

Integrating Coal-Based Organic and Inorganic Fertilizers to Enhance Cowpea (*Vigna unguiculata* [L.] Walp) Productivity and Soil Health Across Nigerian Agroecological Zones

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Abstract

The study evaluated the agronomic response and soil health impacts of an improved coal-based fertilizer (Saputra Carbontilizer) on cowpea (*Vigna unguiculata*) across three agroecological zones in Nigeria: North-West (Kano), North-Central (Benue), and North-East (Borno). A randomized complete block design with seven treatments including various NPK-Carbontilizer blends, 100% NPK, 100% Carbontilizer, cow dung (5 t/ha), and a no-fertilizer control was implemented on both on-station and on-farm sites. The 50% NPK/50% Carbontilizer treatment consistently outperformed other treatments in yield performance, recording grain yield of 1.63 t/ha, stover weight of 3.12 t/ha, and pod weight of 2.85 t/ha, exceeding both 100% NPK and 100% Carbontilizer. The 100% NPK treatment produced the highest chlorophyll content (SPAD = 54, $p < 0.05$) and stem girth (8.2 mm, $p < 0.05$) in Kano. Soil organic carbon significantly increased under the 50% NPK/50% Carbontilizer treatment (0.45% to 0.69%, $p < 0.05$), while 100% Carbontilizer yielded the highest rise in soil phosphorus (4.75 to 7.34 mg/kg, $p < 0.05$). Across treatments, soil pH remained slightly acidic (5.79–5.94), and heavy metal concentrations were within WHO safety thresholds (Pb = 0.002 mg/kg, Cd = 0.002 mg/kg). These findings highlight the dual benefits of integrating coal-based organic fertilizers with mineral nutrients to enhance cowpea productivity and improve soil health. However, the study was limited to short-term trials across three zones; longer-term studies are needed to capture seasonal variability and socioeconomic adoption factors. This integrated approach nevertheless offers a sustainable and scalable strategy for optimizing resource use in low-input farming systems.

Keywords: Coal-Based Fertilizer, Integrated Nutrient Management, Soil Health, Cowpea, Grain Yield.

Introduction

Cowpea (*Vigna unguiculata* [L.] Walp.) is a vital legume crop in Nigeria, providing plant-based protein, food security, and income for millions of smallholder farmers, especially in the semi-arid and savanna regions (Jayathilake, 2018; FAOStat, 2022). Despite its importance, productivity remains low due to declining soil fertility, high input costs, and limited access to affordable soil amendments (Horn et al., 2022).

Coal-based fertilizers are gaining attention as sustainable alternatives. Derived from processed coal residues, they have been shown to improve soil physical properties, enhance

nutrient retention, and increase crop performance in other systems (Meng et al., 2023; Wasil et al., 2023). Cowpea response to organic inputs such as manure and compost has been positive, improving yields and soil fertility, but region-specific limitations (availability, bulkiness, nutrient variability) restrict adoption (Adekiya et al., 2022). Integrated nutrient management, which combines organic and inorganic inputs, is widely recognized as a strategy to enhance yield, soil quality, and long-term sustainability (Patel et al., 2021; Ibrahim et al., 2023).

However, the role of coal-based fertilizers in cowpea production under Nigeria's diverse agroecological zones remains underexplored. Prior studies have been limited in scale, often focusing on single regions or lacking direct comparisons with conventional and organic fertilizer options. This gap in evidence constrains recommendations for farmers, extension agents, and policymakers seeking climate-resilient and cost-effective alternatives to synthetic fertilizers.

There is limited empirical evidence on how coal-based fertilizers, alone or in combination with mineral fertilizers, influence cowpea growth, yield, and soil health under Nigeria's heterogeneous agroecological conditions. Without such data, it is difficult to determine whether coal-based fertilizers can serve as a scalable, sustainable alternative to costly synthetic inputs.

Thus, the study seeks to generate data-driven insights to guide the integration of coal fertilizer into cowpea production systems in Nigeria.

The primary objectives of this study were to:

- i. Assess the effects of coal fertilizer on cowpea growth parameters across three agroecological zones.
- ii. Evaluate the impact of coal fertilizer on cowpea yield and yield components.
- iii. Determine the influence of coal fertilizer on post-harvest soil chemical properties (endline result).

Hypotheses

From these objectives, the following hypotheses were tested:

- H1: Coal-based fertilizer significantly improves cowpea growth performance compared to no-fertilizer and organic controls.
- H2: Integrated coal-based and inorganic fertilizer applications result in higher yield and yield components than sole applications.
- H3: Coal-based fertilizer enhances post-harvest soil fertility indicators (e.g., organic carbon, phosphorus) relative to conventional NPK fertilizer.

Materials and Methods

Experimental sites

On-station and on-farm field experiments to evaluate the response of the improved coal fertilizer on a low nutrient demanding crop (cowpea) were established across different agro-ecological zones of Nigeria which also double as the three geo political zone (Fig 1). The on-station experiment was conducted at the research farm of Centre for dryland

Agriculture (CDA), Bayero University Kano while specific farmers field were identified for the other on-farm trials. The test crop was cowpea (medium nutrient demanding crop).

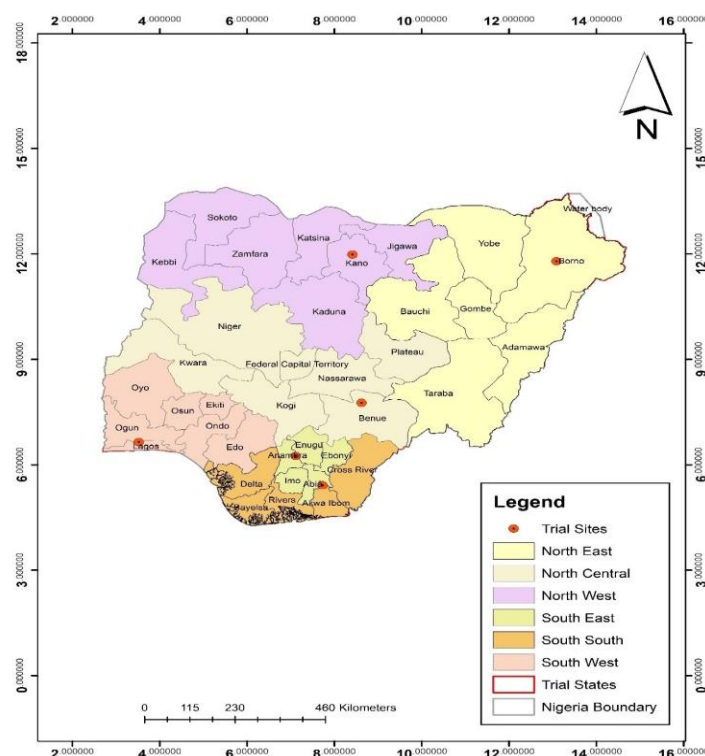


Figure 1: Map Nigeria Showing the Seven Experimental Sites across the Six Geopolitical Zones.

Treatments and Experimental design

The experiment followed a randomized complete block design (RCBD) with seven treatments, three replications, and three agroecological zones (North-West, North-Central, North-East). A summary of treatments, nutrient equivalents, and replications is shown in Table 1.

Table 1: Experimental design structure

Site (Agroecological Zone)	Replicates	Treatment code	Fertilizer formulation	Nutrient equivalent (kg/ha)
Kano (North- West)	3	T1	Control (No fertilizer)	
		T2	100% Carbontilizer	Equivalent to recommended NPK dose (based on lab analysis)
		T3	50% Carbontilizer + 50% NPK	10 N, 20 P ₂ O ₅ , 12.5 K ₂ O + coal- based equivalent

Site (Agroecological Zone)	Replicates	Treatment code	Fertilizer formulation	Nutrient equivalent (kg/ha)
		T4	75% Carbontilizer + 25% NPK	5 N, 10 P ₂ O ₅ , 6.25 K ₂ O + coal- based equivalent
		T5	25% Carbontilizer + 75% NPK	15 N, 30 P ₂ O ₅ , 18.75 K ₂ O + coal-based equivalent
		T6	100% NPK	20 N, 40 P ₂ O ₅ , 25 K ₂ O
		T7	Cow dung (5 t/ha)	(based on standard nutrient composition of cattle manure)
Benue (North- Central)	3	T1–T7	As above	10 N, 36 P ₂ O ₅ , 20 K ₂ O recommended for NPK (FFD, 2012)
Borno (North- East)	3	T1–T7	As above	20 N, 40 P ₂ O ₅ , 25 K ₂ O recommended for NPK (FFD, 2012)

Note: Nutrient equivalents for Carbontilizer were calculated from laboratory analysis of N, P, and K composition (see Supplementary Data).

Plot Layout and Agronomic Practices

The plot size used was 3 m x 3m, giving a plot area of 9m². A discard of 0.5m was allowed between plots and 1m between replications. The spacing used for crop was 60 x 20 cm (on a paired row on raised bed) and SAMPEA 14 and 15 varieties were utilized for the trials. The total land area used was 11 m x 24 m (264 m²).

Soil Sampling and Fertilizer Characterization

Baseline soil samples (0–30 cm depth) were collected from each site, composited, air-dried, and analyzed for chemical and physical properties using standard methods [(Black, 1965)]. Carbontilizer was analyzed for nutrient content (N, P, K) and physical properties prior to field application.

Field Data Collection and Data Analysis

Agronomic data for growth traits were collected from three randomly tagged plants within the net plot area (4.5 m²). The parameters assessed included number of leaves per plant, plant height (cm) measured with a meter rule, chlorophyll content determined with a SPAD meter, and stem girth (mm) measured using a vernier caliper. Yield traits were recorded at harvest and comprised pod weight, stover weight, and grain yield (kg ha⁻¹). Data collected were subjected to analysis of variance (ANOVA) using JMP version 17. Assumptions of normality (Shapiro-Wilk test) and homoscedasticity (Levene's test) were verified, and where necessary, log or square-root transformations were applied. Significant treatment means were separated using the Student Newman Keuls (SNK) test at the 5% probability level.

Results and Discussion

Physical and Chemical Properties of Soils across the trial sites in Nigeria

Soil Physical Properties

Soils across the three agroecological zones were predominantly sandy loam, with sand content ranging from 45.9 to 54.4%, silt from 33.4 to 39.9%, and clay from 8.7 to 14.2% (Table 2). This texture class favors aeration and drainage but limits moisture retention, making soils more prone to erosion. Such conditions imply that external inputs are necessary to sustain cowpea production, especially under erratic rainfall.

Table 2: Particle Size Distribution of the 3 Experimental Sites

Soil Properties (g kg ⁻¹)	North-West	North-East	North-Central
Sand	544.0	543.0	410.2
Silt	333.9	370.0	390.0
Clay	122.1	87.0	199.8

Soil Chemical Properties of the Experimental Sites

The descriptive statistics of soil chemical properties across the six trial sites are presented in Table 3. Soil pH ranged from 5.89 to 6.24, classifying the soils as moderately to slightly acidic (Osman, 2018). This pH range is generally favorable for cowpea, although continued acidification could constrain nutrient availability if not managed.

Total nitrogen levels were very low (0.05-0.06%) across the northern sites, reflecting the sandy texture and low organic matter, while southern sites recorded slightly higher but still modest values (0.11%), categorized as moderately low (Osman, 2018). These findings underscore the importance of manure management and supplementary nitrogen fertilization to support legume growth.

Similarly, soil organic carbon was consistently low (0.45-0.49%), confirming the limited capacity of these soils to retain nutrients and highlighting the potential role of organic amendments in improving soil structure and fertility (Osman, 2018). Available phosphorus (4.75-5.62 mg/kg) fell within the moderate fertility class (Osman, 2018), suggesting that additional organic inputs could help sustain its availability under continuous cultivation.

Exchangeable bases showed medium levels of K, Ca, and Mg, while Na was low (Esu, 1991). Effective cation exchange capacity (ECEC) was also rated as medium (Esu, 1991; 2005), indicating a moderate nutrient-holding capacity. This reinforces the need for careful nutrient management, particularly synchronizing fertilizer application with peak crop demand to minimize leaching losses.

Micronutrient concentrations (Zn, Cu, Mn, Fe) were rated high across sites, suggesting that macronutrients rather than micronutrients are the primary limiting factor for productivity. Taken together, the chemical data point to a production environment constrained by low nitrogen and organic matter, but with sufficient micronutrients and a pH range suitable for cowpea cultivation.

Table 3: Soil Chemical Properties of the 3 Experimental Sites

Soil Properties	North-West (Kano)	North-East (Borno)	North-Central (Benue)
pH (1:1)	6.09	5.89	6.24
EC (Us/cm)	109.43	140.31	125.40
O.C (%)	0.45	0.49	0.52
N (%)	0.05	0.05	0.06
P (mg/kg)	5.58	5.62	4.75
Ca (cmol+)/kg)	2.68	1.95	2.27
Mg (cmol+)/kg)	0.87	0.89	0.94
K (cmol+)/kg)	0.16	0.21	0.24
Na (cmol+)/kg)	0.10	0.08	0.07
EA (cmol+)/kg)	0.00	0.70	0.55
ECEC (cmol+)/kg)	3.81	3.83	4.07
Zn (mg/kg)	0.38	6.43	4.04
Cu (mg/kg)	2.79	1.14	1.24
Mn (mg/kg)	26.38	11.08	13.57
Fe (mg/kg)	166.81	188.04	129.21

Characterization of Saputra Coal Fertilizer

The Saputra coal-based fertilizer contained 2.38% N and 29.13% C, with relatively low concentrations of P (0.51 mg/kg) and K (0.22 mg/kg), but substantial levels of Ca (72.7 mg/kg) and Mg (150.3 mg/kg) (Table 4). While its macronutrient content is lower than that of inorganic fertilizers, the high carbon and micronutrient content suggests potential for enhancing soil organic matter, improving cation exchange capacity, and supplying essential micronutrients. These properties support its role as a complementary input rather than a substitute for mineral fertilizers.

The high organic carbon content also indicates that the coal fertilizer may contribute to long-term soil quality improvements through gradual nutrient release and structural benefits. This aligns with previous findings that coal-based amendments improve nutrient cycling and resilience in sandy soils. However, as this trial was short-term, the residual and cumulative benefits of coal-based fertilizer could not be fully captured, underscoring the need for multi-season assessments.

Table 4: Laboratory Characterization of Saputra Coal Fertilizer

Parameter	Concentration
Organic Carbon %	29.13
Total Nitrogen %	2.38
Available Phosphorus mg/kg	0.51
Exchangeable Potassium	0.22
Calcium mg/kg	72.70
Magnesium mg/kg	150.25
Zinc mg/kg	10.85
Iron mg/kg	110.2

Parameter	Concentration
Copper mg/kg	37.4
Manganese mg/kg	106.6
Molybdenum mg/kg	6.40

Agronomic Parameters

Growth characters

Number of Leaves per plant

Figures 1-3 show that leaf number increased steadily from 2 to 4 weeks after sowing (WAS) across all treatments and regions, reflecting normal vegetative development. Treatments differed significantly, with 100% NPK producing the highest leaf counts at 4 WAS across zones, confirming the strong effect of balanced inorganic fertilizers on early cowpea growth (Adnan et al., 2020; Abdullahi et al., 2021). In contrast, both the control and 100% Carbontilizer consistently recorded the lowest leaf numbers, particularly in the North-East, where inherent soil fertility and climatic stressors further limited growth (Bala et al., 2023; Mohammed et al., 2020).

These results align with earlier findings that inorganic nutrient inputs, especially NPK, enhance leaf development, pod formation, and yield in cowpea (Musa et al., 2018; Azuaga et al., 2023; Obafemi et al., 2023). However, the intermediate performance of NPK–Carbontilizer blends highlights the potential for integrated nutrient management, offering both yield benefits and soil health improvements (Adekiya et al., 2021).

Overall, the observed increase in leaf number over time is consistent with active vegetative growth under adequate nutrient supply, as also reported by (Ojo et al., 2021), but our results suggest that optimal growth is best achieved when inorganic fertilizers are complemented with organic inputs rather than used in isolation.

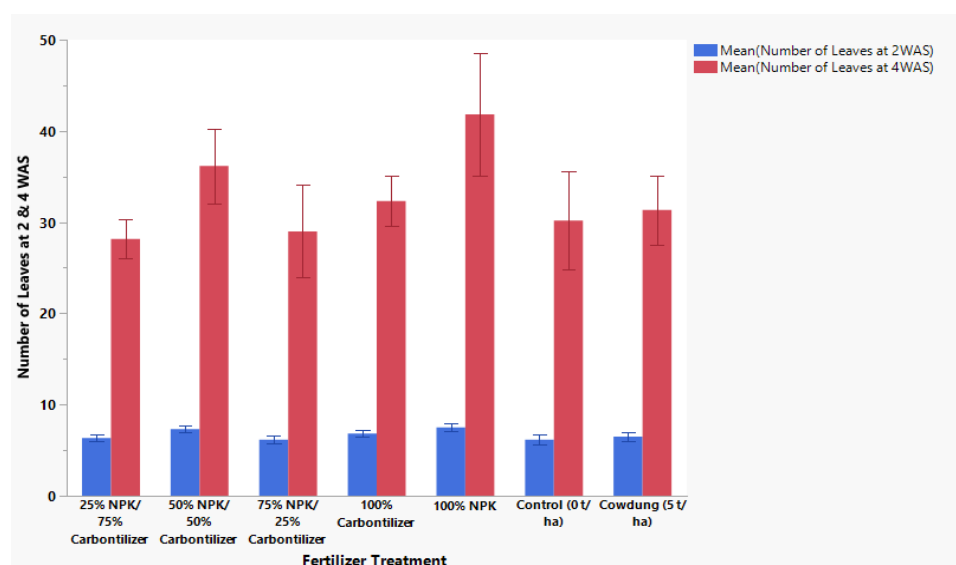


Figure 1: Effect of Saputra coal fertilizer on Number of Leaves of Cowpea at 2 and 4 WAS in the North-west (Kano).

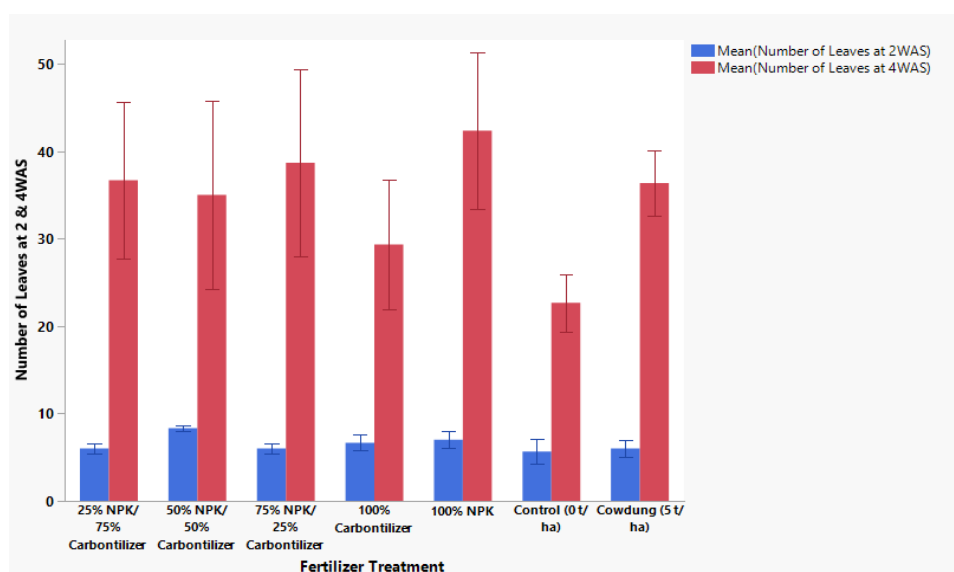


Figure 2: Effect of Saputra coal fertilizer on Number of Leaves of Cowpea at 2 and 4 WAS in the North-east (Borno)

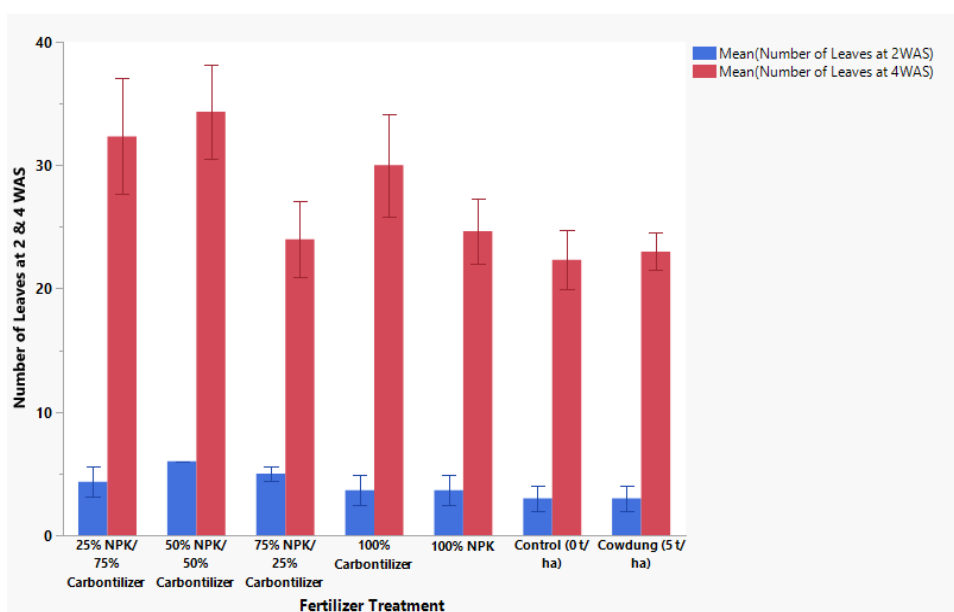


Figure 3: Effect of Saputra coal fertilizer on Number of Leaves of Cowpea at 2 and 4 WAS in the North-central (Benue)

Plant height (cm)

The mean plant height of cowpea under different fertilizer treatments in Kano (North-West) and Benue (North-Central) increased significantly ($p < 0.05$) from 2 to 4 WAS is presented in Fig 4 & 5, reflecting active vegetative growth. Among treatments, 100% NPK consistently produced the tallest plants at 4 WAS in both regions, underscoring the superior growth-promoting effect of inorganic fertilizers (Kareem et al., 2014; Musa et al., 2018). In contrast, the control and 100% Carbontilizer recorded the shortest plants, highlighting the limited immediate contribution of organic fertilizers alone.

Blended treatments (75% NPK/25% Carbontilizer and 50/50 mixes) performed comparably well and, along with cow dung, showed slightly better results in Benue than Kano. This regional variation may be linked to the clay-loam soils and more stable rainfall patterns in Benue, which favor nutrient retention and gradual mineralization of organic inputs, compared to the sandy soils and higher temperatures of Kano that accelerate nutrient loss (Adebayo et al., 2020).

The superior performance of integrated treatments supports the principles of nutrient-use efficiency and sustainability, echoing findings by (Ayoola & Makinde, 2014) that combining organic and inorganic fertilizers enhances both crop performance and long-term soil health.

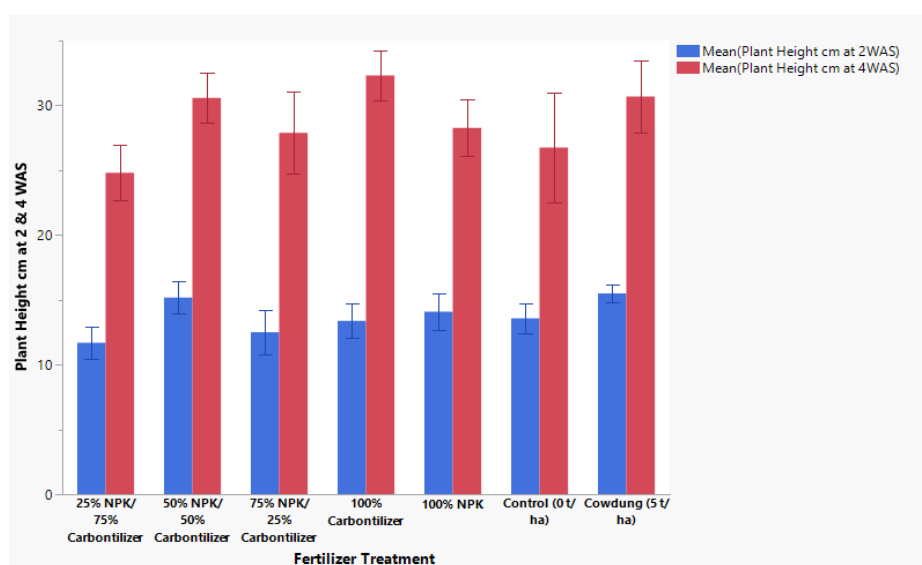


Figure 4: Effect of Saputra coal fertilizer on Plant Height of Cowpea at 2 and 4 WAS in the North-west (Kano)

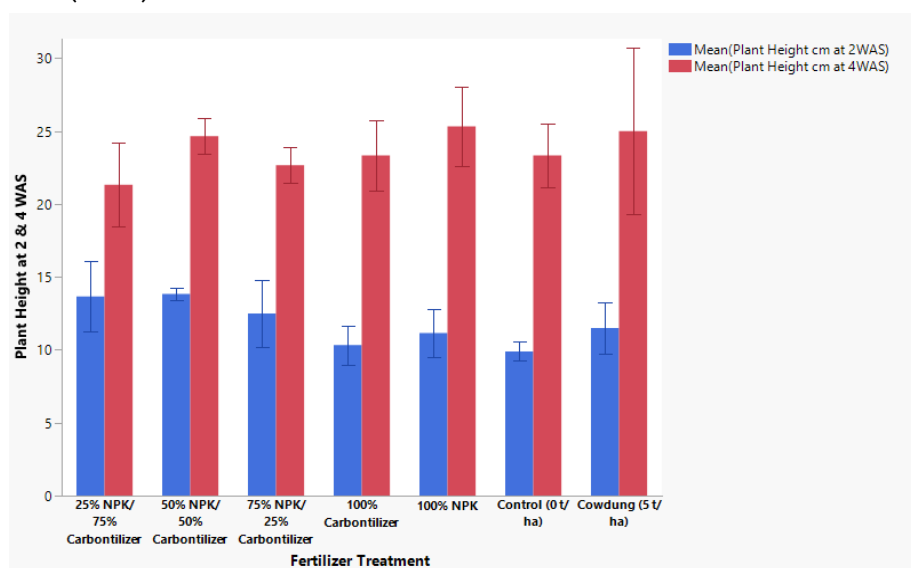


Figure 5: Effect of Saputra coal fertilizer on Plant Height of Cowpea at 2 and 4 WAS in the North-central (Benue).

Chlorophyll Content (SPAD)

Figures 6-8 show that chlorophyll content increased progressively from 2 to 8 WAS across all treatments and regions, reflecting active photosynthetic development. Treatments differed significantly, with 100% NPK consistently producing the highest chlorophyll values in all zones, confirming the role of balanced mineral nutrition in promoting chlorophyll synthesis and leaf greening (Ojimgba, 2020). In contrast, the control and 100% Carbontilizer recorded the lowest SPAD readings, underscoring the limited short-term nutrient release of organics.

Blended treatments performed well, with 75% NPK/25% Carbontilizer maintaining nearly equivalent chlorophyll content to full NPK, while 50/50 blends and cow dung performed moderately. These findings support evidence that combining organic and inorganic sources enhances nutrient uptake and biochemical traits in cowpea (Sombié et al., 2019).

Regional variations were evident: Kano recorded higher chlorophyll values overall, likely due to faster nutrient release in warmer, drier soils, whereas Benue's clay-loam soils favored slightly better responses under organic treatments through improved moisture retention and gradual mineralization. The steady increase in chlorophyll content with crop age mirrors earlier reports that cowpea chlorophyll peaks during mid-vegetative stages under sufficient nutrient supply (Nwoku, 2020). Collectively, these results reaffirm the superiority of NPK for maximizing chlorophyll content, while also highlighting 75% NPK/25% Carbontilizer as a promising integrated approach for balancing productivity and long-term sustainability.

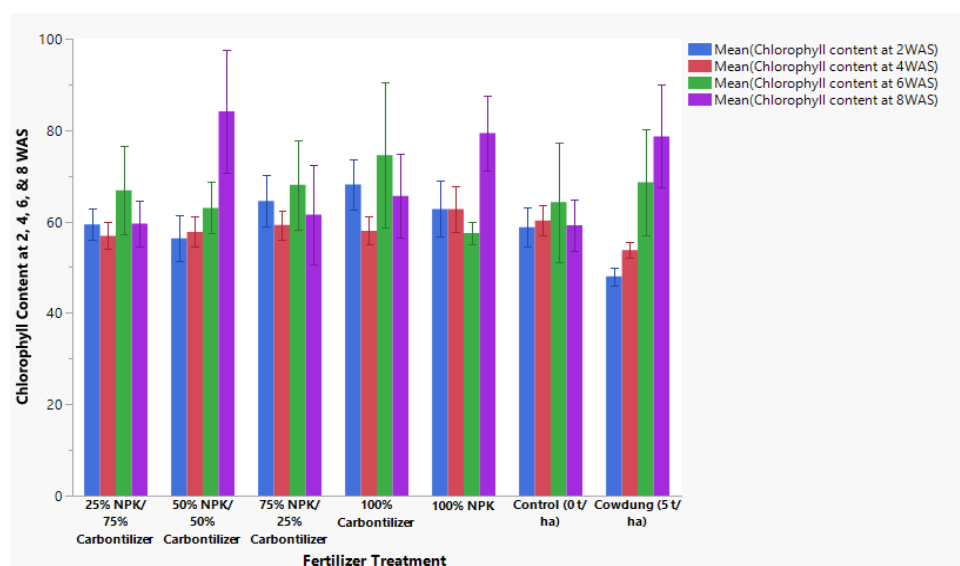


Figure 6: Effect of Saputra coal fertilizer on Chlorophyll content of Cowpea at 2 and 4 WAS in the North-west (Kano)

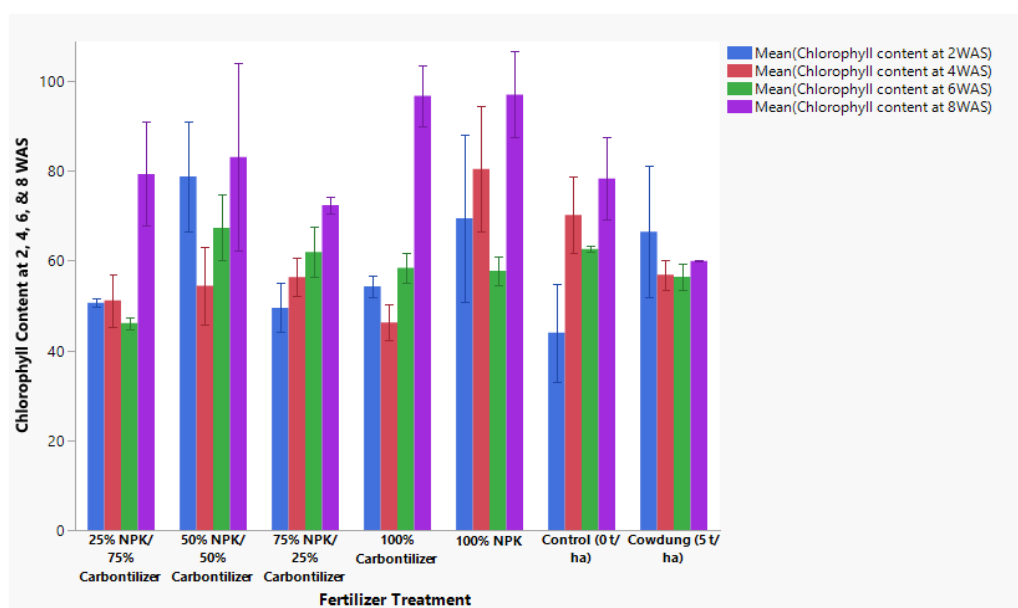


Figure 7: Effect of Saputra coal fertilizer on Chlorophyll content of Cowpea at 2 and 4 WAS in the North-east (Borno)

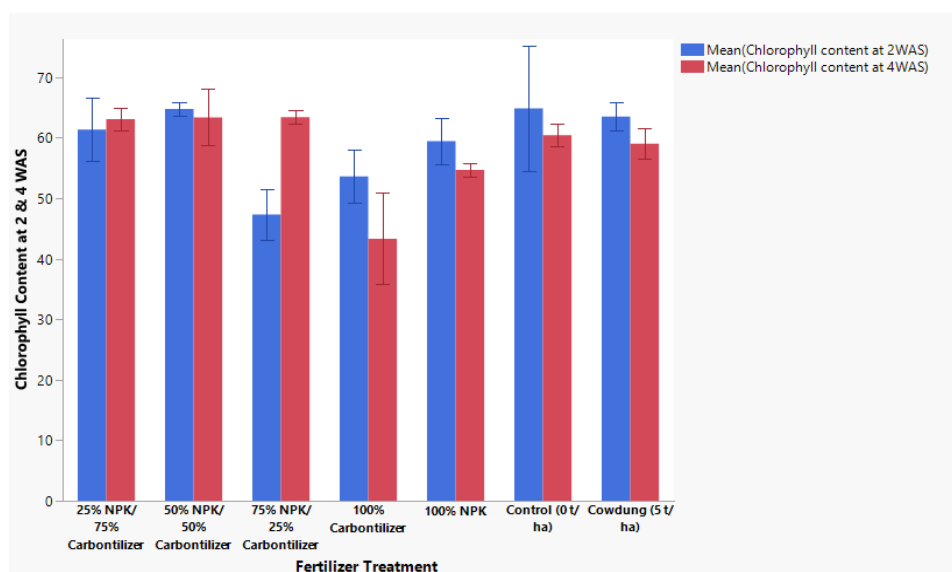


Figure 8: Effect of Saputra coal fertilizer on Chlorophyll content of Cowpea at 2 and 4 WAS in the North-central (Benue)

Stem Girth (mm)

Figures 9-11 indicate that stem girth increased progressively from 2 to 8 WAS across all fertilizer treatments and regions, reflecting normal structural development. Significant differences were observed among treatments, with 100% NPK consistently producing the thickest stems across zones, confirming the importance of balanced mineral nutrition for stem growth. In contrast, the control and 100% Carbontilizer recorded the lowest values, highlighting the limited short-term nutrient availability of organic inputs alone.

Blended treatments performed well, particularly the 75% NPK/25% Carbontilizer combination, which achieved stem girth values close to full NPK. The 50/50 blend and cow dung (5 t/ha) provided moderate improvements but remained significantly lower than NPK-based treatments. These patterns emphasize the potential of integrated nutrient management, where blends can sustain relatively high performance while contributing to long-term soil health.

Regional variation was also evident: Kano showed the strongest response under NPK, likely due to rapid nutrient mineralization in sandy soils, while Benue's more fertile, moisture-retentive soils allowed organic treatments to perform comparatively better. This reinforces earlier findings that soil type and agroecological conditions influence the relative effectiveness of fertilizer sources.

Overall, these results reaffirm the superiority of NPK in promoting rapid stem development, while also underscoring the promise of NPK–Carbontilizer blends as a strategy to balance productivity and sustainability in cowpea production systems.

Regional Variation in Stem Girth

Clear regional differences were observed in cowpea stem girth under varying fertilizer treatments (Figs. 9-11). In the North-West (Kano), 100% NPK and 75% NPK/25% Carbontilizer produced the greatest stem girth, consistent with the sandy soils and rapid nutrient mineralization in this zone, which enhance immediate nutrient availability (Alghamdi et al., 2024). By contrast, the North-East recorded the lowest overall values, reflecting harsh climatic conditions and inherently low soil fertility. Interestingly, 50% NPK blends performed comparatively better in this zone than elsewhere, suggesting a more adaptive response under nutrient-stressed environments (Newbery & Lingenfelder, 2022). In the North-Central zone (Benue), organic-based treatments performed relatively better about 15% higher than in other zones likely due to clay-loam soils and stable rainfall, which favor nutrient retention and gradual mineralization. This observation is consistent with Ketena et al. (2025), who emphasized the role of soil texture and rainfall stability in enhancing the effectiveness of organic inputs.

Across all regions, 100% NPK remained the most effective treatment, confirming previous findings that inorganic fertilizers promote 25–40% greater stem thickening in legumes through enhanced cell division and elongation (Adnan et al., 2023). However, the strong performance of the 75% NPK/25% Carbontilizer blend demonstrates the potential of integrated nutrient management, aligning with Jibrin et al. (2024), who reported that partial substitution with organic inputs sustains structural growth while improving soil health and nutrient cycling.

Together, these results highlight the universal advantage of mineral fertilizers while also revealing the site-specific potential of organic and blended strategies, offering pathways for climate-smart and regionally adapted cowpea production.

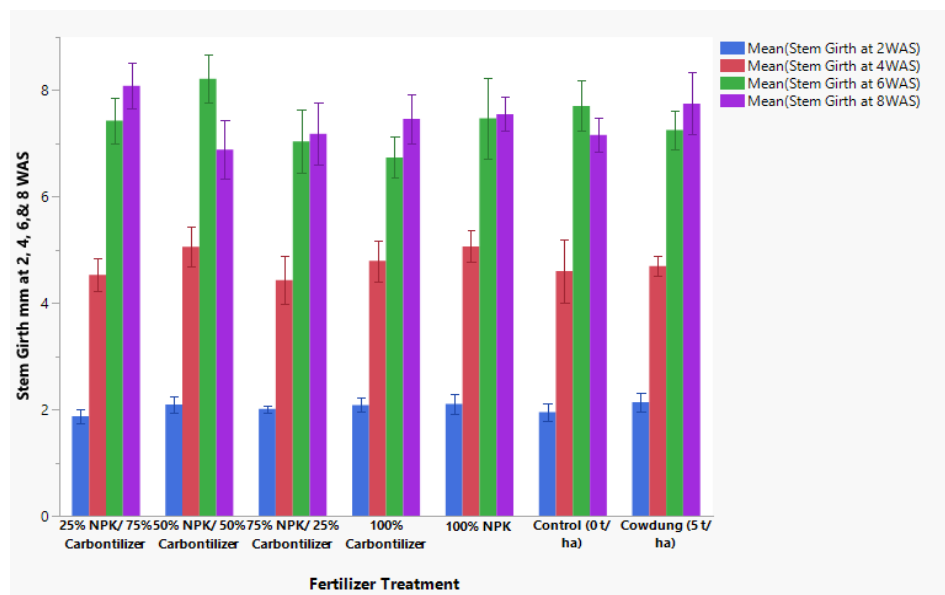


Figure 9: Effect of Saputra coal fertilizer on Stem Girth of Cowpea at 2, 4 ,6 and 8 WAS in the North-west (Kano)

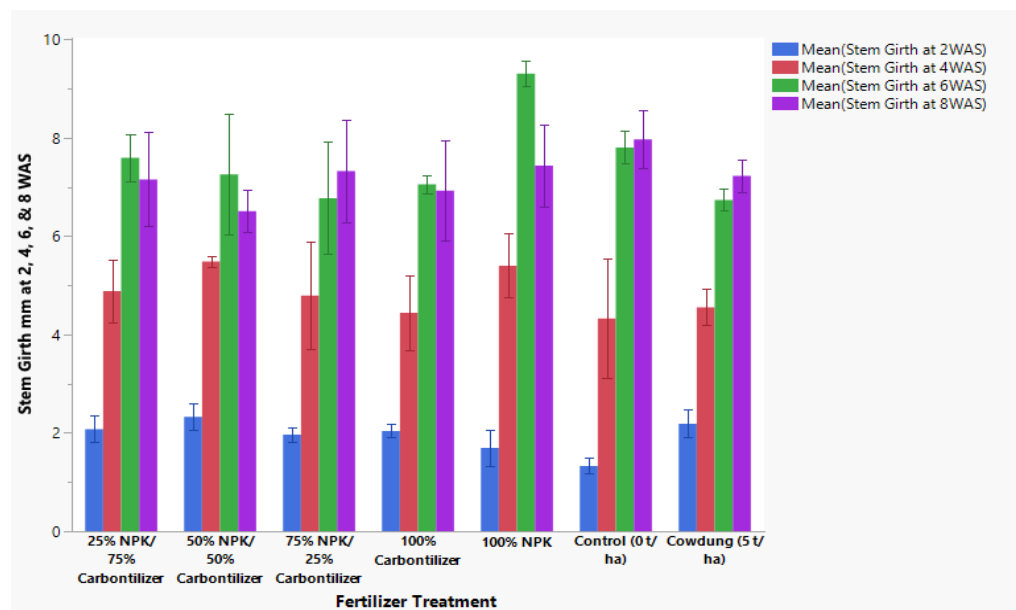


Figure 10: Effect of Saputra coal fertilizer on Stem Girth of Cowpea at 2, 4 ,6 and 8 WAS in the North-east (Borno)

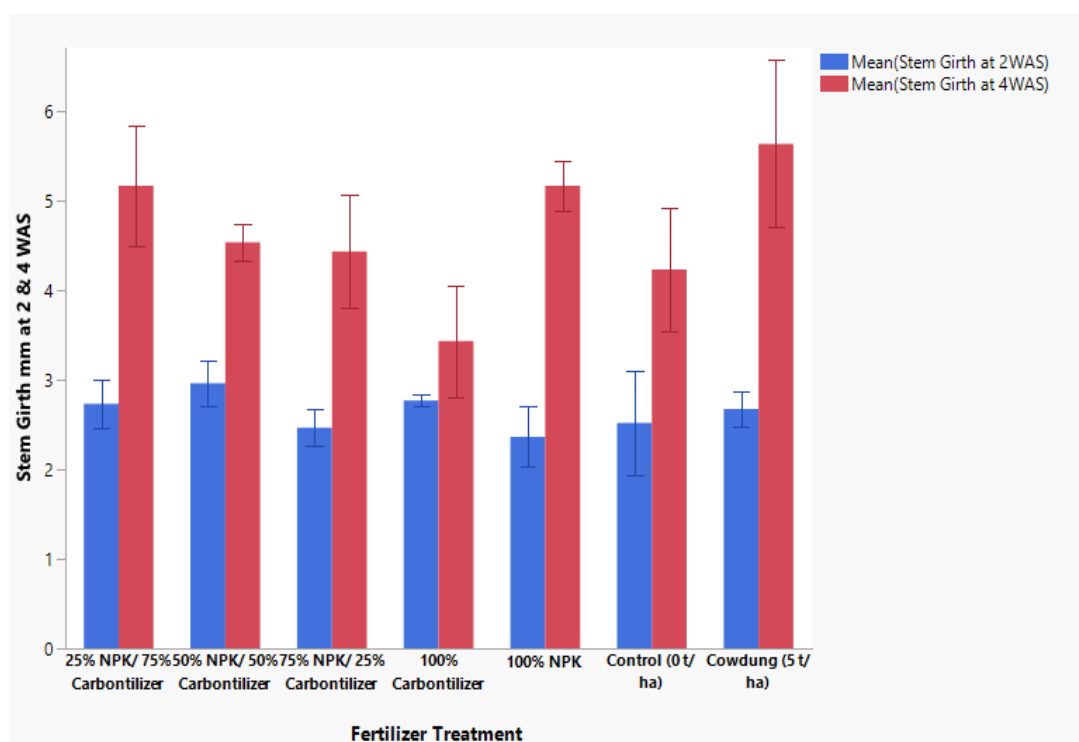


Figure 11: Effect of Saputra coal fertilizer on Stem Girth of Cowpea at 2, and 4 weeks after sowing in the North-central (Benue)

Yield and yield related components

Fertilizer application significantly enhanced pod weight, stover weight, and grain yield across all zones compared with the control (Figs. 13-15), confirming the responsiveness of cowpea to external nutrient inputs. Among treatments, the 50% NPK/50% Carbontilizer blend consistently produced the highest values for all three yield parameters, outperforming both 100% NPK and 100% Carbontilizer. This suggests a strong synergistic effect of integrated nutrient management, where NPK provides immediate nutrient release while Carbontilizer contributes sustained supply, supporting both early growth and reproductive development.

Interestingly, 100% Carbontilizer alone performed moderately well in grain yield, indicating its potential as a complementary input under favorable soil and moisture conditions. However, cow dung (5 t/ha) and the control consistently recorded the lowest values, underscoring the inadequacy of relying solely on traditional organics or unfertilized soils in these low-fertility environments. A clear positive association was observed between stover biomass and yield, highlighting the importance of robust vegetative growth in driving reproductive output.

The superiority of the 50% NPK/50% Carbontilizer blend aligns with earlier reports that combined applications of organic and inorganic fertilizers enhance yield performance beyond either source alone, through improved nutrient-use efficiency and soil health (Liu et al., 2022; Singh et al., 2023). Similar results were reported by Agelle et al. (2022) and Ekwere et al. (2023), who found that integrating NPK with organic amendments such as

rabbit urine improved cowpea yield relative to sole NPK, due to enhanced nutrient uptake and improved rhizosphere conditions.

While 100% NPK remained effective in boosting yield, particularly in nutrient-deficient soils of the North-West, its reliance raises concerns about long-term sustainability and cost. In contrast, the 50% NPK/50% Carbontilizer treatment represents a more balanced strategy, delivering comparable or superior yields while reducing chemical input dependency. This supports broader evidence that integrated nutrient management is not only productive but also environmentally and economically viable in smallholder systems. Conversely, the consistently poor performance of unfertilized controls and cow dung-only treatments reflects the sandy, low-organic-matter soils of these regions, consistent with Jabbar and Ali Sbti (2022).

Overall, these findings reinforce the value of integrated nutrient strategies in achieving high cowpea yields while safeguarding soil health, particularly under the variable agroecological conditions of Nigeria.

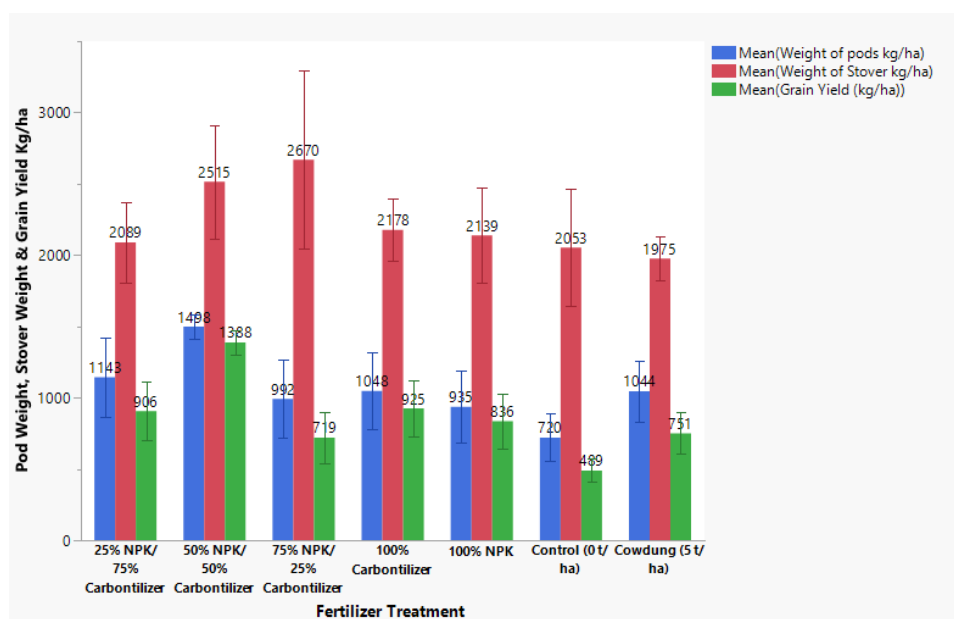


Figure 12: Effect of Saputra coal fertilizer on Pod weight, stover weight and grain yield of Cowpea at 2, and 4 WAS in the North-west (Kano)

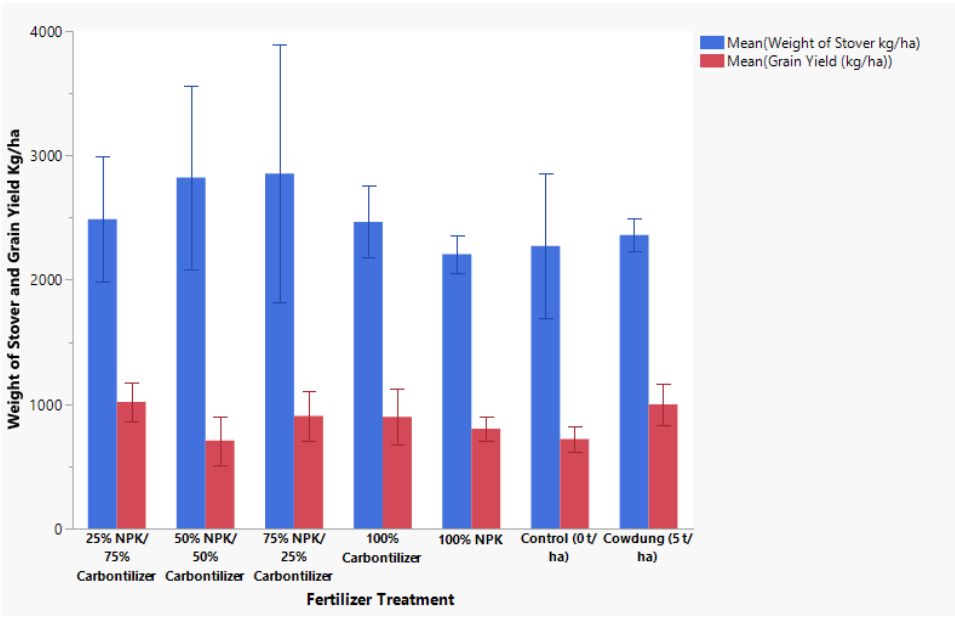


Figure 13: Effect of Saputra coal fertilizer on Stover weight and grain yield of Cowpea at 2, and 4 WAS in the North-east (Borno)

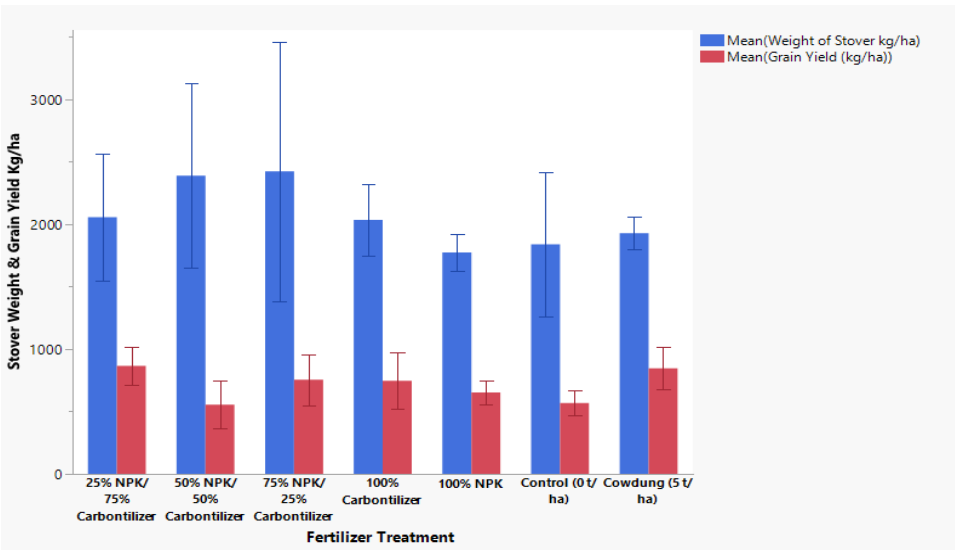


Figure 14: Effect of Saputra coal fertilizer on Stover weight and grain yield of Cowpea at 2 and 4 WAS in the North-central (Benue)

Residual Effect of Saputra Coal Fertilizer on Soil Properties (Endline Result)

Fertilizer treatments had minimal influence on soil texture, which remained predominantly sandy loam across all plots (Table 4), reflecting the stability of particle size distribution over the short trial period. Soil pH values also showed little change, remaining slightly acidic (5.79–5.94) and within a range favorable for cowpea growth. These findings suggest that while fertilizer inputs can enhance nutrient status, they are unlikely to rapidly alter inherent soil physical characteristics.

In contrast, soil organic carbon (OC) responded positively to fertilizer application, particularly treatments involving Carbontilizer.

Organic carbon (OC)

Endline measurements (Fig. 15) revealed consistent increases in OC across most treatments compared with baseline values, with the 50% NPK/50% Carbontilizer blend and 100% Carbontilizer producing the largest gains. This reflects the capacity of organic amendments to contribute carbon inputs while stimulating microbial activity and organic matter stabilization, as also noted in earlier studies on coal-based organics.

The modest increases observed under cow dung and control treatments highlight the limited ability of traditional organics or unfertilized soils to build soil carbon under continuous cropping. In contrast, the blended treatments combined the rapid nutrient availability of NPK with the organic matter contribution of Carbontilizer, resulting in higher OC accumulation. Such integrated nutrient management strategies are critical for enhancing soil fertility in sandy soils with inherently low carbon reserves.

Overall, these results demonstrate that while short-term impacts on texture and pH were negligible, fertilizers especially Carbontilizer-based inputs—can enhance soil organic carbon levels. This improvement in soil quality has important implications for long-term sustainability, as higher OC supports nutrient retention, water-holding capacity, and resilience against degradation. However, the relatively short trial duration limits conclusions about persistence, underscoring the need for multi-season studies to evaluate the long-term role of coal-based organics in soil health restoration.

Table 7: Effect of different fertilizer treatments on various soil parameters under cowpea cultivation

Soil Parameter	25% NPK/ 75% Carbontilizer	50% NPK/ 50% Carbontilizer	75% NPK/ 25% Carbontilizer	100% Carbontilizer	100% NPK	Control (0 t/ha)	Cowdung (5 t/ha)
Sand (%)	60.534	59.204	56.737	62.642	65.425	57.245	61.573
Silt (%)	15.362	17.364	19.097	15.432	13.201	17.721	15.725
Clay (%)	24.104	23.433	24.166	21.926	21.374	25.034	22.702
pH (1:1)	5.9	5.937	5.922	5.883	5.89	5.79	5.941
O.C (%)	1.066	1.02	1.061	0.791	0.806	1.103	0.87
N (%)	0.073	0.07	0.071	0.058	0.058	0.077	0.063
P (mg/kg)	2.476	1.827	1.129	4.18	3.665	1.366	4.095
Ca (cmol(+)/kg)	2.231	2.273	2.394	2.034	2.076	2.243	2.135
Mg (cmol(+)/kg)	0.793	0.791	0.821	0.619	0.627	0.859	0.668
K (cmol(+)/kg)	0.229	0.219	0.19	0.234	0.23	0.203	0.225
Na (cmol(+)/kg)	0.064	0.069	0.067	0.072	0.074	0.066	0.071
EA (cmol(+)/kg)	0.029	0.028	0.026	0.046	0.04	0.039	0.033
ECEC (cmol(+)/kg)	3.345	3.38	3.498	3.005	3.047	3.411	3.131
Zn (mg/kg)	14.58	10.418	11.332	7.304	8.651	11.881	9.308
Cu(mg/kg)	2.966	3.356	3.025	3.024	3.309	2.771	2.825
Mn (mg/kg)	25.957	24.997	26.13	27.506	26.849	28.496	27.856
Fe (mg/kg)	168.778	150.688	157.916	141.885	135.027	168.403	147.615

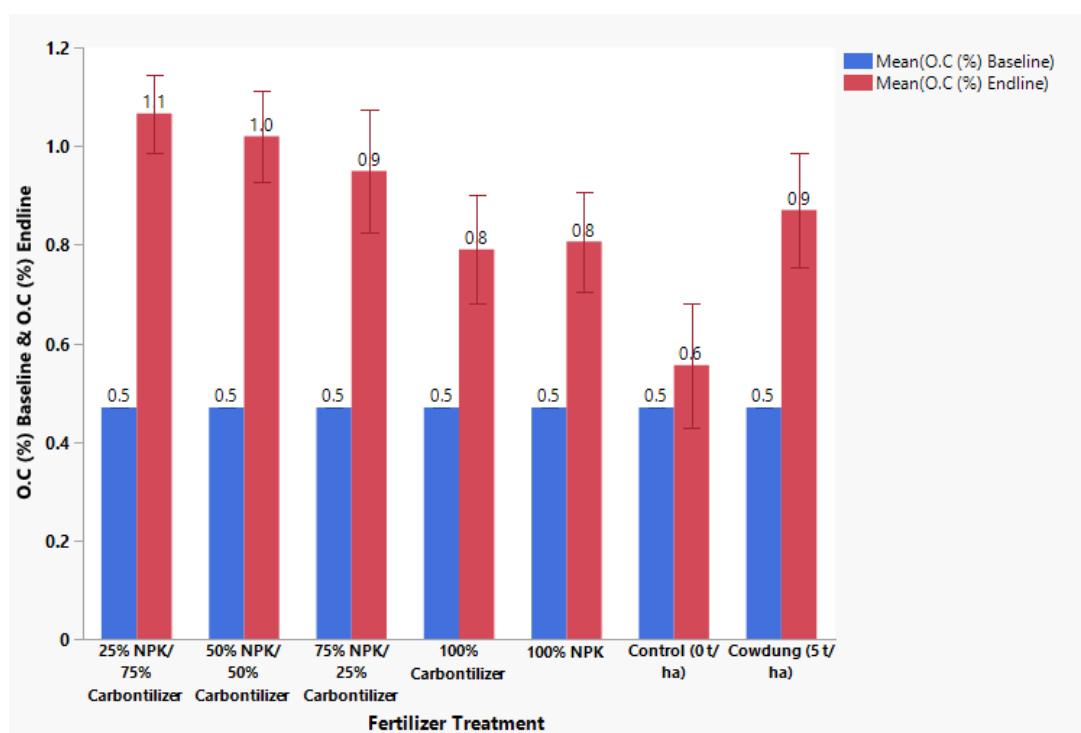


Figure 15: Effect of Saputra coal fertilizer on baseline and endline soil available phosphorus level under cowpea production

Soil Phosphorus (P)

Soil phosphorus (P) content generally increased from baseline to endline across most treatments (Fig. 16), reflecting the positive effect of fertilizer application on nutrient availability. The greatest improvement was observed under 100% Carbontilizer, followed by the 50% NPK/50% Carbontilizer blend, suggesting that coal-based organics play a particularly important role in replenishing soil P. In contrast, only marginal gains were recorded under the control and cow dung treatments, highlighting the limited short-term capacity of traditional organics or unfertilized soils to raise available P levels.

The stronger response to Carbontilizer treatments may be linked to their inherent P content as well as their ability to stimulate microbial activity and improve soil aggregation, thereby enhancing P solubilization and retention in the root zone. This aligns with reports that organic inputs often increase labile P fractions by reducing fixation and promoting mineralization. The superior performance of blends (50% NPK/50% Carbontilizer) further suggests a synergistic mechanism, whereby NPK provides immediately available P while Carbontilizer contributes to longer-term availability through gradual release and improved soil structure.

While the gains in P content were encouraging, the overall magnitude of increase was modest, consistent with the sandy loam texture of the soils, which typically limits P retention. This underscores the importance of complementary soil and water management strategies to maximize fertilizer efficiency. Moreover, the short-term nature of the trial prevents conclusions about persistence of these improvements. Multi-season assessments

are therefore needed to determine whether Carbontilizer-based inputs can sustainably build soil P pools and translate into higher long-term crop productivity.

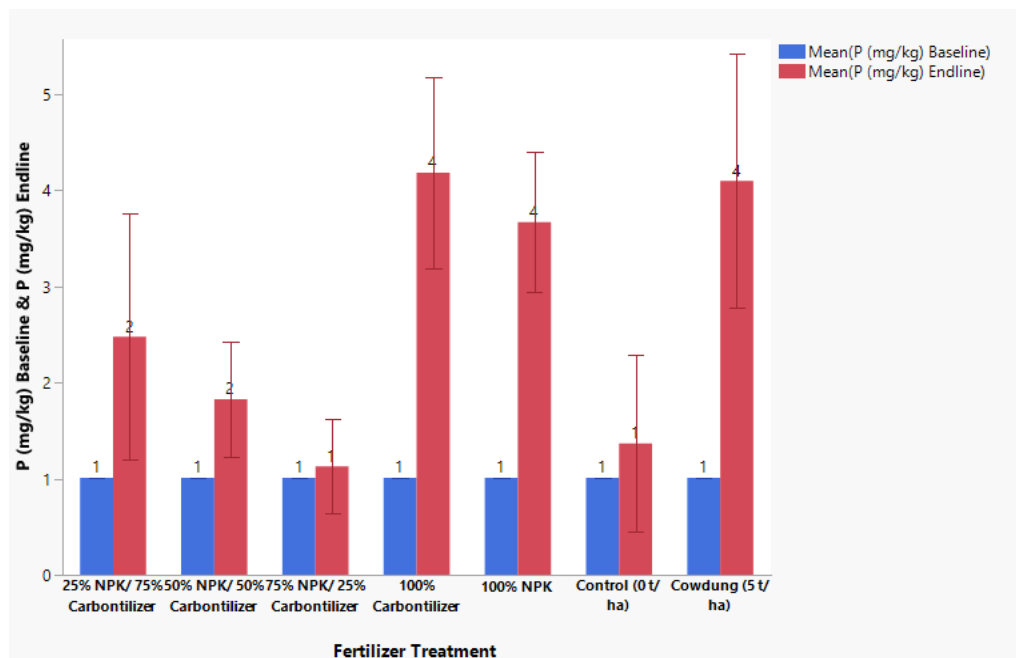


Figure16: Effect of Saputra coal fertilizer on baseline and endline soil available phosphorus level under cowpea production.

Heavy Metal Analysis

The concentrations of heavy metals in Saputra Carbontilizer were found to be within safe limits for agricultural use (Table 8). Lead (0.001-0.002 mg/kg) and cadmium (≤ 0.002 mg/kg) were well below the WHO permissible thresholds of 0.01 mg/kg and 0.003 mg/kg, respectively, while copper, iron, and zinc were also present at safe levels. These results confirm that the fertilizer poses no immediate risk of heavy metal contamination to soils, crops, or human health.

The low concentrations observed may be attributed to the nature of the coal feedstock and the processing techniques used, which minimize accumulation of toxic trace metals. This is particularly important in smallholder contexts, where long-term use of contaminated fertilizers could exacerbate soil degradation and introduce toxic elements into the food chain. By staying within WHO guidelines, Saputra Carbontilizer demonstrates environmental compatibility, supporting its potential as a sustainable soil amendment.

Nevertheless, heavy metals are persistent in soils and may accumulate over multiple seasons of fertilizer application. Continuous monitoring is therefore essential to ensure that prolonged use does not lead to bioaccumulation in crops or ecological harm. Similar caution has been raised in previous studies, which highlight that even low baseline concentrations can become problematic under repeated input cycles if not tracked. Regular heavy metal

analysis should thus remain a key component of fertilizer evaluation protocols to safeguard food security, soil health, and public health outcomes.

Table 8: Average Heavy Metal Composition of Saputra Fertilizer Material

	Pb	Cd	Cu	Fe	Zn
Source	Mg/kg				
Saputra 1	0.002	0.002	0.421	1.034	0.003
Saputra 2	0.001	0.001	0.342	0.934	0.002
Saputra 3	0.001	0.001	0.345	1.235	0.005



Plate 1: North-East (Maiduguri) Cowpea Trial Site at 4 Weeks After Sowing



Plate 2: North-West (Kano CDA) Cowpea Trial Site at 6 Weeks After Sowing



Plate 3: North-Central (Makurdi) Cowpea Trial Site at 4 Weeks After Sowing

Conclusion

This study demonstrated that integrating Saputra Carbontilizer with NPK fertilizer offers both agronomic and soil fertility benefits in cowpea production across Nigeria's major agroecological zones. A 50% NPK + 50% Carbontilizer blend consistently improved pod weight, stover biomass, grain yield (1.63 t/ha), and chlorophyll content (52–54 SPAD), while enhancing post-harvest soil organic carbon (0.69%) and phosphorus availability (7.34 mg/kg). Although 100% NPK promoted vigorous vegetative growth, it lacked the residual soil benefits of Carbontilizer-inclusive treatments, while 100% Carbontilizer alone had limited short-term effects. Importantly, heavy metal levels in Carbontilizer remained well below WHO safety thresholds, confirming its suitability for agricultural use.

The findings provide scientific evidence that organic–inorganic fertilizer integration enhances nutrient use efficiency, crop performance, and soil health. Practically, the 50% NPK + 50% Carbontilizer blend offers a sustainable and climate-smart alternative for smallholder farmers by reducing reliance on costly chemical fertilizers and restoring soil fertility. While the results highlight clear short-term benefits, long-term trials are required to validate the persistence of soil improvements and to assess economic viability across diverse farming systems.

Recommendations

Based on the study's findings, the following recommendations are proposed:

- i. Adoption of the 50% NPK + 50% Carbontilizer blend is recommended for cowpea cultivation across Nigeria's major agroecological zones to simultaneously enhance productivity and improve soil fertility.
- ii. Policymakers should promote site-specific nutrient management strategies that integrate organic–inorganic fertilizer blends, thereby reducing reliance on costly imports and improving farmer access to sustainable alternatives.

- iii. Long-term field experiments and soil quality monitoring should be institutionalized to track the cumulative impacts of coal-based fertilizers on soil microbial dynamics, nutrient cycling, and environmental sustainability.
- iv. Further research should explore the interactions between coal-based fertilizer blends, microbial inoculants, and legume nitrogen fixation dynamics in order to fully harness cowpea's role in sustainable intensification.

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