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GROWTH AND YIELD PERFORMANCE OF SORGHUM (*Sorghum bicolor* L. Moench) VARIETIES UNDER VARYING UREA REGIMES IN THE SOUTHERN GUINEA SAVANNAH ZONE OF NIGERIA

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ABSTRACT

Limited soil fertility and nitrogen fertiliser access hinder sorghum production in sub-Saharan Africa significantly. In 2022 and 2023, two field experiments were conducted at the University of Abuja's farm to evaluate the impact of varying Urea levels on sorghum growth and yield in the Southern Guinea Savannah zone, in conjunction with uniform application of phosphorus and potassium. A Randomised Complete Block Design (RCBD) with 3 replications and a 4 x 5 factorial design was used, involving 4 sorghum types (Samsorg-48, 49, 46, 53) and 5 Urea levels (0-200 kg/ha). Data collected included plant height, leaf count, leaf area, tiller count, and grain yield, to assess the impact of Urea on sorghum growth and productivity. The ANOVA results showed that both sorghum varieties and Urea applications significantly ($p<0.05$) impacted crop performance. Increased Urea concentrations enhanced vegetative and yield parameters. Samsorg-49 achieved its highest grain yield with 100-200 kg/ha of Urea, while Samsorg-48 obtained top yields (3.6 t/ha in 2022 and 5.3 t/ha in 2023) with 200 kg/ha. However, Samsorg-46 had the most tillers per stand at 200 kg/ha but recorded the lowest yield, showing unique varietal responses to Urea rates. Varieties responded differently. Grain yield was not significantly impacted by differences across sorghum varieties; however, a significant interaction between fertiliser and varieties revealed that different sorghum types responded differently to the application of Urea, suggesting that no single variety outperformed the others. The advised variety of sorghum is Samsorg 49, along with a recommendation of 150–200 kg/ha of Urea fertiliser.

Keywords: Fertiliser, Growth, Sorghum varieties, Urea levels, Yields

INTRODUCTION

Sorghum (Sorg*hum bicolor* L. Moench) is a vital cereal crop in Africa, ranking fifth globally and second in Africa after maize (Food and Agriculture Organisation of the United Nations- FAO, 2019; Rashwan *et al.,* 2021). It is a staple food for small-scale farmers in semi-arid tropical regions and is also grown as a forage crop (Mace *et al.,* 2013). Sorghum belongs to the grass family Poaceae and the tribe Andropogoneae, comprising about 25 species and five subgenera (Bhattacharya *et al.,* 2011; USDA, 2019). It is a C4 annual or short-lived perennial grass that typically has one generation per growing season. The root system of sorghum is fibrous, consisting of seminal roots that emerge at germination and nodal, crown or adventitious roots that emerge later from the shoot (Coudert *et al.,* 2010; Singh *et al.,* 2010). Nigeria is the largest sorghum producer in Africa, with an estimated 26 million tons of output in Sub-Saharan Africa (USDA, 2017).

Sorghum's nutritional content and ability to withstand challenging environmental circumstances make it an important crop for food security. It contains large amounts of minerals such as phosphorus (P), potassium (K), calcium (Ca), zinc (Zn), magnesium (Mg), iron (Fe), and sodium (Na), as well as vitamins A, B, D, E, K, and β-carotene, depending on the kind (34;35; Serna-Saldivar & Espinosa-Ramírez, 2019). Generally, 100 g of grain provides about 1,377 KJ of energy and contains roughly 72.1 g of carbohydrates, 12.4 g of water, 10.6 g of protein, 6.7 g of fibre, and 3.5 g of lipids (Food and Agriculture Organisation of the United Nations - FAO, 2019).

Sorghum is used as local food in various forms, including semi-leavened bread, couscous, and porridges (Hariprasanna & Rakshit, 2016). Its grains are also used in manufacturing syrup, sugar, and molasses (Cole *et al.*, 2017; Jiang *et al.*, 2020). Sorghum contributes significantly to food security, particularly in areas where maize does not grow well (Mathur et al., 2017). Due to the crop's industrial potential and heightened market awareness, there is now competition between grain for industrial use and human consumption (Ajeigbe *et al.*, 2017; Kansas Farm Food Connection-KFFC, 2018).

Sorghum is a carbon cycle C4 plant that is well-known for its high productivity and photosynthetic efficiency (Tari *et al.* 2013). One of the grains known for its strong resilience and wide range of adaptability to biotic and abiotic stresses is sorghum (Huang 2018; Zhang *et al.* 2019). Sorghum's increased popularity can be ascribed to its (1) multiple uses as animal feed, biofuel, human food, and fodder; (2) high profitability; (3) greater resistance to adverse environmental conditions than many other cereal crops; and (4) robust performance in environments with limited water and temperature, especially in marginal areas (Hao *et al.* 2021). Because of these qualities, sorghum has garnered a lot of attention as a potential "star" crop to help with the anticipated challenges related to global food security (Kadam *et al.* 2017; Hao *et al.* 2021; Ndlovu *et al.* 2021).

Sorghum production faces constraints like soil infertility, poor pest control, and weed management, which affect crop yields and food security. Agricultural production in West Africa faces significant constraints, including soil infertility, poor pest control, and weed management, leading to low crop yields. These constraints are particularly severe in sub-Saharan Africa, where soil infertility and pest control are major challenges. Sorghum production is affected by biotic factors like weeds, insect pests, and pathogens, as well as abiotic factors like marginal soils and unpredictable rainfall. Weed infestation, particularly from Striga, is a significant biotic pressure that lowers grain yield and biomass, preventing food security yields (Ball *et al.,* 2019). Weeds compete with crops for growth resources, harbour pests and diseases, and have other negative effects (Gage & Schwartz, 2019; Nwosisi *et al.,* 2019; Tibugari *et al.,* 2020; Abraham *et al.,* 2021).

In Nigeria, cultivar selection and soil fertility constraints must be addressed to boost sorghum demand and guarantee food security, as only around 20% of sorghum production areas are planted with improved cultivars (Ndjeunga *et al.,* 2015). Nigeria is the largest sorghum-producing country in West and Central Africa, accounting for about 23% of Africa's sorghum production. FAOSTAT (2023) indicates that while over 110 countries grow sorghum, only ten of these have cultivated it on more than one million hectares. Together, they account for over 68% of the world's sorghum production.

Sorghum is typically grown under rain-fed conditions, where water and soil fertility are major limiting factors. Drought is a significant constraint, but sorghum efficiently transforms available water into dry matter and can utilise water from deep soil depths (up to 270 cm). In 2014, sorghum was grown on 10.845 million hectares, which accounted for 50% of Nigeria's total area under cereal crop production and 13% of all arable land. The crop's water efficiency and adaptability make it an important crop in Nigeria's agricultural landscape, and with its significant production levels and adaptability, it plays a crucial role in the country's agricultural economy and food security. Due to limited external inputs, the average grain yield of sorghum in farmers' fields is estimated to be below 1,000 kg/ha, which results in low yields, soil Urea decline, food insecurity, and environmental degradation. Despite being nutrient-use efficient and able to flourish with lower fertiliser rates than maize and rice (Manzoor *et al.,* 2006), sorghum can increase yields with proper fertiliser applications.

Inorganic fertilisers can boost sorghum yields, improve growth performance, and enhance soil chemical properties (Alam *et al.,* 2009). In Nigeria's Savanna region, Nitrogen is the most limiting nutrient in soil, and a significant amount is lost through leaching due to low N requirements of plants at early growth stages. To maintain a positive nutrient balance, chemical fertilisers are needed to replace lost nutrients. Optimising fertiliser input is crucial for achieving high grain production and maximising economic returns (Khuang *et al.,* 2008). According to Ananthi *et al.* (2010), the optimal mineral fertiliser quantity is that which maximises economic return at the lowest feasible cost. Effective crop nutrition management is essential for efficient fertiliser application, enhancing grain yield and quality. Urea application timing and rate are critical determinants of yield-contributing traits, promoting plant height, leaf size, panicle and spikelet numbers, and filled spikelets per panicle (Shakouri *et al.,* 2012). By optimising Urea application, farmers can improve sorghum yields and quality.

Fertilisers are essential inputs that replenish soil nutrients and increase agricultural output, but they also present significant toxicity hazards to both persons and the environment (Hossain *et al.,*2022). Inappropriate application intervals, the inclusion of hazardous ingredients, and excessive synthetic use all increase these hazards (Nadarajan and Sukumaran, 2021). In order to tackle these issues, we must implement a number of technologies, including fertiliser optimisation and effective nutrient management, which increase agricultural yields and guarantee global food security (Zhang *et al.,* 2020). The most economical method of amending soil and increasing agricultural yields worldwide is still chemical Urea fertiliser (Zhang *et al.,* 2020). However, inappropriate Urea use and management can present serious risks to human health, environmental health, and crop yield (Nadarajan and Sukumaran, 2021; Hossain *et al.,* 2022). Many factors also contribute to the lack of sufficient Soil-Urea availability, such as ongoing cropping, plant uptake, inadequate land tenure structures, population growth that restricts the amount of arable land, erosion, nutrient imbalances in cultivated fields, and leaching into the environment (water bodies), with associated implications (Tyagi *et al.,* 2022).

Urea is a widely used nitrogen-based fertiliser due to its high nitrogen content (approximately 46%) and low cost, making it popular among farmers (Zhang *et al.,* 2020; Naz, 2023; Vaia, 2024). However, proper application is crucial to avoid environmental issues like soil acidification and nitrogen loss. Urea should be applied during active crop growth, avoiding heavy rainfall and frozen soil to minimise runoff and leaching (Bremner, 2019; Guo *et al.,* 2022). Incorporating Urea into the soil or using Urease inhibitors can reduce nitrogen loss (Guo *et al.,* 2022). Soil testing determines the optimal Urea amount based on soil nutrient levels and crop requirements, preventing over-fertilisation and soil acidity (Li *et al.,* 2020). Split applications of Urea throughout the growing season can enhance plant nitrogen uptake while mitigating environmental concerns (Sweeney *et al.,* 2023). Effective Urea management is vital for sustainable agriculture, balancing crop needs with environmental protection by employing proper application techniques and timing to maximise benefits and minimise drawbacks.

Nigeria is facing a severe economic crisis and food shortage, resulting in widespread poverty and hunger, with over 30.6 million Nigerians battling acute food insecurity (Unsal *et al.* 2020; FAO, IFAD, UNICEF, WFP, and WHO., 2021). Sorghum has become a vital crop in addressing this crisis due to its affordability and nutritional value, particularly for low-income households. To maximise sorghum production and help alleviate the food crisis, farmers need to apply fertilisers wisely. This study aimed to determine the optimal Urea application rate for sorghum growth by evaluating the response of different sorghum varieties to varying Urea fertiliser rates while maintaining consistent potassium and phosphorus dosages, with the ultimate goal of informing fertiliser application decisions and boosting sorghum production in Nigeria.

MATERIALS AND METHODS

Two field trials were carried out during the 2022 and 2023 cropping seasons at the Teaching and Research Farm of the Faculty of Agriculture, University of Abuja, Nigeria, Federal Capital Territory (FCT). Gwagwalada is located at 8°59'41.43192" North and 7°10'39.61848" East. The average temperature was 30°C, 14% humidity during the rainy (planting) season and an annual rainfall between 1,100 mm and 1,600 mm (Idoko and Bisong, 2010).

Land Preparation and Soil Sample Collection

Soil samples were randomly collected from 10 locations on the field within each of the experimental sites at 0-30 cm depth using a hand-held soil auger, and a composite soil sample was taken after bulking. The composite sample was air-dried, sieved through a 2mm sieve and subjected to laboratory analysis according to the Walkley-Black (1934) procedure. The field evaluation experimental site was cleared, packed and stumped using machetes, rakes and dibbers. Subsequently, the site was ploughed, harrowed and pulverised into a fine tilth. Beds of 3m x 3m were marked out using pegs 60 cm long.

Experimental Material, Treatment and Design

The candidate experimental materials used were four varieties of (Samsorg-48, Samsorg-49, Samsorg-46 and Samsorg-53) and the experimental treatment of which effects were evaluated are five levels of Urea (46% N) namely 50kg/ha (N1), 100kg/ha (N2), 150kg (N3), 200kg/ha (N4) and 0 kg/ha-control (N5). Phosphorus and Potassium were applied at 45kg per hectare as a blanket application using NPK15:15:15.

A factorial treatment arrangement fitted into a Randomised Complete Block Design (RCBD) with 3 replicates was used. Each replicate contained 20 plots; thus, a total of 60 plots were used in the experiment. Each Plot measured 3 m x 3 m and was separated from the other within the replicate by a 0.5m pathway. Each replicate was separated from the other by a one-meter (1m) alley for easy assessment of to experiment in the field.

Following the National Agricultural Seed Council's (NASC) recommendations, 5–6 seeds were planted in each hole at a depth of 2-4 cm and a spacing of 75 cm x 1.0 m after being submerged in pre-planting Fermasan-D pesticides. Two weeks after planting, all the vacant stands were filled. After germination, 4-5 weeks post-planting, the plants were thinned to 4 plants per stand to achieve a plant population of 53,333.3 stands/ha, and de-tillering was done as needed. Weeding was done by hand using a hoe at 4 and 8 weeks after sowing (WAS). Two split applications of the fertiliser were done 3 WAS, using the broadcast method of application. NPK (15:15:15) at 45 kg/ha was applied as the first dose, and the second dose consisted of 5 kg/ha, 55 kg/ha, 105 kg/ha, and 155 kg/ha of Urea.

Data Collection and Analysis

Data were collected on plant height, number of leaves, leaf area (cm^2), number of tillers/stand and grain yield (t/ha). The data collected were subjected to analysis of variance (ANOVA) using the 'agricolae' package in the R Statistical Programme (Version 4.5.0). Where the treatment means were significantly different ($p \leq 0.05$), the Least Significant Difference (LSD) test was used to separate them. Where significant interactions exist, the Least Squares Mean (LSMEANS) was calculated, and their level of significance was determined using their standard errors (SE) and P values ($p \leq 0.05$).

RESULTS AND DISCUSSION

Tables 1 and 2 illustrate the influence of varying Urea levels on the plant height of specific sorghum varieties during the 2022 and 2023 cropping seasons. In the 2022 trial, the application of higher urea levels resulted in the best plant height. At 8 weeks after sowing (WAS), plants treated with 200 kg Urea/ha reached the highest height (102.8 cm), a result statistically similar to those receiving 100 kg Urea/ha and 150 kg N/ha. In contrast, the smallest plants (85.9 cm) were observed in plots that received 50 kg Urea/ha, though this difference was not significant ($P>0.05$) compared to control plots (0 kg Urea/ha). At 12 WAS, the pattern persisted, with 200 kg Urea/ha maintaining the tallest plants (118.8 cm). This height was statistically comparable to those obtained with 100 kg Urea/ha (111.1 cm) and 150 kg Urea/ha (107.3 cm). The shortest plant heights at 12 WAS were observed in plots with 50 kg Urea/ha (97.1 cm) and control plots (101.5 cm).

In 2023, a similar general trend in plant height was observed concerning Urea application. Compared to 2022, plant heights exhibited minimal variation irrespective of fertiliser application at 12 WAS in both trials, signifying no significant difference. Throughout both seasons, the plant heights varied significantly among the sorghum varieties, with Samsorg 46 consistently being taller than Samsorg 49, while Samsorg 48 and Samsorg 53 exhibited similar heights. The relationship between fertiliser and variety (FxV) was significant ($P\leq0.05$) at 8 WAS in the experiments carried out in both 2022 and 2023.

Table 2 provides additional information on the specific interactions between Urea concentrations and types of Sorghum varieties. The highest recorded plant height was 122.2 cm from the combination of Samsorg 49 and a 200 kg Urea/ha application, while the minimum height (74.8 cm) was noted with Samsorg 48 and 50 kg Urea/ha. Additionally, in the same table, another set of findings indicates that Samsorg 49 with 100 kg Urea/ha reached a maximum height of 52.0 cm, whereas Samsorg 48 with 50 kg Urea/ha produced the minimum height of 32.0 cm.

Table 1: Plant Height of Selected Varieties of Sorghum as Influenced by Urea Levels in 2022 and 2023 Cropping Seasons

Treatments		8 WAS	12 WAS
Year	Fertiliser levels		
2022	0kg	11.3bc	101.5
	50kg	85.9c	97.6
	100kg	98.9ab	111.1
	150kg	95.3ab	109.2
	200kg	102.8a	118.8
	LSD (0.05%)	10.37	NS
	Varieties		
	Samsorg 49	105.1a	124.3a
	Samsorg 46	92.4b	104.8b
	Samsorg 48	89.9b	99.0b
	Samsorg 53	94.3b	104.2b
	LSD (0.05%)	10.39	14.31
Year	Fertiliser levels		
2023	0kg	91.9	102.5
	50kg	87.8	98.5
	100kg	98.5	110.1
	150kg	98.2	108.6

Treatments		**8 WAS**	**12 WAS**
	200kg	96.3	106.7
	LSD (0.05%)	NS	NS
	Varieties		
	Samsorg 49	106.7a	116.8a
	Samsorg 46	101.0b	103.1b
	Samsorg 48	85.9b	96.7
	Samsorg 53	93.6b	104.5b
	LSD (0.05%)	9.51	4.51
	Interaction		
	FxV	*	NS

Means with the same letter(s) are not statistically different at a 5% level of probability
* = Significant at a 5% level of probability. NS = Not significant at a 5% level of probability. WAS = Weeks after sowing

Table 2: The Impact of Urea-Crop Variety Interactions on the Plant Height of Several Sorghum Types at 8 WAP in both Cropping Seasons

		Fertiliser Levels (F)				
Year	Varieties	0kg/ha	50kg/ha	100kg/ha	150kg/ha	200kg/ha
2022	Samsorg 49	97.5[bcde]	97.5[bcde]	101.7[bc]	106.8[ab]	122.2[a]
	Samsorg 46	90.1[bcd]	83.2[def]	101.5[bc]	83.6[def]	93.7[bcde]
	Samsorg 48	90.7[bcdef]	74.8[f]	86.0[cdef]	104.8[bc]	93.2[bcde]
	Samsorg 53	81.1[def]	87.9[cdef]	106.2[ab]	94.0[bcde]	102.3[bc]
		LSD = 17.30				
2023	Samsorg 49	40.6[cdef]	45.6[abc]	52.0[a]	49.5[ab]	44.3[abcd]
	Samsorg 46	39.3[cdef]	43.3[bcde]	41.0[cdef]	35.4[ef]	43.9[abcd]
	Samsorg 48	38.6[cdef]	32.0[f]	41.7[bcde]	43.9[abcd]	36.8[def]
	Samsorg 53	42.8[bcde]	38.9[cdef]	46.4[abc]	41.7[bcde]	44.1[abcd]
		LSD = 8.33				

Means with the same letter(s) are not statistically different at a 5% level of probability

* = Significant at a 5% level of probability. NS = Not significant at a 5% level of probability.
Table 3 illustrates the effect of varying Urea rates on the sorghum tiller count during the 2022 and 2023 growing seasons. In 2022, there was no significant response in tiller production to Urea application at 8 and 12 weeks after sowing (P>0.05). Samsorg 48 yielded 27.4 tillers at 8 WAS, a statistically significant figure (P<0.05), in contrast to Samsorg 49, Samsorg 46, and Samsorg 53, which showed statistical similarity at 12 WAS. Conversely, the 2023 field experiment indicated that elevated Urea levels boosted tiller production. The highest tiller count per plant (35.8 at 12 WAS) occurred at 150 kg Urea per hectare, yet this was not significantly distinct from 200 kg (31.8 tillers/plant) or 100 kg (31.5 tillers/plant). At 12 WAS, the control plots showed the least number of tillers per plant at 28.1. In the 2022 trial, there were no significant varietal differences in tiller output (P>0.05), and no apparent Urea-by-variety (FxV) interaction was observed at 8 WAP.

Table 3: Number of Tillers of Selected Varieties of Sorghum as Influenced by Urea Levels in the 2022 and 2023 Cropping Seasons

		Number of leaves	
Treatments		**8 WAS**	**12 WAS**
Year	Fertiliser level		
2022	0kg	21.2	33.3
	50kg	25.4	29.3
	100kg	23.8	28.3
	150kg	25.5	30.5
	200kg	24.2	32.4
	LSD (0.05%)	NS	NS
	Varieties		
	Samsorg 49	21.6d	37.7
	Samsorg 46	22.5c	32.5
	Samsorg 48	27.4a	31.0
	Samsorg 53	24.4b	31.9
	LSD (0.05%)	3.69	NS
Year	Fertiliser level		
2023	0kg	18.5b	28.1b
	50kg	19.6b	26.9b
	100kg	24.8ab	31.5ab

Treatments		Number of leaves 8 WAS	12 WAS
	150kg	28.2a	35.8a
	200kg	24.2b	31.8ab
	LSD (0.05%)	6.79	6.35
	Significance	NS	NS
	Varieties		
	Samsorg 49	22.0	28.7
	Samsorg 46	21.8	29.3
	Samsorg 48	24.4	32.9
	Samsorg 53	24.1	30.9
	LSD (0.05%)	NS	NS
	Interaction		
	FxV	NS	NS

Means with the same letter(s) are not statistically different at a 5% level of probability

* = Significant at a 5% level of probability. NS = Not significant at a 5% level of probability. WAS = Weeks after sowing.

Table 4 outlines the effects of the Urea-sorghum variety (FxV) interaction on leaf area at 12 weeks after sowing (WAS) across the 2022 and 2023 growing seasons. The highest leaf area (77.2 cm²) was recorded with the combination of Samsorg 48 and 200 kg of Urea/ha of fertiliser, while the lowest (37.9 cm²) was noted with the combination of Samsorg 48 and 50 kg of Urea/ha of fertiliser. Table 4 shows that different Urea levels had a significant effect on this aspect throughout the 2022 cropping season ($P<0.05$). Plots receiving 200 kg of Urea/ha exhibited the highest number of leaves per plant (150.9), although this was not significantly different from those treated with 150 kg of Urea /ha of Urea (150.3 leaves/plant). In contrast, during the 2023 growing season, sorghum stands showed a robust and statistically significant reaction ($P<0.05$) to varying Urea fertiliser levels. Although 200 kg/ha of Urea produced the largest quantity of leaves per plant at both 8 and 12 WAS, this outcome was not considerably different from the Urea levels of 150 kg/ha and 100 kg/ha.

Moreover, the quantity of leaves per plant at 8 and 12 WAS showed no significant variation between control plots and those receiving 50 kg/ha of Urea. Varietal changes themselves exhibited no significant impact on leaf count at 8 and 12 WAS during both growing seasons.

Table 4: Number of Leaves of Specific Sorghum Varieties as Impacted by Urea Levels and Variety Interactions in the 2022 and 2023 Cropping Seasons

Treatments		8 WAS	12 WAS
Year	Fertiliser levels		
2022	0kg	128.8	133.2
	50kg	116.4	144.2
	100kg	120.8	148.2
	150kg	125.2	150.3
	200kg	121.8	150.9
	LSD (0.05%)	12.58	
	Significance	NS	NS
	Varieties		
	Samsorg 49	125.9	135.5
	Samsorg 46	105.5	130.5
	Samsorg 48	149.1	149.1
	Samsorg 53	134.0	135.0
	LSD (0.05%)	NS	NS
	Interaction		
	FxV	NS	*
Year			
2023	Fertiliser levels		
	0kg	91.3b	109.8b
	50kg	94.6b	104.8b
	100kg	141.0a	142.0a
	150kg	136.5a	144.7a
	200kg	148.3a	150.8a
	LSD (0.05%)	26.27	28.16
	Varieties		
	Samsorg 49	124.1	134.2
	Samsorg 46	121.1	131.4
	Samsorg 48	122.9	132.4

Treatments		8 WAS	12 WAS
	Samsorg 53	127.5	137.8
	LSD (0.05%)	NS	NS
	Interaction		
	FxV	*	*

Means with the same letter(s) are not statistically different at a 5% level of probability

* = Significant at a 5% level of probability. NS = Not significant at a 5% level of probability. WAS = Weeks after sowing.

Table 5 shows that, apart from 0 kg/ha and Samsorg 48 and 100 kg of Urea/ha, there was no significant variation in the leaf count at 12 WAS due to the interaction between FxV during both years for Samsorg 46 in the initial and subsequent cropping seasons, respectively.

Table.5: The Combined Impact of Sorghum Cultivars and Urea Levels on the Number of Leaves at 12 WAS in the 2022 and 2023 Planting Seasons

		Fertiliser Levels (F)				
Years	**Varieties**	**0kg/ha**	**50kg/ha**	**100kg/ha**	**150kg/ha**	**200kg/ha**
2022	Samsorg 49	99.3^{ef}	89.7^{f}	147.3^{abcde}	164.3^{abc}	176.7^{ab}
	Samsorg 46	141.0^{abcde}	123.0^{cdef}	132.3^{bcdef}	128.0^{bcdef}	128.0^{bcdef}
	Samsorg 48	185.0^{a}	112.3^{cdef}	147.3^{abcde}	153.0^{abcd}	142.0^{abcde}
	Samsorg 53	107.3^{def}	132.0^{bcdef}	165.7^{abc}	130.0^{bcdef}	140.0^{abcde}
	LSD = 49.08					
2023	Samsorg 49	91.3^{g}	103.3^{fg}	148.0^{abcde}	166.7^{abc}	161.7^{abcd}
	Samsorg 46	116.3^{efg}	105.7^{fg}	132.0^{cdefg}	115.7^{efg}	187.3^{a}
	Samsorg 48	129.3^{cdefg}	107.7^{fg}	138.0^{bcdef}	131.0^{cdefg}	161.7^{abcd}
	Samsorg 53	102.3^{g}	102.7^{g}	186.0^{a}	173.3^{ab}	124.7^{defg}
				LSD = 40.85		

Means with the same letter(s) are not statistically different at a 5% level of probability

* = Significant at a 5% level of probability. NS = Not significant at a 5% level of probability

Tables 6 and 7 show the data on sorghum leaf area for the 2022 and 2023 growing seasons, emphasising the effects of various Urea levels, variety, and their interactions (FxV). Throughout the seasons, Urea concentrations had varying effects on leaf area. Changes in Urea levels in 2022 showed no significant impact on leaf area at 12 WAS ($P<0.05$). In 2023, sorghum leaf area at both 8 and 12 WAS improved due to a significant increase in Urea ($P<0.05$). In 2023, 100 kg/ha of Urea produced the largest leaf area; there was no discernible difference between 150 and 200 kg/ha. During the 2022 and 2023 growing seasons, there were no appreciable variations in the leaf area of the four sorghum varieties. Plant leaf area was affected by interaction effects (FxV) that varied with the seasons; in 2022, they were not significant ($P<0.05$) at 8 WAS, but in 2023, they were significant ($P<0.05$) at 8 and 12 WAS.

Table 6: Leaf Area of Specific Sorghum Varieties as Impacted by Urea Levels, Fertiliser, and Variety Interactions in the 2022 and 2023 Cropping Seasons

Treatments		8 WAS	12 WAS
Year	Fertiliser levels		
2022	0kg	6.1b	59.6
	50kg	36.4b	58.5
	100kg	47.3a	61.7
	150kg	47.9a	61.7
	200kg	50.6	59.9
		LSD =9.21	
	Significance	NS	NS
	Varieties		
	Samsorg 49	47.0	61.8
	Samsorg 46	47.5	61.6
	Samsorg 48	41.6	60.8
	Samsorg 53	43.2	57.8
	LSD (0.05%)	NS	NS
	Interaction		
	FxV	NS	*
Year			
2023	Fertiliser levels		
	0kg	40.9b	53.8b
	50kg	37.4b	49.2b

Treatments		8 WAS	12 WAS
	100kg	51.4a	67.9a
	150kg	44.6ab	59.5ab
	200kg	46.6ab	61.4ab
	Significance	NS	NS
	LSD (0.05%)	9.35	12.53
	Varieties		
	Samsorg 49	46.9	61.9%
	Samsorg 46	48.7	64.2
	Samsorg 48	38.6	51.3
	Samsorg 53	42.5	56.0
	LSD (0.05%)	NS	NS
	Interaction		
	FxV	*	*

Means with the same letter(s) are not statistically different at a 5% level of probability. * = Significant at a 5% level of probability. NS = Not significant at a 5% level of probability. WAS = Weeks after sowing

Table 7: The Effects of Urea and Sorghum Variety Interactions on Leaf Area at 12 WAS Across the 2022 and 2023 Growing Seasons

		Fertiliser levels (F)				
Year	**Varieties**	**0kg/ha**	**50kg/ha**	**100kg/ha**	**150kg/ha**	**200kg/ha**
2022						
	Samsorg 49	58.2^{abcd}	44.17^{d}	72.0^{ab}	71.6^{ab}	62.8^{abcd}
	Samsorg 46	68.1^{ab}	61.8^{abcd}	50.5^{bcd}	53.0^{abcd}	75.0^{a}
	Samsorg 48	57.4^{abcd}	60.9^{abcd}	63.8^{abcd}	65.5^{abcd}	60.6^{abcd}
	Samsorg 53	54.7^{abcd}	67.4^{abc}	60.5^{abcd}	56.5^{abcd}	45.1^{acd}
		LSD = 22.37				
2023	Samsorg 49	53.0^{cde}	44.1^{de}	72.9^{abc}	76.9^{abcd}	62.6^{abcd}
	Samsorg 46	50.9^{de}	64.9^{abcd}	76.2^{ab}	52.0^{de}	77.2^{a}
	Samsorg 48	55.3^{bcde}	37.9^{e}	57.9^{abcde}	57.8^{abcde}	47.8^{de}
	Samsorg 53	56.0^{bcde}	49.7^{de}	64.7^{abcd}	51.4^{de}	58.2^{abcde}
		LSD= 20.92				

Means with the same letter(s) are not statistically different at a 5% level of probability

* = Significant at a 5% level of probability. NS = Not significant at a 5% level of probability.

Table 8 demonstrates the impact of crop season and variety on sorghum grain yield. Regardless of these trends, the 100 kg and 150 kg Urea levels for both cropping seasons showed no significant differences. Furthermore, while variations among individual varieties had no considerable impact on productivity in either year, a notable interaction ($P<0.05$) occurred between fertiliser application and variety (FxV).

Table 8: Grain yield (t/ha) of Sorghum as Impacted by Various Fertiliser Levels, Varieties, and FxV Interactions in the 2022 and 2023 Cropping Seasons

	2022	2023
Fertiliser levels		
0kg	1.9	1.9
50kg	2.1	2.7
100kg	3.0	5.2
150kg	3.1	5.0
200kg	3.6	5.3
LSD (0.05%)	0.03	0.07
Varieties		
Samsorg 49	3.1	4.5
Samsorg 46	3.3	4.2
Samsorg 48	3.1	5.1
FSamsorg 53	3.2	4.7
LSD (0.05%)		
Significance	NS	NS
FxV	*	*

Means with the same letter(s) are not statistically different at a 5% level of probability

* = Significant at a 5% level of probability. NS = Not significant at a 5% level of probability.
Table 9 demonstrates that during the 2022 cropping season, the combination of Samsorg 48 and 100 kg/ha of fertiliser produced the maximum grain weight (2.7 kg), while Samsorg 49 and no fertiliser produced the lowest grain weight (1.1 kg).

Table 9: Interaction of FxV on Grain Weight in 2022 and 2023cropping seasons

	Fertiliser levels (F)				
Variety (V)	**0kg/ha**	**50kg/ha**	**100kg/ha**	**150kg/ha**	**200kg/ha**
Samsorg 49	1.1^{d}	1.4^{bcd}	2.0^{abcd}	2.4^{ab}	1.9^{abcd}
Samsorg 46	1.4^{bcd}	1.6^{bcd}	1.9^{abcd}	1.3^{cd}	2.2^{abc}
Samsorg 48	2.0^{abcd}	1.4^{cd}	2.7^{a}	2.0^{abcd}	2.0^{abcd}
Samsorg 53	1.7^{bcd}	1.6^{bcd}	1.8^{abcd}	2.16^{abc}	2.4^{ab}
			LSD = 0.95		

Means with the same letter(s) are not statistically different at a 5% level of probability

* = Significant at a 5% level of probability. NS = Not significant at a 5% level of probability.
Table 10 shows the physical and chemical properties of the soil at the experimental location before planting and following harvesting. The test site had Sandy Loam (SL) soil with a pH of 4.3 in water and a pH of 4.5 in KCl, indicating its acidic properties. After the harvest, pH significantly rose to 6.3 in water and 6.0 in KCl. The Total N was 0.013 before planting and 0.095 after harvest, whereas the available Phosphorus concentrations were 4.52 mg/kg before planting and 7.07 mg/kg after harvest. Effective Cation Exchangeable Capacity showed increases in Na (0.14 to 0.36 Cmol-1/100g), K (0.54 to 1.55 Cmol-1/100g), Mg (1.22 to 1.82 Cmol-1/100g), Ca (2.45 to 3.65 Cmol-1/100g), and Total Exchangeable Bases (TEB) from 5.82 to 7.47 Cmol-1/100g, respectively, suggesting that the basic cations existed at relatively low concentrations before the two-year research period.

The soil analysis performed before planting revealed low organic matter levels (1.01) and organic carbon content (0.34), along with an electrical conductivity (EC) of 0.21 mS/cm and inadequate base saturation. These results indicated low fertility, aligning with Anyaegbu's (2013) claim that acidic soil (pH 4.5) restricts the yield of crops. Nedunchezhiyan and Ray (2010) suggested a pH range of 5.5 to 6.5 for optimal yields of sweet potatoes and sorghum, highlighting that elevated pH levels may lead to toxicity, pest issues, and disease occurrences. Elevated Urea concentrations after harvest indicated that fertiliser usage enhanced soil fertility. The use of fertilisers enhanced soil fertility, demonstrated by higher nutrient levels following the harvest. The region was found to have a history of consistently being cultivated with sorghum and maize.

Table 10: Results of Laboratory Soil Analysis for the Pre-planting and Post-harvest Soil Tests

Sam Code	**pH in H_20**	**pH in KCL**	**% OC**	**% OM**	**% TN**	**EC mS/cm**	**P mg/kg**	**Effective Cation Exchangeable Capacity (Cmol/Kg)**							**Particle size analysis**			
								Na	K	Mg	Ca	TEB	Ex Acidity	ECEC	SILT gkg^{-1}	CLAY gkg^{-1}	SAND gkg^{-1}	TC
Pre-Planting	4.3	4.5	0.34	1.01	0.013	0.21	4.52	0.14	0.54	1.22	2.45	5.82	0.78	6.55	102.12	188.30	693.40	SL
Post-Harvest	6.3	6.0	1.45	2.52	0.095	0.32	7.07	0.36	1.55	1.82	3.65	7.47	1.10	8.55	118.30	190.30	691.40	SL

OC=Organic Carbon. OM= Organic Matter. TN Total Nitrogen. TEB Total Exchangeable Bases. EC=Electrical conductivity. ECEC=Effective Cation Exchange Capacity

Discussion

After eight weeks of sowing (WAS), plants treated with 200 kg of Urea exhibited the highest height in both trials; however, this did not differ substantially from plants treated with 100 kg and 150 kg of Urea. Control plots, on the other hand, had comparatively short stands, which demonstrated how important Urea is for the growth of vegetative plants. According to Gewaily *et al*. (2021), Urea fertiliser encourages plant growth, especially by lengthening and increasing internodes, which results in taller plants. This observation is consistent with their findings. Thus, a deficiency of Urea is the cause of the slower development observed in the control plots. Similar results of Urea deficiency-induced reduced plant growth have also been reported for sorghum (Jaham, 2014).

The application of 50 kg of Urea did not significantly impact sorghum plant height compared to control plots eight weeks after sowing. However, significant differences in plant height were observed among the four sorghum cultivars, with Samsorg 49 consistently showing higher height regardless of Urea application, possibly due to increased competitiveness against weeds, improved nutrient uptake, or greater nutrient conversion efficiency (Burlacot, 2023; Huang *et al,* 2023). Urea application generally increased plant height, likely due to its stimulating effect on cell division and elongation (Alim, 2012). The provision of adequate nitrogen by Urea fertiliser also supported panicle formation and grain filling, contributing to increased plant growth parameters. Notably, a significant genotype x Urea interaction was observed, indicating that different cultivars responded differently to varying Urea concentrations.

Tiller production generally increased with rising Urea levels. The highest number of tillers per plant was observed at 150 kg/ha of Urea; however, this was not significantly different from the treatments at 100 and 200 kg/ha. This indicates that an application rate of Urea up to 100 kg/ha is sufficient or optimal for robust tiller production. Consequently, fewer tillers resulted from a reduction in the Urea supply, which is supported by other studies (Deiss *et al.* 2014) and is demonstrated by the control plots' lowest tiller counts. Significantly, tiller production did not vary substantially among the four sorghum varieties investigated. The non-significant Genotype x Urea interaction at both 8 and 12 WAS in the 2023 trial suggests that varietal differences did not affect the sorghum plant's response to applied Urea regarding tillering.

At 8 weeks after sowing (WAS) in both seasons, different Urea application levels had no discernible effect on the number of leaves per sorghum plant. According to Meena and Mann (2007) and Ihenetu *et al. (*2021), this is most probable because the plant's genetic composition determines how many leaves it produces. This result may also be influenced by the cultivars' growth cycle, which is dictated by their genetic configuration. According to Fang *et al.*, (2023), Urea administration may not affect the number of leaves, but it can cause nutrient remobilisation from leaves to grains, which could result in a decrease in nutritional content in leaves as the plant matures. According to Yao *et al.* (2016) and Yu *et al.* (2022), crop yield depends on the distribution of photosynthetic products from leaves during the reproductive growth stage as well as the accumulation and dissemination of biomass to reproductive structures. Therefore, it is critical to apply a higher rate of Urea to enhance the accumulation of photosynthetic products during this phase in order to achieve high yields.

Urea application had a substantial impact on the production of sorghum leaves in the second trial. While leaf output in the control plots was similar to that at 50 kg of Urea, the maximum number of leaves per plant was recorded at 200 kg of Urea. In general, it was shown that applying Urea enhanced the area and productivity of sorghum leaves. Increased photosynthetic activity in the crops is made possible by this improvement in the leaf area of individual plants, which raises the overall Leaf Area Index (LAI) per unit land area (Herve, 2017). The four sorghum cultivars employed in this study did not significantly differ in leaf area production, which is consistent with other evaluated parameters.

The application of Urea consistently boosted sorghum grain yield. Fertilisers based on Urea are typically considered to be more effective in enhancing crop yields compared to those that include potassium or phosphate. Urea treatment has a significant effect on growth and yield parameters, such as dry matter, harvest index, oil content, seed output per plant, and various other yield factors (Ibrahim *et al*., 2022). In both trials carried out, the highest grain yields (3.6 t/ha) were obtained with 200 kg of Urea. The increase in the grain yield at higher nitrogen levels might be attributed to the lower competition for nutrients, allowing the plants to accumulate more biomass with a higher capacity to convert more photosynthetic products into sinks, resulting in more grains (Hawkesford & Griffiths, 2019; Adhikari *et al.*, 2021).

On the other hand, Aminul *et al.* (2015) concluded that the optimal dosage was 150–200 kg N/ha in combination with 118 kg P_2O_5/ha, and advised that Urea application should not exceed 150–200 kg per hectare. Control plots consistently produced the lowest grain yields, most likely as a result of the uneven fertility of the trial site. Although differences in sorghum variety did not significantly affect grain output, a strong interaction between fertiliser and varieties showed that no single variety performed better than others and that different sorghum varieties responded differently to Urea administration.

CONCLUSION

The application of Urea was found to be very effective in increasing sorghum growth and yield; the ideal rate of 200 kg/ha produced a maximum grain yield of 3.6 t/ha. High Urea levels (150–200 kg/ha) were particularly effective in promoting vegetative development, leading to taller plants and more tillers, which emphasises the need for tailored fertiliser strategies. Samsorg 46 and Samsorg 48 consistently produced the best results among the tested varieties, although other varieties responded differently to Urea.

Farmers in Nigeria's Southern Guinea Savannah Zone are advised to use the Samsorg 49 sorghum variety and apply 150–200 kg/ha of Urea fertiliser to achieve optimal growth and productivity. To further strengthen these recommendations and ensure their widespread adoption, the government should support farmer training and best practices guidelines, as well as conduct additional research to determine the exact amounts of Urea for specific cultivars and soil types.

REFERENCES

Abraham, P., Banwo, O. O., Kashina, B. D., & Alegbejo, M. D. (2021). Detection of Weed Species Infected by Tomato ringspot virus in Field-grown Tomato in Sudan Savanna, Nigeria. *Nigerian Journal of Plant Protection,* 35 (2): 1-15.

Adhikari, K., Bhandari, S., Aryal, K., Mahato, M., and Shrestha, J. (2021). Effect of different levels of nitrogen on growth and yield of hybrid maize (*Zea mays* L.) varieties. Journal of Agriculture and Natural Resources, 4(2), Pp. 48–62. https://doi.org/10.3126/janr.v4i2.33656

Ajeigbe, H.A., Akinseye, F.M., Angarawai, I.I., Umma, S.A., Inuma, A.H., Adinoyi, A. and Abdulazeez, T. (2017). Enhancing Farmers' Access to Technology and Market for Increased Sorghum Productivity in the Selected Staple Crop Processing Zones. Proceedings of the 51st Annual Conference of the Agricultural Society of Nigeria, Abuja, Nigeria. 1068-1072.

Alam, M.M., Hassanuzzaman, M. and Nahar, K. (2009). Tiller Dynamics of Three Irrigated Rice Varieties under Varying Phosphorus Levels. *American-Eurasian Journal of Agronomy*, 2, 89-94.

Alim, M. (2012). Effect of organic and inorganic sources and doses of nitrogen fertilizer on the yield of boro rice. *Journal of Environmental Science and Natural Resources,* 5, 273–282.

Aminul Islam, Jafis Chandra Biswas, Asm Sirajul Karim, Salma Peruin. (2015). Effect of Potassium fertilisation on growth and yield of wetland rice in Grey Terrace Soils of Bangladesh. Research Gate.

Ananthi, T., Amanullah, M.M. and Subramanian, K.S. (2010) Influence of Mycorrhizal and Synthetic Fertilisers on Soil Nutrient Status and Uptake in Hybrid Maize. *Madras Agricultural Journal,* 97, 374-378.

Anyaegbu P.O. (2013). Effect of combined application of Moringa oleifera and suffocants on the marketable yield of sweet potato. *Journal of Technology and Applied Science*, vol 3; 22-24.

Ball, M. G., Caldwell, B. A., DiTommaso, A., Drinkwater, L. E., Mohler, C. L., Smith, R. G., & Ryan, M. R. (2019). Weed community structure and soybean yields in a long-term organic cropping systems experiment. Weed Science, 67 (6): 673-681.

Bean S, Wilson J, Moreau R, Galant A, Awika J, Kaufman RC, Adrianos S, Ioerger B. (2016). Structure and composition of the grain. In Sorghum: State of the Art and Future Perspectives; Ciampitti, I., Prasad, V., Eds.; ASA and CSSA: Madison, WI, USA.

Bhattacharya A, Rice N, Shapter FM, Norton SL, Henry RJ. Sorghum. (2011). In Wild crop relatives: Genomic and breeding resources. Springer, Berlin, Heidelberg. 2011; 397-406.

Bremner, J. M. (2019). "Nitrogen transformations in soil." Soil Science, 101(4), 217-230.

Burlacot, A. quantifying the roles of algal photosynthetic electron pathways: (2023). A milestone towards photosynthetic robustness. New Phytol. 2023; 240:2197–2203. Doi: https://doi.org/10.1111/nph19328

Cole, M. R., Eggleston, G., Petrie, E., Uchimiya, S. M., & Dalley, C. (2017). Cultivar and maturity effects on the quality attributes and ethanol potential of sweet sorghum. Biomass and Bioenergy, 96, 183–192. https://doi.org/10.1016/j.biombioe.2016.12.001.

Coudert Y, Perin C, Courtois B, Khong NG, Gantet P. (2010). Genetic control of root development in rice, the model cereal. Trends in Plant Science. 2010; 15:219-226.

Deiss L, Moraes A, Pelissari A, Neto FS, Oliveira EB, Silva VP. (2014). Oat tillering and tiller traits under different Urea levels in a eucalyptus agroforestry system in subtropical Brazil. Ciencia Rural44:71–78.doi: https://doi.org/10.25081/jsa.2018.v2.901

Fang L., Martre P., Jin K., Du X., van der Putten P.E., Yin X., Struik P.C. (2023). Neglecting acclimation of photosynthesis under drought can cause significant errors in predicting leaf photosynthesis in wheat. Glob. Chang. Biol. 2023; 29:505 521. doi: https://doi.org/10.1111/gcb 16488.

FAO, IFAD, UNICEF, WFP, and WHO. (2021). the State of Food Security and Nutrition in the World 2021. Transforming food systems for food security, improved nutrition and affordable healthy diets for all. Rome, FAO. https://doi.org/10.4060/cb4474en.

FAO. Food and Agriculture Organisation of the United Nations (2018). Available: FAOSTAT statistics database.11/02/2019 http://www.fao.org/faostat/en/#data/QCProductionofselectedcerealcropsaccessedon4/3/2019.

FAOSTAT (2023). https://www.fao.org/faostat/en/#home

Gage, K. L., & Schwartz-Lazaro, L. M. (2019). Shifting the paradigm: An ecological systems approach to weed management. Agriculture, 9, 179.

Gewaily, E.E. Adel M. G., Marvet M.A. (2021). Effect of Urea levels on growth, yield and Urea use efficiency of some newly released edition rice genotypes.

Guo, X., Ren, H., Ren, B., Zhang, J., Liu, P., Shah, S., Zhao, B. (2022). Long-term application of controlled-release Urea reduced ammonia volatilisation, raising the risk of N2O emissions and improved summer maize yield. Field Crops Research. Volume 306, 109227, ISSN 0378-4290, https://doi.org/10.1016/j.fcr.2023.109227.

Hao H, Li Z, Leng C, Lu C, Luo H, Liu Y et al (2021). Sorghum breeding in the genomic era: opportunities and challenges. Theor Appl Genet 134:1899–1924. https://doi.org/10.1007/s00122-021-03789-z

Hariprasanna, K., & Rakshit, S. (2016). Economic importance of sorghum. In S. Rakshit & Y. H. Wang (Eds.), The sorghumgenome(pp.1–25).Springer.

Hawkesford, M.J., Griffiths, S. (2019). Exploiting genetic variation in nitrogen use efficiency for cereal crop improvement. Curr Opin Plant Biol. Jun; 49:35-42. doi: https://doi.org/10.1016/j.pbi.2019.05.003.

Herve, Djomo Sime (2017). Effects of different doses of NPK fertiliser on the growth and yield of rice in Nolop, North West of Cameroon. *African Journal of Agricultural.* Htsfarms. Ng-agricultural online store, an Agricultural Company in Nigeria.

Hossain, M.E., Shahrukh, S., Hossain, S.A. (2022). Chemical fertilisers and pesticides: impacts on soil degradation, groundwater, and human health in Bangladesh. Environmental Degradation: Challenges and Strategies for Mitigation. Springer International Publishing, Cham, pp. 63–92. https://doi.org/10.1007/978-3-030-95542-7_4.

Huang R (2018). Research progress on plant tolerance to soil salinity and alkalinity in sorghum. J Integr Agric 17:739–746. https://doi.org/10.1016/S2095-3119(17)61728-3

Huang T., Liu H., Tao J.-P., Zhang J.-Q., Zhao T.-M., Hou X.-L., Xiong A.-S., You X. (2023). Low light intensity elongates period and defers peak time of photosynthesis: A computational approach to circadian-clock-controlled photosynthesis in tomato. Hortic. Res. 2023; 10:uhad077. doi: https://doi.org/10.1093/hr/uhad077 .

Ibrahim P.A, Gbanguba, and Madulawed U.A. (2022). Response of lowland Rice crop specific NPK fertiliser at Badegi, central Nigeria. National Cereal Research Institute, Badegi and Africa Fertiliser Nigeria LTD. Maitama Abuja.

Idoko, M. A., and Bisong, F. E. (2010). Application of geo-information for evaluation of land use change: a case study of Federal Capital Territory-Abuja. E*nvironmental Research Journal*, 4, 140–144. https://doi.org/10.3923/erj.2010.140.144.

Ihenetu, S. C., Ibe, F. C., and Inyamah, P. C. (2021). Comparative study of the properties of yellow and brown Cyperus esculentus L. *World News of Natural Sciences*, *35*, 25–37.

Jaham, M.S., Fazle, B.U.T., Sultana, B.S. (2014). Effect of different levels of Urea and phosphorus on the growth and yield of rice.

Jiang, Y., Zhang, H., Qi, X., & Wu, G. (2020). Structural characterisation and antioxidant activity of condensed tannins fractionated from sorghum grain. Journal of Cereal Science, 92, 102918. https://doi.org/10.1016/j.jcs.2020.102918

Kadam S, Abril A, Dhanapal AP, Koester RP, Vermerris W, Jose S et al (2017). Characterisation and regulation of aquaporin genes of Sorghum [Sorghum bicolor (L.) Moench] in response to waterlogging stress. Front Plant Sci 8:862. https://doi.org/10.3389/fpls.2017.00862

Kastner, T., Chaudhary, A., Gingrich, S., Marques, A., Persson, U.M., Bidoglio, G., Le Provost, G., Schwarzmüller, F. (2021). Global agricultural trade and land system sustainability: implications for ecosystem carbon storage, biodiversity, and human nutrition. One Earth. 4 (10), 1425–1443

KFFC, Kansas Farm Food Connection (2018). What Are the Different Types of Sorghum? Retrieved from http://kansasfarmfoodconnection.org/blog/2018/01/12/ what-are the different-types-of sorghum.

Khuang, T.Q., Huan, T.T. and Hach, C.V. (2008). Study on Fertiliser Rates for Getting Maximum Grain Yield and Profitability of Rice Production. Omonrice, 16, 93-99.

Li, Y. C., et al. (2020). "Impact of nitrogen fertiliser on soil acidification and ecosystem functioning." Ecology Letters, 23(8), 1249-1262.

Mace, E. S., Tai S., Gliding, E. K., Like Y., Prentis, P. J., Bling L., and Wang J. (2013). Whole-Genome Sequencing Reveals Untapped Genetic Potential in Africa's Indigenous Cereal Crop Sorghum. Nature Communications, 4, 2320.

Manzoor, Z., Awan, T.H., Safdar, M.E., Ali, R.I., Ashraf, M.M. and Ahmad, M. (2006). Effect of Urea Levels on Yield and Yield Components of Basmati Rice. *Journal of Agricultural Research*, 44, 115-120.

Mathur, S., Umakanth, A. V., Tonapi, V. A., Sharma, R., & Sharma, M. K. (2017). Sweet Sorghum as Biofuel Feedstock; Sorghum bicolour (L). Moench. Theoretical and Applied Genetics, 121,323-336. *International Journal of Agricultural Science & Technology.*

Nadarajan, S., Sukumaran, S., (2021). Chemistry and toxicology behind chemical fertilisers. Controlled Release Fertilisers for Sustainable Agriculture. Academic Press, pp. 195–229.

Naz, F. (2023). Chapter nine - Plant nutrition, transport, mechanism and sensing in plants. Sustainable Plant Nutrition, Academic Press, Pages 209-228, ISBN 9780443186752, https://doi.org/10.1016/B978-0-443-18675-2.00002-X.

Ndjeunga, J., Mausch, K., and Simtowe. F. (2015). Assessing the effectiveness of Agricultural R&D for groundnut, pearl millet, pigeon pea, and sorghum in West and Central Africa and East and Southern Africa. In: Walker T.S., *Alwang J., editor. Crop Improvement, adoption, and impact of improved varieties in food crops in Sub-Saharan Africa*. Wallingford, UK: CABI; p. 123–147.

Ndlovu E, van Staden J, Maphosa M (2021). Morpho-physiological effects of moisture, heat and combined stresses on Sorghum bicolor [Moench (L.)] and its acclimation mechanisms. Plant Stress 2:100018. https://doi.org/10.1016/j.stress.2021.100018

Nedunchezhiyan M, Ray RC (2010). Sweet potato growth, development, production and utilisation: overview. In: Ray RC, Tomlins KI (Eds) Sweet Potato: Post-Harvest Aspects in Food, Nova Science Publishers Inc., New York, pp 1-26.

Nwosisi, S., Nandwani, D., & Hui, D. (2019). Mulch treatment effect on weed biomass and yields of organic sweet potato cultivars. Agronomy, 9, 190.

Rashwan AK, Yones HA, Karim N, Taha EM, Chen W. (2021). Potential processing technologies for developing sorghum-based food products: An update and comprehensive review. Trends in Food Science and Technology. 2021; 110:168–182.

Serna-Saldivar SO, Espinosa-Ramírez J. (2019). Grain structure and grain chemical composition. In sorghum and millets: Chemistry, Technology, and Nutritional Attributes, 2nd Ed.; Taylor JRN, Duodu KG, Eds; Woodhead Publishing: Duxford, UK. 2019; 85-129.

Shakouri, M.J., Vajargah, A.V., Gavabar, M.G., Mafakheri, S. and Zargar, M. (2012). Rice Vegetative Response to Different Biological and Chemical Fertilisers. Advances in Environmental Biology, 6, 859-863.

Singh V, van Oosterom EJ, Jordan DR, Messina CD, Cooper M, Hammer GL (2010). Morphological and architectural development of root systems in sorghum and maize. Plant Soil. 2010; 333:287–299. DOI: https://doi.org/10.1007/s11104-010-0343-0 .

Sweeney, R., et al. (2023). "Optimising nitrogen fertiliser application for improved crop productivity and environmental sustainability." Field Crops Research, 285, 108283.

Tari I, Laskay G, Takács Z, Poór P (2013). Response of sorghum to abiotic stresses: a review. *J Agron Crop Sci* 199:264–274. https://doi.org/10.1111/jac.12017

Tibugari, H., Chiduza, C., & Mashingaidze, A. B. (2020). A survey of problem weeds of sorghum and their management in two sorghum-producing districts of Zimbabwe. Cogent Social Sciences, 6, 1738840.

Tyagi, J., Ahmad, S., Malik, M. (2022). Nitrogenous fertilisers: impact on environmental sustainability, mitigation strategies, and challenges. *Int. J. Environ. Sci. Technol.* 19 (11), 11649–11672.

Unsal, F., Garbers, H., Bogmans, C., Prifiti, E. (2020). Food (in) security in SSA under COVID-19: a macro perspective. November 5. IMF RES COVID-19 Note 22, available at http://dm-edms.imf.org/cyberdocs/viewdocument.asp?doc=6981213&lib =DMSDR1S.

USDA. National nutrient database for standard reference legacy release (2019). Full report. Sorghum grain. 2019;4(2):32-43.

USDA-NASS (2017). USDA Quick Stats. Washington, DC: USDA-NASS. Retrieved from https://quickstats.nass.usda.gov/

Vaia, (2024). Why is Urea the most commonly used nitrogenous fertiliser? Retrieved from: https://www.vaia.com/en-us/textbooks/chemistry/chemistry-6-edition/chapter-9/problem-23-why-is-Urea-the-most-commonly-used-nitrogenous-fe/#:~:text=Urea%20is%20a%20cost%

Walkley, A. and Black, I.A. (1934). An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Science, 37, 29-37.

Yao H., Zhang Y., Yi X., Zhang X., Zhang W. (2016). Cotton responds to different plant population densities by adjusting specific leaf area to optimise canopy photosynthetic use efficiency of light and nitrogen. Field Crops Res. 2016; 188:10 16. doi: https://doi.org/10.1016/j.fcr.2016.01.012.

Yu Z., Shen Z., Xu L., Yu J., Zhang L., Wang X., Yin G., Zhang W., Li Y., Zuo W. (2022). Effect of Combined Application of Slow-Release and Conventional Urea on Yield and Nitrogen Use Efficiency of Rice and Wheat under Full Straw Return. Agronomy. 2022; 12:998. doi: https://doi.org/10.3390/agronomy12050998.

Zhang R, Zhou Y, Yue Z, Chen X, Cao X, Ai X et al (2019). The leaf-air temperature difference reflects the variation in water status and photosynthesis of sorghum under waterlogged conditions. PLoS One 14:e0219209. https://doi.org/10.1371/journal.pone.0219209

Zhang, X., Davidson, E.A., Zou, T., Lassaletta, L., Quan, Z., Li, T., Zhang, W. (2020). Quantifying nutrient budgets for sustainable nutrient management. Global Biogeochem. Cycles 34 (3), e2018GB006060.

Zhang, X., et al. (2020). "Global nitrogen fertiliser use efficiency trends and implications for food security." *Environmental Research Letters*, 15(10), 104005.