

Response of pearl millet (*Pennisetum glaucum* L.) to plant population in the semi-arid environments of Nigeria

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ABSTRACT

Low planting densities and use of unimproved varieties contribute to the low yields of pearl millet (*Pennisetum glaucum* L.) in Nigeria. Field experiments were conducted during the 2013 and 2014 growing seasons, to evaluate the response of pearl millet varieties to varying plant hill population in semi-arid environments of Nigeria. Year, variety and plant hill population had significant ($p \leq 0.05$) effect on days to 50% flowering, grain and stalk yields. With exception of Sosat-C88 at 8,889 hills ha⁻¹, the grain and stalk yields of pearl millet varieties were found to be significantly higher at higher hill populations than lower hill populations in both locations. Plant chlorophyll content (SPAD) at 21 DAS (days after sowing) was higher and significantly correlated with grain yields in Minjibir than value at 42 DAS. Similarly, leaf area index (LAI) at 42 DAS was significantly correlated with grains than at 63 DAS. Increasing hill population to 13,333, 26,667 and 53,333 hills ha⁻¹ increased grain yield by 5.8, 5.3 and 4.5% in Minjibir and by 14.3, 18.7 and 10.1% in Gambawa respectively compared to 8,889 hills ha⁻¹. Similarly, stalk yields increased with increased plant hill population, which ranged from 6 to 23% at Minjibir and 11 to 15% at Gambawa over 8,889 hills ha⁻¹. Sosat-C88 was found to produce higher yield across the different hills population than the other varieties tested with mean yield gained by 17% in Minjibir and 19.3% in Gambawa over local variety. Results suggest no blanket recommendation for the hill population across the varieties; GB8765 attained an optimal yield at a population of 13,333 hills ha⁻¹ in both locations beyond which grain yield decline. Sosat-C88 produced an optimum yield at lower population of 8,889 hills ha⁻¹ at Minjibir and higher population of 26,667 hills ha⁻¹ at Gambawa while local variety an optimal yield was stable at 26,667 hills ha⁻¹ in both locations.

Keywords: Hill populations, leaf area index, productivity, plant chlorophyll, semi-arid tropics.

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INTRODUCTION

In the semi-arid region of West Africa, 97% of the agricultural land is rainfed with cereal crops yield of about 500 to 1000 kg ha⁻¹ (Rockström et al., 2004). In these areas, pearl millet is one of the most reliable cereal crops grown under short duration (4 to 5 months) rainfed condition (Taylor, 2004; Uzoma et al., 2010). It is a drought tolerant, warm-season crop predominantly grown

as a staple food grain and a source of feed and fodder (Yadav, 2010; Sathya et al., 2013). Pearl millet is a high quality forage crop in the developed countries like U.S.A and Australia, and considered as a new experimental forage crop in South America and Korea (Khairwal et al., 2007). It is the only cereal that reliably provides grain and fodder under dryland conditions in shallow and sandy

soils with low fertility and water holding capacity (Andrews and Bramel-Cox, 1993; Wilson et al., 1995). Because of its tolerance to drought, it can be grown in areas where other cereal crops such as maize and sorghum would not survive (Basavaraj et al., 2010) and can yield in areas that receive rainfall as low as 200 to 250 mm (Tabo, 1995; Bidinger and Hash, 2003). In 2009, improved pearl millet varieties accounted for 34.8% adoption among farmers with a total 1,154,261 ha cultivated across Sudano-Sahelian zone of Nigeria (Ndjeunga et al., 2011). Though, the analysis of long-term (20-year) millet production indicated national average yield of 1170 kg ha⁻¹ (FAOSTAT, 2016), significant downward yield production (2011 to 2016), indicated most smallholder farmers still produce as low as average yield of 500 kg ha⁻¹ (Ndjeunga et al., 2011). Hence, modalities to augment or intensify its production will help to increase food security and reduce poverty among the increasing human population in the country.

The present low yield could be attributed not only to variability of water availability related to the erratic rainfall patterns leading to water stress at some critical plant-growth stages (Chakraborty and Newton, 2011), but also to low inherent soil fertility, lack of use of improved varieties, fertilizer and the use of low plant population (Doumbia et al., 2008). Plant population has a profound effect on yield and yield component of most field crops (Mohammed et al., 2008; Tajul et al., 2013). The plant population is not only in terms of the number of plants per unit area, (i.e. plant density), but also in terms of the arrangement of the plants on the ground. West African pearl millet farmers traditionally plant low plant populations of approximately 5000 hills ha⁻¹ (2 to 5 plants hill⁻¹) in order to reduce risk of yield loss from water stress (Bationo et al., 1992) and allows plants to scavenge large soil volumes for the limited nutrients available (Mason et al., 2015). In village surveys conducted in Nigeria, Agber et al. (2012) found that planting density of millet averaged 10,000 hills ha⁻¹ with high variability between farmer's fields while some even planted at much lower rates. When land is not limiting and no inputs such as pesticides, or fertilizer are used, low plant density has little effect on the farmer's profit or labour requirement. As the need to raise production per unit of land area increases, fertilizer use and increase plant density are necessary to optimize production in order to gain maximally from the applied input. Numerous trials conducted in West Africa with maize and sorghum have shown that plant density and inter-row spacing have a significant effect on water use, grain yield, and fertilizer use efficiency (Fatondji et al., 2011). Increased plant populations, combined with the use of improved varieties and recommended fertilizer application, have been found to increase pearl millet grain yields. Bationo et al. (1990) found that increasing population from 5000 to 40,000 hills ha⁻¹ increased yields in years with normal and above average rainfall, with only a slight yield decrease in drought years in Niger. Payne (1997) reported that even

in dry years, higher grain yield and water use efficiency are possible using a plant population of 20,000 hills ha⁻¹ with application of 40 and 18 kg P ha⁻¹. In contrast, De Rouw (2004) reported that higher plant populations increased the risk of crop failure. Pearl millet recommendations for plant population and spacing vary with anticipated seasonal rainfall and soil water holding capacity. Some farmers keep low plant populations to enhance intercropped cowpea yield in intercropping systems (Grema and Odo, 1998) but increased pearl millet yields can be produced by plant populations that are two to four times greater than traditionally used (Bationo et al., 1990; Maman et al., 2000a, b).

Though several high yielding millet varieties are available in the sub-region, there is little information on their response to increased plant population given the long term practice of growing millet at very low populations in the region. The objective of this study was to determine the responses of morphologically different pearl millet varieties to varying plant hill population under semi-arid environments of Nigeria.

MATERIALS AND METHODS

Experimental sites

The experiments were conducted in two locations during 2013 and 2014 growing seasons in the semi-arid region of Nigeria. The first location was ICRISAT Research field situated within Institute for Agricultural Research in Wasai, Minjibir Local Government Area, Kano State (Latitudes 12.17°N and longitude 8.65°E). The second location was ICRISAT Experimental site on a farmer's field at Gambawa, Gumel Local Government Area, Jigawa State (Latitude 12.98°N and Longitude 9.75°E). Both sites have a mono-modal rainfall pattern; most of the rain in the area comes as short-duration, high-intensity storms between June and September with one or two rainfall events in October. About 70% of the total rainfall is received between July and August during the growing season.

Experimental design and treatments

The experimental design was a split-plot with four (4) replications. Millet varieties were assigned to the main plot while plant populations were assigned to the subplot. In both locations, pearl millet varieties used include two improved (Sosat-C88 and GB8735) and one local (*Danmagarawa*). Sosat-C88 was developed by ICRISAT and IER. It is a medium maturing variety (90 days), with an average height of 2 m, medium head length (mean of 28 cm) with compact head. Sosat-C88 was released by the NCVRC (National Crop Variety Release Committee) in Nigeria in the year 2000. This variety is preferred for its good taste, earliness and high grain yield. It is also preferred for early maturity, insect tolerance, grain colour, cooking time, and head filling. It is the most popular of all the improved varieties released in Nigeria (Ndjeunga et al., 2011).

GB8735 is an early maturing variety (65 to 70 days), with average height of 1.5 m and short panicle (mean of 22 cm). This variety is susceptible to stem borers. It is recommended under rainfall condition between 350 and 600 mm on sandy and sandy loam soils (Ndjeunga et al., 2011). Local variety was the common Landrace used in the area. Generally, it is preferred for long head and large stalk, and good food quality. It is a medium maturing variety maturing in 70 to 75 days. The sub-plot consisted of the

population of 8889, 13333, 26667 and 53333 hills ha⁻¹ corresponding to intra-row spacing of 150m, 100, 50 and 25vc cm respectively against the standard inter-row spacing of 75 cm. Each subplot occupied 4 rows of 6m long (6 m × 3 m). There was 1 row blank between the sub plots and between the main plots.

Cultural practices

The land was harrowed and ridged with tractor at Minjibir and ridged with work bulls in Gambawa. The ridges were made 75 cm apart; the plots were then laid out as per treatments. In the 2013 growing season, the seeds were sown on 3rd June at Minjibir and 25th June at Gambawa while 2014 growing season was planted on the 10th June at Minjibir and 7th July at Gambawa respectively. Six (6) seeds were sown per hole, at a depth of 3 to 4 cm and later thinned to 2 seedlings per hill 14 days after sowing (DAS). Fertilizer applications were applied in two split doses at the recommended rate of NPK 60:30:30. The first dose was applied at sowing by drilling at 30 kg N, 30 kg P₂O₅, 30 kg K₂O/ ha and the second dose of 30 kgN was applied at 6 week after sowing using urea (46% N). Weeding was carried out manually twice at 3 and 6 weeks after sowing.

Data collection

Soil physio-chemical properties and weather trends during growing seasons

Prior to sowing in 2013 cropping season, soil was sampled at two profile depth (0 to 15 cm and 15 to 30 cm) and in 2014 cropping season, it was sampled only at 0 to 20 cm depth. The soil sample was air dried at room temperatures, grind and sieved before being analysed for physio-chemical properties determination. The

physical and chemical properties of the soil in the two experimental sites are presented in Table 1a and b. The soils in the two locations were sandy soil characterized by less than 10% clay and silt and more than 88% sand. They were generally acidic with soil pH range from 5.0 to 6.4 topsoil in Minjibir while that of Gambawa site varied from 5.4 to 6.3. In both seasons (2013 and 2014), Minjibir soil had slightly higher fertility status than Gambawa. It contained higher organic carbon (2.21 and 3.58 gkg⁻¹), total N (0.232 and 0.245 gkg⁻¹) and P-Bray1 (7.8 mgkg⁻¹), and Ca (3.0 and 2.014 cmol kg⁻¹) in the top soil which was higher than that of Gambawa which contain 1.42 and 2.45 gkg⁻¹ of organic carbon, 0.147 and 0.207 gkg⁻¹ of total N and P-Bray1 (4.9 and 5.5 mgkg⁻¹), 2.0 and 2.288 cmol kg⁻¹ of Ca, respectively. The exchangeable K in the topsoil was, however, lower at Minjibir (0.223 and 0.269 cmol (+) kg⁻¹) than in Gambawa (0.379 and 0.427 cmol (+) kg⁻¹), but the exchangeable K in the subsoil in Minjibir (0.297 cmol (+) kg⁻¹), was higher than in Gambawa (0.231 cmol (+) kg⁻¹).

Weather data for the trial conducted at Minjibir research station were collected from the ICRISAT Meteorological station adjacent to the experiment plot. Gambawa weather data were obtained from the Jigawa Agricultural and Rural Development Authority (JARDA), Gumel office (about 10 km from the plot). The meteorological data reported include daily rainfall, minimum temperature, maximum temperature and number of rainy days (NRD). A rainy day was determined as a rain event having received over 0.85 mm (Omotosho et al., 2000). The monthly distribution and inter-seasonal trend for both rainfall, number rainy days (NRD) and temperature in both locations indicated high variability (Table 2). Average monthly minimum temperature varied from 21.6 to 26.4°C at Minjibir. The average monthly maximum temperature varied from 31.1 to 40.8°C at Minjibir. The average monthly minimum temperature in Gambawa ranged from 23.3 to 27.3°C and average monthly maximum temperature varied from 33.5 to 40.5°C (Table 2b). Both sites indicate warming throughout the growing season; however, Gambawa was warmer than Minjibir year round.

Table 1a. Soil physio-chemical properties of the experimental site in 2013 cropping season at Minjibir and Gambawa.

Depth	Sand	Silt	Clay	PH (H ₂ O)	Organic carbon	Total-N	P-Bray1	Ca	K	Zn	Pb
cm	%	%	%		g/kg	g/kg	mg/kg	Cmol (+) /kg	Cmol (+) /kg	mg/kg	mg/kg
Minjibir											
0-15	91.7	4.0	4.2	5.1	2.21	0.232	7.8	3.00	0.223	0.012	Traces
15-30	89.8	4.2	6.0	5.0	1.55	0.181	4.6	17.79	0.297	Traces	Traces
Gambawa											
0-15	88.9	4.6	6.5	5.4	1.42	0.147	4.9	2.00	0.379	Traces	Traces
15-30	92.8	4.6	2.5	5.7	1.56	0.152	4.1	1.32	0.231	Traces	Traces

Crop measurements: Soil-plant-analysis development (SPAD) and leaf area index (LAI) and number of productive tillers

SPAD and LAI measurements were randomly taken at three points within the two middle rows in each plot and averaged value was recorded for that plot. The chlorophyll index was measured by the SPAD-502 meter. LAI was measured with an AccuPAR LP-80. Samplings were performed twice during crop growth at 21 DAS and 42 DAS for chlorophyll, and at 42 DAS and 63 DAS for LAI. However, at harvest average number of productive tillers per hill was determined from five (5) randomly selected hills within the net plot area.

Number of days to 50% flowering and 1000-seed weight

The number of days from sowing to the stage when 50% of the plants in each net plot had flowered was taken and recorded. The number of days from sowing to 95% maturity was recorded for each net plot. 1000 seeds were counted using Numigral seed counter and then weighed using a 1036SVSSDR Salter sensitive balance.

Grain yield and stalk yield

Panicles were harvested at physiological maturity stage and sun

Table 1b. Soil physio-chemical properties of the experimental site in 2014 cropping season at Minjibir and Gambawa.

Depth	Sand	Silt	Clay	PH (H ₂ O)	Organic carbon	Total-N	P-Bray1	Ca	K	CEC	Pb
cm	%	%	%		g/kg	g/kg	mg/kg	Cmol (+) /kg	Cmol (+) /kg	g/kg	mg/kg
Minjibir											
0-20	93.5	2.5	4.0	6.40	3.58	0.245	7.8	2.014	0.269	25.60	Traces
Gambawa											
0-20	90.8	4.3	4.9	6.32	2.45	0.207	5.5	2.288	0.427	22.53	Traces

Table 2a. Meteorological data of the experimental sites at Minjibir in the 2013 and 2014 growing seasons.

Month	2013				2014			
	Rainfall (mm)	Number of rainy days (NRD)	T _{min} (°C)	T _{max} (°C)	Rainfall (mm)	Number of rainy days (NRD)	T _{min} (°C)	T _{max} (°C)
Jan	0	0	14.2	31.7	0	0	15.3	31.4
Feb	0	0	18.0	34.4	0	0	18.4	32.9
Mar	0	0	19.9	41.5	0	0	22.8	38.3
Apr	12.8	2	25.1	39.1	36	2	25.7	40.3
May	33.2	1	26.4	40.8	7.7	1	26.2	37.8
Jun	84.2	6	22.3	30.5	69.0	5	25.1	36.6
Jul	262.4	9	22.5	33.4	151.1	4	23.9	32.8
Aug	522.9	13	21.6	31.1	443.4	10	22.8	34.8
Sept	159.3	4	22.4	34.4	135.5	5	23.1	32.4
Oct	4	1	22.9	36.3	20.1	2	21.7	34.3
Nov	0	0	15.5	35.8	0	0	18.7	34.3
Dec	0	0	13.6	32.3	0	0	15.3	30.5
Total/Mean	1078.5	36	20.4	35.1	826	29	21.6	34.7

Source: IITA Minjibir Research Station, Kano.

dried to constant weight. After drying, manual threshing was done to separate grains from shaft. The panicles in the net plots were cut and sun dried to constant weight. The weight recorded as panicle weight per plot. The sun dried panicles were threshed, winnowed and the grains were weighed using Salter sensitive balance with model number 1036SVSSDR. The grain weight per plot was extrapolated to grain yield (kg ha⁻¹). The plants, whose panicles have been harvested, were cut at the ground level. The stalks were left on the field for sun-dried to constant weight, which lasted until twenty days. Thereafter, the stalk weight per plot was extrapolated to the stalk yield (kg ha⁻¹). The stalk and panicle weight, including the grain were given as biomass weight and used in the calculation of harvest index.

Data analysis

The data collected were subjected to analysis of variance (ANOVA) which was used to determine the effects of different fertilizer application, variety and planting density on the growth, development, yield and yield components parameters using Genstat 15th version. The treatment means that were significantly different at 5% were compared using Least Significant Difference (LSD). The relationship between the characters evaluated was established at LSD (5%) probability level using Pearson's

correlation coefficient.

RESULTS

Soil-plant-analysis development (SPAD), leaf area index (LAI) and tillering

Table 3 shows the effect of pearl millet variety and hill population on SPAD measurement and LAI in both locations. SPAD value increased from high population (53,333 hills ha⁻¹) to low population (8,889 hills ha⁻¹) and varied among the varieties in both locations. At 21 DAS, SPAD differed significantly among the varieties and hill population in Gambawa but significant differences were not observed in Minjibir. However, GB8765 recorded mean SPAD value that was significantly higher than the other varieties in both locations while there were no significant differences between local and Sosat-C88. Hill populations of 8,889 and 13,333 ha⁻¹ had mean SPAD values of 55.6 and 57.1 in Minjibir and 51.7 and 50.6 at Gambawa respectively. These were significantly higher

Table 2b. Meteorological data of the experimental sites at Gambawa in the 2013 and 2014 growing seasons.

Month	2013				2014			
	Rainfall (mm)	Number of rainy days (NRD)	T_min (°C)	T_max (°C)	Rainfall (mm)	Number of rainy days (NRD)	T_min (°C)	T_max (°C)
Jan	0	0	16.6	33.1	0	0	14.7	33.0
Feb	0	0	18.4	36.2	0	0	17.9	34.9
Mar	0	0	22.4	40.6	0	0	22.0	38.8
Apr	0	0	24.8	40.1	0	0	26.2	41.3
May	7	4	26.6	41.4	0	4	26.8	40.5
Jun	133	7	26.8	39.6	64	11	27.3	40.3
Jul	153	16	25.3	36.5	268	9	26.0	37.0
Aug	187	19	23.3	33.8	432	14	23.0	33.5
Sept	70	9	24.0	37.1	193	12	22.9	35.4
Oct	0	1	22.8	38.0	30	2	22.4	37.7
Nov	0	0	19.2	36.9	0	0	19.0	36.1
Dec	0	0	16.8	33.3	0	0	14.6	32.2
Total/Mean	550	56	22.3	37.2	986.5	52	21.9	36.7

Source: JARDA office, Jigawa.

Table 3. Effect of pearl millet varieties and hill population density on soil-plant-analysis development (SPAD) leaf area index (LAI) and tillering in in both locations.

Treatments	Minjibir					Gambawa				
	SPAD (21DAS)	SPAD (42DAS)	LAI (42DAS)	LAI (63DAS)	#Tiller/hill	SPAD (21DAS)	SPAD (42DAS)	LAI (42DAS)	LAI (63DAS)	#Tiller/hill
Variety (V)										
GB8765	56.04	49.31	2.21	2.36	2.69	51.74	49.15	2.19	2.07	2.77
Sosat-C88	53.04	42.86	2.68	2.59	2.33	46.23	47.91	2.75	2.36	2.3
Local	55.24	49.64	2.40	2.41	2.86	49.23	46.15	2.42	2.6	2.47
P of F	0.403	0.041	0.028	0.287	0.314	0.037	0.6	0.052	0.099	0.026
SED	2.135	2.27	0.129	0.141	0.325	2.008	2.852	0.176	0.2	0.127
LSD	5.224	5.555	0.315	0.346	0.794	3.912	6.979	0.43	0.49	0.31
Hill population (ha ⁻¹)										
8889	55.63	50.85	2.7	2.46	3.24	51.7	51.33	2.53	2.42	3.35
13333	57.05	49.44	2.65	2.41	3.79	50.59	50.2	2.51	2.51	3.03
26667	54.40	44.33	2.1	2.46	1.85	47.82	44.83	2.55	2.23	1.98
53333	52.02	44.44	2.25	2.47	1.61	46.17	44.58	2.23	2.23	1.68
P of F	0.145	<.001	0.015	0.992	<.001	0.019	0.03	0.228	0.447	<.001
SED	2.157	1.655	0.206	0.206	0.286	1.81	2.681	0.172	0.209	0.212
LSD	4.427	3.395	0.422	0.282	0.587	3.714	5.501	0.354	0.43	0.435
Mean	54.77	47.27	2.43	0.423	2.62	49.07	47.74	2.45	2.35	2.51
CV	9.6	8.6	20.8	20.6	26.7	9	13.8	17.2	21.9	20.6
V*P	ns	ns	ns	ns	**	ns	*	ns	ns	ns

than populations of 26,667 and 53,333 hills ha⁻¹ in Minjibir (54.4 and 42.0) and Gambawa (47.8 and 46.2) respectively. Similarly, significant differences were found among varieties and hill populations for SPAD values at 42 DAS in both locations.

Significant differences were observed among the pearl millet varieties and hill population for mean LAI at 42 DAS in both locations except for hill population at Gambawa. In contrast, were no significant differences among the millet varieties and hill population for mean LAI at 63 DAS

in both locations. Although, there were no significant differences in mean LAI across the hill population at both locations at 63 DAS, significant differences were observed at 42 DAS at Minjibir. The low hill population of 8,889 hills ha⁻¹ had significantly higher LAI in Minjibir and Gambawa.

Similarly, significant differences were observed among millet varieties and among plant hill population for tillering. In Gambawa GB8765 (2.77/hill) produced significantly higher number of tillers than the local (2.47/hill) and Sosat-C88 (2.3/hill) millet varieties Gambawa,. However, there were no significant differences among the pearl millet varieties for tillering in Minjibir. The lower hill population produced significantly higher number of tillers than the higher plant hill populations in both locations. In Minjibir, mean number of tillers range from 1.61/hill (53,333 hills ha⁻¹) to 3.79 tiller/hill (13,333 hills ha⁻¹), while in Gambawa it ranged from 1.68 tillers hill⁻¹ (53,333 hills ha⁻¹) to 3.35 tillers hill⁻¹ (8,889 hills ha⁻¹). In general, there was no significance interaction between variety and hill population across the parameters except for the number of tiller/hill at Minjibir and SPAD value at 42 DAS in Gambawa.

Days to 50% flowering, thousand seed weight (1000-sw), grain and stalk yields

Significantly differences were observed between the year for 50% days, 1000-sw, grain and stalk yields of pearl millet at both locations except for 1000-sw in Minjibir (Table 4). The hill population (HP) had significant effect on days to 50% flowering, 1000-sw and stalk yield in Minjibir while only 1000-sw and grain yields were significantly affected in Gambawa (Table 4). Significant differences were also observed among the millet varietal (V) for all traits measured except for 1000-sw in both locations. Meanwhile, the interaction between the hill population and variety (HP × V) was significant for days to 50% flowering and grain yield in Minjibir while only stalk yield was significant in Gambawa. Table 4 also shows that there are no interaction of year, hill population and variety (Y × HP × V) in both locations.

In Minjibir, 2013, the millet flowered at a mean of 56 DAS, this was significantly earlier than 61 DAS for 50% flowering in 2014. In contrast, at Gambawa, millet flowered at 64 DAS in 2013 indicating 4-day delay compared to 2014 (Table 5). Although, there was no significant difference between the years for 1000-seed weight at Minjibir, in Gambawa the mean 1000-seed weight in 2014 was significantly higher than in 2013. The mean yields recorded were higher in Minjibir than Gambawa in both seasons (Table 5). While, mean grain yields recorded in the 2014 cropping season were significantly higher than the mean grain yields in 2013 cropping season. Minjibir mean stalk yields, in 2013 (9471 kg ha⁻¹) was significantly higher than mean stalk

yields in 2014 (6385 kg ha⁻¹), while contrast were observed in Gambawa where mean stalk yield in 2013 (3934 kg ha⁻¹) was significantly lower than mean stalk yield (4934 kg ha⁻¹) in 2014 cropping season.

Plant hill population had no significant effect on number of days to 50% flowering in both location (Table 6). However significant differences were observed among the millet varieties. Sosat-C88 recorded the highest number of days to flowering at 63 days while the least value of 52 days was observed by GB8765. In Gambawa, the local variety recorded the mean value of 65days to flowered indicating much longer vegetative growth compared to other varieties while the GB8765 recorded mean lowest value of 50 days to flowering. The results further showed that higher pearl millet hill population recorded significantly lower mean 1000-sw in both locations (Table 6). GB8765 recorded the highest mean 1000-sw of 11.3 and 8.2 g per 1000-sw in Minjibir and Gambawa respectively, while the least mean value (10.4 and 7.5 g per 1000-sw) was recorded by Sosat-C88 in Minjibir and Gambawa, respectively.

Sosat-C88 produced the highest mean grain yield (3169 and 2169 kg ha⁻¹) while GB8765 produced the least grain yield (2168 and 1573 kg ha⁻¹) in Minjibir and Gambawa (Table 7). Significant population by variety interactions were observed for grain yields in Minjibir. The highest yield of GB8765 was obtained at a population of 13,333 hills ha⁻¹ but yield decline with further increase in hill population. Sosat-C88 produced the highest yield at low population of 8,889 hills ha⁻¹ in Minjibir and 26,667 hills ha⁻¹ in Gambawa. The local variety recorded its lowest mean grain yields at hill population of 13,333 hills ha⁻¹ in Minjibir and 8,889 hills ha⁻¹ in Gambawa, while its highest yields were obtained at higher population 26,667 hills ha⁻¹ in both locations. There were no significant differences among the hill population treatments for millet grain yields in Minjibir, though the differences were significant in Gambawa where the highest mean grain yield of 1962 kg ha⁻¹ was recorded at hill population of 26,667 hills ha⁻¹. Although, there were no significant differences observed among the hill population for stalk yield at Gambawa, highly significant differences were observed at Minjibir. The highest plant hill population (53,333 ha⁻¹) produced the highest stalk mean yields (Table 7). Also significant differences were observed among the millet varieties for stalk yields in about locations, as well as significant hill population by Variety interactions in Gambawa. GB8765 produced significant lower mean stalk yields under all treatments.

Growth parameters and yield components association with grain yield

Table 8 shows the correlation coefficients among millet growth parameters and grain yields in both locations. LAI at 42 DAS and Stalk yield were significantly and

Table 4. F-probability values for the ANOVA of both the observed and measured parameters of pearl millet varieties at varying hill population in both locations.

Effect	50% Flowering (days)	1000-seed weight (g)	Grain (kg ha^{-1})	Stalk (kg ha^{-1})
Minjibir				
Year (Y)	<.001	0.799	0.032	<.001
Hill Population(HP)	0.031	0.001	0.327	<.001
Y \times HP	0.664	0.030	0.295	0.008
Variety(V)	<.001	0.131	<.001	<.001
Y \times V	0.161	0.003	<.001	0.031
HP \times V	0.040	0.964	<.001	0.077
Y \times HP \times V	0.803	0.215	0.629	0.696
Gambawa				
Year (Y)	<.001	<.001	<.001	<.001
Hill Population(HP)	0.185	0.045	0.022	0.141
Y \times HP	0.699	0.817	0.005	0.049
Variety(V)	<.001	0.607	0.012	0.011
Y \times V	0.746	0.551	0.505	0.208
HP \times V	0.088	0.552	0.544	0.004
Y \times HP \times V	0.931	0.613	0.115	0.146

Table 5. Year effects on agronomic parameters of pearl millet in Minjibir and Gambawa.

Effect	50% Flowering (days)	1000-seed weight (g)	Grain yield (kg ha^{-1})	Stalk yield (kg ha^{-1})
Minjibir				
Year				
2013	55.9	10.79	2563	9471
2014	60.5	10.74	2750	6385
SED*	0.55**	0.22 ^{ns}	83.8*	302**
Gambawa				
2013	64.2	6.91	1383	3934
2014	60.1	8.79	2277	4934
SED*	0.73**	0.41**	58.1**	208**

positively associated with grain yield in both locations. In addition, SPAD at 21 DAS and 50% flowering were significantly and positively correlated (0.22* and 0.61**) with grain yield in Minjibir while non-significant correlation with grain yield was observed in Gambawa. In contrast, 1000-sw and harvest index showed highly significant and positive correlation (0.32** and 0.38**) with grain yield in Gambawa but no significant correlation was observed at Minjibir.

DISCUSSION

The selected locations for the trial had varied soil and rainfall distributions which provided contrasting environments which represent the semi-arid region of Nigeria. The two locations had sandy-loamy soils and the

major soil micro-nutrients varied from low to very low contents. However, Gambawa had lower content of most nutrients than Minjibir, with lower organic carbon, total N, total P and Ca in the top soil. Rainfall was higher in amount and intensity in Minjibir than Gambawa. The higher soil fertility status and rainfall recorded in Minjibir compared to Gambawa was reflected in higher grain and stalk yields as well as observed responses of the millet to some treatments in Minjibir. The lower 1000-seed weight measured in Gambawa compared to Minjibir could be attributed to water stress most especially during grain filling, resulting from the erratic rainfall distribution at the site. This is in agreement with Do and Winkel (1993) who found that water stress, decrease pearl millet yields by 14 and 40% depending on the variety and amount of stress.

Climatic conditions as well as inherent soil fertility can be attributed to variations in response of hill population

Table 6. 50% Flowering and 1000-seed weight of pearl millet varieties as influenced by hill population in both locations.

Variety	Minjibir					Gambawa				
	Hill population (ha ⁻¹)									
	8889	13333	26667	53333	Mean	8889	13333	26667	53333	Mean
	50% flowering									
GB8765	51.6	53.4	50.9	52.3	52.0	49.9	48.9	50.4	50.4	49.9
Sosat-C88	63.4	61.6	63.3	64.1	63.1	59.3	60.1	58.6	59.1	59.3
Local	59.3	58.9	58.9	61.4	59.6	63.5	64.5	64.9	66.8	64.9
Mean	58.1	58.0	57.7	59.3		57.5	57.8	58.0	58.8	
SED (HP)	0.53*					0.56ns				
SED (V)	1.02**					1.52**				
SED (HPxV)	1.29*					1.23ns				
SED (HPxV)	0.38**					0.24 ^{ns}				
	1000-seed weight (g)									
GB8765	11.7	11.9	11.2	10.5	11.3	8.4	8.2	9.0	7.1	8.2
Sosat-C88	11.0	10.7	10.0	9.9	10.4	8.6	7.3	7.9	6.4	7.5
Local	11.0	10.8	10.6	9.7	10.5	8.4	8.3	7.0	7.6	7.8
Mean	11.2	11.1	10.6	10.0		8.5	8.0	8.0	7.0	
SED (HP)	0.29**					0.56*				
SED (V)	0.39 ^{ns}					0.61 ^{ns}				
SED (HPxV)	0.59 ^{ns}					1.04 ^{ns}				

Table 7. Grain and stalk yields of pearl millet varieties as influenced by hill population in both locations.

Variety	Minjibir					Gambawa				
	Hill population (ha ⁻¹)									
	8889	13333	26667	53333	Mean	8889	13333	26667	53333	Mean
	Grain yield (kg ha ⁻¹)									
GB8765	1706	2600	2227	2137	2168	1453	1746	1550	1541	1573
Sosat-C88	3362	3044	3047	3221	3169	1913	2156	2420	2185	2169
Local	2621	2492	2746	2677	2634	1594	1765	1917	1722	1750
Mean	2563	2712	2673	2678		1653	1889	1962	1816	
SED (HP)	83 ^{ns}					96*				
SED (V)	132**					135*				
SED (HPxV)	274**					198 ^{ns}				
	Stalk yield (kg ha ⁻¹)									
GB8765	3631	5140	5323	5927	5005	2798	4246	2910	3048	3251
Sosat-C88	10390	9348	10062	10458	10065	4865	5010	5660	5490	5256
Local	7448	8229	9198	9983	8715	4458	5240	5108	5375	5045
Mean	7156	7572	8194	8789		4040	4832	4559	4638	
SED (HP)	372**					272ns				
SED (V)	471**					446*				
SED (HPxV)	516 ^{ns}					605**				

and varieties on the growth and phenological development (e.g. SPAD, LAI, days to 50% flowering).

While the pearl millet plants flowered earlier in 2013, the number of days to flowering was the same as in 2014

Table 8. Correlation analysis of grain yield with growth parameters and yield components of sorghum in Minjibir and Gambawa.

Character	Minjibir		Gambawa	
	R	P-value	R	P-value
SPAD (21 DAS)	0.221	0.033	0.042	0.194
SPAD (42 DAS)	0.052	0.725	0.092	0.133
LAI (42 DAS)	0.239	0.051	0.316	0.009
LAI (63 DAS)	0.037	0.802	0.128	0.096
50% flowering (days)	0.608	<.0001	-0.044	0.446
#Tiller/hill	0.010	0.948	0.219	0.135
1000-seed weight	-0.074	0.471	0.326	0.001
Stalk yield (kg ha ⁻¹)	0.424	0.001	0.551	<.0001
Harvest index (%)	0.134	0.194	0.384	<.001

cropping season. Also, slight delay in flowering occurs at higher hill population than lower population in Minjibir when compared to Gambawa. The level of significant interactions between the hill population and variety of days to 50% flowering suggests that pearl millet varieties responded to population differently in both locations. This may depend on the environment, especially rainfall distribution and soil fertility. To further confirm the impacts of variability in the growing season on pearl millet, the results indicated that grain yields in 2014 were higher by a mean of 7% in Minjibir and 65% higher in Gambawa than 2013 cropping season. However, stalk yields were higher by a mean of 48 and 26% in 2013 than 2014 in Minjibir and higher by 25% in 2014 than 2013 in Gambawa.

The recommended plant spacing for millet is 0.75 × 0.5 m providing population of 26,666 ha⁻¹ (ICRISAT, 2006) while farmer traditionally plant millet in inter-crop at 1.5 to 2 m between rows and 1 within rows, this gives a population of 6,667 to 8,889 hills ha⁻¹. In the present study, higher hill populations of 13,333 (0.75 × 1 m), 26,667 (0.75 × 0.5 m) and 53,333 (0.75 × 0.25 m) had an average yield increase (5.8, 4.3 and 4.5% in Minjibir) and (14, 19 and 10% in Gambawa) compared to a population of 8,889 hills ha⁻¹ (0.75 × 1.5 m) while stalk yield significantly increased with increase plant hill population. This agrees with Mason et al. (2015) who reported that, increase plant population, combined with the use of improved varieties and recommended fertilizer application increased pearl millet grain yields. Higher grain and stalk yields observed in some treatments at closer spacing across locations indicated the risk in making blanket recommendation on hill population on the varieties. GB8765 produced optimum yield at a population of 13,333 hills ha⁻¹ beyond which grain yield decline in both locations. Sosat-C88 produced optimal grain yield at low population of 8,889 hills ha⁻¹ at Minjibir but the optimum yield was produced at a population of 26,667 hills ha⁻¹ in Gambawa. The optimum yield at low population (8,889 hills ha⁻¹) at Minjibir can be attributed to

early plant vigour resulting to more tillers due to higher soil micro-nutrients compared to Gambawa. Local variety produced an optimum grain yield at a population of 26,667 hills ha⁻¹ in both locations. This result agreed closely with the finding by Maman *et al.*, (2000a) which was cited by Mason et al. (2015) that even in a dry year in Niger, higher grain yield and water use efficiency are possible with higher plant populations of 20,000 hills ha⁻¹ with application of 40 kg N ha⁻¹ and 18 kg P ha⁻¹. In contrast, De Rouw (2004) reported that higher plant populations increased the risk of crop failure. In Minjibir, across the hill population, GB8765 produced grain and stalk yields that were lower by 26.5 and 46.4% than those produced by Sosat-C88 and local variety, respectively. Sosat-C88 had 24.2 and 31.8% higher grain yield stalk yields than other varieties. Similar results were found in Gambawa, where GB8765 recorded 19.3 and 47% grain and stalk yield decreased compared to other varieties, while Sosat-C88 had 23.4% higher grain yield and 21% stalk yield than other varieties. Sosat-C88 is therefore a preferred variety among the varieties tested for the semi-arid of Nigeria under the normal planting window.

In Minjibir, it was observed that grain yields were significant and positively correlated with SPAD at 21 DAS, LAI at 42 DAS, 50% flowering and stalk yields. In Gambawa LAI at 42 DAS was significantly and positively correlated with grain yield. This indicates that these traits are very important for the growth and yield of pearl millet. Management practices such as selection of appropriate varieties and plant population, which improves LAI, and leaf greenness are therefore recommended.

Conclusion

There was a significant response by pearl millet varieties to varying hill populations across locations. Variation in grain yield across locations is attributed to varying in amounts of rainfall received and soil fertility. Sosat-C88 yielded higher than other varieties across the varying

population in both locations. Based on plant populations, GB8765, Sosat-C88, and Local variety had better on performances at plant population of 13,333, 8,889 and 26,667 hills ha⁻¹, respectively. Contrary to widely used population of 8,889 or 13,333 hills ha⁻¹ by farmers for pearl millet productivity in the semi-arid of Nigeria, the optimal yield measured in these two growing seasons suggests that population recommendations for pearl millet should vary by variety and environmental conditions. Thus, for GB8765 we recommend a population of 13,333 hills ha⁻¹ beyond which grain yield may decline. Sosat-C88 should be planted at low population of 8,889 hills ha⁻¹ in a more fertile area and good rainfall pattern, but increased population of 26,667 hills ha⁻¹ in a drier and less fertile area while the Local variety should be planted at a population of 26,667 hills ha⁻¹ in the two locations

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