



Coal-based fertilizer effect on soil carbon gains and soybean yield in the Nigerian Sudan Savannah

Olorunshola Monday OLUSEGUN¹ Abbati Muhammad UMAR,²

e-mail: olusegunolorunshola@gmail.com

e-mail: abbatimumar@gmail.com

Dahiru Wakili HABIB³

e-mail: dwhabib.ssc@buk.edu.ng

^{1, 2, 3} Department of Soil Science, Faculty of Agriculture, Bayero University, Kano, Nigeria

Abstract: Increasing concern over long-term nutrient availability in cultivated soils of the Sudan Savannah of Nigeria has raised interest in carbon-enriched soil amendments. This study evaluates the changes in soil organic carbon and soybean productivity resulting from the impact of coal-based fertilizer during the 2023/2024 rainy season at Bayero University Kano and Shidar, Dambatta LGA. The trial was arranged in a randomized complete block design (RCBD) with seven nutrient treatments. Measurements included soil carbon gains and yield components. The combined application of 50% coal fertilizer and 50% NPK produced the highest carbon gain (15.79) and seed weight (25.36 g). Overall, results indicate that coal-based fertilizer can enhance soil quality and crop performance in marginal soils.

Keywords: soil fertility, organic amendment, carbon sequestration

1. Introduction

The Nigerian Sudan Savannah agroecological zone is marked by low organic matter content, erratic rainfall, and soils with low fertility, posing challenges for the sustainable production of crops [1]. Traditional chemical fertilizers offer short-term productivity boosts, however often leading to long-term soil degradation [2]. Coal-based fertilizers, derived from carbonaceous material, are being explored globally as slow-release nutrient sources that also enhance carbon sequestration [3]. Coal, primarily known for energy, is rich in humic substances and stable carbon forms that contribute to soil organic matter (SOM) accumulation [4]. Previous research in sub-Saharan Africa has shown that organic fertilizers, including biochar and composted materials, significantly boost organic carbon and improve soil structure [5, 6]. However, there is limited research on the use of indigenous coal resources for fertilizer formulation in Nigeria.

This research was designed to evaluate the efficacy of coal-based fertilizer on carbon gains in the soil and crop yield performance in the Nigerian Sudan Savannah zone.

2. Materials and methods

2.1. Study area

Two field experiments were carried out during the rainy season of the 2024 cropping season. The research was conducted in Kano State at Bayero University, Kano Teaching & Research Farm of Agriculture Faculty (longitude 11°59'N; latitude 8°25'E) and in the Shidar community, Dambatta LGA, Kano (longitude 12°22'N; latitude 8°34'E), which are both Sudan Savannah ecological zones of Nigeria.

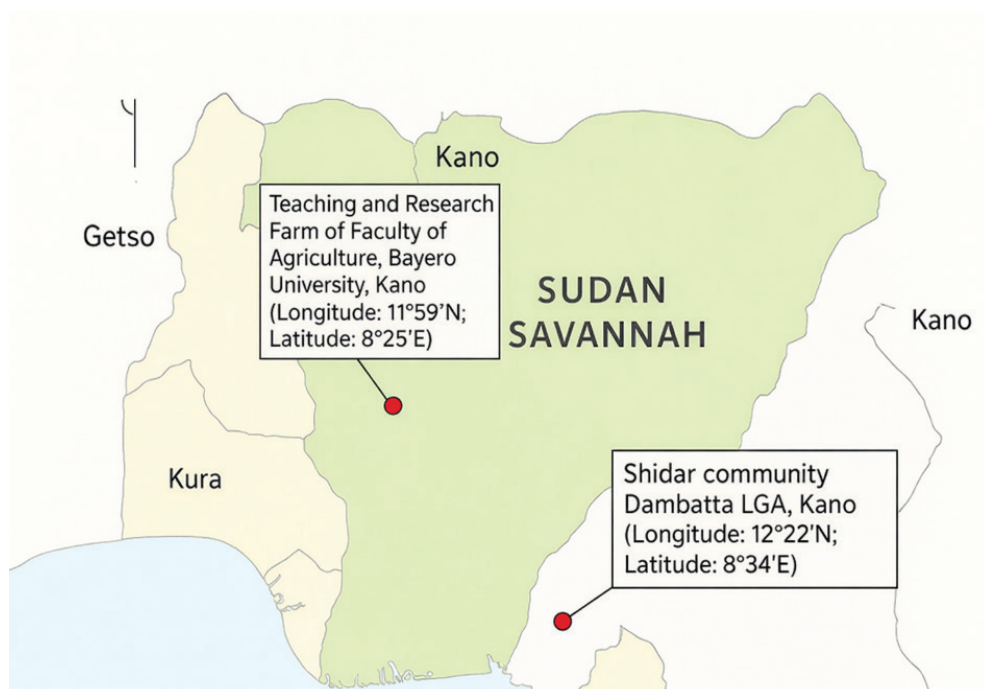


Figure 1. Map of the study area

The region experiences an annual precipitation between 600 and 800 mm and has sandy loam soils with low SOM [7].

2.2. Experimental design, treatments, and layout

Each field had a total of 21 experimental plots, which were arranged in a 2 x 7 factorial trial using a randomized complete block design (RCBD). The treatments included:

- T1: Control (no fertilizer)
- T2: 100% Coal-based fertilizer (20 kg N)
- T3: 50% Coal fertilizer (10 kg N) + 50% NPK (10 kg N, 20 kg P₂O₅, 10 kg K₂O)
- T4: 75% Coal fertilizer (15 kg N) + 25% NPK (5 kg N, 10 kg P₂O₅, 5 kg K₂O)
- T5: 25% Coal fertilizer (5 kg N) + 75% NPK (15 kg N, 30 kg P₂O₅, 15 kg K₂O)
- T6: 100% NPK (20 kg N, 40 kg P₂O₅, 20 kg K₂O).
- T7: Cow dung

The experimental layout consisted of plots measuring 4.5 m x 3 m (13.5 m²), with a spacing of 0.5 m maintained between plots and replication spacing measured at 1.5 m. The entire experimental area measured 20.5 m x 28 m, covering 574 m². Each plot's net size was 3 m x 2 m (6 m²), surrounded by a 2-m border. Plant spacing was 20 cm within rows and 75 cm between rows, with six ridges per plot. The soybean variety sown is TGX 1448.

2.3. Data collection

2.3.1. Weight of seeds per plant

The total seed mass produced by each plant was determined by weighing the seeds from 3 stands per plot, and then the average was determined.

2.4. Carbon gain determination

Estimation of carbon gains was done using a relationship described by [8]. The relation estimates the difference in carbon gains of the control and other soil treatment data collected.

$$CG = \frac{C_{treatment} - C_{control}}{C_{control}} \times 100, \quad (1)$$

where CG is carbon gains in %, C_{treatment} is carbon treatment, and C_{control} is carbon control.

2.5. Statistical analysis

All data analyses were conducted using the JMP® statistical package, version 16 (SAS Institute Inc., Cary, North Carolina, USA). The data collected were analysed

using a two-way analysis of variance (ANOVA) GLM procedure with randomized complete block design in order to compare the impact of coal-based fertilizer on soil carbon accumulation and the yield of soybean in the Nigerian Sudan Savannah. Mean comparison was carried out using least significant difference (LSD) at the 5% significance level.

3. Results and discussions

3.1. Results

3.1.1. Physical and chemical properties of the soils at the two experimental sites

The pre-planting soil analysis results of the experimental sites are shown in *Table 1*. The soil at BUK was classified as having a sandy loam texture, with a particle size composition dominated by sand, followed by silt and clay. Moderate levels of organic carbon and nitrogen content were found in the soil, while plant-available phosphorus was relatively low. Exchangeable bases showed that calcium and magnesium in the soil sample are the dominant cations, with lower amounts of potassium and sodium. The sample also had a moderate effective cation exchange capacity (ECEC), slightly acidic pH values in both water and CaCl_2 , and a low electrical conductivity (EC). At Dambatta, the analysed soil was identified as loamy sand, with sand as the predominant fraction. The soil carbon and overall nitrogen contents were slightly lower compared to those at BUK, but the soil phosphorus was comparatively higher. Among the exchangeable bases, calcium and magnesium were present in greater amounts than potassium and sodium. The sampled soil exhibited moderate ECEC, low EC, and an acidic reaction (pH) in both water and CaCl_2 media, which is similar to that of the BUK soil.

3.1.2. Composition of the Satupra coal fertilizer

The coal fertilizer used in the experiment was analysed, and its compositions are shown in *Table 2*. Carbon and nitrogen content were high, and moderate levels of phosphorus were observed. The fertilizer also contained essential exchangeable bases such as potassium, calcium, and magnesium, as well as other beneficial micronutrients, including manganese, zinc, boron, iron, copper, and molybdenum in different concentrations.

3.1.3. Nutrient composition of cow dung

Table 3 reveals that the cow dung contained high amounts of phosphorus and significant levels of organic carbon and nitrogen, while macronutrients like potassium, calcium, and magnesium and trace amounts of micronutrients such as manganese, zinc, iron, and copper are also contained in the cow dung.

Table 1. The physical and chemical properties of baseline soil in the experimental sites

Soil properties	BUK	Dambatta
Sand (%)	70.00	85.00
Silt (%)	20.00	8.00
Clay (%)	10.00	7.00
Textural class	Sandy loam	Loamy sand
Soil pH (H ₂ O)	5.51	5.67
Soil pH (CaCl ₂)	4.93	5.09
Electrical conductivity (dSm ⁻¹)	0.03	0.07
Organic carbon (%)	0.53	0.43
Nitrogen (%)	0.11	0.14
Available P (mgkg ⁻¹)	9.96	13.77
K (cmolkg ⁻¹)	0.16	0.38
Ca (cmolkg ⁻¹)	2.22	1.52
Mg (cmolkg ⁻¹)	1.93	2.01
Na (cmolkg ⁻¹)	0.29	0.41
ECEC (cmolkg ⁻¹)	6.11	5.83
Ea (cmol/kg)	0.501	0.501

Table 2. The carbontilizer's chemical composition as provided by the manufacturer

Element	Content
Organic carbon (%)	± 30
Nitrogen (total) (%)	± 2
Phosphorus (available) (mg/kg)	± 0.89
Potassium (available) (cmol/kg)	± 0.38
Calcium (mg/kg)	± 6.62
Magnesium (mg/kg)	± 900
Manganese (mg/kg)	± 252

Element	Content
Zinc (mg/kg)	± 84
Boron (mg/kg)	± 42
Iron (mg/kg)	± 134
Copper (mg/kg)	± 4.2
Molybdenum (mg/kg)	± 1.70

Table 3. The nutrient composition of cow dung

Element	Content
Organic carbon (%)	5.29
Total nitrogen (%)	3.33
Total phosphorus (g/kg)	21.86
pH	7.4
Potassium (g/kg)	0.08
Calcium (g/kg)	5.55
Magnesium (g/kg)	2.17
Manganese (mg/kg)	0.01
Zinc (mg/kg)	0.04
Iron (mg/kg)	0.84
Copper (mg/kg)	0.04

3.1.4. Grain weight

Table 4 shows the effect of coal-based fertilizer on soybean grain weight in the Sudan Savannah. Grain weight was significantly influenced by location, with Dambatta recording the highest values. Moreover, there was no notable effect among the treatments though 50% NPK + 50% CF produced the greatest grain weight, followed by 75% NPK + 25% CF. No significant interaction was observed between location and treatment.

3.1.5. Carbon gains

The effect of coal-based fertilizer on soil carbon gains is also presented in Table 5. Carbon gain was not significantly influenced by location although Dambatta recorded the highest carbon gain. Treatments did not significantly affect carbon gain, but plots with 100% CF showed the highest increase, followed by 50% NPK + 50% CF, while cow dung plots showed the least. No significant interaction occurred between location and treatment for carbon gains.

Table 4. Coal-based fertilizer effects on the seed weight of soybean

Treatment	Grain weight (g)
Locations (L)	
BUK	11.01 ^b
Dambatta	23.81 ^a
<i>p</i> -value	0.003
LSD	**
SE±	2.857
Fertilizer (F)	
Control	12.90
100% CF	18.25
50% NPK + 50% CF	25.36
25% NPK + 75% CF	14.18
75% NPK + 25% CF	21.69
100% NPK	16.54
Cow dung	12.96
<i>p</i> -value	0.593
LSD	NS
SE±	5.345
Interaction	
L x F	NS

Notes: Means that are followed by the same letter(s) in the same column are not significantly different at 5% level of probability. Keys: SE = standard error, CF = coal fertilizer, LSD = least significant difference, NS = not significant, * = significant, ** = highly significant.

Table 5. Coal-based fertilizer effects on carbon gains in the soil

Treatment	Carbon gains (%)
Locations (L)	
BUK	8.20
Dambatta	10.24
<i>p</i> -value	0.742
LSD	NS
SE±	4.35
Fertilizer (F)	
100% CF	16.58
50% NPK + 50% CF	15.79
25% NPK + 75% CF	6.76
75% NPK + 25% CF	5.60
100% NPK	9.58

Treatment	Carbon gains (%)
Cow dung	1.03
<i>p</i> -value	0.67
LSD	NS
SE±	7.53
Interaction	
L x F	NS

Notes: Means that are followed by the same letter(s) in the same column are not significantly different at 5% level of probability. Keys: SE = standard error, CF = coal fertilizer, LSD = least significant difference, NS = not significant, * = significant, ** = highly significant.

3.2. Discussion

3.2.1. The physical and chemical properties of baseline soil in the experimental sites

Results of the physio-chemical properties of the soils where the research was conducted indicated that the fertility status of the experimental soils was generally low. Soil pH was strongly acidic in BUK and Dambatta using the ratings of [9]. The acidic pH values recorded at both sites could be owing to the leaching of basic cations from the top soil layer [10].

Electrical conductivity shows that the soils in BUK and Dambatta had low salinity. Total N and organic carbon were low in both locations. Phosphorus was low at both sites, and ECEC was also low in both locations. The low total N, total organic C, and ECEC, recorded at both experimental sites, were likely attributable to the low amount of clay and organic materials in the soil; likewise, the type of clay must have influenced the level of exchange of cations. Considering that savannahs are known to be extremely low in organic materials, especially because of the continuous removal of organic matter during crop harvest, coupled with failure to return crop residues, further intensifies nutrient deficiency, which might be another underlying reason [11, 12, 13].

The exchangeable K content was observed to be low in both BUK and Dambatta, while Na was reportedly classified as medium in both locations by [9]. Exchangeable Ca was medium in BUK and low in Dambatta, while Mg was high in both experimental sites.

Comparatively, the sampled soil in Dambatta was more fertile compared to the soil in BUK. This may be the reason why the growth and yield parameters recorded in Dambatta were higher than those in BUK. In addition, the soils in the two sites have a high sand fraction. The soil in BUK was classified under the sandy loam textural class while the soil in Dambatta as loam sand, which implies a higher percentage of sand. Sandy soils have been observed and reported to be extremely

susceptible to nutrient loss through the soil profile because of their low water- and nutrient-holding capacity. Sandy soils and soils highly prone to losing nutrients through the soil profile generally have low available organic carbon content [14].

3.2.2. Coal-based fertilizer effects on the seed weight of soybean

Application of coal-based amendment greatly influenced soybean seed weight though fertilizer inputs alone did not produce statistical significance. Among the treatments, 50% NPK + 50% coal-based fertilizer (CF) reported the highest seed weight, followed closely by 75% NPK + 25% CF and 100% CF. Control and cow dung treatments produced relatively lower grain weights of 12.90 g and 12.96 g, respectively, which implies that coal-based nutrients can greatly enhance seed yield parameters when integrated with mineral fertilizers. Multiple studies support these observations. [15] and [16] reported that coal-based fertilizers enhance the soil's nutrient-holding capacity and yield in soybeans.

Results revealed a clear agronomic influence of coal-based fertilizers, especially when applied with NPK, because it enhanced soybean grain development. However, the fertilizer effects were not statistically significant, and the effects are likely due to improved soil structure, nutrient availability, and moisture retention, which are crucial during grain filling. [17] observed improved maize grain yield from coal-treated soils due to better nutrient synchronization and microbial activity.

The impact of location was highly significant, Dambatta outperforming BUK by a notable margin. This difference may be due to the more favourable edaphic or climatic conditions in Dambatta that supported a more effective utilization of applied nutrients and better grain filling.

3.2.3. The coal-based fertilizer effect on carbon gains in the soil

Coal-based inputs increase soil carbon gains by supplying stable organic carbon forms that enhance soil structure, microbial activity, and nutrient holding. Their carbon-rich composition promotes long-term carbon sequestration and soil fertility.

Carbon gain was slightly higher at Dambatta than at BUK, although this difference was not significant at 5% level. At Dambatta, the higher carbon gain could be ascribed to differences in microclimate, organic matter decomposition, or microbial activities in the soil. This validates the study of [18], which revealed that soil carbon gains are influenced by abiotic factors such as sunlight, rainfall, and micro-organism activities, which differ by location. The study of [19] showed that various agroecological zones led to changes in organic content in the soil as a result of the differences in soil properties and management history. However, the location did not drastically influence the impact of fertilizer treatments on carbon gains because the interaction (L x F) was not significant.

The most carbon gain in the soil was observed in 100% CF (16.58%), followed by 50% NPK + 50% CF (15.79%), showing that coal-based soil amendment either alone or in a balanced joint application with NPK greatly increased carbon build-up in the soil. These results suggest that coal-based fertilizer improves organic materials in the soil, likely by adding stable carbon compounds and the stimulation of microbial activity that stabilizes organic residues. Similar effects were documented by [16], [20], and [21], who confirmed that coal-based fertilizers increase organic carbon content in the soil and enhance the capturing of carbon. 100% NPK resulted in a moderate rise in soil carbon gain, most likely due to increased biomass production from roots and crop residues, which indirectly adds to soil organic matter. However, this is far less than solely CF or CF + NPK blends, as inorganic fertilizers lack organic carbon themselves. [22], [23], and [24] suggest that mineral fertilizers can produce modest soil organic carbon (SOC) increases (often via greater biomass returns), but combined organic + mineral systems or organic inputs generally produce larger and more persistent SOC gains. Cow dung (1.03%), although organic, resulted in the lowest carbon gain, which may be due to rapid mineralization and low carbon recalcitrance compared to coal-based sources. [25] reported that organic manures like cow dung decompose rapidly and may lead to short-term fertility improvement but have a long-term carbon sequestration potential.

Results show that although coal-based fertilizer (CF) and its combinations with NPK produced numerically higher soil carbon gains, the effects were not statistically significant at 5% level of significance, which was to be expected because soil carbon sequestration occurs slowly and short-term field experiments often fail to capture measurable changes [26, 27]. Also, soil organic carbon content is highly spatially different, especially in Sudan Savannah environments where high sunlight and seasonal drought increases organic matter breakdown, leading to increased experimental error and suppressing the effects of various treatments [27, 28]. Inorganic inputs mainly facilitate soybean growth rather than directly enhancing stable soil carbon stocks, whereas carbon-based inputs such as coal-derived amendments tend to add stable organic carbon that requires longer periods to be incorporated into soil organic carbon stocks [29].

In addition, preliminary studies often suggest that soil organic carbon has an observed increase without significant effect, stressing the importance of long-term experiments to affirm carbon gains on fertilizer-amended soil [26, 28].

4. Conclusions

The study reveals that when NPK is combined with coal-based fertilizer in soybean production, it increases soil carbon gains and leads to sustainable soil fertility management. 100% CF and 50% CF + 50% NPK treatments, which

reported the highest soil carbon gains, indicated that coal fertilizer contributes to long-term carbon storage through improved organic matter stability and nutrient sequestration.

This research on soybean further revealed that applying coal-based fertilizer would impact the yield component. The application of 50% NPK + 50% CF treatment had the highest influence on the yield parameter (seed weight) of soybean. Further research should assess long-term effect on soil health and verify these findings across different agro-ecological zones.

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