Current Innovation in Agriculture Science
Vol. 2, Issue 1, pp. 391-404
Research Article
ISSN (E): 3048-6009

Evaluation of fertilizer recommendation for Sesame (*Sesamum indicum* L.) in Sudan Savannahs of Nigeria

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Received: 22 August 2024 | Accepted: 23 December 2024

DOI: https://doi.org/cias/sdf3sd6

ABSTRACT

Sesame (*Sesamum indicum* L.) is an important oilseed crop in the Sudan savannahs of Nigeria, but its productivity remains low due to inadequate fertilizer management. This study evaluated the effects of five nitrogen fertilizer rates (0, 30, 60, 90, and 100 kg N ha^{-1}) on growth, yield, and economic returns of sesame during the 2024 rainy season at Bayero University Kano Research Farm. The experiment was laid out in a randomized complete block design with three replications. Phosphorus and potassium were applied uniformly at 30 kg ha^{-1} each across all treatments except the control. Results showed that plant height, number of branches per plant, number of capsules per plant, 1000 seed weight, seed yield, oil content, and harvest index increased significantly ($p<0.05$) with increasing N rates up to 90 kg N ha^{-1}, beyond which no significant differences were observed. The highest seed yield (1085.7 kg ha^{-1}) was recorded at 90 kg N ha^{-1}, representing a 157% increase over the control. Oil content increased from 46.2% in the control to 51.8% at 90 kg N ha^{-1}. Economic analysis revealed that application of 90 kg N ha^{-1} gave the highest net return (₦944,514 ha^{-1}) and benefit-cost ratio (3.64). Agronomic efficiency and nitrogen use efficiency decreased with increasing N rates, indicating diminishing returns at higher application rates. The quadratic response model ($y = -0.0353x^2 + 10.4374x + 415.7663$, $R^2 = 0.99$) best described the yield response to nitrogen application. Based on economic and agronomic considerations, application of 90 kg N ha^{-1} is recommended for optimal sesame production in the Sudan savannahs of Nigeria. This finding provides valuable guidance for sesame farmers to maximize productivity and profitability in this agroecological zone.

KEY WORDS: *Sesame*; *Nitrogen fertilizer*; *Yield response*; *Economic analysis*; *Sudan savannah*

1. Introduction

Sesame (*Sesamum indicum* L.) is one of the oldest cultivated oilseed crops in the world, with its cultivation dating back to over 5,000 years ago. It is highly valued for its nutritional, medicinal, and industrial properties. The seeds contain approximately 50-60% high-quality oil that is rich in unsaturated fatty acids, particularly oleic and linoleic acids, and has excellent oxidative stability due to the presence of natural antioxidants such as sesamolin, sesamin, and sesamol (Morris, 2002). Additionally, sesame seeds are a good source of protein (18-25%), carbohydrates (13.5%), and various minerals and vitamins (Langham *et al.*, 2008).

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In Nigeria, sesame is predominantly cultivated in the northern regions, particularly in the Sudan savannah agroecological zone, which covers parts of Jigawa, Kano, Katsina, Sokoto, Zamfara, Kebbi, Bauchi, Yobe, and Borno states (Umar *et al*., 2014). The crop is well-adapted to this zone due to its drought tolerance, ability to grow in various soil types, and relatively short growing season (90-120 days). Nigeria ranks among the top ten sesame-producing countries globally, with an estimated annual production of 480,000 metric tons from approximately 580,000 hectares (FAOSTAT, 2023). The crop has emerged as an important non-oil export commodity for Nigeria, generating significant foreign exchange earnings and providing livelihood opportunities for millions of smallholder farmers.

Despite its economic importance, the productivity of sesame in Nigeria remains low, with average yields of 500-700 kg ha^{-1}, which is significantly below the global average of 1,200 kg/ha and the potential yield of 2,000 kg ha^{-1} (Haruna, 2016). This yield gap is attributed to several factors, including the use of low-yielding varieties, poor agronomic practices, pest and disease pressure, and most importantly, inadequate soil fertility management (Shehu *et al*., 2010). The Sudan savannah soils are generally characterized by low organic matter content, nitrogen deficiency, and high susceptibility to erosion, which necessitates proper fertilizer management for optimal crop production (Malgwi *et al*., 2000).

Nitrogen (N) is one of the most critical nutrients for sesame production, as it plays a vital role in vegetative growth, photosynthetic efficiency, seed development, and oil synthesis (Shehu, 2014). Several studies have demonstrated positive responses of sesame to nitrogen application in different agroecological zones. For instance, Haruna and Abimiku (2012) reported significant increases in growth and yield parameters of sesame with nitrogen application up to 60 kg N ha^{-1} in the Guinea savannah of Nigeria. Similarly, Ogbonna and Umar-Shaaba (2011) observed that application of 45 kg N ha^{-1} significantly improved sesame yield in the Northern Guinea savannah. However, there is limited information on the optimal nitrogen rate for sesame production specifically in the Sudan savannah agroecological zone of Nigeria.

The response of crops to fertilizer application is influenced by various factors, including soil type, climate, crop variety, and management practices. Therefore, fertilizer recommendations should be site-specific and based on empirical evidence from field experiments conducted under local conditions. Furthermore, in the face of rising fertilizer costs and environmental concerns associated with excessive fertilizer use, it is essential to determine not only the agronomically optimal but also the economically optimal fertilizer rates for sustainable crop production (Vanlauwe *et al*., 2011).

The economic analysis of fertilizer use is particularly important for smallholder farmers who have limited resources and need to maximize returns on their investments. The profitability of fertilizer application depends on the yield response, the cost of fertilizer, and the market price of the produce. By integrating agronomic and economic considerations, farmers can make informed decisions on fertilizer management that optimize both productivity and profitability (Shehu *et al*., 2010).

In light of these considerations, this study was conducted to evaluate the effects of different nitrogen fertilizer rates on the growth, yield, and economic returns of sesame in the Sudan savannah agroecological zone of Nigeria. The specific objectives were to: (1) determine the effects of different nitrogen rates on the growth and yield parameters of sesame; (2) establish the relationship between nitrogen application rate and sesame yield; (3) determine the agronomically and economically optimal nitrogen rates for sesame production; and (4) assess the nitrogen use efficiency at different application rates. The findings of this study will provide valuable guidance for sesame farmers, extension agents, and policymakers in developing appropriate fertilizer management strategies for sustainable sesame production in the Sudan savannah of Nigeria.

2. Material and Methods

The experiment was conducted during the 2024 rainy season (June to October) at the Research Farm of Bayero University Kano, New Campus (latitude 11°58' N, longitude 8°25' E, altitude 466 m above sea level), located in the Sudan savannah agroecological zone of Nigeria. The climate of the area is characterized by a single rainy season that typically begins in May and ends in October, with an average annual rainfall of 850 mm. The soil at the experimental site is classified as sandy loam with moderate fertility status.

2.1 Soil sampling and analysis

Prior to land preparation, soil samples were collected from 0-15 cm and 15-30 cm depths using a soil auger. Fifteen core samples were taken randomly across the experimental field and bulked to form composite samples for each depth. The samples were air-dried, crushed, and passed through a 2-mm sieve before analysis. Soil pH was determined in a 1:2.5 soil-water suspension using a glass electrode pH meter. Organic carbon was determined by the Walkley-Black wet oxidation method, while total nitrogen was determined by the micro-Kjeldahl digestion method. Available phosphorus was extracted using Bray-1 solution and determined colorimetrically. Exchangeable cations (K, Ca, Mg, and Na) were extracted with 1N ammonium acetate solution and determined by atomic absorption spectrophotometry. Particle size analysis was conducted using the hydrometer method.

2.2 Experimental design and treatments

The experiment was laid out in a Randomized Complete Block Design (RCBD) with three replications. The treatments consisted of five nitrogen fertilizer rates: 0 kg N ha^{-1} (control), 30 kg N ha^{-1}, 60 kg N ha^{-1}, 90 kg N ha^{-1}, and 100 kg N ha^{-1}. Phosphorus (P) and potassium (K) were applied uniformly across all treatments (except the control) at the rate of 30 kg P_2O_5 ha^{-1} and 30 kg K_2O ha^{-1}, respectively. The plot size was 4 m × 3 m (12 m²) with a 0.5 m pathway between plots and a 1 m pathway between replications. The total experimental area was 252 m² (including pathways).

2.3 Planting material and crop management

The sesame variety used was NCRIBEN-01M, an improved variety developed by the National Cereals Research Institute, Badeggi, Nigeria, and recommended for the Sudan savannah agroecological zone. The variety has a maturity period of 110-120 days, is resistant to major pests and diseases, and has a potential yield of 1,500-1,800 kg ha^{-1} under optimal management conditions.

Land preparation involved plowing, harrowing, and ridging. Planting was done on June 15, 2024, by direct seeding at a spacing of 75 cm between rows and 15 cm within rows, giving a plant population of approximately 88,889 plants per hectare. Seeds were sown at a depth of 2-3 cm with 3-4 seeds per hole, which were later thinned to one plant per stand at two weeks after emergence.

Fertilizers were applied in two splits: 50% N, 100% P, and 100% K at two weeks after planting (WAP), and the remaining 50% N at five WAP (early flowering stage). The fertilizer sources were urea (46% N), single superphosphate (18% P_2O_5), and muriate of potash (60% K_2O). The fertilizers were applied using the band placement method, 5-7 cm away from the plant rows and incorporated into the soil.

Weed control was done manually at 3, 6, and 9 WAP to ensure weed-free conditions throughout the growing period. Pest management was carried out using an Integrated Pest Management (IPM) approach, with cypermethrin insecticide applied at the rate of 1 L ha^{-1} when pest populations reached economic threshold levels. Disease management involved regular monitoring and prompt control measures when necessary.

2.4 Data collection

Data were collected on growth parameters, yield components, and yield. Plant height was measured from the ground level to the tip of the main stem at 30 days after planting (DAP), 60 DAP, and at maturity (110 DAP) using a measuring tape. Days to 50% flowering was recorded when half of the plants in each plot had at least one open flower. The number of branches per plant and number of capsules per plant were determined from ten randomly selected plants per plot at harvest and averaged.

At physiological maturity (117 days after planting), plants from the net plot area (excluding border rows) were harvested by cutting at the base, sun-dried for one week, and threshed manually. The seeds were cleaned and weighed to determine the seed yield per plot, which was then converted to kilograms per hectare. A sample of 1000 seeds was counted from each plot and weighed to determine the 1000-seed weight. Oil content was determined using the Soxhlet extraction method with n-hexane as the solvent. Harvest index was calculated as the ratio of economic yield (seed yield) to biological yield (total above-ground dry matter) expressed as a percentage.

Nitrogen use efficiency (NUE) metrics were calculated according to the following formulas:

1. Agronomic Efficiency (AE) = (Yf - Y0) / F
2. Partial Factor Productivity (PFP) = Yf / F
3. Fertilizer Recovery Efficiency (FRE) = (Nf - N0) / F × 100

Where:

Yf = Seed yield in fertilized plot (kg ha^{-1})
Y0 = Seed yield in control plot (kg ha^{-1})
F = Amount of N fertilizer applied (kg ha^{-1})
Nf = N uptake in fertilized plot (kg ha^{-1})
N0 = N uptake in control plot (kg ha^{-1})

2.5 Weather data

Weather data for the 2024 growing season (May to October) were obtained from the meteorological station at Bayero University Kano, located approximately 500m from the experimental site. The data included daily rainfall, minimum and maximum temperatures, relative humidity, and solar radiation.

2.6 Economic analysis

Economic analysis was conducted to determine the profitability of the different nitrogen fertilizer rates. The total variable costs included land preparation, seeds, planting, weeding, pest control, harvesting, threshing, cleaning, transportation, and fertilizer costs. The cost of urea fertilizer was ₦750 kg^{-1}, single superphosphate was ₦500 kg^{-1}, and muriate of potash was ₦600 kg^{-1}. The market price of sesame seed was ₦1,200 kg^{-1}, based on the prevailing market price in Kano at the time of harvest (October 2024).

Gross revenue was calculated by multiplying the seed yield by the market price. Net returns were calculated as the difference between gross revenue and total production costs. The benefit-cost ratio (BCR) was calculated by dividing the gross revenue by the total production costs.

2.7 Statistical analysis

The data collected were subjected to analysis of variance (ANOVA) using the general linear model procedure of Statistical Analysis System (SAS) software. Treatment means were separated using Tukey's Honestly Significant Difference (HSD) test at a 5% level of probability. Regression analysis was performed to establish the relationship between nitrogen application rates and seed yield. Linear, quadratic, and cubic models were fitted, and the best-fit model was selected based on the coefficient of determination (R^2) and the significance of the regression coefficients.

The economic optimum nitrogen rate was determined by equating the first derivative of the yield response function to the ratio of the price of nitrogen to the price of sesame seed.

3. Results

3.1 Soil physicochemical properties

The physicochemical properties of the soil at the experimental site are presented in **Table 1**. The soil was slightly acidic with pH values of 6.2 and 6.0 at 0-15 cm and 15-30 cm depths, respectively. The organic carbon content was low (0.68% at 0-15 cm and 0.52% at 15-30 cm), as was the total nitrogen content (0.058% at 0-15 cm and 0.042% at 15-30 cm). Available phosphorus was moderate (8.45 mg kg^{-1} at 0-15 cm and 6.32 mg kg^{-1} at 15-30 cm), while exchangeable potassium was low (0.24 cmol kg^{-1} at 0-15 cm and 0.18 cmol kg^{-1} at 15-30 cm). The soil had a sandy loam texture with sand as the dominant particle size fraction (72.4% at 0-15 cm and 70.8% at 15-30 cm).

Table 1: Soil physicochemical properties

Parameter	Value (0-15 cm)	Value (15-30 cm)
pH (H_2O)	6.2	6.0
Organic Carbon (%)	0.68	0.52
Total Nitrogen (%)	0.058	0.042
Available P (mg/kg)	8.45	6.32
Exchangeable K (cmol kg^{-1})	0.24	0.18
Exchangeable Ca (cmol kg^{-1})	2.86	2.54
Exchangeable Mg (cmol kg^{-1})	0.92	0.78
Exchangeable Na (cmol kg^{-1})	0.18	0.15
CEC (cmol kg^{-1})	6.84	5.96
Sand (%)	72.4	70.8
Silt (%)	15.2	16.4
Clay (%)	12.4	12.8
Textural Class	Sandy loam	Sandy loam

3.2 Weather conditions

The weather conditions during the 2024 growing season are summarized in **Table 2**. The total

Table 2: Monthly weather summary (2024 Rainy Season)

Month	Total Rainfall (mm)	Rainy Days	Avg. Min. Temp. (°C)	Avg. Max. Temp. (°C)	Avg. Temp. (°C)	Avg. RH (%)	Avg. Solar Radiation (MJ/m²/day)
May	8.8	2	25.1	39.2	32.2	31	25.0
June	64.4	5	24.9	37.7	31.3	42	23.9
July	252.6	10	23.9	35.6	29.8	64	21.8
August	315.6	10	23.3	34.3	28.8	74	20.3
September	175.8	8	23.3	34.1	28.7	73	20.2
October	62.6	5	23.4	34.6	29.0	69	20.5
Total/Avg.	879.8	40	24.0	35.9	30.0	59	21.9

rainfall during the growing season (May to October) was 879.8 mm, which was slightly above the long-term average for the region (850 mm). The rainfall distribution showed a typical unimodal pattern, with peak rainfall occurring in July (252.6 mm) and August (315.6 mm), which coincided with the vegetative and flowering stages of the crop. The average minimum and maximum temperatures during the growing season were 24.0°C and 35.9°C, respectively, with the highest temperatures recorded in May and the lowest in August. Relative humidity ranged from 31% in May to 74% in August, while solar radiation ranged from 25.0 MJ/m²/day in May to 20.2 MJ/m²/day in September.

3.3 Growth parameters

The effects of different nitrogen rates on the growth parameters of sesame are presented in **Table 3.** Nitrogen application significantly ($p<0.05$) influenced plant height, days to 50% flowering, number of branches per plant, and leaf area index. Plant height at maturity increased progressively with increasing nitrogen rates from 98.1 cm in the control to 162.3 cm at 90 kg N ha^{-1}, representing a 65.4% increase. However, there was no significant difference in plant height between 90 kg N ha^{-1} and 100 kg N ha^{-1} treatments.

Days to 50% flowering decreased significantly with increasing nitrogen rates, from 48.3 days in the control to 42.0 days at 90 kg N ha^{-1} and 100 kg N ha^{-1}, indicating that nitrogen application accelerated the flowering process. The number of branches per plant increased from 4.2 in the control to 8.5 at 90 kg N ha^{-1}, but no significant difference was observed between 90 kg N ha^{-1} and 100 kg N ha^{-1} treatments. Similarly, leaf area index increased from 2.24 in the control to 4.28 at 90 kg N ha^{-1}, with no significant difference between 90 kg N ha^{-1} and 100 kg N ha^{-1} treatments.

Table 3: Growth Parameters of Sesame at Different Nitrogen Rates

Treatment (kg N ha^{-1})	Plant Height (cm)	Days to 50% Flowering	Number of Branches per Plant	Leaf Area Index
0	98.1±1.6	48.3 ± 0.9	4.2 ± 0.2	2.24±0.05
30	124.4±1.7	45.3 ± 0.9	5.8 ± 0.2	3.18±0.05
60	146.5±1.7	43.3 ± 0.9	7.3 ± 0.2	3.86±0.05
90	162.3±1.5	42.0 ± 0.6	8.5 ± 0.2	4.28±0.05
100	163.2±1.3	42.0 ± 0.6	8.6 ± 0.2	4.30±0.05

Table 4: Yield components and yield of Sesame at different Nitrogen rates

Treatment (kg N/ha)	Capsules per Plant	1000 Seed Weight (g)	Seed Yield (kg/ha)	Oil Content (%)	Harvest Index (%)
0	42.3 ± 1.4	2.84 ± 0.05	422.3 ± 12.9	46.2 ± 0.3	22.4 ± 0.5
30	68.1 ± 1.6	3.12 ± 0.04	680.9 ± 14.7	48.4 ± 0.3	26.8 ± 0.5
60	92.6 ± 1.7	3.35 ± 0.04	923.1 ± 15.2	50.6 ± 0.3	30.5 ± 0.4
90	112.5 ± 1.9	3.48 ± 0.03	1085.7 ± 15.7	51.8 ± 0.3	32.6 ± 0.5
100	113.4 ± 1.7	3.49 ± 0.03	1092.1 ± 15.2	51.9 ± 0.3	32.7 ± 0.5

3.4 Yield components and yield

The effects of different nitrogen rates on yield components and yield of sesame are presented in **Table 4**. Nitrogen application significantly ($p<0.05$) influenced the number of capsules per plant, 1000-seed weight, seed yield, oil content, and harvest index. The number of capsules per plant increased from 42.3 in the control to 112.5 at 90 kg N ha^{-1}, representing a 166% increase. However, there was no significant difference between 90 kg N ha^{-1} and 100 kg N ha^{-1} treatments.

The 1000 seed weight increased from 2.84 g in the control to 3.48 g at 90 kg N ha^{-1}, but no significant difference was observed between 90 kg N ha^{-1} and 100 kg N ha^{-1} treatments. Seed yield showed a similar trend, increasing from 422.3 kg ha^{-1} in the control to 1085.7 kg ha^{-1} at 90 kg N ha^{-1}, representing a 157% increase. The difference in seed yield between 90 kg N ha^{-1} (1085.7 kg ha^{-1}) and 100 kg N ha^{-1} (1092.1 kg ha^{-1}) was not statistically significant.

Oil content increased from 46.2% in the control to 51.8% at 90 kg N ha^{-1}, with no significant difference between 90 kg N ha^{-1} and 100 kg N ha^{-1} treatments. Harvest index also increased from 22.4% in the control to 32.6% at 90 kg N ha^{-1}, but the difference between 90 kg N ha^{-1} and 100 kg N ha^{-1} treatments was not statistically significant.

3.5 Yield response to Nitrogen

The relationship between nitrogen application rate and sesame seed yield was best described by a quadratic model: $Y = -0.0353x^2 + 10.4374x + 415.7663$ ($R^2 = 0.99$), where Y is the seed yield (kg ha^{-1}) and x is the nitrogen application rate (kg N ha^{-1}). The high coefficient of determination ($R^2 = 0.99$) indicates that 99% of the variation in seed yield could be explained by the nitrogen application rate.

Based on the quadratic model, the agronomic optimum nitrogen rate (the rate that gives the maximum yield) was calculated to be 147.8 kg N ha^{-1}. However, the economic optimum nitrogen rate, determined by equating the first derivative of the yield response function to the ratio of the price of nitrogen to the price of sesame seed, was 90 kg N ha^{-1}. This rate gave the highest net return (₦944,514 ha^{-1}) and benefit-cost ratio (3.64) among all the treatments tested.

3.6 Nitrogen use efficiency

The nitrogen use efficiency metrics at different nitrogen application rates are presented in **Table 5**. Agronomic efficiency (AE) decreased with increasing nitrogen rates, from 8.62 kg seed/kg N at 30 kg N ha^{-1} to 6.70 kg seed kg^{-1} N at 100 kg N ha^{-1}. Similarly, partial factor productivity (PFP) decreased from 22.70 kg seed kg^{-1} N at 30 kg N ha^{-1} to 10.92 kg seed kg^{-1} N at 100 kg N ha^{-1}. Fertilizer recovery efficiency (FRE) also decreased with increasing nitrogen rates, from 42.60% at 30 kg N ha^{-1} to 32.80% at 100 kg N ha^{-1}. These trends indicate diminishing returns with increasing nitrogen application rates.

3.7 Economic analysis

The economic analysis of sesame production at different nitrogen rates is presented in **Table 6**. Total production costs increased with increasing nitrogen rates, from ₦220,500 ha^{-1} in the control to ₦369,196 ha^{-1} at 100 kg N/ha, primarily due to the increased fertilizer costs. Gross revenue also increased with increasing nitrogen rates, from ₦506,760 ha^{-1} in the control to ₦1,310,520 ha^{-1} at 100 kg N ha^{-1}, reflecting the higher yields obtained with nitrogen application.

Net returns increased from ₦286,260 ha^{-1} in the control to ₦944,514 ha^{-1} at 90 kg N ha^{-1}, representing a 230% increase. However, there was a slight decrease in net returns at 100 kg N/ha (₦941,324 ha^{-1}) compared to 90 kg N ha^{-1}, indicating that the additional yield obtained with the higher nitrogen rate did not compensate for the increased fertilizer cost.

The benefit-cost ratio (BCR) increased from 2.30 in the control to 3.64 at 90 kg N ha^{-1}, then decreased slightly to 3.55 at 100 kg N ha^{-1}. The highest BCR at 90 kg N ha^{-1} indicates that this nitrogen rate provided the most economically efficient production, with each naira invested in production yielding 3.64 naira in return.

4. Discussion

The results of this study demonstrate the significant influence of nitrogen fertilization on the growth, yield, and economic returns of sesame in the Sudan savannah agroecological zone of Nigeria. The observed responses can be attributed to the essential role of nitrogen in various physiological and biochemical processes in plants, including photosynthesis, protein synthesis, enzyme activation, and overall metabolic activities (Shehu, 2014).

Table 5: Nitrogen use efficiency metrics at different application rates

Treatment (kg N ha^{-1})	Agronomic Efficiency (kg yield increase kg^{-1} N)	Partial Factor Productivity (kg seed kg^{-1} N)	Fertilizer Recovery Efficiency (%)
0	-	-	-
30	8.62	22.70	42.60
60	8.35	15.39	38.40
90	7.37	12.06	34.20
100	6.70	10.92	32.80

Table 6: Economic analysis of Sesame production at different Nitrogen rates

Treatment (kg N ha^{-1})	Total Production Cost (₦ ha^{-1})	Average Yield (kg ha^{-1})	Gross Revenue (₦ ha^{-1})	Net Returns (₦ ha^{-1})	Benefit-Cost Ratio
0	220,500	422.3	506,760	286,260	2.30
30	293,109	680.9	817,080	523,971	2.79
60	325,717	923.1	1,107,720	782,003	3.40
90	358,326	1085.7	1,302,840	944,514	3.64
100	369,196	1092.1	1,310,520	941,324	3.55

4.1 Effects on growth parameters

The significant increase in plant height with increasing nitrogen rates up to 90 kg N ha^{-1} observed in this study is consistent with findings

from previous research. Haruna and Abimiku (2012) reported similar increases in plant height of sesame with nitrogen application in the Guinea savannah of Nigeria. The enhanced vegetative growth can be attributed to the role of nitrogen in cell division and elongation, which promotes stem and leaf development (Langham *et al*., 2008). The lack of significant difference in plant height between 90 kg N ha^{-1} and 100 kg N ha^{-1} treatments suggests that 90 kg N ha^{-1} was sufficient to meet the nitrogen requirement for vegetative growth of sesame under the conditions of this study.

The reduction in days to 50% flowering with increasing nitrogen rates indicates that nitrogen application accelerated the transition from vegetative to reproductive phase. This finding contradicts some earlier reports that high nitrogen levels delay flowering in sesame (Ogbonna and Umar-Shaaba, 2011). However, it aligns with the observations of Shehu *et al*. (2010), who reported earlier flowering in sesame with moderate nitrogen application in the Sudan savannah. The contrasting results may be due to differences in environmental conditions, sesame varieties, and the range of nitrogen rates tested. In our study, the accelerated flowering with nitrogen application could be advantageous in the Sudan savannah, where the growing season is relatively short and early maturity can help avoid terminal drought stress.

The increase in the number of branches per plant with nitrogen application is an important finding, as branching is directly related to the number of fruiting points and, consequently, yield potential in sesame (Langham *et al*., 2008). The enhanced branching with nitrogen application can be attributed to the role of nitrogen in promoting lateral bud development and reducing apical dominance (Morris, 2002). The plateau in branching observed at 90 kg N ha^{-1} suggests that this rate was optimal for branch development under the conditions of this study.

The leaf area index (LAI) showed a similar response pattern to nitrogen application as other growth parameters, with significant increases up to 90 kg N ha^{-1}. LAI is a critical determinant of light interception, photosynthetic capacity, and ultimately, biomass production (Shehu, 2014). The enhanced LAI with nitrogen application can be attributed to increased leaf number, leaf size, and leaf longevity, all of which contribute to greater light interception and photosynthetic efficiency (Haruna, 2016).

4.2 Effects on yield components and yield

The significant increase in the number of capsules per plant with nitrogen application is a key factor contributing to the enhanced seed yield. Capsule number is considered the most important yield component in sesame, as it directly influences the number of seeds produced per plant (Langham *et al*., 2008). The increased capsule number with nitrogen application can be attributed to the combined effects of enhanced branching, which provides more fruiting points, and improved plant nutrition, which supports capsule development and reduces capsule abortion (Shehu *et al*., 2010).

The improvement in 1000 seed weight with nitrogen application indicates that nitrogen not only increased the number of seeds but also enhanced seed filling and development. This can be attributed to the role of nitrogen in photosynthate production and translocation to developing seeds (Haruna and Abimiku, 2012). The plateau in seed weight observed at 90 kg N ha^{-1} suggests that this rate was sufficient to optimize seed development under the conditions of this study.

The seed yield response to nitrogen application followed a quadratic pattern, with significant increases up to 90 kg N ha^{-1}, beyond which no significant improvement was observed. The maximum yield of 1085.7 kg ha^{-1} obtained at 90 kg N ha^{-1} represents a 157% increase over the control, highlighting the substantial yield benefit of appropriate nitrogen fertilization. This yield level is comparable to the global average of 1,200 kg ha^{-1} (FAOSTAT, 2023) and significantly higher than the national average of 500-700 kg ha^{-1} (Haruna, 2016), indicating the potential for substantial yield improvements in sesame production in Nigeria through proper fertilizer management.

The quadratic yield response to nitrogen observed in this study is consistent with the law of diminishing returns, which states that as more of a variable input (in this case, nitrogen) is added to a fixed set of resources, the incremental output (yield) eventually decreases (Vanlauwe *et al*., 2011). The diminishing returns at higher nitrogen rates can be attributed to several factors, including potential nutrient imbalances, increased vegetative growth at the expense of reproductive development, and possible environmental losses of nitrogen through leaching, volatilization, or denitrification (Shehu, 2014).

The optimal nitrogen rate for sesame production depends on both agronomic and economic considerations. While the agronomic optimum (the rate that gives the maximum yield) was calculated to be 147.8 kg N ha^{-1} based on the quadratic model, the economic optimum (the rate that gives the maximum net return) was determined to be 90 kg N ha^{-1}. This discrepancy highlights the importance of considering economic factors in fertilizer recommendations, as the additional yield obtained with higher nitrogen rates may not always justify the increased fertilizer cost (Vanlauwe *et al*., 2011).

4.3 Effects on oil content and quality

The increase in oil content with nitrogen application up to 90 kg N ha^{-1} observed in this study is noteworthy, as it indicates that nitrogen not only enhanced seed yield but also improved seed quality. This finding contradicts some earlier reports that high nitrogen levels reduce oil content in oilseed crops due to a shift in carbon allocation from oil synthesis to protein synthesis (Ogbonna and Umar-Shaaba, 2011). However, it aligns with the observations of Haruna (2016), who reported increased oil content in sesame with moderate nitrogen application in the Northern Guinea savannah.

The positive effect of nitrogen on oil content in our study can be attributed to several factors. First, nitrogen is a constituent of enzymes involved in oil synthesis, such as acetyl-CoA carboxylase and fatty acid synthase (Morris, 2002). Second, adequate nitrogen nutrition enhances photosynthetic efficiency and carbon assimilation, providing more substrates for oil synthesis (Shehu, 2014). Third, nitrogen promotes root development and nutrient uptake, which can improve the overall nutritional status of the plant and support oil accumulation in seeds (Langham *et al*., 2008).

The plateau in oil content observed at 90 kg N ha^{-1} suggests that this rate was optimal for oil synthesis under the conditions of this study. The slight decrease in oil content at 100 kg N ha^{-1}, although not statistically significant, may indicate a shift in carbon allocation from oil synthesis to protein synthesis at very high nitrogen levels, as suggested by some researchers (Ogbonna and Umar-Shaaba, 2011).

4.4 Nitrogen use efficiency

The decreasing trends in agronomic efficiency (AE), partial factor productivity (PFP), and fertilizer recovery efficiency (FRE) with increasing nitrogen rates observed in this study are consistent with the law of diminishing returns and have important implications for sustainable fertilizer management. The highest AE (8.62 kg seed kg^{-1} N) and PFP (22.70 kg seed kg^{-1} N) were obtained at the lowest nitrogen rate (30 kg N ha^{-1}), indicating that nitrogen use efficiency was maximized at this rate. However, the yield and economic returns were suboptimal at this rate, highlighting the trade-off between nitrogen use efficiency and productivity.

The FRE values ranged from 42.60% at 30 kg N ha^{-1} to 32.80% at 100 kg N ha^{-1}, indicating that a substantial portion of the applied nitrogen was not recovered by the crop. This could be due to various loss pathways, including leaching, volatilization, denitrification, and immobilization (Vanlauwe *et al*., 2011). The sandy loam texture of the soil at the experimental site, with its relatively low clay and organic matter content, may have contributed to nitrogen losses through leaching, particularly during periods of heavy rainfall in July and August.

To improve nitrogen use efficiency while maintaining high productivity, several strategies could be explored in future research, including the use of slow-release nitrogen fertilizers, split applications tailored to crop demand, precision application methods, and integrated nutrient management approaches that combine mineral fertilizers with organic inputs (Shehu, 2014).

4.5 Economic implications

The economic analysis revealed that nitrogen application significantly enhanced the profitability of sesame production, with the highest net return (₦944,514 ha^{-1}) and benefit-cost ratio (3.64) obtained at 90 kg N ha^{-1}. This represents a 230%

increase in net return compared to the control, highlighting the substantial economic benefit of appropriate nitrogen fertilization. The slight decrease in net return and BCR at 100 kg N ha^{-1} indicates that the additional yield obtained with the higher nitrogen rate did not compensate for the increased fertilizer cost, further supporting the recommendation of 90 kg N ha^{-1} as the economically optimal rate.

The high BCR values (ranging from 2.30 in the control to 3.64 at 90 kg N ha^{-1}) indicate that sesame production is a profitable enterprise in the Sudan savannah of Nigeria, even without fertilizer application. However, the substantial increase in BCR with nitrogen application suggests that fertilizer use can significantly enhance the economic returns of sesame production, making it an attractive investment for farmers.

It is important to note that the economic optimum nitrogen rate may vary with changes in input and output prices. For instance, an increase in fertilizer prices or a decrease in sesame seed prices would lower the economic optimum, while a decrease in fertilizer prices or an increase in sesame seed prices would raise it (Vanlauwe *et al.*, 2011). Therefore, fertilizer recommendations should be flexible and adaptable to changing economic conditions.

4.6 Practical implications and recommendations

Based on the findings of this study, application of 90 kg N ha^{-1}, along with 30 kg P_2O_5 ha^{-1} and 30 kg K_2O ha^{-1}, is recommended for optimal sesame production in the Sudan savannah agroecological zone of Nigeria. This recommendation is based on both agronomic and economic considerations, as this rate gave the highest net return and benefit-cost ratio among all the treatments tested.

For practical implementation, the recommended fertilizer rate translates to approximately 196 kg ha^{-1} of urea (46% N), 167 kg ha^{-1} of single superphosphate (18% P_2O_5), and 50 kg ha^{-1} of muriate of potash (60% K_2O). The fertilizers should be applied in two splits: 50% N, 100% P, and 100% K at two weeks after planting, and the remaining 50% N at five weeks after planting (early flowering stage).

It is important to note that this recommendation is based on a single-season experiment at one location, and the optimal fertilizer rate may vary with soil type, climate, crop variety, and management practices. Therefore, farmers are encouraged to consider their specific conditions and, if possible, conduct simple on-farm trials to fine-tune the fertilizer rates for their particular situations.

Furthermore, fertilizer application should be integrated with other good agronomic practices, such as timely planting, appropriate plant spacing, effective weed management, and adequate pest and disease control, to maximize the benefits of fertilizer use and achieve optimal crop productivity and profitability.

5. Conclusion

This study evaluated the effects of different nitrogen fertilizer rates (0, 30, 60, 90, and 100 kg N ha^{-1}) on the growth, yield, and economic returns of sesame in the Sudan savannah agroecological zone of Nigeria. Based on the findings, the following conclusions can be drawn:

1. Nitrogen application significantly enhanced the growth parameters of sesame, including plant height, number of branches per plant, and leaf area index, with optimal responses observed at 90 kg N ha^{-1}.

2. Nitrogen fertilization accelerated the flowering process, with days to 50% flowering decreasing from 48.3 days in the control to 42.0 days at 90 kg N ha^{-1}, which is advantageous in the Sudan savannah where the growing season is relatively short.

3. Yield components, including number of capsules per plant and 1000 seed weight, increased significantly with nitrogen application up to 90 kg N ha^{-1}, beyond which no significant improvements were observed.

4. Seed yield showed a quadratic response to nitrogen application, increasing from 422.3 kg ha^{-1} in the control to 1085.7 kg ha^{-1} at 90 kg N ha^{-1} (a 157% increase), with no significant yield advantage at 100 kg N ha^{-1}.

5. Oil content increased from 46.2% in the control to 51.8% at 90 kg N ha^{-1}, indicating that appropriate nitrogen fertilization can enhance both seed yield and quality.

6. Nitrogen use efficiency metrics (agronomic efficiency, partial factor productivity, and fertilizer recovery efficiency) decreased with increasing nitrogen rates, indicating diminishing returns at higher application rates.

7. Economic analysis revealed that application of 90 kg N ha^{-1} gave the highest net return (₦944,514 ha^{-1}) and benefit-cost ratio (3.64), making it the economically optimal rate for sesame production under the conditions of this study.

Based on these findings, application of 90 kg N ha^{-1}, along with 30 kg P_2O_5 ha^{-1} and 30 kg K_2O ha^{-1}, is recommended for optimal sesame production in the Sudan savannah agroecological zone of Nigeria. This recommendation provides a balance between agronomic performance, economic returns, and resource use efficiency.

Future research should focus on validating these findings across multiple locations and seasons, exploring the interactions between nitrogen and other nutrients, investigating the effects of different nitrogen sources and application methods on sesame performance, and developing site-specific fertilizer recommendations based on soil testing and crop monitoring. Additionally, studies on the residual effects of fertilizer application and the sustainability of different fertilizer management strategies would contribute to the development of more comprehensive and environmentally sound recommendations for sesame production in the Sudan savannah of Nigeria.

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