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Research Article
Grain Yield and Growth Parameters of Pearl Millet Genotypes Grown in an Arid Environment under Variable Plant Densities

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Abstract
Background and Objective: Pearl millet has the potential for dryland production in the North West Coastal arid regions of Egypt, compared to other cereal crops. The objective of the current study was to identify the genotype(s) that would produce the highest grain yield under variable plant densities. **Materials and Methods:** A 2-year field trial was conducted during the summers of 2018 and 2019, to evaluate the grain yield and some agronomic characteristics of four newly introduced (IP19586, IP19612, IP6105, IP13150) and one local (Shandaweel 1) pearl millet genotypes under three plant densities (71400, 57100 and 47600 plant ha^{-1}). **Results:** Increasing plant density resulted in the production of taller plants, the least number of tillers and panicles and lowest panicle and 1000-grain weights, which were inturn, reflected on a significant reduction in final grain yield. On the other hand, the intermediate plant density improved the agronomic characteristics of the evaluated genotypes, which uplifted the productivity and grain yield. The new genotype IP19612 was superior to the other evaluated genotypes and produced a maximum grain yield of 2.76 and 3.00 t ha^{-1}, when sown at 57100 plant ha^{-1} during 2018 and 2019, respectively. **Conclusion:** In similar arid environments to the current study, expand the cultivation of the new pearl millet genotype IP19612 using 57100 plant ha^{-1} for optimum grain production.

Key words: Pearl millet, plant density, grain yield, dryland farming, ICRISAT

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Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Egypt is generally known for its arid desert climate. Western and Eastern deserts comprise an area of around 68 and 22% of Egypt's total area, respectively. Due to the negligible amount of precipitation, the reclaimed desert areas are completely dependent on irrigation with groundwater, that is mainly extracted from the Nubian Sandstone and carbonate aquifers, providing irregular water supply[1]. Water deficit is, thus, the main challenge facing agriculture in these areas that are classified as arid and hyper-arid regions with their hot and almost rainless climate. In such adverse conditions, the expansion of cultivated land is not considered as a viable option for agricultural intensification, instead, the utilization of high yielding, stress-tolerant crops would be more feasible. Therefore, there is a pressing need to expand the production of crops and varieties known for their tolerance to adverse environmental conditions, especially drought, for feeding the continuously growing population. In Egypt, the main summer staple crops are rice and maize, with their production restricted to the delta region due to their high-water requirements and need for special soil and climate[2].

Pearl millet (*Pennisetum glaucum* L.) is widely known as a multipurpose crop in many regions of the world. It provides nutritious food for humans, feed for poultry and fodder for ruminants. Compared to other cereal crops, pearl millet is advantaged with its high nutritive value, in terms of high lipids, carbohydrates and proteins, beside its high vitamins, zinc and iron contents[3,4]. Its flour was, therefore, suggested to substitute 10-20% of wheat flour in baking different types of bread[5]. Therefore, pearl millet as a cereal crop has become an important source of nutrition for populations with substandard economic conditions that inhibit different parts of the world, especially in Asia and Africa[6]. In addition, pearl millet is tolerant to drought and high temperatures[3,7], driven by its high tillering capacity and deep root system that help the crop to withstand adverse conditions that may cause yield reductions or crop failure in other summer crops. Moreover, due to its low demand for nutrients, pearl millet produces a reasonable amount of yield when grown in low fertility soils[8]. Therefore, it provides staple food especially for rural communities living in areas subject to harsh environments and unfavorable farming contexts mainly because of drought and poor soils[3].

A wide range of pearl millet genotypes is frequently developed by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). They possess variability in their grain yield and yield components among the different environments. Successful genotypes represent a package of superior traits that address the needs of diverse consumers in a specific environment. Especially in arid regions, the productivity of pearl millet is variable among the different genotypes and their response to the different production constraints in those regions, in addition to the applied management practices. Therefore, prior to the adoption of new genotypes to a certain area, they have to be intensively evaluated under the conditions of this specific area[9].

Plant density is among the agricultural practices that greatly influence grain yield and yield components of pearl millet as it determines the inter- and intra-plant competition for groundwater and soil nutrients along the growing season. Controversial observations were reported regarding the response of different pearl millet genotypes to elevated plant densities, adjusted in terms of inter- or intra-row spacing or seeding rate. Legwaila *et al.*[10] reported that wide-spaced plants (reflecting less dense canopies) had better growth and development parameters than narrow-spaced plants. On the other hand, Kumari *et al.*[11] reported a linear increase in yield and yield attributes of pearl millet in response to increasing plant densities, while, Talasila *et al.*[4] reported non-significant differences among high and low plant densities for grain yield and its components. The reported contradictory results proposed that the optimum plant density is genotype- site- and environment-dependent and should be adjusted to every specific farming context[12].

The present investigation aimed to evaluate the grain yield and some agronomic characteristics of four newly introduced (IP19586, IP19612, IP6105, IP13150) and one local (Shandaweel 1) pearl millet genotypes under three plant densities (71400, 57100 and 47600 plant ha^{-1}) when grown in the arid conditions of the North West Coast of Egypt.

MATERIALS AND METHODS

Study area: Field experiments were carried out at the Agricultural Research Station, Faculty of Desert and Environmental Agriculture (Fuka), Matrouh University, during the successive summer growing seasons of 2018 and 2019. The experimental site is located at the North West Coast of Egypt (N = 31° 04, E = 27° 54) and is characterized by high summer temperature, causing high rates of evaporation with zero rainfall. Average monthly temperature (°C) and humidity (%) for the 2 seasons are illustrated in Fig. 1. Mechanical and chemical properties of the upper 30 cm layer of soil in the experimental site for 2018 and 2019 seasons are presented in Table 1.

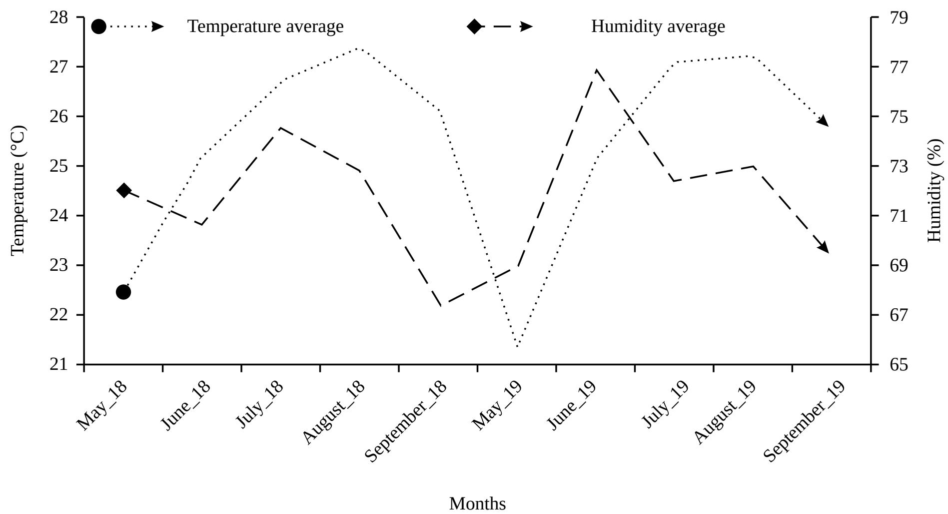

Fig. 1: Average monthly temperature (°C) and humidity (%) for 2018 and 2019 seasons

Table 1: Physical and chemical soil properties during 2018 and 2019 seasons

Soil properties	2018 season	2019 season
Particles size distribution (%)		
Texture	Sandy loam	Sandy loam
Clay	10.30	9.53
Silt	1.29	1.32
Sand	88.41	89.15
Chemical analysis		
pH	8.18	8.21
EC (ds/m)	2.24	2.30
Total N (%)	0.29	0.31
P (ppm)	81.50	80.40
Ca^{2++} (meq L^{-1})	3.90	4.10
Mg^{2++} (meq L^{-1})	3.60	3.40
Na^{+} (meq L^{-1})	16.60	17.00
K^{+} (meq L^{-1})	0.50	0.40
CO_3^{-}	0.00	0.00
HCO_3^{-}	5.60	5.90
Cl^{-}	14.30	15.10
SO_4^{-}	4.70	5.20
$CaCO_3$ (%)	12.04	12.82
Organic matter (%)	0.53	0.50

Design and treatments: The experiment was laid out as factorial 2-factor in a Randomized Complete Block Design (RCBD), with three replicates. The three tested plant densities were, 71400 (D_1), 57100 (D_2) and 47600 (D_3) plant ha^{-1}, while the five evaluated pearl millet genotypes included four newly introduced genotypes from the ICRISAT, namely, IP19586 (G_1), IP19612 (G_2), IP6105 (G_3) and IP13150 (G_4) in addition to one local cultivar, Shandaweel 1 (G_5). Experimental plot size in both seasons was 8.4 m^2 (each plot contained 4 ridges, 3 m long and 0.7 m wide). The three tested plant densities were applied through adjusting the hill spacing to 20, 25 and 30 cm for D_1, D_2 and D_3, respectively. Sowing was done on the 13th and 15th of May during 2018 and 2019, respectively.

Farm management practices: Pearl millet genotypes were sown at 4 seeds/hill on one side of the ridge and then thinned to one plant per hill after 2 weeks. Phosphorus fertilizer as calcium monophosphate (15.50% P_2O_5) was added with seedbed preparation at the rate of 54.0 kg P_2O_5 ha^{-1}. Nitrogen fertilizer was applied at the rate of 140 kg N ha^{-1} in the form of ammonium nitrate (33.5% N), split into three doses, i.e., 28,56 and 56 kg N applied at sowing, tillering and booting, respectively. A total amount of 4000 m^3 ha^{-1} water was applied as drip irrigation that was scheduled according to the crop's growth stage. Irrigation was done every 2-3 days during the early growth and crop establishment, then every 4-5 days during the vegetative growth, while during grain development, irrigation was scheduled every 6-8 days and stopped 2 weeks prior to harvesting. Early in the season weeds were manually controlled.

Data collection and measurements: At crop maturity, data were collected from the experimental plots prior to harvesting. Plant height (cm) was determined for five randomly chosen plants per plot by measuring stems from the ground surface to the tip of the upper leaf blade. Number of tillers and number of panicles were counted in 1 m^2 in each plot. Harvesting was manually done by cutting the stems of the guarded plants in the inner two rows in each plot, with a sickle directly above ground level. Fresh biological yield (t ha^{-1}) was weighed directly after harvesting. Panicle length (cm) and panicle weight (g) were determined for five random plants from each plot. Threshing was done using a stable threshing machine, grain weight per plot was recorded. The 1000-grain weight (g) was determined as an average of three random grain samples taken from each plot. Finally, harvest index was calculated as grain yield/fresh biological yield.

Statistical analysis: Data (D) of yield and agronomic parameters were subjected to analysis of variance using SAS 9.4 mixed procedure (SAS Institute, Cary, North Carolina, USA) with replicate considered the random effect, while plant density and genotype were considered fixed effects according to the following statistical model[13]:

$$D_{ijk} = \mu + B_i + D_j + G_k + (D \times G)_{jk} + e_{ijk}$$

Where:

- μ = Overall mean
- B_i = Replicate effect (i = 1, 2, 3)
- D_j = Plant density effect (j = 1, 2, 3)
- G_k = Genotype effect (k = 1, 2, 3, 4, 5)
- e_{ijk} = Experimental error

Prior to the analysis of variance, total number of tillers and number of panicles per m^2 were subjected to square root transformation, while, harvest index was arcsine transformed and expressed as a percentage. Means were compared, using the Least Significant Difference procedure (LSD) and significances were declared at 5% level of probability.

RESULTS

Levels of significance presented in Table 2 revealed that the investigated plant densities exerted significant influence on all the studied parameters except the harvest index in the two seasons. Similarly, all parameters, except the harvest index, were significantly variable among the five tested genotypes during 2018 and 2019. All tested parameters,

Table 2: F-values and levels of significance of the grain yield and growth parameters of pearl millet during 2018 and 2019 seasons

		Biological yield (t ha^{-1})		Grain yield (t ha^{-1})		Total number of tillers (m^{-2})	
Source of variation	d.f.	2018	2019	2018	2019	2018	2019
Plant density (D)	2	9.32**	11.15**	43.89**	30.60**	421.61**	157.68**
Genotype (G)	4	119.36**	134.60**	375.60**	158.42**	227.75**	73.05**
D×G	8	02.99**	03.07**	09.17**	06.15**	06.39**	05.97**
		Number of panicles (m^{-2})		Plant height (cm)		Panicle length (cm)	
Plant density (D)	2	76.53**	132.51**	16.05**	1062.45**	61.42**	38.27**
Genotype (G)	4	36.05**	63.33**	14.56**	1095.27**	09.27**	05.10**
D×G	8	04.68**	05.96**	10.42**	035.37**	01.48^{ns}	00.98^{ns}
		Panicle weight (g)		1000-grain weight (g)		Harvest index (%)	
Plant density (D)	2	287.11*	160.81*	19.48*	07.14**	1.50^{ns}	1.74^{ns}
Genotype (G)	4	170.70**	97.84**	104.84**	21.19**	2.13^{ns}	0.45^{ns}
D×G	8	01.23^{ns}	01.38^{ns}	00.45^{ns}	01.22^{ns}	1.07^{ns}	1.21^{ns}

*Significant at $p \le 0.05$, **Significant at $p \le 0.01$, ns: Non-significant, d.f.: Degrees of freedom

Table 3: Mean values of biological and grain yields (kg ha^{-1}) as affected by the plant density x genotype interaction during 2018 and 2019 seasons

		Biological yield		Grain yield	
Treatments	Genotype (G)	2018	2019	2018	2019
Plant density (D)					
71400 (D_1)	IP19586 (G_1)	5.08^{bA}	5.36^{bA}	1.75^{bAB}	1.83^{bAB}
	IP19612 (G_2)	6.84^{aB}	7.33^{aB}	2.44^{aB}	2.46^{aB}
	IP6105 (G_3)	4.36^{cA}	4.54^{cA}	1.50^{cAB}	1.56^{cA}
	IP13150 (G_4)	4.43^{cA}	4.59^{cA}	1.40^{cAB}	1.45^{cA}
	Shandaweel 1 (G_5)	5.21^{bA}	5.51^{bA}	1.68^{bA}	1.75^{bA}
57100 (D_2)	IP19586 (G_1)	5.15^{bA}	5.44^{bA}	1.82^{bA}	1.96^{bA}
	IP19612 (G_2)	7.73^{aA}	8.21^{aA}	2.76^{aA}	3.00^{aA}
	IP6105 (G_3)	4.59^{cdA}	4.72^{cA}	1.58^{dA}	1.61^{cdA}
	IP13150 (G_4)	4.23^{dA}	4.40^{cBC}	1.46^{eA}	1.55^{dA}
	Shandaweel1(G_5)	5.04^{bcA}	5.29^{bA}	1.70^{cA}	1.78^{cA}
47600 (D_3)	IP19586 (G_1)	5.04^{bA}	5.25^{bA}	1.68^{bB}	1.72^{bB}
	IP19612 (G_2)	6.37^{aB}	6.76^{aC}	2.15^{aC}	2.20^{aC}
	IP6105 (G_3)	4.34^{cdA}	4.50^{cdA}	1.43^{cB}	1.45^{cA}
	IP13150 (G_4)	4.08^{dA}	4.20^{dC}	1.37^{cB}	1.38^{cA}
	Shandaweel 1 (G_5)	4.59^{bcB}	4.72^{cB}	1.60^{bA}	1.67^{bA}
L.S.D $_{0.05}$		0.499	0.523	0.104	0.183

Means followed by different small letter(s) within the plant density or different capital letter(s) within the same genotype, for each studied parameters and experimental season are significantly different at $p \le 0.05$

Table 4: Mean values of total number of tillers (m^{-2}), number of panicles (m^{-2}) and plant height (cm) as affected by the plant density$\times$genotype interaction during 2018 and 2019 seasons

		Total number of tillers		Number of panicles		Plant height	
Treatments	Genotype (G)	2018	2019	2018	2019	2018	2019
Plant density (D)							
71400 (D_1)	IP19586 (G_1)	42.66^{cC}	44.96^{cC}	33.77^{cC}	35.80^{cC}	195.90^{cA}	204.60^{cA}
	IP19612 (G_2)	56.41^{aC}	58.71^{aC}	50.62^{aC}	52.66^{aC}	206.60^{bA}	216.28^{bA}
	IP6105 (G_3)	50.63^{bC}	52.60^{bC}	40.21^{bC}	41.80^{bC}	202.30^{bcA}	213.22^{bA}
	IP13150 (G_4)	36.21^{dC}	39.51^{dC}	27.82^{dC}	29.10^{dC}	230.00^{aA}	262.63^{aA}
	Shandaweel1 (G_5)	52.31^{bC}	54.61^{bC}	43.75^{bC}	45.31^{bC}	210.50^{bA}	220.77^{bA}
57100 (D_2)	IP19586 (G_1)	50.31^{cB}	51.94^{cB}	44.91^{cB}	47.15^{cB}	186.50^{cAB}	193.92^{dB}
	IP19612 (G_2)	67.32^{aB}	69.62^{aB}	61.52^{aB}	62.37^{aB}	191.80^{bcB}	200.78^{cdB}
	IP6105 (G_3)	60.84^{bB}	61.81^{bB}	55.61^{bB}	56.72^{bB}	200.30^{bA}	209.47^{bcA}
	IP13150 (G_4)	44.72^{dB}	49.02^{dB}	38.46^{dB}	39.28^{dB}	220.10^{aAB}	239.90^{aB}
	Shandaweel 1 (G_5)	60.46^{bB}	62.43^{bB}	53.15^{bB}	55.46^{bB}	209.70^{bA}	219.07^{bA}
47600 (D_3)	IP19586 (G_1)	60.47^{cA}	62.44^{cA}	50.66^{dA}	52.70^{cA}	178.60^{cB}	184.45^{cB}
	IP19612 (G_2)	76.10^{aA}	77.73^{aA}	72.31^{aA}	73.44^{aA}	181.70^{cC}	187.75^{cB}
	IP6105 (G_3)	72.63^{bA}	75.93^{aA}	67.82^{bA}	68.10^{bA}	177.10^{cB}	181.35^{cB}
	IP13150 (G_4)	52.65^{dA}	56.95^{dA}	48.57^{eA}	49.93^{dA}	210.30^{aB}	221.73^{aC}
	Shandaweel 1 (G_5)	70.20^{bA}	71.17^{bA}	61.44^{cA}	63.77^{bA}	192.80^{bB}	201.18^{bB}
$L.S.D_{0.05}$		03.55	03.60	04.32	05.10	09.91	10.21

Means followed by different small letter(s) within the plant density or different capital letter(s) within the same genotype, for each studied parameters and experimental season are significantly different at $p \leq 0.05$

except panicle length, panicle weight, 1000-grain weight and harvest index during 2018 and 2019 were significantly affected by the plant density$\times$genotype interaction.

It was clear from the means presented in Table 3, that the genotype G_2 was superior to the other tested genotypes in biological yield production during both seasons across all plant densities. On the other hand, for the low and intermediate plant densities the genotype G_4 and for the high plant density, the genotypes G_4 and G_3 produced the lowest significant amount of biological yield during both seasons. Moreover, during 2018, the genotypes G_1, G_3 and G_4 produced significantly similar amounts of biological yield under the three plant densities, while, the genotype G_2 performed better with the intermediate plant density and the local cultivar Shandaweel 1 (G_5) was better under the high and intermediate densities. Slight shifts in the performances of the genotypes in response to the plant densities occurred in 2019. Similar to 2018, the genotypes G_1 and G_3 were non significantly affected by the plant density, while G_2, G_4 and G_5 were significantly superior with the intermediate, high and both high and intermediate plant densities, respectively. Similar to the biological yield, means of grain yield revealed superiority for the genotype G_2 over all the tested genotypes, across the three plant densities during both seasons (Table 3), while, again, the genotypes G_3 and G_4 produced the lowest significant grain yield. As a result of the significant interaction, variations among the five genotypes were dependent on the plant density. While G_3, G_4 and G_5 were non-significantly affected by the plant densities, G_1 produced the highest grain yield with the highest and intermediate plant densities, whereas, G_2 performed better under the intermediate plant density (D_2) followed by D_1 than D_3. In general, the highest significant grain yield during 2018 was 2.76 t ha^{-1} and the lowest was 1.37 t ha^{-1}, while in 2019 the highest value was 3.00 t ha^{-1}, against 1.38 t ha^{-1}, for the $G_2\times D_2$ and $G_4\times D_3$, respectively.

The total number of tillers and the number of panicles significantly decreased with each incremental increase in plant density for all tested genotypes (Table 4). In general, the genotype G_2 produced the highest significant number of tillers and panicles across all plant densities, compared to other genotypes. On the contrary, the genotype G_4 produced the lowest significant number of tillers and panicles. Noticeably, variations in plant height as affected by the interaction between genotype and plant density followed an opposite trend to number of tillers and panicles (Table 4). Where, the genotype G_4 was characterized by the tallest significant plants across all plant densities in both growing seasons. Obviously, the tallest significant plants from the genotypes G_1, G_2, G_4 and G_5 were produced with the highest plant density (D_1), while for G_3, the tallest plants were produced with D_1 and D_2. Reducing the plant density was accompanied with a consequent reduction in plant height for all genotypes in both seasons.

Means of panicle length presented in Table 5, reveals that the highest significant panicle length was obtained from the intermediate density (D_2), amounting to 21.34 and 22.44 cm for 2018 and 2019, respectively, followed by D_1 and D_3, which were insignificantly different. Regarding the five tested genotypes, G_2 and G_1 were characterized by the longest significant panicles for the 2 seasons. As for the panicle weight, the lowest plant density (D_3) resulted in the

Table 5: Mean values of panicle length (cm), panicle weight (g), 1000-grain weight (g) and harvest index (%) as affected by plant density and genotype during 2018 and 2019 seasons

	Panicle length		Panicle weight		1000-grain weight		Harvest index	
Treatments	2018	2019	2018	2019	2018	2019	2018	2019
Plant density (D)								
71400 (D_1)	19.72[b]	20.82[b]	29.15[b]	29.39[b]	11.32[b]	11.50[b]	33.7[a]	33.1[a]
57100 (D_2)	21.34[a]	22.44[a]	29.62[b]	29.90[b]	12.33[a]	12.46[a]	34.7[a]	35.1[a]
47600 (D_3)	19.08[b]	20.18[b]	30.77[a]	30.94[a]	11.56[b]	11.44[b]	33.7[a]	33.1[a]
$L.S.D_{0.05}$	00.71	00.93	00.96	00.88	00.65	00.71	01.56	02.75
Genotype (G)								
IP19586 (G_1)	20.50[a]	21.49[a]	29.35[cd]	29.68[cd]	11.30[c]	11.43[bc]	34.4[a]	34.3[a]
IP19612 (G_2)	20.83[a]	21.93[a]	30.86[a]	31.07[a]	12.48[a]	12.52[a]	35.0[a]	34.2[a]
IP6105 (G_3)	19.66[b]	20.88[ab]	29.81[bc]	30.11[bc]	11.52[c]	11.77[ab]	34.0[a]	33.6[a]
IP13150 (G_4)	19.50[b]	20.60[b]	28.95[d]	29.10[d]	11.31[c]	10.69[c]	33.2[a]	33.1[a]
Shandaweel 1 (G_5)	19.73[b]	20.83[b]	30.23[ab]	30.39[b]	12.04[b]	12.59[a]	33.6[a]	33.6[a]
$L.S.D_{0.05}$	00.53	00.65	00.71	00.66	00.41	00.83	03.68	03.87

Means followed by different letter(s) within the same studied parameter and experimental season for each treatment are significantly different at $p \leq 0.05$

production of the heaviest significant panicles (Table 5), for the two respective seasons, reaching 30.77 and 30.94 g whereas, D_1 and D_2 gave comparable panicle weights. Genotype G_2 had the heaviest panicles in the two respective seasons (30.86 and 31.07 g). Data of the 1000-grain weight (Table 5), revealed that the highest significant values were recorded fo D_2 whereas D_1 and D_3 gave comparable values. Moreover, G_2 was characterized by the heaviest 1000-grain weight in the two seasons (12.48 and 12.52 g, respectively) followed by G_3 and G_5 during the second season. Observably, the three tested plant densities as well as the five genotypes were insignificantly different regarding the harvest index (Table 5). In general, the harvest index ranged from 33.70-34.70% (in 2018) and from 33.10-35.10% (in 2019).

DISCUSSION

Variability in the grain yield and agronomic characteristics of the evaluated pearl millet genotypes in response to the tested plant densities was detected in the current study, when pearl millet was grown in an arid environment. The experimental location of the current study is known for its harsh nature, where crop growth is constrained by several abiotic stresses, like drought and heat stresses. Therefore, research related to the development of genotypes that can tolerate such harsh environments and grow and produce under stress has been a priority in that area. Plant density is a very important determinant to the growth and productivity of different genotypes. It is evident that the optimal plant density for pearl millet is variable among different geographic regions[10]. Especially in arid environments and low-fertility soils, where growth requirements are limited, the accurate adjustment of plant density becomes crucial to minimize competition and secure optimum resource use-efficiency. Generally, when millets are intended for grain production, less plant density is recommended, than in case of forage production, especially in dryland farming[14]. Increasing the number of plants per unit area, lead to increasing plant competition, for light, soil moisture and nutrients along the plant's life cycle. This effect is similar to the effect of increasing plant population density by any other means, such as narrowing inter- or intra-row spacing or increasing the seeding rate.

Plant height is a very important agronomic characteristic that is directly related to plant growth[15]. A consistent increase in pearl millet plant height was detected with increasing plant density. Thus, the increased plant competition, due to high plant densities, resulted in the production of the tallest plants. In fact, under high plant densities, the plants strive for more solar radiation[16], where they tend to utilize stem elongation as a common mechanism to increase their chance of capturing more light. This explanation was confirmed with the early observations of Schmitt and Wulff[17], who reported an increase in internode length with high plant densities. Similar observations were reported by several researchers, e.g., Faramarzie *et al.*[18] and Yasin *et al.*[19]. Nonetheless, it is evident that taller plants usually have thin and slender stems and are thus, more susceptible to lodging[20,21], which might object the use of the highest plant densities. For the same reason, the genotype G_4 was disadvantaged by the production of the tallest plants compared to the other tested genotypes. On the other hand, G_2 being characterized with the shortest plants, would be less prone to lodging thus, highly recommended in the area.

Obeng *et al.*[22] identified three types of tillering in pearl millet, i.e., synchronous and non-synchronous tillering, where tillers arise from the basal leaf buds and sub-terminal tillering, where tillers arise from the auxiliary buds. Altering plant density is known to significantly affect total number of tillers, especially those arising from the auxiliary buds[10]. The ability of pearl millet to effectively compensate for lower plant density through enhanced tillering, might explain the higher number of tillers produced with lower plant densities in the current study. Noticeably, the low and intermediate plant densities, not only produced higher number of tillers but also converted around 89-90%, respectively, of those tillers to productive panicles (the percentage between number of tillers to number of panicles) compared to only 82% conversion percentage for the highest plant density. A similar negative correlation between plant density and number of tillers and panicles was reported by several researchers[10]. Tillering capacity was variable among the evaluated genotypes, it is usually dependent on the genotype ability to produce and accumulate dry matter in the main stem during the early growth stages. As indicated by Van Oosterom *et al.*[23], high tillering potential is a very important phenotypic adaptation strategy of pearl millet genotypes to secure yield stability in cropping systems with extreme arid desert conditions. It is thus, very useful to identify genotypes with high tillering potential to aid their incorporation in breeding for increased adaptability. In the current study, the genotype G_2 was superior to the other genotypes regarding the number of tillers and panicles while G_4 was inferior, which was obvious based on the previously reported negative correlation between plant height and tillering ability of the plant. Although all genotypes responded similarly to increasing the plant density by reducing the number of tillers and panicles, lower magnitude of reduction was reported for G_2 compared to G_4, confirming the superiority of G_2 and explaining the reported significant interaction for those traits.

Pearl millet, in general, is characterized by short and compact panicles, with panicle length and weight being important selection's criteria, affecting the farmer's acceptance to the variety, especially in arid and semi-arid environments[24]. In the current study the highest plant density (71400 plant ha^{-1}) was not in favor of the panicle length, weight and 1000-grain weight. Meanwhile, highest panicle length and 1000-grain weight were produced in response to the intermediate plant density (57100 plant ha^{-1}) and heaviest panicles resulted from the lowest plant density (47600 plant ha^{-1}). The increase in panicle length and weight is a result of the cumulative effects of growth and vigor of the plants, which represent a reflection of higher rates of photosynthesis accompanied with better translocation of photosynthates to various plant parts[25]. The intermediate plant density in the current study was probably sufficient to secure optimum and stable mobilization of nutrients towards the sink (panicle) as clarified by Jat *et al.*[26]. Similarly, less dense pearl millet plant canopies, driven by increased intra-row spacings or decreased seeding rates[18] resulted in higher panicle length, weight and 1000-grain weight, which was attributed to the reduced competition for growth resources. Ouendeba *et al.*[27] reported that farmers and breeders tend to prefer genotypes with longer and heavier panicles. In this regard, G_2 showed good potentials for the production of long, heavy panicles and thus could be used for breeding purposes to improve panicle length and weight.

Grain yield is a complex characteristic, which is a function of several overlapping responses of the evaluated genotypes to the tested plant densities. Contradictory results concerning the response of grain yield to plant density were reported in previous studies. While, several researchers indicated that grain yield, generally increased with increasing plant density[28], others reported that dense canopies tended to produce more straw than grain yields[29]. In the current study the highest plant density was not in favor of grain production. In an attempt to explain the negative impact of high densities on grain yield of pearl millet, Ajeigbe *et al.*[12] reported that, in dense canopies, plants are subject to high competition for growth resources and, thus are pushed to early maturation as a mechanism to escape the competition stress, which is directly reflected on less grain production. This was confirmed by the study of Craufurd and Bidinger[30], who suggested that less dense populations, matured later and produced more tillers with higher grain weights and, thus better grain yields. In addition, the relatively high genetic correlation between panicle weight, 1000-grain weight on the one hand and grain yield on the other hand as reported by Haryanto *et al.*[31], suggests them as the components mostly affecting grain yield. In the current study the treatments that resulted in the highest agronomic characteristics also led to the highest grain production. The highest grain yield was reported for the intermediate plant density and G_2. Similar association between grain yield and agronomic characteristics was reported by Faramarzie *et al.*[17] and Nandini and Sridhara[32] for proso and foxtail millets, respectively.

Harvest Index (HI) indicates the ability of the genotype to convert the accumulated dry matter into the economic component (grains). Especially when subject to unfavorable conditions, HI is proposed as an important selection criterion indicating the plant's ability to set grains under stress[33]. The reported non-significant variations in the HI among the treatments in the current study, suggest that the direction and magnitude of variations of both biological and grain yields in response to the treatments were homogenous. Therefore, despite the significant variations in the HI components in response to the treatments, the HI itself was non-significantly variable.

CONCLUSION

In conclusion, this study highlights the feasibility of pearl millet production in the arid desert environments, characterized by high temperatures and limited resources. The study provided precise information about the optimum plant density that should be used under arid conditions and the promising genotype(s) that could be further utilized for breeding purposes. In general, the low (47600 plant ha^{-1}) and intermediate (57100 plant ha^{-1}) plant densities supported the production of a higher number of tillers and panicles with heavier panicles and grains, which were clearly reflected on higher final grain yields with the intermediate plant density being superior to the low. Additionally, the shorter plants produced with decreased plant densities are more resistant to lodging, reducing the risk of crop failure. Among the evaluated genotypes, the newly introduced genotype IP19612 demonstrated superiority concerning all the agronomic characteristics and grain yield and thus could be incorporated in breeding programs to improve the productivity and adaptability of other genotypes.

SIGNIFICANCE STATEMENT

The present study revealed that the yield and agronomic characteristics of pearl millet genotypes are greatly variable in response to different plant densities when grown in arid environments. These results will help the researchers to uncover some critical areas concerning pearl millet grain production in arid regions. In addition, the evaluation of the newly released genotypes in different regions of the world, especially those characterized by harsh arid environments, like the current study, would help the plant breeders to identify potential parents for particular genetic improvement programs.

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