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Optimizing Nitrogen Fertilization and Variety for Millet Grain Yield and Biomass Accumulation in Dry Regions

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Abstract: Meeting foxtail millet (*Setaria italica* L.) (FM) production targets of high grain yield requires appropriate genotype selection and nitrogen (N) fertilization. However, high input costs and low crop yields are the major concerns for FM production systems, particularly in dry regions. To reduce the production costs without sacrificing yield, we assumed that N fertilization would increase the grain yield of FM varieties by improving reproductive organ biomass accumulation. To test this hypothesis, a two-year (2017 and 2018) field investigation in a randomized complete block design with split plot arrangement and three replicates was carried out on FM varieties, namely, V_1 (Zhangzagu 8; hybrid) and V_2 (Bagu 214; common) to ascertain the effects of five N levels (N_1—15; N_2—61; N_3—108; N_4—155; N_5—201 kg N ha^{-1}) on biomass accumulation and grain yield at different growth stages. Results showed that the V_1 variety had a 34.8% and 28.5% higher grain yield compared to V_2 treatment in both years, respectively. The interaction between variety and nitrogen was also significant. The combination of V1 and N4 produced a higher grain yield in both years. This increase in V_1 grain yield was supported by the evidence of greater reproductive organ biomass formation, with a 113 and 120 kg ha^{-1} higher-than-average rate of biomass accumulation in both years, respectively. Among N rates, the N4 level resulted in a higher grain yield (3226 kg ha^{-1}) and (3437 kg ha^{-1}) compared with other N rates in the 2017 and 2018 growing seasons. This higher yield under N4 treatment was confirmed by a higher reproductive organ biomass accumulation at various growth phases, with 138 kg ha^{-1} and 124 kg ha^{-1} in 2017 and 2018, respectively. We also noticed that further increases in nitrogen levels did not increase FM grain yield. Conclusively, these data display the significance of proper FM production management techniques. Growing the varieties Zhangzagu 8 at 155 kg N ha^{-1} fertilization and Bagu 214 at 108 kg N ha^{-1} fertilization could be promising options to achieve higher grain yield.

Keywords: variety; vegetative biomass; reproductive biomass; fertilization; yield

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1. Introduction

Foxtail millet (*Setaria italica* L.) is highly adaptable to drought and low fertility, uses water efficiently, and is considered an important food crop worldwide [1]. Due to its high adaptability to low fertility, its effective water use [2–4], small genome size, short plant size and rapid growth, FM has been used as a model plant for cereals [5]. In Nigeria, FM yield is mainly constrained due to the mismanagement, or the reduced use, of nitrogen (N) fertilizer. Hence, there is a need to optimize N rates for FM production in this region through the appropriate use of nitrogen fertilizer. Hybrid varieties have a higher demand for fertilizer N compared with open-pollinated varieties, and generally give higher yields. Many factors are involved in the crop response to N, for example, yield potential, soil residual N, soil water content and other essential nutrients [6]. In crop production, nutrient management, especially N, is cumbersome. Its application and production require large amounts of energy, and the excessive application of N results in the generation of nitrous oxide, a potent greenhouse gas emission in the environment [7]. Among major nutrients, N is the most abundant element in the atmosphere and is a key component of nucleotides and proteins which are required for life [8]. In crop production, the appropriate use of nutrients can increase crop root morphological traits, root enzyme activities, biomass formation, nutrients absorption, translocation, utilization and consequently yield [9]. Low N application can enhance FM root biomass yield, N utilization efficiency, soluble proteins, upregulates the expression levels of the SiNRT1.1, SiNRT2.1, and SiNAR2.1 nitrate transporters and also the nitrate influx in the root, but decreases root length, chlorophyll content, crown root number and root density [10]. A balanced nutrient supply, i.e., nitrogen, phosphorus, potassium, sulphur, zinc and boron improves the above-ground biomass formation and grain yield, as well as drought resistance, due to increased water productivity, but seasonal flexibility imposes a remarkable impact on yield when compared with cultivars and applied N [11]. The split application of N, i.e., 60% as a basic fertilizer at sowing, 20% at elongation and 20% at heading, were suggested as the best combinations to achieve better growth and millet grain yield [12]. However, the N requirement and application technique varies with different varieties of FM. Foliar N application at 2% (percentage of total N dose) could increase FM yield by 8%, but the application of more than 3% would decrease grain yield [13]. N fertilization increases crude protein, vegetative organs N content and pearl millet grain yield [11]. Long-term use of N fertilization can maintain yield and enhance soil health, by improving carbon sequestration [14]. It has been reported that N sprayed over leaves is assimilated by plants 50–100% more efficiently than nitrogen introduced to the soil [15]. N management is cumbersome in cotton production systems, but it has a higher impact on yield, maturity, and the lint quality of a cotton crop than other primary plant nutrients. The application and production of N fertilizers consumes large amounts of energy, and excess application can cause environmental concerns, i.e., nitrate in ground water, and the production of nitrous oxide, a highly potent greenhouse gas (GHG) in the atmosphere, which is a global concern [7]. Therefore, it is important to identify efficient N management options to increase FM grain yield and reduce production costs, without sacrificing the environment.

However, local farmers usually use less or inappropriate nitrogen fertilizers on the farm, thus inhibiting the growth of local crop varieties. The inadequate use, or poor N fertilizer management, and the selection of the appropriate variety, may be the reasons for low FM yield formations and the high input costs in northern Nigeria. Among the millet varieties, Zhangzagu 8 is a nitrogen-efficient and high yielding variety in China, but its production in dry regions of Nigeria has not been reported. In low input production regions under limited N use, N-efficient varieties are a key solution for increasing crop yield. In this context, the optimization of N levels and the selection of appropriate varieties are important for optimal yield formation. The objectives of this study were to: (1) to explore Chinese FM grain yield, vegetative and reproductive organ biomass accumulation in response to various N fertilization rates at different growth phases, and (2) determine the quantitative relationship between N level and variety to achieve optimal FM grain yield in dry environments. The tested hypothesis was that N application would increase the grain yield of FM varieties by enhancing the reproductive organ biomass accumulation.

2. Materials and Methods

2.1. Experimental Site Details

A two-year (2017–2018) field experiment was performed at the Institute for Agricultural Research, Kebbi, Nigeria. Prior to sowing, surface soil (0–30 cm) samples were randomly collected from twelve different points in the experimental field. These soil samples were bulked, air-dried and sieved using a 2 mm sieve. Soil pH was assessed using a digital pH meter (Walk lab Ti 9000; Trans Instruments, Singapore) in a 2:1 0.01 M $CaCl_2$ solution to soil suspension [16]. Soil organic carbon content was determined using a colorimetric method [17]. Soil available N was determined using the method in [17,18]. Soil available P was obtained by $NaHCO_3$ extraction and analyzed using the Mo-Sb colorimetric method with flame atomic absorption spectroscopy (spectrophotometer UV 2550, Shimadzu Corporation, Kyoto, Japan) [19]. Available K was extracted with neutral 1 M NH_4OAc [20]. The soil of the experimental site was composed of 2.5% clay, 3.7% silt and 3.8% sand. The soil was composed of 4.9 g kg^{-1} organic carbon with a pH of 5.8. The available nitrogen, phosphorus, and potassium were 38.0, 20.2, 76.7 mg kg^{-1} in 2017, and 36.2, 22.4, and 79.3 mg kg^{-1} in the 2018 growing seasons, respectively. Mean monthly temperature and rainfall data for both years are shown in Figure 1.

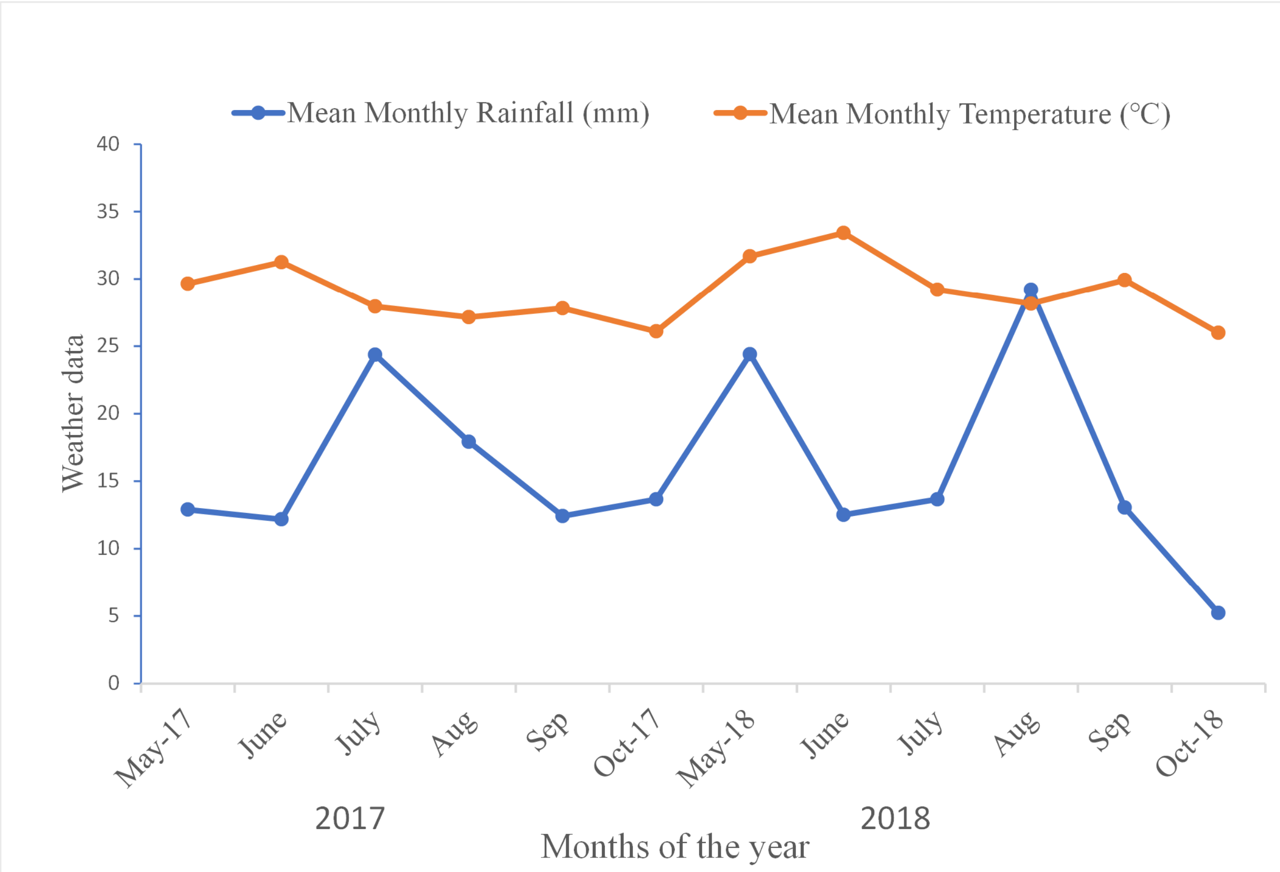

Figure 1. Mean monthly rainfall and temperature during the experimental period.

2.2. Experimental Design and Cultivar Details

In this study, two factors were targeted: nitrogen and variety. A split-plot arrangement with randomized complete block design was used. In total, five N application rates (N1 = 15 kg N ha^{-1}), (N2 = 61 kg N ha^{-1}), (N3 = 108 kg N ha^{-1}), (N4 = 155 kg N ha^{-1}) and (N5 = 201 kg N ha^{-1}), and two varieties, Zhangzagu 8 (V1) (hybrid; drought resistant and high yielding) and Bagu 214 (V2) (common; drought prone), were used. The varieties were assigned to the main plots, and N rates were allotted to subplots. The total growth period of millet is 80–90 days. Before sowing, basal applications of phosphorus (P_2O_5) as 60 kg P ha^{-1}, nitrogen (N) as 150 N kg ha^{-1}, potash (K_2O) as 60 kg K ha^{-1} were applied using superphosphate (12% P_2O_5), urea (46% N), potassium chloride (59% K_2O), respectively. Urea was used as a source of N fertilizer in both years. N fertilizer (urea) was applied in two splits, i.e., half during planting time and the rest at the reproductive stage. These treatment combinations accounted for 10 subplots per replication, and each were replicated three times. Each plot was 10 m × 2.4 m, consisting of 10 rows with 25 cm row-to-row distance and 10.7 cm plant-to-plant distance, respectively. Crops were harvested at 80–90 days after sowing.

2.3. Field Preparation and Crop Management

Before sowing, the experimental field was ploughed (15–20 cm) deep using a tractor, and plots were raised approximately three weeks prior to planting and covered with plastic film to conserve moisture and suppress weed germination. Seeds were hand-sown (2–3 cm in depth) during both years. At 3–4 leaf stage, seedlings were hand-thinned twice to maintain the desired planting density for each plot. No pesticide was applied during crop growth; insects and pests were controlled manually during both years. Intertillage and weeding were carried out before the heading stage in both years. Fertilizer was applied in two splits using the band placement method. After fertilizer application, the field was irrigated to avoid the loss of fertilizer. These operations were employed during both study years.

2.4. Vegetative and Reproductive Organ Biomass Accumulation

To assess vegetative and reproductive organ biomass accumulation, ten plants were randomly selected at germination, elongation, heading, flowering and the maturity stage in each plot. These plants were carefully uprooted, washed in water to remove traces of sand and separated into vegetative (roots, stems, leaves) and reproductive organs (panicles). These samples were enveloped separately and oven dried at 105 °C for 30 min and then at 80 °C for 48 h to achieve a constant weight.

2.5. Foxtail Millet (FM) Grain

To determine grain yield, plants were grown until maturity. The crop was harvested 80–90 days after sowing. Panicles in each plot were manually harvested, air-dried and threshed to assess grain yield. Grain moisture content was measured with a Grain Moisture Tester (PM-830-2, Kett, Japan). The grain was weighed separately and expressed in kg ha^{-1} for each treatment.

2.6. Biomass Simulation

Biomass accumulation was modelled using a logistic regression model according to Yang et al. [21], as follows:

$$Y = \frac{K}{1 + ae^{bt}} \quad (1)$$

In the Equation (1), t (d) indicates days after emergence (DAE), Y represents the biomass at time, t, K is the maximum biomass and a, b are the constants to be determined.

$$t_1 = \frac{1}{b}\ln\left(\frac{2+\sqrt{3}}{a}\right) \quad (2)$$

$$t_2 = \frac{1}{b}\ln\left(\frac{2-\sqrt{3}}{a}\right) \quad (3)$$

$$t_m = -\frac{\ln a}{b} \quad (4)$$

$$V_m = -\frac{bK}{4} \quad (5)$$

$$V_t = \frac{Y_2 - Y_1}{t_2 - t_1} \quad (6)$$

V_m (g d^{-1}) is the highest biomass formation rate; t_m (d) is the largest biomass formation period, which begins at time t_1 and ends at t_2; Y_1 and Y_2 are the biomass at t_1 and t_2; V_t is the average biomass accumulation, i.e., t_1–t_2.

2.7. Statistical Analysis

Data were processed using Microsoft Excel 2016 (Microsoft Corporation, Albuquerque, NM, USA). Analysis of variance (ANOVA) was performed to compare differences between all studied parameters caused by the variation in nitrogen levels and variety. Data were analyzed using SAS 8.1 (SAS Institute, Cary, NC, USA) and Data Processing System (DPS) software. Figures were plotted using Sigma Plot 12.5 software (Inpixon HQ, Palo Alto, CA, USA). The full model considered genotype, nitrogen level and their interaction as fixed effects. Differences among treatments imply statistical differences (p = 0.05). The mean differences among the treatments were calculated using the least significant difference test at the 95% confidence level.

3. Results

3.1. Foxtail Millet (FM) Grain

Nitrogen levels, variety and their interaction, significantly impacted FM grain yield in the 2017 and 2018 growing seasons (Table 1). Across varieties, V1 had a 34.8% and 28.5% higher yield than V2 in 2017 and 2018, respectively. Across N levels, an increasing N level gradually increased grain yield across both years, where N4 and N5 produced higher yields than lower N rates. Further increments in N levels beyond N5 did not contribute to a higher grain yield, suggesting that plants cannot efficiently utilize surplus N fertilizer. Interactively, V1 in combination with N5 resulted in the highest yield of all combinations across both years. The interaction between nitrogen and variety was also significant. V1 at N3 resulted in a higher yield than V2 at N3–5. In response to increasing N to N4, V1 reacted with a further increase in grain yield, and only N5 was statistically unjustified for this variety. For V2, N4 was no longer justified, with a generally significantly lower yield compared to V1.

Table 1. Millet grain yield in response to different varieties and nitrogen rates during the 2017 and 2018 growing seasons.

Treatment	Grain Yield (kg ha^{-1})	
	2017	2018
Variety (V)		
V1	2813.5a	3048.3a
V2	2087.0b	2370.9b
Nitrogen (N)		
N1	1058.2d	1304.1d
N2	1841.0c	2203.4c
N3	2946.1b	3252.2b
N4	3225.9a	3436.6a
N5	3181.1a	3351.8ab
Interaction (V × N)		
V1N1	1227.7f	1401.3g
V1N2	2179.6d	2386.9e
V1N3	3156.4b	3444.8b
V1N4	3730.2a	3977.0a
V1N5	3773.5a	4022.2a
V2N1	888.7g	1197.8g
V2N2	1502.3e	2019.9f
V2N3	2734.0c	3059.5c
V2N4	2721.6c	2896.1cd
V2N5	2588.6c	2681.4de
Source of variance (SOV)		
V	<0.0001	<0.0001
N	<0.0001	<0.0001
V × N	<0.0001	<0.0068

V1 and V2 represent FM hybrid (Zhangzagu 8) and FM local Variety (Bagu 214), respectively, while N1, N2, N3, N4 and N5 represent nitrogen application rates at 15, 61.7, 108.4, 155.1 and 201.8 kg ha^{-1}, respectively. Means (n = 3) with different letters in each column are significantly different at the 5% probability level according to the least significant difference test.

3.2. Millet Plant Biomass Accumulation

Vegetative organ biomass (VOB) accumulation was significantly affected by N levels and varieties at germination, elongation, heading, flowering and maturity stages (10 to 85 days after emergence) in both years (Figure 2). The millet crop biomass accumulation gradually increased when the crop transitioned from one stage to the next in both years. In 2018, VOB accumulation was higher than in the 2017 growing season. In 2017, VOB accumulation rapidly increased from elongation to flowering and decreased at flowering and maturity stages. Between varieties, V1 had a 28.7, 319, 2455, 4135 and 3434 kg ha^{-1} higher biomass yield at germination, elongation, heading, flowering and maturity stages, respectively, over V2, respectively. The V1 variety, coupled with different fertilization rates, showed the following trends: V1N5, V1N4, V1N3 > V1N2, V1N1 (heading); V1N5 > V1N4, V1N3 > V1N2 > V1N1(flowering); and V1N5 > V1N4 > V1N3 > V1N2 > V1N1 (maturity stage). A similar trend was noticed at heading, flowering and maturity as V2N5, V2N4, V2N3 > V2N2 > V1N1.

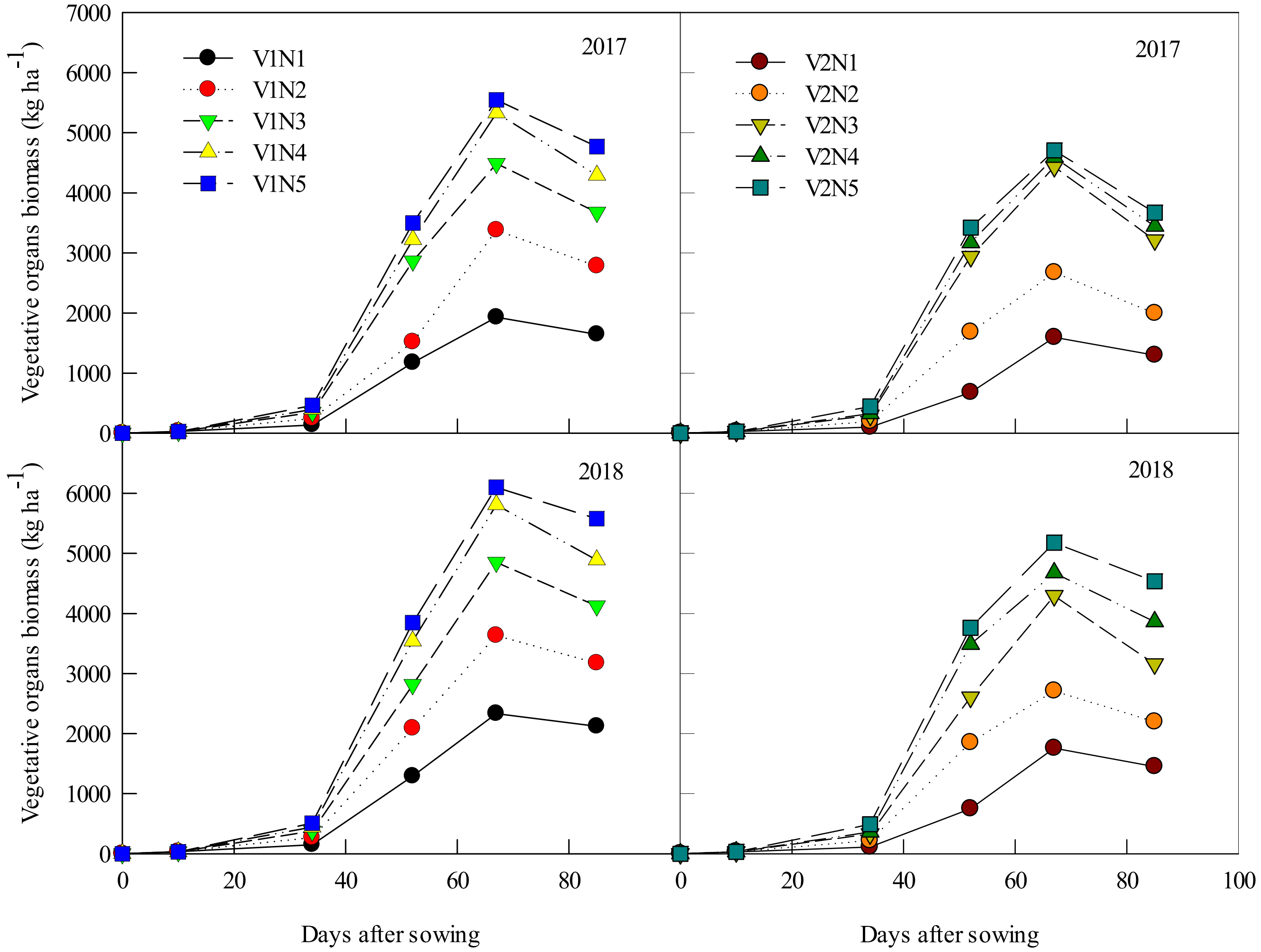

Figure 2. Changes in vegetative organ biomass yield in response to nitrogen fertilization and variety in 2017 and 2018. (n = 3). V1 and V2 represent FM hybrid (Zhangzagu 8) and FM local variety (Bagu 214), respectively, while N1, N2, N3, N4 and N5 represent nitrogen application rates at 15, 61.7, 108.4, 155.1 and 201.8 kg ha^{-1}, respectively.

Reproductive organ biomass (ROB) yield was substantially influenced by variety and N rates in both years (Figure 3), with the ROB accumulation curve showing an increasing trend from elongation to maturity stages in both years. Between varieties, V1 resulted in a higher biomass than V2 after the heading stage. ROB accumulation was 24, 337, 1477 and

3519 kg ha^{-1} higher at elongation, heading, flowering and maturity stages, respectively, for V1 compared with V2. Reproductive organ biomass accumulation was in the following combination: V1N5 > V1N4, V1N3 > V1N2, V1N1 and maturity, V1N5, V1N4 > V1N3 > V1N2 > V1N1. However, in the flowering and maturity stages, biomass yield was in the following trend V2N5, V2N4, V2N3 > V2N2 > V2N1.

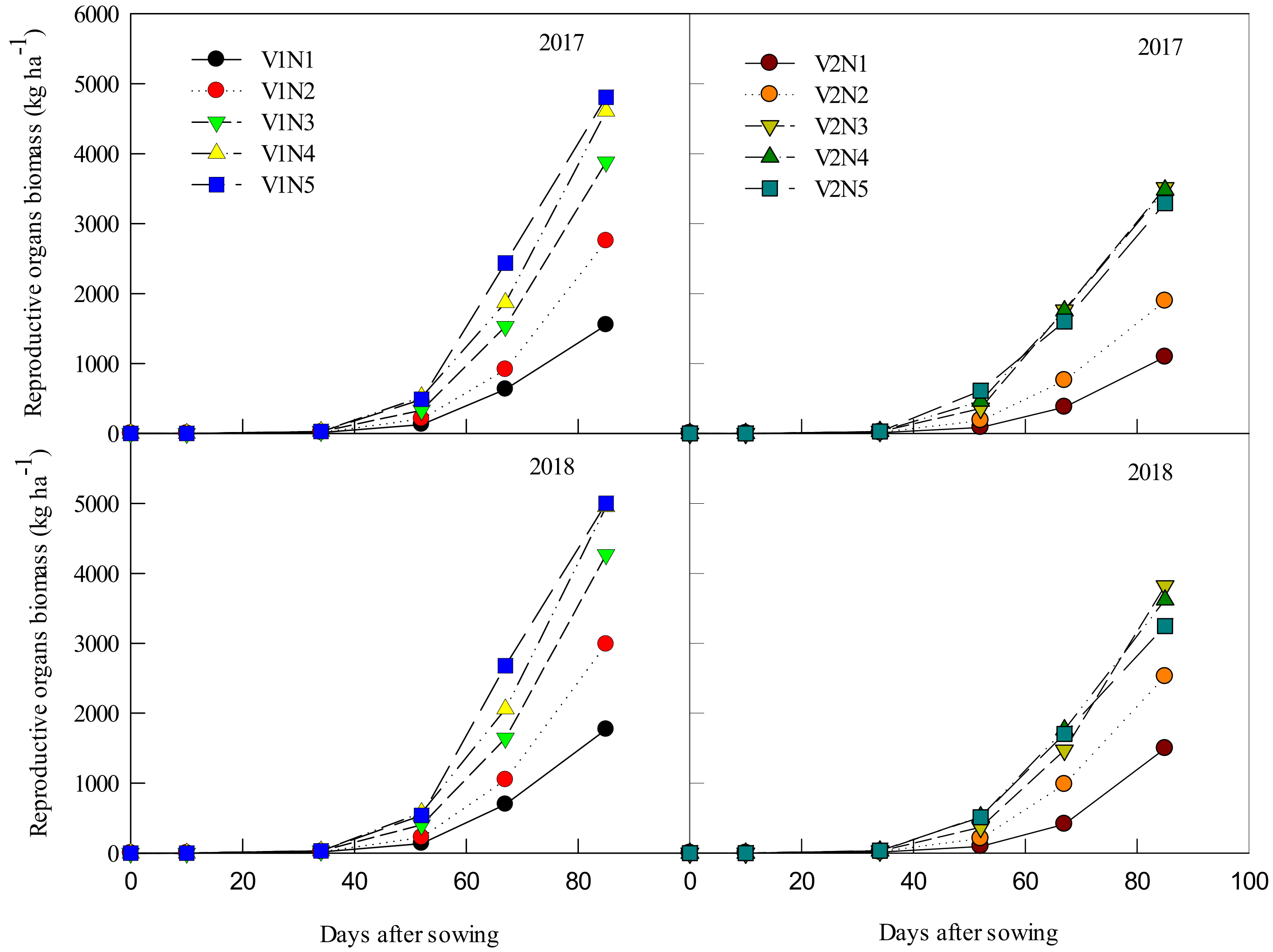

Figure 3. Changes in reproductive organ biomass yield in response to nitrogen fertilization and variety in 2017 and 2018. (n = 3). V1 and V2, represent FM hybrid (Zhangzagu 8) and FM local Variety (Bagu 214), respectively, while N1, N2, N3, N4 and N5 represent nitrogen application rates at 15, 61.7, 108.4, 155.1 and 201.8 kg ha^{-1}, respectively.

3.3. *Average Accumulation Rate of Vegetative Organs Biomass*

The average accumulation rate of vegetative organ biomass (VOB) was affected by variety and nitrogen rate in 2017 and 2018 (Table 2). VOB accumulation rate was significantly affected by variety and their interaction at 10–85 DAS. Between varieties, the VOB accumulation for V1 gradually increased with the days after sowing compared with the V2 variety in both years. The average accumulation rate of V1 was 37.3% and 47.2% higher than V2 in 2017 and 2018, respectively, at 52–67 DAS. Nitrogen application initially increased the average accumulation rate of VOB at 34–52 DAS or 52–67 DAS, and then declined. Among N levels, N4 and N5 levels resulted in a higher rate of VOB accumulation during 34–67 DAS over other counterparts during both years. However, N3 and N4 levels had a greater accumulation rate at 67–85 DAS over N4 and N5 treatment. From Table 2, it is clear that varieties differed in their responses to N fertilization. Initially, no significant differences in N treatments for V1 and V2 at 0–10 DAS were observed. The accumulation rate increased with the increase in N levels for both V1 and V2 in 2017 and 2018. V1N5 or V2N5 combinations had the highest rates of VOB accumulation compared with other treatments. The V1N4 and V2N3 combinations had the highest rates of VOB accumulation in both years.

Table 2. Average accumulation rate of vegetative organ biomass (kg ha^{-1}) under different variety and nitrogen fertilization rates in 2017–2018.

Year	Treatment	DAS 0–10	DAS 10–34	DAS 34–52	DAS 52–67	DAS 67–85
			Variety			
2017	V1	2.9	12.1a	118.7a	112.0a	−39.0a
	V2	3.0	10.2b	116.8a	81.6b	−48.7b
2018	V1	3.2	13.2a	131.6a	121.9a	−31.5a
	V2	3.2	11.2b	121.6b	82.8b	−38.0b
			Nitrogen			
2017	N1	3.0	3.8e	44.8d	55.8c	−16.1a
	N2	3.0	8.1d	76.6c	87.3b	−35.5b
	N3	2.9	12.2c	143.2b	112.0a	−56.5d
	N4	2.9	14.0b	157.3a	117.8a	−60.7d
	N5	2.8	17.8a	166.9a	111.2a	−50.4c
2018	N1	3.3	4.1e	49.4d	68.3b	−14.4a
	N2	3.2	8.8d	95.9c	80.4b	−27.2b
	N3	3.1	13.3c	131.2b	124.2a	−51.7c
	N4	3.2	15.5b	172.9a	115.3a	−48.2c
	N5	3.1	19.6a	183.6a	122.3a	−32.3b
			Source of variance (SOV)			
2017	V	0.307	<0.0003	0.5983	0.0004	0.0002
	N	0.5348	<0.0001	<0.0001	0.0002	<0.0001
	V × N	0.6455	0.5298	0.0294	0.0241	0.0252
2018	V	0.4052	<0.0003	0.015	<0.0001	0.028
	N	0.5559	<0.0001	<0.0001	<0.0001	<0.0001
	V × N	0.5452	0.4492	0.0663	0.0546	0.0756

V1 and V2 represent FM hybrid (Zhangzagu 8) and FM local variety (Bagu 214), respectively, while N1, N2, N3, N4 and N5 represent nitrogen application rates at 15, 61.7, 108.4, 155.1 and 201.8 kg ha^{-1}, respectively. DAS shows days after sowing, and means (n = 3) with different letters in each column are significantly different at a 5% probability level according to the least significant difference test.

3.4. Average Accumulation Rate of Reproductive Organ Biomass (ROB)

Variety, nitrogen and their interaction substantially influenced average ROB accumulation rate in both years (Table 3). Between varieties, V1 resulted in a 16.5% and 34.7% higher biomass accumulation rate at 52 DAS than V2 in 2017 and 2018, respectively. At 67–85 DAS, the average accumulation rate was 45.5 and 29.5% higher than V2 in 2017 and 2018, respectively. With an increasing N application from 0–10 DAS to 52–67 DAS, ROB increased at N4 and N5 levels. However, later in the season (67–85 DAS), N3 and N4 levels gave the highest rates of ROB accumulation. The ROB accumulation rate of V1N5 or V2N4 was the highest among other treatments. However, varieties differed in their response to nitrogen application at 67–85 DAS. The accumulation rate of ROB was higher for V1N4 and V2N3 in both years. With respect to average ROB accumulation rate, V2N3, V2N4 and V2N5 were comparable at 67–85 DAS.

Table 3. Average accumulation rate of reproductive organ biomass accumulation (kg ha^{-1}) under different variety and nitrogen fertilization levels in 2017–2018.

Year	Treatment	DAS 0–10	DAS 10–34	DAS 34–52	DAS 52–67	DAS 67–85
			Variety			
2017	V1	0	1.0	17.4	70.6a	113.5a
	V2	0	1.0	17.7	60.6b	78.0b
2018	V1	0	1.1	19.5	83.3a	120.6a
	V2	0	1.1	17.5	61.8b	93.1b

Table 3. *Cont.*

Year	Treatment	DAS 0–10	DAS 10–34	DAS 34–52	DAS 52–67	DAS 67–85
			Nitrogen			
2017	N1	0	0.5c	5.3d	26.4d	45.5d
	N2	0	0.8b	10.0c	42.6c	82.7c
	N3	0	1.3a	17.6b	78.3b	113.8ab
	N4	0	1.3a	25.8a	91.3ab	124.0a
	N5	0	1.3a	28.9a	102.9a	112.9b
2018	N1	0	0.6b	5.7d	29.2d	59.8c
	N2	0	0.8b	10.7c	53.3c	96.7b
	N3	0	1.2a	19.8b	78.1b	138.3a
	N4	0	1.3a	28.9a	90.8b	132.1a
	N5	0	1.4a	27.3a	111.3a	107.3b
			Source of variance (SOV)			
2017	V	0	0.4152	0.8086	0.0035	<0.0001
	N	0	<0.0001	<0.0001	<0.0001	<0.0001
	V × N	0	0.0062	<0.0001	0.0078	0.0064
2018	V	0	0.7564	0.0907	0.0004	<0.0001
	N	0	<0.0001	<0.0001	<0.0001	<0.0001
	V × N	0	0.6529	0.9722	0.0697	0.0595

V1 and V2 represents FM hybrid (Zhangzagu 8) and local variety (Bagu 214), respectively, while N1, N2, N3, N4 and N5 represent nitrogen application rates at 15, 61.7, 108.4, 155.1 and 201.8 kg ha^{-1}, respectively. DAS shows days after sowing, and means (n = 3) with different letters in each column are significantly different at the 5% probability level according to the least significant difference test.

4. Discussion

The main objective of this study was to optimize nitrogen fertilization levels with foxtail millet varieties and to evaluate optimal combinations to achieve higher yields, particularly in dry regions. The current research has developed new data regarding the common perception that nitrogen and choice of variety are important agronomic players for enhancing the biomass production and yield of millet crops. The use of the N4 level in conjunction with the hybrid variety led to a higher reproductive organ biomass, and the accumulation rate led to a higher grain yield in both years. This suggests that an appropriate use of N is positively allied with reproductive organ biomass and grain yields. However, depleting soil fertility not only affects crop productivity, but often risks crop failures.

Nitrogen is an important macronutrient for all developmental processes in plants, and its deficiency can negatively affect plant growth [22]. In this study, a positive response of FM to N application was observed in growing years. The application of N up to the N4 level increased FM yield during both years. A further increase in N level did not contribute to a higher grain yield. In this study, the increase in yield was the result of a higher biomass formation and a faster accumulation rate of reproductive organ biomass. Balanced N fertilization increases pearl millet yield and biomass formation [11]. A low application of N resulted in a lower yield of millet crops. This was probably due to a decreased leaf area index and leaf chlorophyll content, which inhibited photosynthesis and photosynthetic products, leading to a lower yield under low N application [23]. Between varieties, the hybrid variety had a higher grain yield over the local variety in both study years. This increment in yield was allied with the genetic variability, various agronomic characteristics and yield components, or from being more N efficient [22]. In this study, the interactive effects of N and variety were significant in both years. Yield increased for the hybrid variety with relatively higher nitrogen levels, i.e., N4, while with the local variety, yield increased at the N3 level. This reduction in yield for the common variety was associated with over vegetative organ formation and low reproductive organ biomass formation (Figures 1 and 2). This shows that the hybrid variety uses higher N rates more effectively compared to the local common variety.

Millet yield is determined by transported nutrients from vegetative organs and photosynthesis products after the heading stage [24]. N is the basic nutrient for enhancing crop growth and development, and over usage of N is detrimental to the environment [25]. To continue normal plant growth, plants need an adequate nutrient supply, and nutrient absorption may vary in quantity and rate during different growth periods [26]. Hence, dry matter accumulation is the prerequisite for FM yield formation. Previous studies have reported similar trends in the dry matter accumulation of vegetative and reproductive organs or the total plant in millet [6,27]. However, the relationship between vegetative organ and reproductive organ biomass accumulation in terms of dry matter accumulation during the whole growth period, have not yet been discussed. In this study, different trends in vegetative organ biomass and reproductive organ biomass accumulation at different growth periods were observed in both years. Millet crop vegetative organ biomass accumulation was increased from germination to the peak during the filling period, and then decreased at the maturity stage, while reproductive organ biomass increased from germination to maturity throughout the growing season. An increasing nitrogen rate up to N4 significantly increased reproductive organ biomass accumulation for the hybrid variety, but it decreased in the common variety. The increment in reproductive organ biomass accumulation may be associated with a greater N uptake which may have led to a higher photosynthetic rate and sustained biomass [24]. The hybrid variety had a higher demand for N fertilizer compared to the common variety, and generally gave higher yields [28,29]. Many factors are involved in crop response to N; yield potential, soil residual N, soil water and other essential nutrients [30].

Changes in dry matter partitioning are more likely to occur with water availability, CO_2 concentration, sowing date, cultivar, planting density and nitrogen supply, and these affect the duration of reproductive organ growth [21,24]. The rate of dry matter accumulation of hybrid and common millet varieties showed a "slow-fast-slow" model to nitrogen application in this study. The application of N at 155 kg ha^{-1} produced a higher reproductive organ biomass accumulation, which was the result of a faster transition of vegetative organ biomass to reproductive organ biomass in both years. This proved that nitrogen could improve plant dry matter yield in terms of higher accumulation rates [24]. Clearly, a higher-than-optimum N rate could reduce transfer rate of vegetative organ biomass to reproductive organ biomass in the late growth period of millet. This further reduced single ear weight. These data are in good agreement with previous research [25,28]. Between varieties, the hybrid variety had a lower rate of transfer from vegetative organ biomass to reproductive organ biomass formation at 67–85 DAS, but had a higher accumulation rate of reproductive organ biomass accumulation. This increment was probably due to higher flag leaf areas and chlorophyll content, which may lead to higher levels of photosynthesis for the hybrid during the later growth period [25]. This suggests that rational fertilizer application coupled with appropriate variety selection is a promising solution for increasing millet production in dry regions of Nigeria.

5. Conclusions

Nitrogen fertilization and choice of variety are the yield improvement decisions in any cropping system. In this study, nitrogen levels and varieties substantially affected millet grain yield and biomass accumulation during both years. The interaction between nitrogen and variety was also found significant during both years. However, an FM hybrid variety yielded better than the local common variety. This improvement in yield was strongly allied with the greater rate of reproductive organ biomass accumulation in both years, as observed in this study. The use of nitrogen fertilizer at 155 kg ha^{-1} for hybrid and 108 kg ha^{-1} for the common variety led to higher grain yields. This demonstrates that the hybrid variety requires a relatively higher amount of nitrogen fertilizer than the common variety. The increment in grain yield was associated with a greater and quicker reproductive organ biomass yield in both years. We also noticed that further increments in nitrogen fertilization rates did not improve grain yield. This shows that the excessive application of N can negatively affect plant performance. Therefore, it is suggested that the hybrid variety can be grown under the nitrogen fertilizer rate of 155 kg ha^{-1}, while the common variety can utilize 108 kg ha^{-1} efficiently. Further exploration of these findings under other soil and climatic conditions is required for the optimization of N in different large-scale millet cultivation systems.

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References

1. Wang, C.; Jia, G.; Zhi, H.; Niu, Z.; Chai, Y.; Li, W. Genetic diversity and population structure of Chinese foxtail millet landraces. *Genes Genome Genet.* **2012**, *2*, 769–777. [CrossRef]
2. Liu, F.; Liu, M.; Zhao, Y.; Nan, C.; Xia, X.; Li, S.; Xu, L. Development trends of China's foxtail millet and broomcom millet industries. *Agric. Outlook* **2017**, *13*, 40–43.
3. Doust, A.N.; Kellogg, E.A.; Devos, K.M.; Bennetzen, J.L. Foxtail millet: A sequence-driven grass model system. *Plant Physiol.* **2009**, *149*, 137–141. [CrossRef] [PubMed]
4. Diao, X.M.; Schnable, J.; Bennetzen, J.L.; Li, J.Y. Initiation of Setaria as a model plant. *Front. Agric. Sci. Eng.* **2014**, *1*, 16–20.
5. Zhang, G.; Liu, X.; Quan, Z.; Cheng, S.; Xu, X.; Pan, S. Genome sequence of foxtail millet (*Setaria italica*) provides insights into grass evolution and biofuel potential. *Nat. Biotechnol.* **2012**, *30*, 549–554. [CrossRef]
6. Joshi, N.L.; Kalla, J.C. Economizing nitrogen use of pearl millet in the Indian arid zone. *Ann. Arid. Zone* **1986**, *25*, 321–325. [CrossRef]
7. Khan, A.; Tan, D.K.Y.; Munsif, F.; Afridi, M.Z.; Shah, F.; Wei, F.; Zhou, R. Nitrogen nutrition in cotton and control strategies for greenhouse gas emissions: A review. *Environ. Sci. Pollut. Res.* **2017**, *24*, 23471–23487. [CrossRef]
8. Khan, A.; Tan, D.K.Y.; Afridi, M.Z.; Luo, H.; Tung, S.A.; Ajab, M.; Fahad, S. Nitrogen fertility and abiotic stresses management in cotton crop: A review. *Environ. Sci. Pollut. Res.* **2017**, *24*, 14551–14566. [CrossRef]
9. Chen, Z.; Khan, A.; Shi, X.; Hao, X.; Tan, D.K.Y.; Luo, H. Water-nutrient management enhances root morpho-physiological functioning, phosphorus absorption, transportation and utilization of cotton in arid region. *Ind. Crops Prod.* **2020**, *143*, 1–8. [CrossRef]
10. Nadeem, F.; Ahmad, Z.; Wang, R.; Hassam, M.; Diao, X.; Li, X. Adaptation of Foxtail Millet (*Setaria italica* L.) to Abiotic Stresses: A Special Perspective of Responses to Nitrogen and Phosphate Limitations. *Front. Plant Sci.* **2018**, *11*, 11–187. [CrossRef]
11. Uppal, R.K.; Wani, S.P.; Garg, K.K.; Alagarswamy, G. Balanced nutrition increases yield of pearl millet under drought. *Field Crops Res.* **2015**, *177*, 86–97. [CrossRef]
12. Zhang, X.; Wang, X.; Yang, J.; Cheng, B.; Luo, S. Effects of different using methods of nitrogen fertilizer on the growth and yield of millet. *J. Agric. Sci.* **2015**, *36*, 25–28. [CrossRef]
13. Yan, Z.; Guo, P.; Yuan, X.; Xiao, X.; Wang, D. Effect of foliar application of nitrogen fertilizer on photosynthetic characteristics and yield of foxtail millet cultivar 'zhang zagu 10′ *Setaria italic* (L.) Beauv. *J. Shanxi Agric. Univ.* **2018**, *38*, 37–41.
14. Wani, S.P.; Sahrawat, K.L.; Sreedevi, T.K.; Bhattacharyya, T.; Srinivasa, R.C. Carbon sequestration in the semi-arid tropics for improving livelihoods. *Int. J. Environ. Stud.* **2007**, *64*, 719–727. [CrossRef]
15. Ciećko, Z.; Żołnowski, A.; Mierzejewska, A. Effect of foliar nitrogen and magnesium fertilization on the total, protein nitrogen and nitrates(V) content in potato tubers. *Ecol. Chem. Eng.* **2010**, *17*, 593–600.
16. Sumner, M.E.; Miller, W.P. Cation exchange capacity and exchange coefficients. In *Methods of Soil Analysis, Part 3, Chemical Methods*; Soil Science Society of America and American Society of Agronomy: Madison, WI, USA, 1996; pp. 1201–1229. [CrossRef]
17. Nelson, D.W.; Sommers, L.E. Total carbon, organic carbon, and organic matter. In *Methods of Soil Analysis, Part 3. Chemical Methods*; Black, C.A., Ed.; Soil Science of America and American Society of Agronomy: Madison, WI, USA, 1996; pp. 961–1010.
18. Dorich, R.A.; Nelson, D.W. Evaluation of manual cadmium reduction methods for determination of nitrate in potassium chloride extracts of soils. *J. Soil Sci. Soc. Am.* **1984**, *48*, 72–75. [CrossRef]

19. Kosteckas, R.; Marcinkevicienee, A. The integrated evaluation of the influence of catch crops and manure on spring barley agrocenosis in organic farming. *Agron. Res.* **2009**, *1*, 355–362.
20. Bao, S.D. *Soil and Agricultural Chemistry Analysis*; Chinese Agriculture Press: Beijing, China, 2012; pp. 8–9.
21. Knudsen, D.; Peterson, G.A.; Pratt, P.F. Lithium, sodium, and potassium. In *Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties*; Page, A.L., Ed.; Soil Science Society of America and American Society of Agronomy: Madison, WI, USA, 1982; pp. 225–246. [CrossRef]
22. Yang, G.; Tang, H.; Nie, Y.; Zhang, X. Response of cotton growth, yield, and biomass to nitrogen split application ratio. *Eur. J. Agron.* **2011**, *35*, 164–170. [CrossRef]
23. Khan, A.; Kong, X.; Najeeb, U.; Zheng, J.; Tan, D.K.Y.; Akhtar, K.; Zhou, R. Planting density induced changes in cotton biomass yield, fiber quality, and phosphorus distribution under beta growth model. *Agronomy* **2019**, *9*, 500. [CrossRef]
24. Song, M.; Li, Z.; Feng, H. Effects of irrigation and nitrogen regimes on dry matter dynamic accumulation and yield of winter wheat. *Trans. Chin. Soc. Agric. Eng.* **2016**, *32*, 119–126. [CrossRef]
25. Khan, A.; Najeeb, U.; Wang, L. Planting density and sowing date strongly influence growth and lint yield of cotton crops. *Field Crops Res.* **2017**, *209*, 129–135. [CrossRef]
26. Zhang, Y.; Du, J.; Wang, Y. Effect of drought stress on dry matter accumulation and yield of summer millet. *J. Northeast Agric. Univ.* **2016**, *47*, 15–22.
27. Zhang, Y.; Wang, Z.; Fu, Y.; Meng, A.; Feng, G.; Hu, X. Effect of nitrogen application amount on the growth and yield of foxtail millet by drip irrigation under mulch. *J. Xinjiang Agric. Sci.* **2017**, *54*, 1061–1065.
28. Ali, H.; Afzal, M.N.; Ahmad, S.; Muhammad, D. Effect of cultivars and sowing dates on yield and quality of (*Gossypium hirsutum*). *J. Food Agric. Environ.* **2009**, *7*, 244–247.
29. Khan, A.; Wang, L.; Ali, S.; Tung, S.A.; Hafeez, A.; Yang, G. Optimal planting density and sowing date can improve cotton yield by maintaining reproductive organ biomass and enhancing potassium uptake. *Field Crops Res.* **2017**, *214*, 164–174. [CrossRef]
30. Khan, A.; Munsif, F.; Akhtar, K.; Afridi, M.Z.; Ahmad, Z.; Fahad, S.; Ullah, R.; Khan, F.A.; Din, M. Response of fodder maize to various levels of nitrogen and phosphorus. *Am. J. Plant Sci.* **2014**, *5*, 2323–2329. [CrossRef]