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Research Article

Productivity, Water- and Nitrogen-Use Efficiency, and Profitability of Pearl Millet (*Pennisetum glaucum*) under Different Nitrogen Applications in Semiarid Region of Nigeria

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An experiment was conducted to examine the performance of pearl millet under different nitrogen (N) fertilizer rates in two locations in the semiarid zone of Nigeria. The objective was to evaluate the effects of different N rates on pearl millet yields, water- and nitrogen-use efficiency, and profitability. Grain yield increased by 23, 26, 32, 32, and 27% and by 38, 41, 54, 58, and 56% compared to unfertilized plots when applying 20, 40, 60, 80, and 100 kg Nha^{-1} in Minjibir and Gambawa, respectively. Similarly, stalk yield increased by 4, 3, 9, 9, and 9% and by 16, 24, 36, 40, and 37% compared to unfertilized plot when applying 20, 40, 60, 80, and 100 kg Nha^{-1} in Minjibir and Gambawa, respectively. The variations in GY that could be explained by TWU and NUE were 28% and 26% in Minjibir and 46% and 41%, respectively, in Gambawa. There was a strong and positive correlation ($R = 0.81$ and $R = 0.95$) between WUE and GY across N-fertilizer rates and pearl millet varieties in both locations. An increase in N-fertilizer levels increased WUE, confirming the optimal application of 60 kg Nha^{-1} in Minjibir and of 80 kg Nha^{-1} in Gambawa. Similarly, the highest net economic return (NER) of US\$610 ha^{-1} was obtained at 60 kg Nha^{-1} in Minjibir and the highest NER of US\$223 ha^{-1} was obtained at an application rate of 80 kg Nha^{-1} in Gambawa. Break-even yield was above 1000 kg ha^{-1}, signifying that average farmer with a mean yield of less than 1000 kg ha^{-1} produces millet at a loss.

1. Introduction

Pearl millet (*Pennisetum glaucum* (L.) R. Br.) is drought-tolerant and early maturing with high water-use efficiency, but productivity may be greatly influenced using appropriate nitrogen (N) inputs for maximum profitability [1]. Pearl millet provides grain for human consumption and stover for livestock in the arid and semiarid tropics [1, 2]. It has high nutritional value and exceptional tolerance to drought and high temperature [3, 4]. Under semiarid conditions, rainfall and soil fertility dictate crop performance and cropping patterns [5, 6]. Pearl millet flourishes satisfactorily and can be cultivated under low rainfall (200–250 mm), which makes it one of the most reliable cereal crops in the arid and semiarid tropics [7, 8]. The annual pearl millet production in Nigeria between 2014 and 2016 ranged from 1.15 to 1.55 million tons, representing about 5% of total world production with the average yield of 903 kg ha^{-1}, which ranked Nigeria as the third world's largest producer after Niger and India [1]. In Nigeria, pearl millet is grown primarily for grain used for human consumption. The stover is also of great economic importance for livestock feed, building materials, and fuel. Although average pearl millet yields worldwide are lower than the average yields of other cereal crops [4], improved agronomic practices and varieties have been found to lead to more efficient use of photosynthetically active radiation (PAR), water, and nutrients, especially N, resulting in a significant increase in grain and stover yields [9].

Despite the fact that the crop can be grown in low rainfall belt, studies have shown that millet production in West Africa is primarily constrained by limited water supply that determines the amount of water used for growth and productivity [10, 11]. Rainfall and soils are the major environmental resources that merit detailed analysis, in the efforts to increase millet production [11]. The inadequate supply of plant nutrients by most farmers restricts the efficient use of limited rainfall, and this results in unstable low productivity of millet [5]. Similarly, studies have shown that greater water-use efficiency could be achieved through efficient use of fertilizers [11, 12], without underestimating the role of plant genetics [13]. Additionally, demand for food by the growing population in Nigeria will require that we increase resource-use efficiency of water and nutrient for cereal crops including pearl millet. Among the nutrients, N is the most limiting nutrient for cereal production on degraded semiarid soils although P is also a major problem [5]. Monitoring plant N to ensure an adequate supply for plant requirements is necessary to have optimum growth, improved NUE, and to reduce N losses [14]. In rainfed cropping systems, adapting N management to water constraints may help to mitigate N losses and therefore increase NUE. In its simplest definition, NUE is the grain yield per unit of supplied N [15]. It is affected by several factors and processes including N uptake, translocation, assimilation, and remobilization [16]. NUE is an important target for crop improvement [17], though crop-specific management strategies may be required. Improvement of NUE is a way to efficiently use inorganic fertilizer, which is an essential prerequisite for the expansion of crop production into marginal lands with low nutrient availability [18]. The understanding of NUE in pearl millet across the growing areas is very important for economic, environmental, and productivity reasons [19]. This is due to unbalanced application and high cost of fertilizer or fertilizer availability, which constitute a big constrain to resource-poor farmers in Nigeria [20]. In addition, with the advocacy of improved production practices and cultivars, the use of nitrogen fertilizers is increasing quantitatively, but responsive yields to N are substantially fading over the years in all crops [19] including pearl millet [21]. Thus, balancing the N rate, WUE, and yield is an important problem in dryland farming systems. Classical reviews of fertilizers and efficient use of water for maize [6] concluded that, in most cases when the water supply is fixed, any management factor that increases yield would increase water-use efficiency. It was reported in [11] that under Sahelian conditions, 84% increase of WUE in millet (grain yield per mm rain) is due to the application of mineral fertilizers. The application of N increases WUE by 15% and grain yield by 400 kg over control for sorghum crop cultivated under rainfed condition [22]. Although improvements in yield may be brought about by judicious applications of fertilizer, a better understanding of interactions among precipitation, fertilization, and crop production is essential for efficient utilization of water resources and N-fertilizers [23]. A good plant N nutritional status enhances millet tolerance to drought and enhances morphological traits, thereby increasing yields [24]. With average or above rainfall, N application and high plant density increased millet grain yield four- to fivefold. Nitrogen application increased stover production by 33% in a dry year and by 100% in a wetter year [25]. N supply of ~30 kg Nha in two split applications achieved good yields in average and wet years, with only a small yield reduction in the drought year [25]. A moderate increase of N supply for sorghum was reported to improve water-use efficiency (WUE) under semiarid environments [12]. To attain high stable yields of pearl millet by smallholder farmers that will deliver higher profitability in the region would therefore require combinations of improved varieties, optimum amounts of fertilizer, and good cultural management practices for efficient utilization of limited water. There is limited information on the response of new improved diverse millet varieties to applied N in terms of grain yield (GY), total water use (TWU), nitrogen-use efficiency (NUE), and water-use efficiency (WUE). The objectives of the trial were to assess the direct effect of nitrogen application and varieties on productivity and water- and nitrogen-use efficiency of pearl millet and to identify optimal N-fertilizer rate for higher profitability of pearl millet production relative to the study areas.

2. Materials and Methods

2.1. Description of the Experimental Sites. The experiments were conducted during the 2014 and 2015 growing seasons at two sites within the semiarid region of Nigeria. The first location was ICRISAT research field situated within the Institute for Agricultural Research (IAR) station, Wasai village, Minjibir Local Government Area of Kano State (latitude 12.17°N and longitude 8.65°E 455 m ASL), while the second location was within farmers' field in Gambawa, Gumel Local Government Area of Jigawa State (latitude 12.625°N and longitude 9.325°E, 370 m ASL). Both sites are located in the Sudan Savanna agroecological zone where soils are mainly sandy and loamy of low fertility [26]. The trials were conducted in different parts of the research farm (Minjibir) and farmers field (Gambawa) in the 2 years. Undisturbed soil samples were randomly taken at a depth (0–20 cm) prior to sowing for each location in both growing seasons. Soil samples were analysed at the Soil Science Department Laboratory, Bayero University Kano, Nigeria. They were analysed for particle size distribution, organic carbon (OC), pH, and other chemical properties as described in [27].

2.2. Experimental Design. The experiment was a split plot design with four replications. The main plot had six nitrogen (N) fertilizer levels (0, 20, 40, 60, 80, and 100 kg ha^{-1}), and the subplots randomised within the main plots had three pearl millet varieties (Jirani, Super SOSAT, and local control). The details of the varieties used (Jirani, Super SOSAT, and local) have been described by Ajeigbe et al. [1]. The gross size of each subplot was 15 m^2 (5 m long by 3 m wide). This consisted of four ridges 5 m long spaced at 75 cm apart. Planting was done at 50 cm between plants, giving a total plant population of 26,667 hills ha^{-1}.

2.2.1. Field Management, Data Collection, and Analysis. The land was harrowed and ridged at 75 cm apart and sown on 7th July in Minjibir and 10th July in Gambawa in 2014 cropping season while in 2015 growing season, the experiments were sown on 3rd July in Minjibir and 22nd July in Gambawa, respectively. Sowing was done by placing 5–7 seeds per hole at a depth of 3–5 cm and seeds were thinned to two (2) plants per hill between 2 and 3 weeks after planting (WAP). The N-fertilizer (urea) was applied in two splits (at planting and 4 weeks after planting (WAP)), while 30 kg P_2O_5 ha^{-1} and 30 kg K_2O ha^{-1} were applied during planting across N-fertilizer levels as single super phosphate and muriate of potash, respectively. Weeding was carried out manually to keep the fields weed-free. The two centre rows (7.5 m^2) in each subplot were taken as the net plot, and data were collected from these net plots. In both locations, leaf chlorophyll contents were measured at 3 and 6 WAP using a SPAD-502 portable chlorophyll meter (Minolta, Tokyo, Japan). All chlorophyll meter readings were taken midway between the stalk and the tip of the leaf. Leaf area index (LAI) at 6 and 9 WAP was measured with Accupar LP-80 portable canopy analyser. Days to 50% flowering and physiological maturity were recorded when 50% of the plants per plot have flowered and 80% of the plot attained maturity. Plant height was recorded and taken as the mean of five randomly plants/plot at maturity and measured from the ground base of the plant to the tip of the panicle. At maturity, stalk from the net plots was cut at the base and laid on the ground to sun dry until a constant weight was obtained. Panicles were separated from the stalk and sun-dried until a constant weight was obtained (this took about 2 weeks) which was recorded as panicle weight per plot. The panicles were then threshed, and the weight of grains was recorded as grain weight per plot. The dry stalks were weighed and recorded. These were extrapolated as panicle, grain, and stalk yield per ha (kg ha^{-1}), respectively. A thousand seeds were picked per plot using a seed counter and weighed using a sensitive scale and recorded as 1000-seed weight. Harvest index (HI) was computed as the ratio of grain yield (GY) to the total aboveground dry matter (TDM).

2.2.2. Total Water Use and Water-Use Efficiency under Different N Applications. The estimation of total water use (TWU) for each N-fertilizer level between sowing and physiological maturity was calculated. Firstly, we applied equation (2) to compute daily evapotranspiration (ET_o) using the daily records of minimum temperature, maximum temperature, and solar radiations observed from the automatic weather station near the field experimental plots (<2 km radius). Other parameters are constant values based on the agroecological zone of reference. Thereafter, the cumulative reference evapotranspiration (ET_o) was computed from sowing to physiological maturity multiplied by a recommended crop coefficient (K_c) for pearl millet [28] as described in equation (1). The Penman–Monteith equation was used to calculate daily reference evapotranspiration (ET_o) equation (2). The variables of this equation were described in FAO Irrigation and Drainage Paper no. 56 [29]. The method is of quite good accuracy and is usually used for calculations of evapotranspiration from farmlands:

$$\mathrm{TWU} = K_c \mathrm{ET}_o, \tag{1}$$

$$\mathrm{ET}_o = \frac{0.408\Delta\left(R_n - G\right) + \gamma\left(900/T + 273\right)u_2\left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34u_2\right)}, \tag{2}$$

where ET_o is the daily reference evapotranspiration (mm day^{-1}) from sowing to physiological maturity, R_n is the net radiation at the crop surface (MJ m^{-2} day^{-1}), G is the soil heat flux density (MJ m^{-2} day^{-1}), T is the air temperature at 2 m height (°C), u_2 is the wind speed at 2 m height (m s^{-1}), e_s is the saturation vapour pressure (kPa), e_a is the actual vapour pressure (kPa), $e_s - e_a$ is the saturation vapour pressure deficit (kPa), D is the slope vapour pressure curve (kPa°C^{-1}), and γ is the psychrometric constant (kPa°C^{-1}).

From the above daily ET_o computed, cumulative values from sowing to physiologically maturity at each N-fertilizer level were derived.

Total water use (TWU) obtained from equation (1) was used to calculate water-use efficiency (WUE) in equation (3). Water-use efficiency refers to the ratio of water used in plant metabolism to water lost by the plant through transpiration and soil evaporation (evapotranspiration). Water-use efficiency was calculated for only final grain yield at harvest maturity, using the following equations [30]:

$$\mathrm{WUE} = \frac{Y}{\mathrm{TWU}}, \tag{3}$$

where Y is the grain yield (kgha^{-1}) and TWU is the total water use at a different level of N (mm).

2.3. Nitrogen-Use Efficiency (NUE). The nitrogen-use efficiency was calculated using the following formula [16,31] and reported as kg grain/kg N applied:

$$NUE = \frac{Y_f - Y_c}{N_a}, \tag{4}$$

where Y_f is the grain yield (kg/ha) in the fertilized plot, Y_c is the grain yield (kg/ha) in control plot, and N_a is the nitrogen (N) applied (kg/ha).

2.3.1. Economic Analysis. Partial budgeting analysis was used to estimate the net income and benefit-cost ratio [32–34] for both sites. The economic analyses were performed to compare the profitability of producing pearl millet varieties under different N-fertilizer rates in both locations based on the current agronomic practices. The average pearl millet prices at the prevailing market price were surveyed at harvest in the study areas. The millet grain and stalk value per unit were determined based on the prevailing price in the different locations and extrapolated for value per ha based on their respective yield per ha, assuming there was no cost borne for storage. The total cost of production (TCP) is the cost of all recommended and variable inputs including labour that was used per treatment. These include expenditure towards land preparation, seed and sowing, fertilizers and their application, harvesting, threshing, and bagging. Total revenue (TR) is the total value of the grain and stalk harvested from the plot. Net economic returns (NERs) are the difference between TR and TCP. Benefit-cost ratio (B : C) is the ratio of NER by TCP (B : C = NER/TCP). Break-even yield was calculated by dividing the cost of production by the average market price of pearl millet at each location.

2.3.2. Statistical Analyses. All the data collected and computed were subjected to analysis of variance (ANOVA) using GenStat analytical tool (19th edition). Year, N-fertilizer levels, and variety are taken as factors to determine their effect and interactions on different variables. 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 [35]. In addition, regression analysis was used to establish the relationship of TWU and NUE on grain yield across the N rate as an expression of their contribution.

3. Results

3.1. Soil Characteristic and Weather Indices. Table 1 presents the results of the soil analysis of the experimental sites at profile depth (0–20 cm). The soil texture is characterized as sandy to sandy loam; soil pH is slightly acidic (5.5 to 6.4). The soil organic carbon (OC) content was generally low, and higher values (1.96 g kg^{-1} and 2.59 g kg^{-1}) were recorded in each year in Minjibir compared to Gambawa (1.45 g kg^{-1} and 2.01 g kg^{-1}) for 2014 and 2015, respectively. The total nitrogen content was 0.16 and 0.70 g kg^{-1} at Minjibir, and 0.12 and 0.70 g kg^{-1} at Gambawa while the available phosphorus varied from 3.9 to 4.5 mg kg^{-1} in both seasons.

The intensity and total rainfall were high, indicating daily rainfall ≥40 mm for many days in 2014 (827 mm in 34 rainy days) compared to 2015 (598 mm in 38 rainy days) at Minjibir (Figures 1(a) and 1(b)). In Gambawa (Figures 1(c) and 1(d)), the rainfall received in both seasons were close with the total amount of rainfall 440 mm with 34 rainy days in 2014 compared to 2015 (500 mm in 28 days). As shown in Figures 1(a)–1(d), daily evapotranspiration (ET_o) shows high variations. Lowest values were recorded during the cropping seasons and thereafter the value increases. The ET_o ranged from 2.3 to 7.6 mm in both seasons at Minjibir and varied from 2.6 to 7.8 mm at Gambawa.

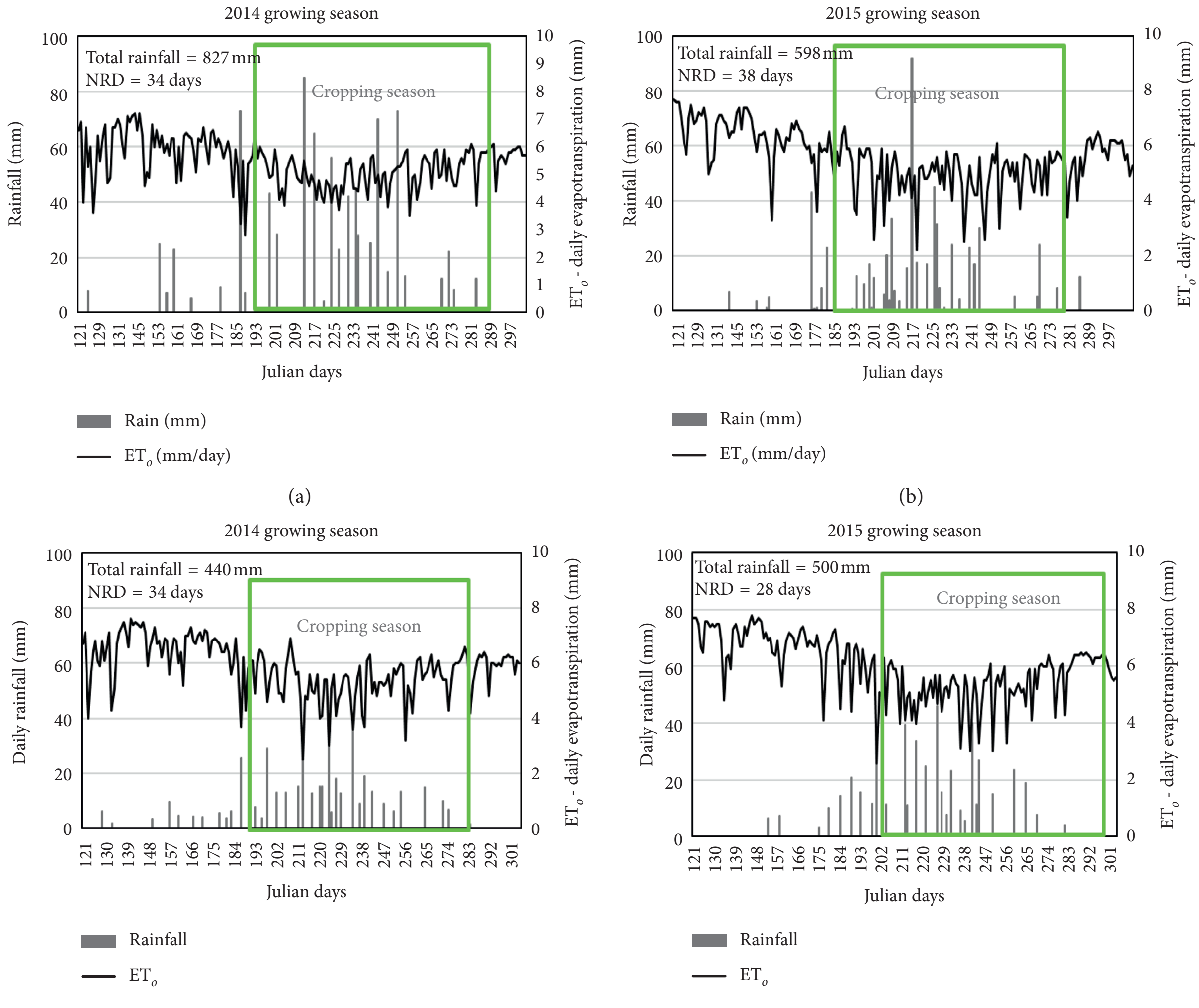
3.2. Leaf Chlorophyll Content (SPAD Readings), Leaf Area Index, and Plant Height. Table 2 shows the effect of N-fertilizer and pearl millet varieties on leaf chlorophyll (SPAD readings) content, leaf area index (LAI), and plant height in both locations and growing seasons (2014 and 2015). Significant differences ($P \leq 0.05$) were observed among the N treatments for SPAD readings at 3 WAS. SPAD readings were significantly higher at N rates of 80 and 100 kg Nha^{-1} than at other N levels in both locations. Similar observations were made at 6 WAS in Gambawa. There were no significant differences among N treatments for SPAD at 6 WAS in Minjibir. In both locations, there were no significant differences in SPAD readings at 80 and 100 kg Nha^{-1}. There were also no significant differences among the varieties SPAD reading at 3 and 6 WAS except for SPAD at 6 WAS in Minjibir, where the local variety recorded the highest mean SPAD value of 50.1.

N-fertilizer level had no significant effect on LAI at 6 WAS and 9 WAS in Minjibir. N application, however, significantly influenced LAI at 6 WAS in Gambawa. At both sites, there were significant differences among varieties for LAI at 6 WAS. At 9 WAS, there were significant differences among the millet varieties in Minjibir but not in Gambawa. Super SOSAT recorded the highest mean LAI of 2.2 and 2.6 at 6 WAS and 9 WAS, respectively, in Minjibir and 1.8 at 6 WAS in Gambawa. Plant height was not significantly affected by N-fertilizer level in Minjibir, but significant effects were observed in Gambawa (Table 2). The plant height at Gambawa increases with increase in N-fertilizer levels up to 60 kg Nha^{-1} and a further increase in fertilizer reduced the plant heights. Super SOSAT recorded the highest mean of 190 cm in Minjibir, while the local variety recorded highest plant height value of 176 cm in Gambawa. In both locations, Jirani recorded the lowest mean height of 157 and 143 cm.

3.3. Pearl Millet Productivity, Total Water Use, and Water-Use Efficiency. The mean grain yield (GY), stalk yield (SY), harvest index (HI), total water use (TWU), and water-use efficiency (WUE) of selected pearl millet varieties grown under different N-fertilizer levels in two locations over two growing seasons are presented in Table 3. N application significantly affected mean GY in both locations. Grain yield increased with increasing N-fertilizer rates. The highest mean GY of 2273 kg ha^{-1} at Minjibir and 1714 kg ha^{-1} at Gambawa was obtained at the application rate of 80 kg Nha^{-1}. The lowest mean GY was recorded at 0 kg Nha^{-1} in both locations. There was no significant difference in GY among the pearl millet varieties in both locations. Stalk yield (SY) of millet varieties was not significantly affected by N application in Minjibir, but there were significant differences among the varieties in Gambawa. At 80 kg Nha^{-1}, the highest mean SY of 3944 kg ha^{-1} was recorded at Gambawa. The SY increased significantly with increased N-fertilizer and peaked at 80 kg Nha^{-1}; then, a further increase in N reduced SY. The local variety had the highest SY with mean values of 4872 kg ha^{-1} at Minjibir and 4069 kg ha^{-1} at Gambawa. N application did not significantly affect harvest Index (HI) at Minjibir. In Minjibir, HI increased with increased N level and peaked at 60 kg Nha^{-1} and a further increase in N level reduced HI. There were significant differences among the N rates for HI in Gambawa. Application of 80 kg Nha^{-1} and 100 kg Nha^{-1} recorded the highest mean HI of 0.26 each, while the lowest mean of 0.21 was recorded for 0 kg Nha^{-1} at Gambawa. The variety Jirani had the highest mean HI of 0.35 and 0.29 for Minjibir and Gambawa, respectively. These values were higher and

Table 1: Analysis of physical and chemical properties of the soils (0–20 cm depth) at Minjibir and Gambawa.

Parameters	Minjibir		Gambawa	
	2014	2015	2014	2015
Soil texture	Sandy loam	Sandy	Sandy loam	Sandy loam
Particle size analysis (%)				
Sand	82.0	90.6	85.7	80.6
Silt	6.5	3.3	5.9	3.3
Clay	11.4	6.1	8.5	16.1
Soil pH (H_2O)	6.4	5.5	6.2	5.9
EC (1 : 2.5 soils: water) (dS/m)	0.031	0.044	0.031	0.049
Soil organic carbon (g kg^{-1})	1.96	2.59	1.45	2.01
Total nitrogen (g kg^{-1})	0.16	0.70	0.12	0.70
Available P (mg kg^{-1})	4.0	4.5	3.9	4.1
Available K (cmol/kg)	0.35	0.37	0.36	0.39



(a) (b)

(c) (d)

Figure 1: Daily rainfall distribution and evapotranspiration (ET_o) during 2014 and 2015 growing seasons: (a, b) Minjibir and (c, d) Gambawa.

significantly different from those of the other pearl millet varieties used in both locations.

Significant differences were observed among the N-fertilizer levels and millet varieties for TWU (Table 3). TWU value generally decreases with increase in the N-fertilizer level in both locations, but it was more evident in Gambawa than in Minjibir. Among the N treatments, unfertilized plots had the highest TWU in both locations

Table 2: Effect of N-fertilizer rates and pearl millet variety on soil plant analysis development (SPAD), leaf area index (LAI), and plant height over two growing seasons in the semiarid zone of Nigeria.

Treatment	Minjibir					Gambawa				
Nitrogen (N)	SPAD		LAI		Plant height	SPAD		LAI		Plant height
	3 WAS	6 WAS	6 WAS	9 WAS	cm	3 WAS	6 WAS	6 WAS	9 WAS	cm
0 kg ha^{-1}	50.9	46.4	1.8	2.3	178	46.2	40.7	1.5	2.0	142
20 kg ha^{-1}	50.2	49.4	1.9	2.3	173	46.0	43.3	1.4	1.9	153
40 kg ha^{-1}	48.5	48.4	1.9	2.3	178	46.2	43.5	1.5	2.0	155
60 kg ha^{-1}	51.9	49.1	2.0	2.3	181	48.4	46.8	1.8	2.0	189
80 kg ha^{-1}	54.2	49.6	1.9	2.4	176	50.3	47.4	1.8	2.0	156
100 kg ha^{-1}	53.6	49.2	2.1	2.5	180	51.4	47.3	1.7	1.9	161
LSD ($P \leq 0.05$)	3.99^{*}	2.39^{ns}	0.37^{ns}	0.33^{ns}	9.47^{ns}	3.86^{*}	2.09^{**}	0.29^{**}	0.26^{ns}	0.26^{*}
Variety (V)										
Jirani	51.3	48.0	1.6	2.0	157	49.1	45.2	1.4	1.9	143
Super SOSAT	51.2	47.9	2.2	2.6	190	47.1	44.4	1.8	2.0	159
Local	52.2	50.1	2.0	2.5	186	48.1	44.9	1.7	2.0	176
Grand mean	51.5	48.7	2.0	2.4	178	48.1	44.8	1.6	2.0	159
LSD ($P \leq 0.05$)	2.64^{ns}	1.79^{*}	0.18^{**}	0.18^{**}	8.37^{**}	1.70^{ns}	1.58^{ns}	0.17^{**}	0.15^{ns}	0.19^{**}
CV (%)	12.6	9.1	22.6	18.9	11.6	8.6	8.5	24.4	19.8	29.0

LSD: least significant differences of means; CV: coefficient of variations.

Table 3: Effect of N-fertilizer rates and pearl millet variety on grain yield (GY), stalk yield (SY), harvest index (HI), total water use (TWU), and water-use efficiency (WUE) in the semiarid zone of Nigeria.

Treatment	Minjibir					Gambawa				
Nitrogen (N)	GY	SY	HI	TWU	WUE	GY	SY	HI	TWU	WUE
0 kg ha^{-1}	1535	3917	0.27	286.3	5.4	727	2361	0.21	320	2.3
20 kg ha^{-1}	1990	4083	0.28	283.5	7.1	1179	2800	0.24	307	3.9
40 kg ha^{-1}	2072	4039	0.30	284.8	7.4	1242	3089	0.24	303	4.2
60 kg ha^{-1}	2263	4317	0.31	283.3	8.0	1565	3711	0.24	304	5.2
80 kg ha^{-1}	2273	4283	0.30	282.9	8.2	1714	3944	0.26	302	5.7
100 kg ha^{-1}	2108	4281	0.29	285.0	7.5	1638	3728	0.26	301	5.5
LSD ($P \leq 0.05$)	215^{**}	582^{ns}	0.04^{ns}	2.51^{*}	0.76^{**}	233^{**}	735^{**}	0.03^{**}	4.1^{**}	0.81^{**}
Variety (V)										
Jirani	1985	2976	0.35	250.1	7.94	1332	2283	0.29	270	4.96
Super SOSAT	2042	4611	0.26	299.4	6.87	1364	3464	0.24	314	4.37
Local	2094	4872	0.27	303.4	6.95	1337	4069	0.2	335	4.05
Grand mean	2040	4153	0.29	284.3	7.25	1344	3272	0.24	306.2	4.46
LSD ($P \leq 0.05$)	152.6^{ns}	380^{**}	0.02^{**}	1.84^{**}	0.56^{**}	129^{ns}	367^{**}	0.02^{**}	3.5^{**}	0.44^{**}
CV (%)	18.4	22.5	18.8	1.6	18.9	21.4	26.2	22.8	2.9	22.3

LSD: least significant differences of means; CV: coefficient of variations; GY and SY (kg/ha); TWU (mm); WUE (kg ha^{-1} mm^{-1}) for final grain yield.

(286.3 and 380 mm in Minjibir and Gambawa, respectively), while the local control had the highest TWU among the millet varieties in both locations (303 and 335 mm in Minjibir and Gambawa, respectively). Similarly, Jirani recorded the lowest mean TWU in both locations (250 and 270 mm Minjibir and Gambawa, respectively). The quadratic function obtained by regression analysis (Figure 2) described the relationship between grain yields and TWU across the N rates and pearl millet varieties in both locations. The coefficient of determination (R^2) implied the variation of grain yield based on the contribution of TWU indicated 27.7% at Minjibir and 46.3% at Gambawa. The results suggest higher water demand for pearl millet production in Gambawa than in Minjibir.

Table 3 further reveals a highly significant effect of N-fertilizer levels and pearl millet varieties on water-use efficiency (WUE) in both locations. The results show that N-fertilizer levels increased WUE until it reached 80 kg Nha^{-1} after which it slightly decreased in both locations. There was no significant difference for WUE between 60 and 80 kg Nha^{-1} in Minjibir. In Gambava, WUE however differed significantly between rates of 60 and 80 kg Nha^{-1}. The highest mean WUE of 8.2 kg ha^{-1} mm^{-1}(Minjibir) and 5.7 kg ha^{-1} mm^{1} (Gambawa) was obtained at 80 kg Nha^{-1}. The lowest mean WUE of 5.4 kg ha^{-1} mm^{-1} in Minjibir and 2.3 kg ha^{-1} mm^{-1} in Gambawa was recorded at 0 kg N ha^{-1}. WUE differed significantly among the varieties with Jirani producing the highest mean of 7.94 and 4.96 kg ha^{-1} mm^{-1} in Minjibir and Gambawa, respectively. There was a strong and positive correlation ($R = 0.81$ and $R = 0.95$) between WUE and GY across N-fertilizer rates and pearl millet varieties in both Minjibir and Gambawa (Figure 3).

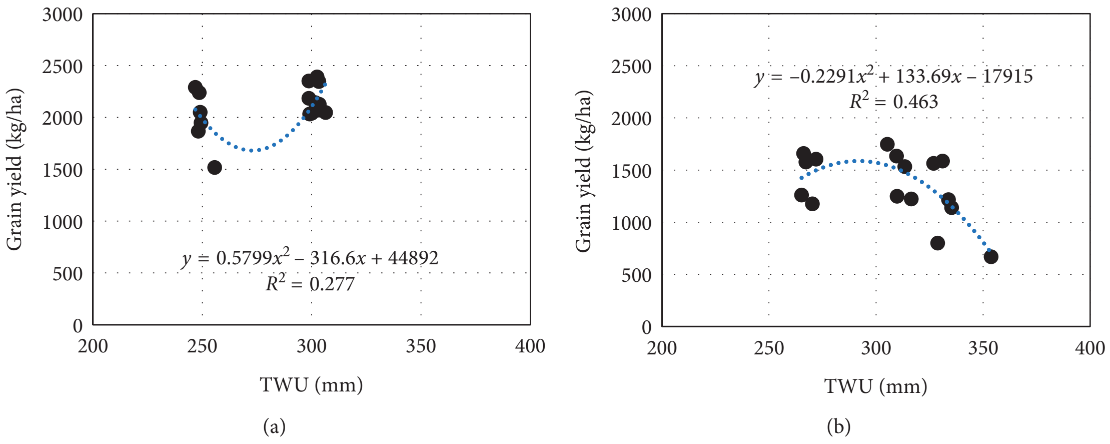


Figure 2: Quadratic relationship between total water use (TWU) and grain yield (GY) of pearl millet in Minjibir and Gambawa sites. Each data point represents mean grain yield and TWU across N-fertilizer rates over two growing seasons (2014 and 2015). (a) Minjibir and (b) Gambawa.

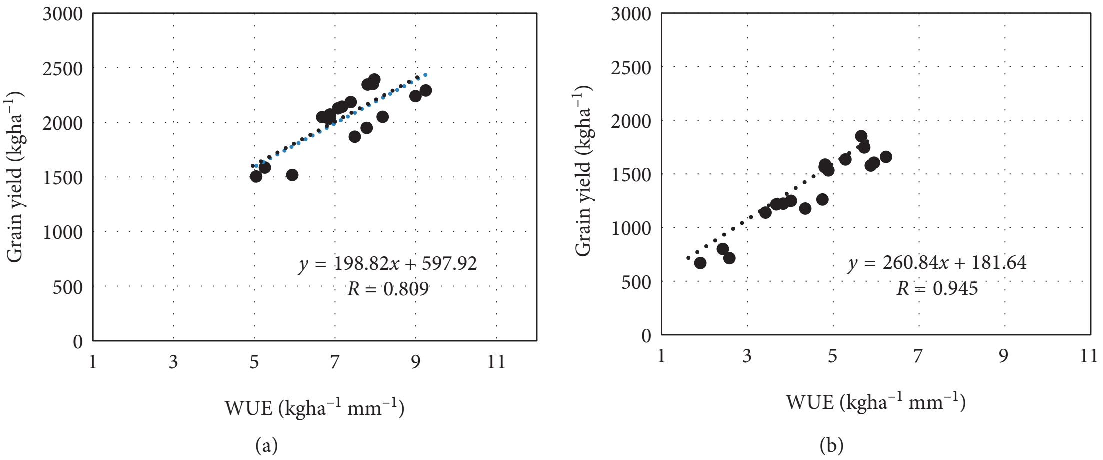


Figure 3: Linear relationship between pearl millet WUE and grain yield (Y) in Minjibir and Gambawa sites. Each data point represents mean grain yield and TWU across N-fertilizer rates over two growing seasons (2014 and 2015). (a) Minjibir and (b) Gambawa.

3.4. Nitrogen-Use Efficiency and Its Effect on Productivity.

Figure 4 depicts nitrogen-use Efficiency (NUE) of pearl millet varieties in both locations. The result shows NUE decreased with increase in N-fertilizer levels. There were also significant differences in NUE among pearl millet varieties in both locations. In Minjibir, Super SOSAT recorded the highest mean NUE (27 ± 5.7 kg grain/kg N) at 20 kg Nha^{-1}. In Gambawa, the local variety had the highest mean NUE (23.5 ± 4.9 kg grain/kg N), while the lowest mean NUE (21 ± 5 kg grain/kg N) was recorded for Super SOSAT at 20 kg Nha^{-1}. The quadratic relationship between GY and NUE indicates strong associations (Figure 5). However, the coefficient of determination (R^2) which expresses variation of GY by the contribution of NUE suggests 26.3% yield variations at Minjibir and 40.9% at Gambawa.

3.5. Profitability of Different N-Fertilizer Rates on Pearl Millet.

The effect of nitrogen fertilizer application and millet varieties on the economics of millet production in the semiarid zone of Nigeria is given in Table 4. Nitrogen fertilizer application significantly affected the mean total cost of production (TCP), total revenue (TR), net economic returns (NER), benefit-cost (B/C) ratio, and break-even yields of millet production in both locations. The total cost of production increased directly with the increase in nitrogen rate, while other economic variables depended on the effect of the N level on productivities. The TR increased from 797 and 363 USD/ha (Minjibir and Gambawa, respectively) at 0 kg Nha^{-1} to 1078 and 764 USD/ha (Minjibir and Gambawa, respectively) at 80 kg Nha^{-1} above which the value dropped. In Minjibir, the increase in N-fertilizer rate increased NER up to 60 kg Nha^{-1}, and thereafter, NER declined significantly, while in Gambawa the increase in N-fertilizer rate increased NER up to 80 kg Nha^{-1}, and thereafter, NER declined significantly. Local variety (597 and 217 US\$/ha) and Super SOSAT (567 and 223 US\$/ha) in Minjibir and Gambawa, respectively, had similar NER which were significantly higher than NER obtained by Jirani in both locations. In Minjibir, highest benefit (1.33) was obtained at 20 kg Nha^{-1} though it was not

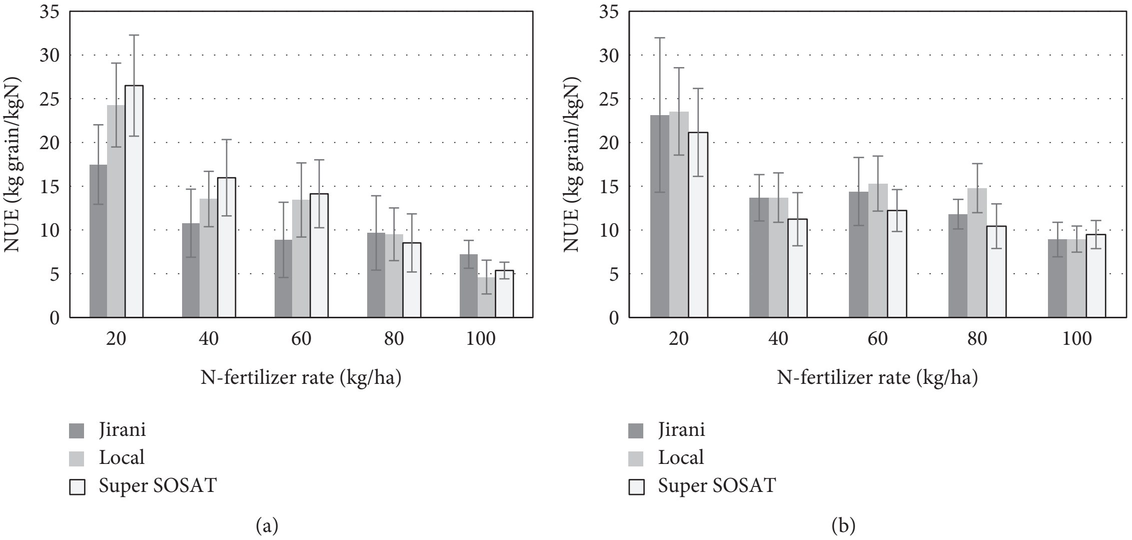


Figure 4: Nitrogen-use efficiency of pearl millet cultivars across N-fertilizer rates in Minjibir and Gambawa (mean of 2014 and 2015 cropping season). LSD ($P \leq 0.05$) for nitrogen was 6.6** and variety was 3.3* at Minjibir; LSD ($P \leq 0.05$) for nitrogen was 5.3** and variety was 3.1$^{\text{ns}}$ at Gambawa. (a) Minjibir and (b) Gambawa.

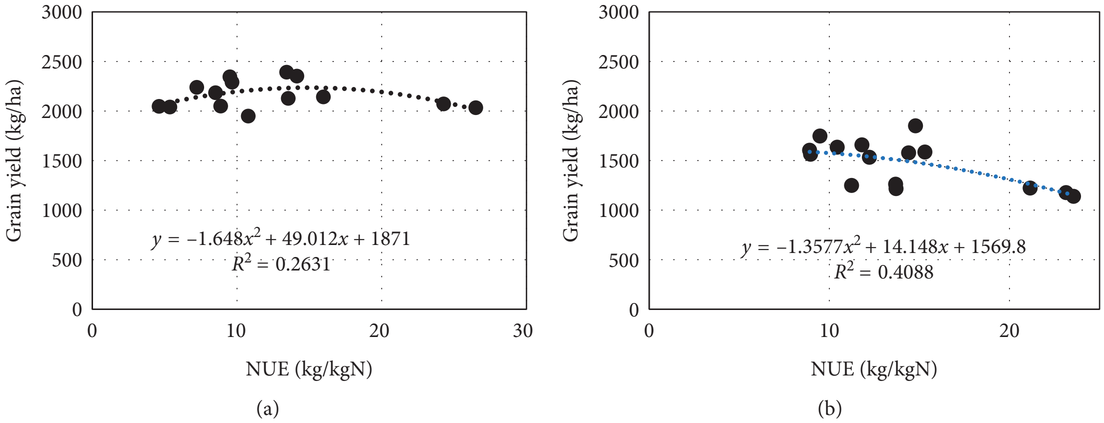


Figure 5: Quadratic relationship between NUE and grain yield (GY) of pearl millet in Minjibir and Gambawa sites. Each data point represents mean grain yield and NUE across N-fertilizer rates over two growing seasons (2014 and 2015). (a) Minjibir and (b) Gambawa.

significantly different from 40 kg Nha^{-1} (1.23) and 60 kg Nha^{-1} (1.27). However, in Gambawa, the highest B : C (0.64) was obtained at 80 kg Nha^{-1} though it was not significantly different from 60 kg Nha^{-1} (0.60), 100 kg Nha^{-1} (0.49), 20 kg Nha^{-1} (0.43), and 40 kg Nha^{-1} (0.42). Among the varieties, while there was no significant differences between Super SOSAT and the local varieties for B : C in both locations, the two were significantly higher than Jirani.

Expectedly, the BEY increased with an increased level of nitrogen fertilizer application in both locations. Significant differences were obtained among the different N application rates (Table 4). The control (0 kg N/ha) had the lowest (1058 and 1073 kg/ha in Minjibir and Gambawa, respectively) BEY, while 100 kg N/ha had the highest (1467 and 1556 kg/ha in Minjibir and Gambawa, respectively) BEY. Each treatment had BEY that was significantly higher than that of N level below it. There were no significant differences among the millet varieties in both locations for BEY.

4. Discussion

This study evaluated the productivity, water use, and economic benefits of pearl millet at different N-fertilizer rates in the semiarid region of Nigeria. The two sites are located within the Sudan Savanna zone, and the total rainfall and distribution during the two growing seasons (2014 and 2015) differed significantly. The analysis of soil chemical properties suggests that soil fertility such as soil organic carbon (SOC), total N, and available phosphorus were relatively low in both locations but still higher in Minjibir than in Gambawa. The low SOC and total N analysed from both sites indicated a need for nitrogen fertilizer application for profitable cereal production. The differences in fertility status and rainfall of the two sites accounted for the differences in grain and stover yields, TWU, and WUE between the two locations and year. The results agreed with the findings of Sivakumar and Salaam

Table 4: Economic analysis of pearl millet varieties under N-fertilizer application in the semiarid zone of Nigeria (mean of 2014 and 2015 growing seasons).

Treatment	Minjibir					Gambawa				
	TCP	TR (US\$ ha^{-1})	NER	B : C	BEY (kg ha^{-1})	TCP	TR (US\$ ha^{-1})	NER	B : C	BEY (kgha^{-1})
Nitrogen (N)										
0 kg ha^{-1}	371	797	426	1.15	1058	337	363	26	0.08	1073
20 kg ha^{-1}	413	965	552	1.33	1177	376	537	161	0.43	1199
40 kg ha^{-1}	440	986	546	1.23	1254	402	568	166	0.42	1283
60 kg ha^{-1}	471	1077	610	1.27	1344	437	701	264	0.60	1395
80 kg ha^{-1}	496	1078	582	1.16	1415	466	764	298	0.64	1488
100 kg ha^{-1}	514	1014	500	0.97	1467	487	722	236	0.49	1556
LSD ($P \leq 0.05$)	8.3^{**}	92.3^{**}	84.8^{*}	0.16^{**}	23.1^{**}	7.2^{**}	113^{**}	106^{**}	0.23^{**}	20.5^{**}
Variety (V)										
Jirani	449	891	442	0.98	1280	417	553	136	0.31	1332
Super SOSAT	451	1018	567	1.25	1285	418	641	223	0.52	1329
Local	453	1050	597	1.32	1292	417	634	217	0.50	1336
Grand mean	451	986	535	1.18	1286	417	609	192	0.44	1332
LSD ($P \leq 0.05$)	5.9^{ns}	64.3^{**}	58.9^{**}	0.11^{**}	16.7^{ns}	4.1	52.2^{**}	48.5^{**}	0.11^{**}	13.2 ns
CV (%)	3.2	16.0	27.0	25.4	3.2	2.4	25.7	41	38.8	2.6

TCP: total cost of production; TR: total revenue (grain and stalk yields); NER: net economic return; B : C: benefit-cost ratio; BEY: break-even yield at current price (kg/ha); LSD: least significant differences of means; CV: coefficient of variation.

[11] that millet yields in Sahelian region are driven largely by the climatic pattern (especially rainfall distribution) and soil fertility status during growth stages. In addition, the sandy to sandy loam soils found in both sites promote good permeability of roots into the soil. The soil texture retains less water, which suggests that good establishment and growth of millet can only be favoured by rains that are more frequent during the cropping season that can at least partially meet the continuing high evaporative demand while keeping the rooting zone wet and offer the possibility of a rapid movement of the wetting front towards the stored water. In addition, the results at both sites confirmed close interaction between water use and nutrient applied on growth and yields resulting in a significant increase in GY, SY, and HI due to different N-fertilizer levels. Our study found that the application of N at 80 kg/ha enhances water-use efficiency leading to a greater increase in yield relative to that in evapotranspiration [12, 36, 37].

The results of our study show that N requirements for millet may be site-specific with the optimal application rate of 60 kgNha^{-1} for Minjibir and 80 kg Nha^{-1} for Gambawa. At the optimal rate of 60 kg Nha^{-1}, grain yield increased by 32%, 12%, and 8% compared to the applied rate of 0, 20, and 40 kg Nha^{-1}, respectively, in Minjibir. Similarly, at the optimal rate of 80 kg Nha^{-1}, grain yield increased by 58%, 31%, 28%, and 8% compared to the applied rate of 0, 20, 40, and 60 kg Nha^{-1}, respectively, in Gambawa. The optimal N rate observed at Gambawa was compared favourably with that reported in the study conducted in southern India which indicated that higher growth, yield attributes, and yield of pearl millet can be obtained by fertilizing the crop with 80 kg N/ha [38]. However, a study in a similar environment in West Africa [25] reported a response at 30 kg N/ha and a significant plant population by N-fertilizer interaction as well as N-fertilizer by rainfall interaction. As observed from this study, blanket N rates should not be applied by farmers in all locations even within the same agroecological zone, but rather the N application should be based on the knowledge of inherent soil fertility and rainfall amount and distribution. The results are in agreement with many other studies including that of Joshi et al. [38] who demonstrated a parabolic relationship between N and grain yield which implies that when N rate surpassed a certain threshold, the grain yield greatly decreased. However, the study found that under certain conditions, increased N application rates may reduce TWU, thereby increasing WUE as was clearly observed in Gambawa. WUE did not significantly differ between N rates of 80 and 100 kg ha^{-1}, which indicates that excessive N application had no favourable effect on WUE. The maximum WUE corresponds to the maximum grain yield in both locations, which implies that the higher WUE by pearl millet crop would result in higher yield gain with less water demands [11]. Meanwhile, when evapotranspiration is less affected by management, any factor that increases yield will increase WUE. In addition, N-fertilizer could be seen as beneficial to the rapid early growth of leaves leading to higher SY across different N-fertilized treatments compared to unfertilized N treatment. The direct evaporation from the soil on the millet field varied between 35 and 45% of rainfall, with the higher proportions occurring in the lower rainfall [39]. Thus, strategies such as the use of fertilizer, which can promote rapid early growth, can contribute to the reduction of soil evaporative losses and increased WUE. NUE significantly decreased as a linear function with increasing N levels with the application of N at 20 kg Nha^{-1} having the highest NUE values at the application rate of 20 kg Nha^{-1}. This result was in agreement with several studies reported on various crops, e.g., sorghum [12, 40], millet [41], and maize [42]. This shows that higher NUE is recorded at lower rates of N application than higher rates of N application. This agrees with the findings that NUE in pearl millet declines because of an increase in rates of N application [43, 44]. The NUE may be increased if farmers apply N in 3-4 splits such that N is applied at several peak demands and wastage in the form of leakage is minimised. The economic analysis revealed low TCP, TR, NER, and B : C for unfertilized plots compared to the different N-fertilizer levels in both locations. Therefore, to increase the productivities of pearl millet farmers, input and judicious use of the inputs are necessary. Low input specifically low N-fertilizer input to pearl millet production in the semiarid zones may result in low labour productivity for farmers particularly in a drier area (e.g., Gambawa site) due to low nutrients in the soil (e.g., organic carbon, total nitrogen, and available phosphorus). Our results suggest that farmers in Minjibir can profitably grow pearl millet between N rate of 20 and 60 kg ha^{-1} leading to the same benefit-cost ratio (B : C = 1 : 1.33 to 1 : 1.27) while in Gambawa it can be extended to 80 kg Nha^{-1} (B : C = 1 : 0.43 to 1 : 0.64). This implies that farmers in Minjibir would make US$ 1.3 on every US$ 1 invested by applying N-fertilizer at 20 kg Nha^{-1} and US$ 1.27 on every US$ 1 by applying N-fertilizer at 60 kg Nha^{-1}. It is therefore necessary to increase the NUE of pearl millet especially at the higher N application rate. Agronomic strategies such as plant population, number of split fertilizer application, and type of N-fertilizer applied should be investigated to increase the NUE of applied N in pearl millet cultivation. The work of other researchers [25] has shown that N application and high plant density increased millet grain yield four- to fivefold. The break-even yield at the current price indicates that farmers must produce significantly higher grain than 1000 kg/ha^{-1} even under no fertilizer input. This implies that majority of farmers are producing at a loss considering that the present average yield of pearl millet in Nigeria is 801 kg/ha [2] to 850 kg/ha [45].

5. Conclusion

Our study has shown that N fertilization affected the growth, grain yield, stalk yield, TWU, WUE, and NUE of the two improved and local pearl millet varieties tested in both Minjibir and Gambawa. The economic analysis also showed that TR, NER, and B : C were significantly affected by nitrogen fertilizer application as well as pearl millet varieties. Dissemination campaigns of improved pearl millet production technologies should be encouraged to increase adoption and pearl millet on-farm yield since an average farmer may presently be producing at less than the break-even yields. There were significant differences in grain and stalk yields of the pearl millet varieties tested, between the two locations irrespective of N-fertilizer rates applied. This is probably due to differences in total rainfall and distribution and the inherent soil fertility in those two locations. There was a strong interaction between water use and nitrogen supply on pearl millet varieties, resulting in an increase in WUE. It is therefore clear that the use of chemical fertilizers, particularly nitrogen, is advantageous for the profitability of pearl millet production in the semiarid zone, by applying appropriate dose in order to meet the crop and soil demand for higher productivity. Based on the study, we therefore recommend that farmers in Minjibir and other similar wetter areas of semiarid could apply N between 40 and 60 kg ha^{-1} for pearl millet. Meanwhile, at Gambawa, the application rates of 60 and 80 kg Nha^{-1} is recommended for pearl millet for higher productivity and profitability.

Data Availability

The raw data for the experiment are available as international public goods and can be made available on request to the International Crops Research Institute for the Semi-Arid Tropics (a member of the CGIAR).

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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