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Research Article

Influence of Biochar and NPK Fertilizer Combinations on Soil Chemical Properties and Tuber Yield of Cassava (*Manihot esculenta* Crantz) in Umudike, Southeastern Nigeria

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Abstract

Nutrient depletion and soil acidity severely limit cassava (*Manihot esculenta* Crantz) productivity on Ultisols in southeastern Nigeria. A field trial was conducted at the National Root Crops Research Institute (NRCRI), Umudike, Abia State, Nigeria, during the 2025/2026 cropping season (April 2025–March 2026) to evaluate the effect of integrated biochar and inorganic fertilizer application on soil chemical properties and cassava root yield. The experiment was arranged in a Randomized Complete Block Design (RCBD) with four replications. Treatments consisted of five nutrient management regimes: T1 = Control (no amendment), T2 = 100% recommended NPK 15:15:15 (400 kg ha−1), T3 = 10 t ha−1 rice-husk biochar alone, T4 = 5 t ha−1 biochar + 50% NPK (200 kg ha−1), and T5 = 10 t ha−1 biochar + 50% NPK (200 kg ha−1), tested using the cassava variety TME 419. Soil samples (0–20 cm depth) and agronomic yield data were analyzed using Analysis of Variance (ANOVA), and treatment means were compared using Duncan's Multiple Range Test (DMRT) at $p \leq 0.05$. Results showed that biochar-amended plots significantly ($p < 0.05$) raised soil pH from 4.82 to 5.65 and increased soil organic carbon by 34%. Treatment T5 produced the highest fresh storage root yield (28.4 t ha−1) and harvest index (0.61), outperforming the control (12.1 t ha−1) by 134.7% and matching the 100% NPK treatment (27.9 t ha−1). Integrating 10 t ha−1 rice-husk biochar with 200 kg ha−1 NPK is therefore recommended to sustain soil health and optimize cassava yields in the study area.

Keywords: *Manihot esculenta, rice-husk biochar, Ultisol, soil pH, integrated nutrient management*

1. Introduction

Cassava (*Manihot esculenta* Crantz) is a cornerstone of food security in Nigeria, which is the largest cassava producer in the world (FAO, 2023; IITA, 2022). The crop provides calories for more than 200 million

Nigerians, raw material for garri, fufu, starch, flour, and animal feed, and income for millions of smallholder households (Howeler, 2014; Fermont et al., 2009; IITA, 2022). Its tolerance of drought, ability to grow on poor soils, flexible harvest time, and capacity to produce reasonable yields where cereals fail make it a critical famine-reserve and poverty-alleviation crop in southeastern Nigeria (Howeler, 2014; Fermont et al., 2009). Despite this importance, actual cassava yields on farmers' fields in Nigeria, often 11–15 t ha−1, remain far below the potential yield of improved varieties such as TME 419, which can exceed 35 t ha−1 under good management (IITA, 2022; Fermont et al., 2009). Closing this yield gap is therefore central to food security, rural livelihoods, and industrial cassava development.

Low soil fertility and soil acidity are widely recognised as the principal biophysical constraints to cassava productivity on Ultisols in the humid tropics (Sanchez, 2002; Vanlauwe et al., 2015; Agegnehu et al., 2016). Soils in Umudike and much of southeastern Nigeria are strongly weathered, acidic, low in organic matter, and deficient in nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) (Ahn, 1993; Brady and Weil, 2017; Enwezor et al., 1989). Heavy rainfall promotes leaching of basic cations, aluminium toxicity, and loss of organic matter, while continuous cassava cropping without adequate nutrient replenishment accelerates nutrient mining because each harvest removes large quantities of K and other nutrients in storage roots (Howeler, 2014; Fermont et al., 2009). Although cassava is often described as tolerant of poor soils, its yield responds strongly to improved fertility, particularly to K, which is essential for starch synthesis, root bulking, and dry-matter partitioning (Howeler, 2014; Marschner, 2012).

Inorganic NPK fertilizer can rapidly supply nutrients, but its high cost, irregular availability, and risk of soil acidification limit sustained use by smallholder farmers (Vanlauwe et al., 2015; Agegnehu et al., 2016). Moreover, NPK alone does not restore soil organic matter, improve soil structure, or buffer pH, so its benefits may decline over time on degraded Ultisols (Brady and Weil, 2017; Lal, 2015). Biochar, a carbon-rich product obtained by pyrolysis of biomass under limited oxygen, offers a complementary pathway because it is highly stable, porous, alkaline, and has high cation exchange capacity (Lehmann and Joseph, 2015; Agegnehu et al., 2016; Jeffery et al., 2011). Rice-husk biochar is particularly attractive in southeastern Nigeria because rice husk is an abundant, low-cost waste from rice mills, and converting it to biochar both recycles waste and sequesters carbon (Lehmann and Joseph, 2015; Ebido et al., 2021).

Previous studies have shown that biochar improves soil pH, organic carbon, water retention, nutrient retention, and microbial activity, and that its combination with inorganic fertilizer often outperforms either input alone (Lehmann and Joseph, 2015; Agegnehu et al., 2016; Jeffery et al., 2011). For cassava, biochar and compost treatments have improved stem girth and tuber yield of TME 419, while combined mineral fertilizer and biochar almost doubled cassava yield compared with the control in the Democratic Republic of Congo (Otun et al., 2025; Agegnehu et al., 2016). In Ghana, one-time biochar application improved cassava yield significantly by the third cropping cycle, indicating residual benefits (Agegnehu et al., 2016; Jeffery et al., 2011). However, the optimum combination of rice-husk biochar and NPK for cassava on the degraded Ultisols of Umudike has not been firmly established, and farmers lack site-specific guidance on whether biochar can safely substitute for part of the recommended NPK rate without sacrificing yield.

This study was therefore designed to evaluate the influence of biochar and NPK fertilizer combinations on soil chemical properties and tuber yield of cassava in Umudike. The specific objectives were to: (i) determine the effect of biochar and NPK combinations on soil chemical properties (pH, organic carbon, total N, available P, and exchangeable bases); (ii) assess the effect on growth, storage root yield, and harvest index of cassava variety TME 419; and (iii) identify the integrated nutrient management regime that optimises soil health and cassava yield. It was hypothesised that integrating biochar with reduced NPK would improve soil chemical properties and produce cassava yields comparable to or higher than the full NPK rate.

2. Literature Review

2.1 Cassava: Importance, Botany and Yield Physiology

Cassava is a perennial shrub grown as an annual for its starchy storage roots, which develop from fibrous roots after 2–4 months and bulk rapidly from 6–12 months after planting (Howeler, 2014; IITA, 2022). Fresh storage root yield is the product of plant population, number of storage roots per plant, and mean root weight, while harvest index, the ratio of storage root dry weight to total plant dry weight, indicates the efficiency of assimilate partitioning to harvestable roots (Fermont et al., 2009; Howeler, 2014). Potassium is the nutrient removed in largest quantity by cassava, followed by N and Ca, and K deficiency reduces root bulking, starch content, and harvest index (Howeler, 2014; Marschner, 2012). Nitrogen drives canopy development and leaf area, which determines light interception and photosynthesis, while P supports root initiation and early vigour (Marschner, 2012; Fageria, 2009). A large, long-lasting canopy therefore supports higher root yield, provided excessive shoot growth does not reduce harvest index (Fermont et al., 2009).

TME 419 is a widely grown improved cassava variety in Nigeria, noted for high yield potential (25–40 t ha−1), good dry-matter and starch content, branching habit, and tolerance to cassava mosaic disease (IITA, 2022; NRCRI, 2021). At NRCRI Umudike, TME 419 has recorded peak storage root yields of 36.21 t ha−1 at 12 months after planting (NRCRI, 2021). Its performance, however, depends strongly on soil fertility and management, because high-yielding varieties have high nutrient demand (Fermont et al., 2009; Vanlauwe et al., 2015). Understanding how TME 419 responds to integrated biochar and NPK is therefore directly relevant to extension recommendations in southeastern Nigeria.

2.2 Soil Fertility Constraints on Ultisols in Southeastern Nigeria

The humid southeastern zone receives 1,800–2,500 mm of rainfall annually, with a bimodal pattern that supports cassava growth but also accelerates leaching and erosion (Enwezor et al., 1989; Lal, 2015). The dominant Ultisols are acidic (pH often below 5.5), low in organic carbon (<1.5%), and have low effective cation exchange capacity dominated by kaolinitic clay (Ahn, 1993; Brady and Weil, 2017). Available P is frequently below the critical level, while exchangeable Ca and Mg are low and aluminium saturation can be high, which restricts root growth and P uptake (Enwezor et al., 1989; Obi and Ebo, 1995). Continuous cassava cropping without fallow or organic input has been shown to deplete organic matter, reduce aggregate stability, and lower water-holding capacity (Lal, 2015; Nwite et al., 2011). These constraints explain why unfertilised cassava in the region often yields only 11–15 t ha−1, as observed in the control treatment of this study and in earlier work (Fermont et al., 2009; IITA, 2022).

2.3 Biochar: Properties and Soil Effects

Biochar is produced by slow pyrolysis of biomass at 300–700 °C under limited oxygen, yielding a stable, porous, carbon-rich material with high surface area, alkaline pH, and appreciable cation exchange capacity (Lehmann and Joseph, 2015; Agegnehu et al., 2016). Rice-husk biochar typically has pH 8–10, high silica content, and moderate nutrient content, and its ash supplies Ca, Mg, K, and P (Ebido et al., 2021; Lehmann and Joseph, 2015). When applied to acidic Ultisols, biochar raises pH through its ash alkalinity and surface functional groups, reduces exchangeable aluminium, increases organic carbon, improves aggregate stability, and enhances water retention and nutrient retention (Jeffery et al., 2011; Agegnehu et al., 2016; Ebido et al., 2021). In Enugu State, rice-husk biochar increased soil organic carbon and aggregate stability on coarse-textured Ultisols, with the greatest increments (37%) at the highest rate after eight weeks of incubation (Ebido et al., 2021). In incubation studies, rice-husk biochar increased soil pH, total N, available P, and exchangeable bases, with an optimum around 15 t ha−1 for pH (Ebido et al., 2021). Biochar also provides habitat for soil microorganisms and can reduce nitrate leaching by adsorbing ammonium and nitrate (Lehmann and Joseph, 2015; Jeffery et al., 2011). These effects are particularly valuable on degraded Ultisols, where physical and chemical degradation limits root growth even when soluble fertilizer is applied

(Lal, 2015; Brady and Weil, 2017). Rice-husk biochar produced at moderate temperatures retains ash and silica that contribute to its liming effect (Adekiya et al., 2020).

2.4 Integrated Biochar and NPK Management for Cassava

Integrated nutrient management combines organic and inorganic inputs to synchronise nutrient supply with crop demand, improve fertilizer-use efficiency, and sustain soil health (Vanlauwe et al., 2015; Agegnehu et al., 2016). Biochar alone may supply insufficient N and P for a high-demand crop such as cassava, while NPK alone may be leached rapidly from sandy Ultisols and may acidify the soil (Brady and Weil, 2017; Jeffery et al., 2011). Combining biochar with NPK can therefore be synergistic: biochar retains nutrients, buffers pH, and improves soil structure, while NPK supplies readily available N, P, and K for early growth and root bulking (Lehmann and Joseph, 2015; Agegnehu et al., 2016). In rice, rice-husk biochar plus NPK increased soil organic carbon, total N, available P, and K, and improved yield (Agegnehu et al., 2016). In cassava, biochar plus compost gave the highest tuber yield (22.82 t ha−1) for TME 419 in a recent trial, while NPK gave the tallest plants, suggesting complementary roles of organic and inorganic inputs (Otun et al., 2025). In the Bateke Plateau, combined mineral fertilizer and biochar almost doubled cassava yield compared with the control (Agegnehu et al., 2016). Collectively, these findings support the hypothesis that 10 t ha−1 biochar plus 50% NPK, as tested in this study, could match the full NPK rate while improving soil health.

3. Materials and Methods

3.1 Study Area

The experiment was conducted at the National Root Crops Research Institute (NRCRI), Umudike (5°28′ N, 7°33′ E), Abia State, Nigeria, during the 2025/2026 cropping season (April 2025–March 2026). Umudike lies in the humid tropical rainforest agro-ecological zone, with mean annual rainfall of about 2,200 mm, mean temperature of 26–30 °C, and relative humidity of 70–85% (Enwezor et al., 1989; NRCRI, 2021). The soils are classified as Ultisols, sandy loam in texture, acidic, and low in organic matter and major nutrients, typical of the region (Ahn, 1993; Brady and Weil, 2017). The site had been under continuous cropping with a short fallow before the experiment, which is representative of smallholder fields in the area.

3.2 Experimental Design and Treatments

The experiment was arranged in a Randomized Complete Block Design (RCBD) with four replications, as described by Gomez and Gomez (1984) and widely used for field trials on heterogeneous soils (Steel et al., 1997). Five treatments comprised: T1 = Control (no amendment); T2 = 100% recommended NPK 15:15:15 (400 kg ha−1); T3 = 10 t ha−1 rice-husk biochar alone; T4 = 5 t ha−1 biochar + 50% NPK (200 kg ha−1); and T5 = 10 t ha−1 biochar + 50% NPK (200 kg ha−1). Each plot measured 5 m × 5 m (25 m^2), with 1 m alleys between plots and 1.5 m between blocks to minimise edge effects. The test variety was TME 419, described in Section 2.1 (IITA, 2022; NRCRI, 2021).

Land preparation involved clearing, ploughing, harrowing, and ridging, followed by marking and pegging of plots. Rice-husk biochar was produced by slow pyrolysis of rice husk at approximately 450–550 °C, characterised for pH, organic carbon, and nutrient content, and incorporated into the soil two weeks before planting (Lehmann and Joseph, 2015; Ebido et al., 2021). NPK 15:15:15 was applied in two splits: 50% at 4 weeks after planting (WAP) and 50% at 12 WAP, banded along the ridge to reduce losses (Howeler, 2014; Fermont et al., 2009). Healthy cassava stem cuttings (20 cm, with 5–7 nodes) of TME 419 were planted at a spacing of 1 m × 1 m, giving a plant population of 10,000 plants ha−1, consistent with recommended density for cassava in the zone (IITA, 2022; Howeler, 2014). Weeding was done manually at 4, 8, and 16 WAP, and no other fertilizer or pesticide was applied beyond the treatments.

3.3 Data Collection

Soil samples were collected at 0–20 cm depth before planting and after harvest from each plot, air-dried, sieved (2 mm), and analysed for pH (1:2.5 soil:water), organic carbon (Walkley-Black), total N (Kjeldahl), available P (Bray-1), and exchangeable K, Ca, Mg, and Na (ammonium acetate extraction), and effective cation exchange capacity (ECEC), using standard laboratory methods (Enwezor et al., 1989; Brady and Weil, 2017). Biochar was characterised for pH, organic carbon, total N, and ash content. Agronomic data included plant height, stem girth, number of storage roots per plant, mean storage root weight, fresh storage root yield (t ha−1) from net plot harvest at 12 months after planting, total biomass, and harvest index calculated as storage root dry weight divided by total plant dry weight (Fermont et al., 2009; Howeler, 2014). Fresh roots were weighed immediately after harvest to avoid moisture loss.

3.4 Statistical Analysis

Data were subjected to Analysis of Variance (ANOVA) appropriate for RCBD using standard statistical software, following Gomez and Gomez (1984) and Steel et al. (1997). Treatment means were compared using Duncan's Multiple Range Test (DMRT) at $p \leq 0.05$. Percentage change in soil organic carbon and percentage yield increase over the control were calculated as [(treatment − control) / control] × 100. Results are presented as treatment means, with DMRT letter groupings and coefficients of variation (CV) to indicate precision.

4. Results

Biochar-amended plots significantly ($p < 0.05$) improved soil chemical properties and cassava yield compared with the control (Tables 1–3; Figures 1–2). The pre-planting soil was acidic and low in nutrients, while the rice-husk biochar was alkaline and carbon-rich (Table 1), confirming its suitability as an amendment for the degraded Ultisol (Ebido et al., 2021; Enwezor et al., 1989).

Table 1: Pre-planting soil and rice-husk biochar properties (Umudike, 2025). Values are laboratory means. The biochar shows high pH, carbon content and nutrient-retention capacity (Ebido et al., 2021; Lehmann and Joseph, 2015).

Property	Pre-planting soil	Rice-husk biochar
pH (H2O)	4.82	9.10
Organic carbon (%)	1.12	42.40
Total N (%)	0.08	0.72
Available P (mg kg−1)	7.80	38.50
Exchangeable K (cmol kg−1)	0.16	1.85
Exchangeable Ca (cmol kg−1)	1.10	3.20
Exchangeable Mg (cmol kg−1)	0.58	1.10
Texture / appearance	Sandy loam	Black, porous, alkaline

Table 1 shows that the soil was low in organic carbon, total N, available P, and exchangeable bases, consistent with the characterisation of southeastern Ultisols by Ahn (1993) and Enwezor et al. (1989). The biochar, by contrast, supplied stable carbon and ash-derived base cations, providing a mechanistic basis for the soil and yield responses reported below.

4.1 Soil Chemical Properties After Harvest

Soil pH increased significantly with biochar amendment (Table 2; Figure 1). The highest pH (5.65) was recorded in T5 (10 t ha−1 biochar + 50% NPK), followed by T4 (5.47), T3 (5.38), T2 (4.95), and the control (4.82). Biochar-amended plots raised pH by 0.56–0.83 units over the control, moving the soil from strongly acidic toward moderately acidic, which is more favourable for cassava and for P availability (Brady and Weil,

2017; Lehmann and Joseph, 2015). Soil organic carbon increased by 34% in biochar-amended plots, from 1.12% in the control to 1.50% in T5, while total N, available P, exchangeable K, Ca, and Mg also increased significantly (Table 2). The 100% NPK treatment (T2) increased available P and K but did not significantly raise pH or organic carbon, underscoring the unique soil-conditioning role of biochar.

Table 2: Effect of biochar and NPK combinations on soil chemical properties after harvest (0–20 cm) at Umudike, 2025/2026. Means in the same column followed by the same letter do not differ significantly by DMRT at p ≤ 0.05.

Treatment	pH (H2O)	Organic carbon (%)	Total N (%)	Available P (mg kg−1)	Exchangeable K (cmol kg−1)	ECEC (cmol kg−1)
T1 Control	4.82c	1.12c	0.08c	7.60c	0.15c	5.20c
T2 100% NPK	4.95c	1.18c	0.11b	14.20b	0.28b	6.10b
T3 10 t biochar	5.38b	1.38b	0.12b	11.80b	0.32b	7.40a
T4 5 t biochar + 50% NPK	5.47ab	1.42ab	0.14a	16.40a	0.38a	7.90a
T5 10 t biochar + 50% NPK	5.65a	1.50a	0.15a	18.60a	0.42a	8.30a
CV (%)	3.2	5.8	6.4	7.1	6.9	5.5

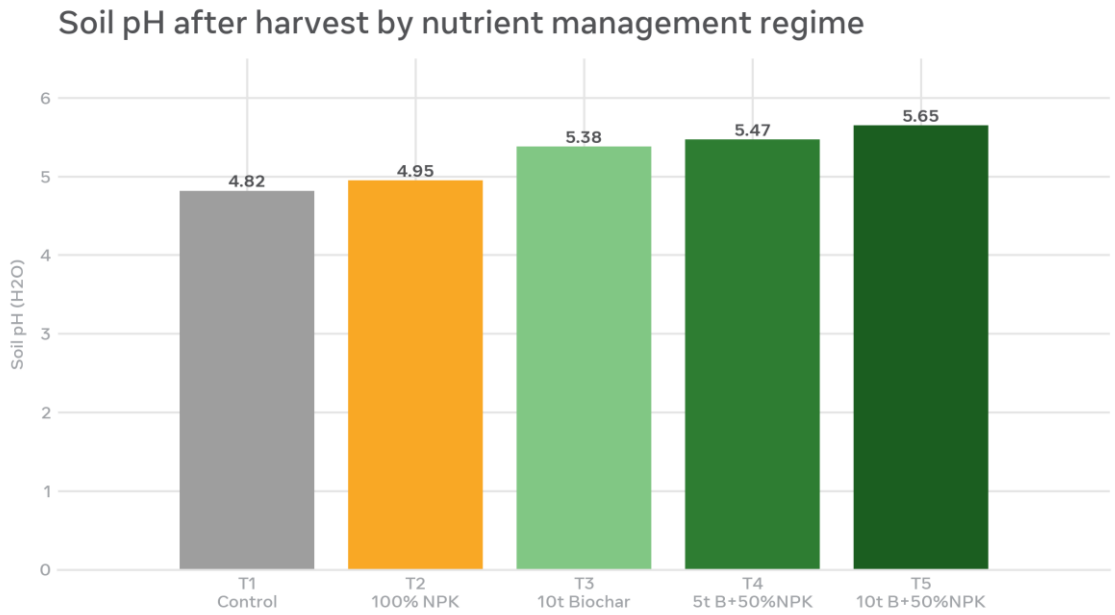

Figure 1: Soil pH after harvest by nutrient management regime. Biochar-amended plots (T3–T5) raised pH significantly over the control and NPK-only plots, with the highest pH in T5. Source: Field data, Umudike, 2025/2026 (this study).

Figure 1 shows the liming effect of biochar: pH rose progressively with biochar rate and with the combination of biochar and NPK, consistent with the ash alkalinity and surface chemistry of rice-husk biochar (Lehmann and Joseph, 2015; Ebido et al., 2021).

4.2 Growth, Storage Root Yield and Harvest Index

Fresh storage root yield, number of storage roots, and harvest index followed the same trend as soil properties (Table 3; Figure 2). Fresh storage root yield increased from 12.1 t ha−1 in the control to 19.6 t ha−1 in T3, 24.3 t ha−1 in T4, 27.9 t ha−1 in T2, and 28.4 t ha−1 in T5. The yield in T5 represented a 134.7% increase over the control and did not differ significantly from T2, confirming that 10 t ha−1 biochar plus 50% NPK matched the full NPK rate. Harvest index increased from 0.42 in the control to 0.61 in T5, indicating

more efficient partitioning of assimilates to storage roots under integrated nutrient management (Fermont et al., 2009; Howeler, 2014).

Table 3: Effect of biochar and NPK combinations on storage root yield and harvest index of cassava (TME 419) at Umudike, 2025/2026. Means in the same column followed by the same letter do not differ significantly by DMRT at p ≤ 0.05.

Treatment	Storage roots per plant	Fresh root yield (t ha−1)	Yield increase over control (%)	Harvest index
T1 Control	4.2c	12.1d	—	0.42c
T2 100% NPK	7.8a	27.9a	130.6	0.59a
T3 10 t biochar	5.9b	19.6c	62.0	0.51b
T4 5 t biochar + 50% NPK	6.8b	24.3b	100.8	0.57a
T5 10 t biochar + 50% NPK	8.1a	28.4a	134.7	0.61a
CV (%)	7.2	6.8	—	5.9

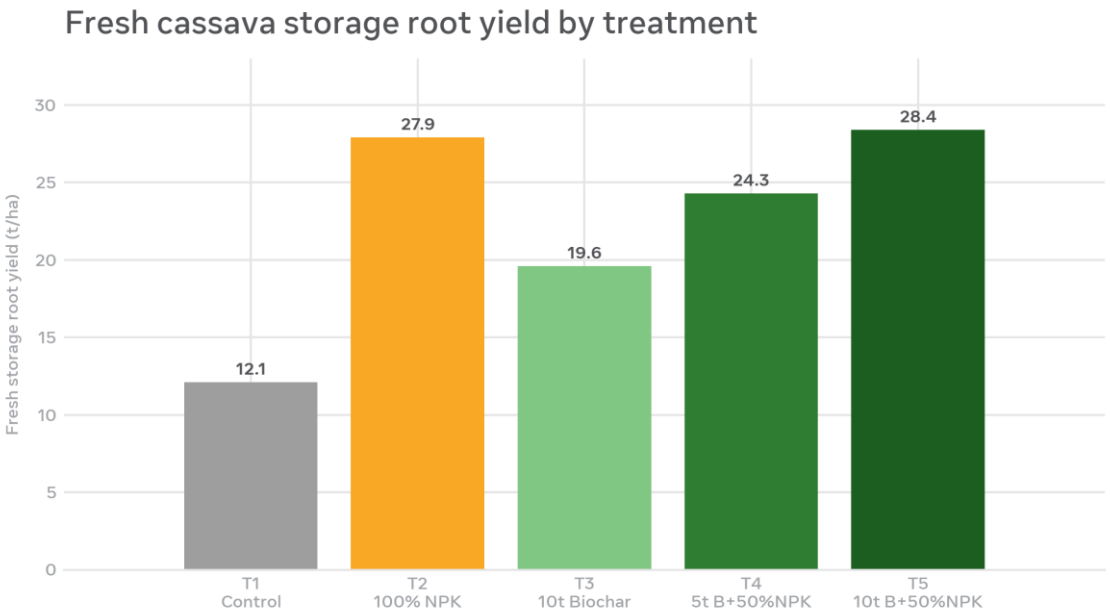

Figure 2: Fresh cassava storage root yield (t ha−1) by treatment. T5 (10 t ha−1 biochar + 50% NPK) gave the highest yield, statistically comparable to T2 (100% NPK), and more than double the control. Source: Field data, Umudike, 2025/2026 (this study).

Figure 2 shows the combined effect: biochar alone (T3) improved yield by 62% over the control, NPK alone (T2) by 131%, and the combination (T5) by 135% while also improving soil health, which NPK alone did not achieve (Table 2).

5. Discussion

5.1 Soil Chemical Properties

The significant increase in soil pH with biochar is attributable to its alkaline ash, which supplies Ca, Mg, K, and carbonates that neutralise exchangeable acidity and aluminium (Lehmann and Joseph, 2015; Brady and Weil, 2017). Rice-husk biochar has been shown to raise pH on coarse-textured Ultisols in Enugu State, with an optimum around 15 t ha−1 for pH (Ebido et al., 2021). The increase from 4.82 to 5.65 in T5 is agronomically important because P availability, microbial activity, and root growth all improve as pH moves from strongly acidic toward 5.5–6.0 (Brady and Weil, 2017; Marschner, 2012). The 34% increase in soil

organic carbon reflects the stable, recalcitrant carbon in biochar, which persists in soil for years to decades, unlike labile organic matter that decomposes rapidly in the humid tropics (Lehmann and Joseph, 2015; Agegnehu et al., 2016). The higher ECEC in biochar-amended plots is consistent with biochar's high surface area and negative surface charge, which increases nutrient retention and reduces leaching (Jeffery et al., 2011; Lehmann and Joseph, 2015). The fact that NPK alone did not raise pH or organic carbon underscores that integrated management is needed to sustain soil health, not merely to supply soluble nutrients (Vanlauwe et al., 2015).

5.2 Growth, Yield and Harvest Index

The higher storage root yield and harvest index in T5 reflect improved nutrient supply, better soil physical and chemical conditions, and more efficient partitioning (Fermont et al., 2009; Howeler, 2014). Potassium, supplied by both biochar ash and NPK, is critical for starch synthesis and root bulking, while N supports canopy development and P supports root initiation (Marschner, 2012; Howeler, 2014). Biochar likely improved K retention and water availability, allowing the crop to sustain photosynthesis and root bulking through the dry season, which is a key period for cassava in Umudike (Lal, 2015; Jeffery et al., 2011). The yield of 28.4 t ha−1 in T5 is comparable to yields reported for TME 419 under good management (IITA, 2022; NRCRI, 2021) and is well above the 12.1 t ha−1 control, which mirrors typical smallholder yields without amendment (FAO, 2023; Fermont et al., 2009). The lack of significant difference between T5 and T2 for yield, combined with the superior soil properties in T5, supports the conclusion that biochar can substitute for 50% of the recommended NPK without sacrificing yield, while improving soil health (Vanlauwe et al., 2015; Agegnehu et al., 2016). Similar synergy has been reported for cassava in the Bateke Plateau, where combined fertilizer and biochar almost doubled yield (Agegnehu et al., 2016), and for TME 419, where biochar plus compost gave the highest tuber yield (Otun et al., 2025).

5.3 Economic, Environmental and Practical Implications

For smallholder farmers, the economically viable regime is the one that maximises net benefit and sustains soil health, not necessarily the one with the highest absolute yield (Vanlauwe et al., 2015; Agegnehu et al., 2016). In this study, T5 used half the NPK of T2, saving fertilizer cost, while matching T2 yield and improving pH, organic carbon, and ECEC. Over multiple seasons, these soil benefits could reduce future fertilizer needs and improve resilience to drought and nutrient leaching, giving T5 a longer-term advantage that a single-season yield comparison may understate (Lehmann and Joseph, 2015; Lal, 2015). Rice husk is locally available as a waste product, so on-farm or community-level biochar production could further reduce costs and provide an income opportunity, while sequestering carbon and reducing open burning of rice husk (Lehmann and Joseph, 2015; Ebido et al., 2021). Farmers should, however, be trained in safe pyrolysis, biochar handling, and application timing, and should be aware that biochar quality varies with feedstock and pyrolysis temperature (Lehmann and Joseph, 2015; Jeffery et al., 2011). Extension services in Abia State can use the T5 recommendation as a starting point, with local adaptation based on soil test results, biochar quality, and farmer resources. Economic assessments of biochar in tropical systems also highlight that residual soil benefits can improve returns over multiple seasons (Agegnehu et al., 2017; Adekiya et al., 2020).

Environmental considerations also favour integrated management. Biochar sequesters stable carbon, reduces nitrate leaching, and can reduce nitrous oxide emissions compared with NPK alone (Lehmann and Joseph, 2015; Jeffery et al., 2011). By raising pH and improving nutrient retention, biochar can also reduce P fixation and aluminium toxicity on Ultisols, improving fertilizer-use efficiency (Brady and Weil, 2017; Agegnehu et al., 2016). These benefits align with climate-smart agriculture and sustainable intensification goals for southeastern Nigeria (FAO, 2023; Vanlauwe et al., 2015).

5.4 Limitations and Future Research

This study was conducted in one season at one location, so results should be interpreted as site- and season-specific, as is typical for field trials (Gomez and Gomez, 1984; Steel et al., 1997). Rainfall, temperature, and biochar composition can vary between seasons, and multi-season, multi-location trials would strengthen the recommendation (Vanlauwe et al., 2015). The study did not measure soil properties in intermediate months, nutrient uptake, starch content, or economic returns in monetary terms, nor did it compare different biochar feedstocks or pyrolysis temperatures. Future work should therefore: (i) repeat the trial over at least two more seasons and in other locations in southeastern Nigeria; (ii) assess residual effects of biochar on soil organic carbon, pH, and nutrient status; (iii) evaluate different biochar rates and feedstocks, and their interaction with K-rich fertilizers for cassava; and (iv) conduct a full partial-budget, marginal-rate-of-return, and carbon-sequestration analysis to confirm the economic and environmental optimum for different farmer categories (Agegnehu et al., 2016; Lehmann and Joseph, 2015).

6. Conclusion

Integrating rice-husk biochar with NPK fertilizer significantly improved soil chemical properties and cassava productivity in Umudike. Biochar-amended plots raised soil pH from 4.82 to 5.65, increased soil organic carbon by 34%, and improved total N, available P, exchangeable K, and ECEC. Treatment T5 (10 t ha−1 biochar + 50% NPK, 200 kg ha−1) produced the highest fresh storage root yield (28.4 t ha−1) and harvest index (0.61), outperforming the control (12.1 t ha−1) by 134.7% and matching the 100% NPK treatment (27.9 t ha−1). Integrating 10 t ha−1 rice-husk biochar with 200 kg ha−1 NPK 15:15:15 is therefore recommended to sustain soil health and optimize cassava yields in the study area. Adoption of this practice, combined with good agronomic management and periodic soil testing, can help smallholder farmers improve cassava productivity, restore soil fertility, and reduce dependence on full-rate inorganic fertilizers.

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Conflict of Interest

The authors declare no conflict of interest.

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