well observed in our study that inbred lines exhibited differential response under HDP. Hence, it is imperative to understand the response of yield and yield contributing traits and the relationship pattern under each plant density regime. A comparison among traits correlated with grain yield in both the planting regimes has been conducted. This would help to understand traits underlying high plant density stress tolerance.

Under NDP, the traits exhibiting significant correlation with grain yield were LAA (-0.30), cob girth (0.30), and 1000 kernel weight (0.62). Under HDP, LAA and ASI had significant negative correlation of -0.34 and -0.36, respectively with GY. The comparison of cob trait correlations exhibited a changed trend of relationship with grain yield under varied plant densities. Under NDP, CG was significantly correlated with grain yield (0.30) whereas, it was non-significant under HDP. Similarly, CL was significantly correlated with GY under HDP (0.38) whereas, it was non-significant under NDP. TKW was significantly associated with grain yield under both NDP and HDP, though the level of relationship was higher under NDP (0.62) as compared to HDP (0.45).

Path coefficient analysis was also undertaken to understand the trend of direct and indirect effects of yield contributing traits on grain yield. Under NDP, three traits *viz.*, LAA (-0.31), CG (0.34) and TKW (0.50) showed direct effect on grain yield (Fig. 2). Under HDP, a greater number of traits *viz.*, LAA (-0.29), ASI (-0.13), CL (0.28), and TKW (0.27) had direct effect on grain yield (Fig. 3).

Evaluation of hybrids for grain yield

In the 34 test hybrids (Table 3), mean value of GY was 22.2 q/acre under NDP exhibiting a significant ($p < 0.05$) increment of 21.9% under HDP (27.1 q/acre). The yield evaluation of hybrids under NDP recorded three hybrids *viz*. JH20184 (PML46 × PML1228), JH20203 (PML1250 × PML1228), and JH20209 (PML243 × PML368) yielded significantly higher than the superior check PMH 11. Under HDP, out of 32 test hybrids, 10 hybrids yielded significantly higher than the

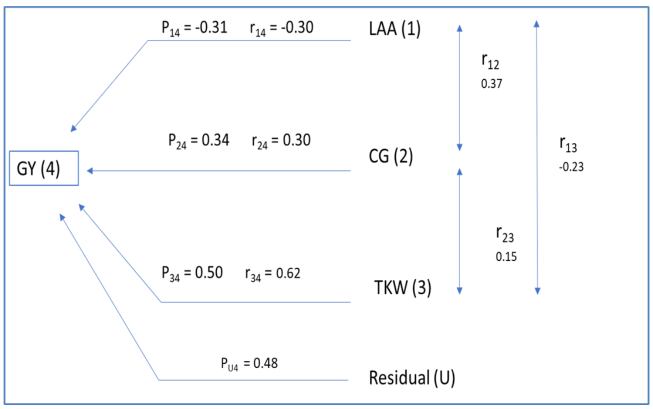

Fig. 2. Path diagram showing interrelationships among four traits. 1. LAA: Leaf angle of first leaf above ear (^{0}); 2. CG: Cob girth (cm); 3. TKW: 1000kernel weight (gm); 4. GY: Grain yield (q/acre). P and r indicate direct path coefficient and correlation coefficient, respectively.

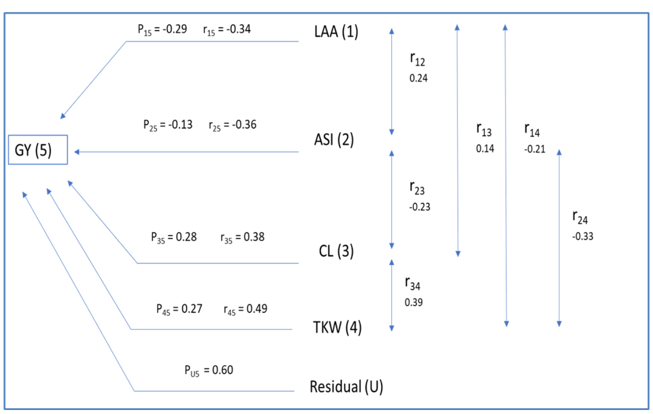

Fig. 3. Path diagram showing interrelationships among five traits 1. LAA: Leaf angle of first leaf above ear (^{0}); 2. ASI: Anthesis silking interval (days); 3. CL: Cob length (cm); 4. TKW: 1000 kernel weight (gm); 5. GY: Grain yield (q/acre). P and r indicate direct path coefficient and correlation coefficient, respectively

Table 3. Evaluation of hybrids for grain yield under different plant densities

S. No.	Hybrids	Parentage	Grain yield (q/acre)	
			Normal density planting	High density planting
1	JH 20180	LM14 × LM6	22.76	31.88**
2	JH 20181	PML5 × LM6	22.72	26.64
3	JH 20182	PML34×PML 1228	19.48	23.60
4	JH 20183	PML34 × CML451	20.04	24.56
5	JH 20184	PML46 × PML1228	30.56**	30.24**
6	JH 20185	PML97 × LM6	24.88	27.64
7	JH 20186	PML112 × PML1228	24.88	35.32**
8	JH 20187	PML112 × LM6	20.28	22.56
9	JH 20188	PML166 × LM13	21.40	29.52
10	JH 20189	PML207 × PML368	23.40	29.48
11	JH 20190	PML420 × LM6	20.00	26.48
12	JH 20191	PML1230 × LM6	21.08	21.00
13	JH 20192	PML1230× PML1228	22.56	25.44
14	JH 20193	PML1149 × PML1228	27.60	33.12**
15	JH 20194	PML1170 × LM6	19.40	22.48
16	JH 20195	PML1170 × CML451	19.04	22.56
17	JH 20196	PML1173 × LM13	20.52	20.56
18	JH 20197	PML898 × LM6	20.64	24.52
19	JH 20198	PML898 × LM13	20.08	24.40
20	JH 20199	PML898 × PML368	23.00	28.96
21	JH 20200	PML1124 × LM6	18.56	24.16
22	JH 20201	PML1124 × PML1228	15.64	19.56
23	JH 20202	PML1124 × PML368	22.56	22.84
24	JH 20203	PML1250 × PML1228	27.88**	32.96**
25	JH 20204	PML1250 × PML368	21.92	30.00
26	JH 20205	PML1267 × LM6	25.28	31.84**
27	JH 20206	PML1245 × LM6	22.32	27.04
28	JH 20207	PML1247 × LM6	21.12	30.20**
29	JH 20208	PML1247 × PML1228	23.08	30.76**
30	JH 20209	PML243 × PML368	27.88**	39.00**
31	JH 20210	PML1266 × CML451	22.64	30.48**
32	JH 20211	PML1268× CML451	20.32	25.12
33	PMH 1 (check)	LM 13x LM 14	21.44	23.12
34	PMH 11 (check)	LM 25 x LM 11	21.48	24.20
Mean			22.24	27.12
Critical difference			6.19	5.94
Coefficient of variance (%)			13.62	10.71

** significant at 1%, * significant at 5%

Table 4. Characterization of maize inbred lines, recommended as parents, to breed for high plant density stress tolerant hybrids

S. No.	Genotypes	Plant height (cm)		Leaf angle of first leaf above ear (^{0})		Leaf angle of first leaf below ear (^{0})		Anthesis silking interval (days)		1000 kernel weight (gm)		Grain yield (q/acre)	
		NDP	HDP	NDP	HDP	NDP	HDP	NDP	HDP	NDP	HDP	NDP	HDP
1	LM6	135.65	136.00	16.83	22.35	25.60	25.00	1	1	256.44	259.88	6.92	7.43
2	LM14	145.40	151.65	37.06	37.14	32.50	34.75	2	2	267.13	265.56	6.17	6.35
3	PML46	147.85	148.80	23.18	23.29	20.75	31.00	1	2	216.31	217.00	3.70	5.65
4	PML112	114.60	124.30	38.65	38.72	46.03	39.26	1	1	262.44	257.88	5.80	7.20
5	PML243	162.35	167.70	17.90	17.97	24.10	26.04	1	1	268.25	265.06	6.75	6.91
6	PML368	160.15	164.75	21.15	21.22	44.00	39.55	2	3	261.13	266.44	6.34	7.44
7	PML1149	124.30	125.05	18.65	18.72	30.28	27.46	1	2	254.56	252.13	5.30	5.53
8	PML1228	144.25	146.25	19.02	19.10	41.48	39.02	2	2	260.00	263.44	5.31	4.59
9	PML 1247	149.20	166.75	38.02	38.10	24.00	29.82	1	2	244.00	243.00	5.25	4.97
10	PML 1250	133.80	137.35	11.40	11.47	24.63	24.26	1	3	250.30	249.56	3.90	5.30
11	PML 1266	138.05	159.75	36.77	36.85	36.93	35.69	1	2	260.56	256.38	5.28	5.62
12	PML1267	131.55	135.35	33.65	31.48	24.20	25.64	4	5	256.44	253.69	4.53	4.44
13	CML451	61.25	65.75	19.02	19.10	31.13	30.38	4	4	253.13	257.69	5.60	6.80

superior check PMH 11.

The critical analysis of the parental lines of the 10 top-performing hybrids (Table 4) revealed that their parents harbor the traits amenable to HDP. Mean values of these 13 parental lines under HDP for plant height (< 150cm), LAA (< 30^0), LAB (> 30^0), ASI (2 days), TKW (> 250 gm), and grain productivity (>6 quintals/ acre) indicated that these lines have been developed for optimum morphological and productivity values to cope up with high plant density stress.

Discussion

An increase in plant height, with a menace of lodging, was generally reported in maize lines under high plant density stress. A slight increase in mean PH of 45 inbred lines was observed under HDP. This indicates higher plant density increases vegetative growth. A similar finding was previously reported by other investigators (Monneyeux et al. 2005) and (A1 Naggar and Atta 2017). At the high density, plants exhibit shade avoidance mechanisms due to which assimilates are directed more towards the vegetative growth at the expense of reproductive growth (Kebrom and Brutnell 2007; Khan et al. 2008). These findings indicate that, during the selection process, taller plants should not be preferred as height further increases under HDP increasing the risk of lodging. LAA of the genotypes used in this study was narrow (<30^0) and LAB was wide (>30^0). Narrow leaf angle is a very crucial trait for obtaining higher yield under higher plant populations. Plants with upright leaf angles allow light to penetrate the canopy, thereby increasing photosynthetic efficiency and allowing plants to grow at larger densities, which has been critical in improving maize output in recent decades (Lambert and Johnson 1978; Duvick 2005). Several researchers have suggested that upright leaf angles on the upper canopy, less erect leaves in the medium canopy, and more horizontally oriented leaves in the lower canopy provide the best plant architecture (Ort et al. 2015). Efforts were also made to select inbred lines with lesser TBN. While breeding for high plant density stress, plants with sparse tassel architecture should be selected as smaller tassels reflect and re-radiate lower amounts of solar radiation possibly available to the photosynthetic canopy (Sangoi and Salvador 1998). The protandrous behavior of tassel is also more prominent under higher plant densities due to which pollen is produced and dispersed at the expense of ear development leading to barrenness (Sangoi and Salvador 1998). ASI generally increases under high plant density stress leading to barrenness and ultimately a decline in yield. In our study, delayed silking at high plant densities has been observed in the inbred lines and this phenomenon has been recorded in several other findings. According to Kiniry and Ritchie (1985), pollen shed must coincide with silking period in plants of density tolerant genotypes which would assure viable pollen and silk availability simultaneously.

Correlation analysis in inbred lines revealed that cob girth was significantly correlated with grain yield under NDP, and this has also been reported in several other studies (Pavan et al. 2011; Kumar et al. 2014; Ahmed et al. 2020; Aman 2021). It is well documented that leaf angle, being a critical trait imparting narrow architecture, has more significance under high density than normal planting. Negative correlation of leaf angle with grain yield under high density indicates that a smaller leaf angle is more desirable to tolerate the shading stress under HDP although extremely small leaf angles (<10^0) has not proved beneficial for yield enhancement Sandhu and Dhillon (2021). Negative correlation of ASI with grain yield under HDP indicated that a shorter ASI is associated with higher grain yield. This result is in accordance with findings of Mansfield and Mumm (2014). A shorter ASI was found to be a beneficial factor in plant density tolerance (Brekke et al. 2011). TKW had the highest level of correlation with GY under both planting regimes. Highly significant positive correlation of TKW with grain yield has also been previously well documented by many researchers (Yahaya et al. 2021; Rathod et al. 2021). Path analysis also revealed the highest direct effect of TKW under both the planting densities which implied that it was one of the major factors affecting grain yield. There is no previous report of path coefficient analysis on HDP. Direct impact of greater number of traits under HDP implies that we need to modify the plant architecture to make it adept to HDP stress.

As plant density increased from 33,333 plants/acre to 43,333 plants/acre, the mean grain yield of hybrids increased by 21.9% demonstrating a highly significant relationship between plant population and grain yield. Similar results were reported by other researchers too (Widdicombe and Thelen 2002; Testa et al. 2016; A1-Naggar and Atta 2017). On the contrary, elevated plant density caused a reduction in yield per plant by 8% but it was non-significant. Previous studies on HDP by several other researchers have reported a significant reduction in yield per plant at higher populations (Duvick 2005; Gonzalo et al. 2010). The major yield increase, hence was mainly due to increase in number of plants per unit area and the reduction in yield per plant was well compensated in generated hybrids. This indicates very good adaptation of our developed hybrids to high density providing more grain bearing plants. However, many studies have reported that yield enhances with increasing density up to some extent and then declines due to limitation of resources.The reason behind this trend has been attributed to declining harvest index, plant biomass production and barrenness (Boomsma et al. 2009; Mandic et al. 2013). Singh et al. (2021) characterized 40 maize inbred lines under nitrogen stress conditions and identified inbred lines having the potential for developing maize hybrids with improved nitrogen use efficiency.

Based on grain yield, three hybrids were found superior under NDP but 10 hybrids were performing better than check under HDP which exhibited their specific adaptation to high plant population. The critical analysis of the parental lines of the top 10 performing hybrids revealed that their parents harbor the traits amenable to HDP. Hence, these lines could be potential genetic resources in future breeding programs for the development of high plant density stress-tolerant hybrids in tropical maize. Hence, this study indicated that prior selection of parental lines and their evaluation under HDP is a prerequisite for the development of hybrids for HDP. The significant increase in productivity of hybrids needs to be manifested with multi-site screening and nutrient management for commercial level utilization.

Authors' contribution

Conceptualization of research (SS); Designing of the experiments (AS, SS); Contribution of experimental materials (SS, LP); Execution of field/lab experiments and data collection (AS, LP, AK, MK); Analysis of data and interpretation (AS, SS, LP, AK, MK); Preparation of the manuscript (AS, SS).

References

Ahmed N., Chowdhury A., Uddin M. and Rashad M. 2020. Genetic variability correlation and path analysis of exotic and local hybrid maize (*Zea mays* L.) genotypes. Asian J. Med. Biol. Res., **6**: 8-15.

Al-Naggar A. and Atta M. 2017. Elevated Plant Density Effects on Performance and Genetic Parameters Controlling Maize (*Zea mays* L.) Agronomic Traits. J. Adv. Biol., **12**: 1-20.

Al-Naggar A., Atta M., Ahmed M. and Younis A. 2016. Direct vs Indirect Selection for Maize (*Zea mays* L.) Tolerance to High Plant Density Combined with Water Stress at Flowering. J. Appl. Life Sci. Int., **7**: 1-17.

Aman M. 2021. Genetic Variability Heritability and Association of Quantitative Traits in Maize (*Zea mays* L.) Genotypes. Bioinformatics, **25**: 534-536.

Anonymous. 2019. Area production and yield of maize worldwide. http://www.usda.gov.

Boomsma C., Santini J., Tollenaar M. and Vyn T. 2009. Maize Morphophysiological Responses to Intense High plant density and Low Nitrogen Availability: An Analysis and Review. Agron. J., **101**: 1426-1452.

Brekke B., Edwards J. and Knapp A. 2011. Selection and Adaptation to High Plant Density in the Iowa Stiff Stalk Synthetic Maize (*Zea mays* L.) Population. Crop. Sci., **51**: 1965-1972.

Chakradhar T., Hindu V. and Reddy P. 2017. Genomic-based-breeding tools for tropical maize improvement. Genetica, 145: 525-539.

Doebley J., Stec A. and Hubbard L. 1997. The evolution of apical dominance in maize. Nature, **386**: 485-488.

Duvick D.N. 2005. Genetic progress in yield of United States maize (*Zea mays* L.). Maydica, **50**: 193-202.

Gonzalo M., Holland J., Vyn T. and McIntyre L. 2010. Direct mapping of density response in a population of B73 × Mo17 recombinant inbred lines of maize (*Zea mays* L.). Heredity, **104**: 583-599.

Kebrom T. and Brutnell T. 2007. The molecular analysis of the shade avoidance syndrome in the grasses has begun. J. Exp. Bot., **58**: 3079-3089.

Khan A., Shah P., Rahman H. and Shah Z. 2008. Plant density and nitrogen effects on growth dynamics light interception and yield of maize. Arch. Agron. Soil Sci., **54**: 401-411.

Kiniry J. and Ritchie J. 1985. Shade-Sensitive Interval of Kernel Number of Maize 1. Agron. J., **77**: 711-715.

Kumar G. P., Prashanth Y., Reddy V. N., Kumar S. S. and Rao P. V. 2014. Character Association and Path Coefficient Analysis in Maize (*Zea mays* L.). Plant. Cell. Rep., **25**: 1498-1519.

Lambert R. and Johnson R. 1978. Leaf Angle Tassel Morphology and the Performance of Maize Hybrids 1. Crop. Sci., **18**: 499-502.

Leivar P., Tepperman J., Cohn M., Monte E., Al-Sady B., Erickson E. and Quail P. 2012. Dynamic Antagonism between Phytochromes and PIF Family Basic Helix-Loop-Helix Factors Induces Selective Reciprocal Responses to Light and Shade in a Rapidly Responsive Transcriptional Network in Arabidopsis. The Plant Cell., **24**: 1398-1419.

Mandic V., Krnjaja V., Bijelic Z., Tomic Z., Simic A. and Stanojkovic A. 2013. The effect of crop density on yield of forage maize. Biotehnologija U Stocarstvu, **31**: 567-575.

Mansfield B. D. and Mumm R. H. 2014. Survey of plant density tolerance in US maize germplasm. Crop. Sci., **54**: 157-173.

Monneveux P., Zaidi P. and Sanchez C. 2005. Population Density and Low Nitrogen Affects Yield-Associated Traits in Tropical Maize. Crop. Sci., **45**: 535-545.

Ort D. R., Merchant S. S., Alric J., Barkan A., Blankenship R. E., Bock R. and Zhu X. G. 2015. Redesigning photosynthesis to sustainably meet global food and bioenergy demand. PNAS, **112**: 8529-8536.

Pavan R., Lohithaswa H. C., Wali M C., Prakash G. and Shekara B. G. 2011. Correlation and path coefficient analysis of grain yield and yield contributing traits in single cross hybrids of maize (*Zea mays* L.). Electron. J. Plant Breed., **2**: 253-257.

Rathod S., Shinde G. and Shinde S. 2021. Genetic diversity studies in forage maize genotypes. Int. J. Chem. Stud., **9**: 2918-2921.

Sandhu S. and Dhillon B. 2021. Breeding plant type for adaptation to high plant density in tropical maize—A step towards productivity enhancement. Plant Breed., **140**: 509-518.

Sangoi L. and Salvador R. J. 1998. Influence of plant height and of leaf number on maize production at high plant densities. Pesqui. Agropecu. Bras., **33**: 297-306.

SAS Institute Inc. 2011. Base SAS 9.3 procedure guide. SAS Institute Inc Cary.

Sass J. and Loeffel F. 1959. Development of Axillary Buds in Maize in Relation to Barrenness 1. Agron J., **51**: 484-486.

Singh P., Tomar R.S., Kumar K., Kumar B., Rakshit S. and Singh I. 2021. Morpho-physiological and biochemical characterization of maize genotypes under nitrogen stress conditions. Indian J. Genet. Plant Breed., 81(2): 255-265. DOI: 10.31742/IJGPB.81.2.8.

Sumalini K., Pradeep T. and Sravani D. 2020. G × E interaction studies in relation to heterosis and stability of grain yield in maize (*Zea mays* L.). Indian J. Genet. Plant Breed., **80**(03): 250-260. https://doi.org/10.31742/IJGPB.80.3.3

Testa G., Reyneri A. and Blandino M. 2016. Maize grain yield enhancement through high plant density cultivation with different inter-row and intra-row spacings. Eur J Agron., **72**: 28-37.

Tokatlidis I. and Koutroubas S. 2004. A review of maize hybrids' dependence on high plant populations and its implications for crop yield stability. Eur J Agron., **88**: 103-114.

Widdicombe W. and Thelen K. 2002. Row Width and Plant Density Effects on Corn Grain Production in the Northern Corn Belt. Agron J., **94**: 1020.

Yahaya M. S., Bello I. and Unguwanrimi A. Y. 2021. Correlation and path-coefficient analysis for grain yield and agronomic traits of maize (*Zea mays* L.). Sci. World J., **16**: 10-13.

Yan P., Pan J., Zhang W., Shi J., Chen X. and Cui Z. 2017. A high plant density reduces the ability of maize to use soil nitrogen. PLoS One., **12:** e0172717.