



Biochar and poultry manure impacts on soil characteristics and yam productivity in a degraded tropical Alfisol

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Abstract

Background and Objective: Soil degradation remains a significant constraint to sustainable production of white yam (*Dioscorea rotundata* Poir) in tropical regions, largely due to continuous cultivation and progressive nutrient depletion. While organic amendments like biochar and poultry manure have been studied in cereal and vegetable systems, their combined effects on yam-based systems remain underexplored. This study evaluated the effects of cocoa pod husk biochar (CPHB) and poultry manure (PM) on soil properties, leaf nutrient concentrations, growth, and tuber yield of yam grown on a degraded Alfisol in Owo, southwestern Nigeria.

Methodology: A two-year (2023–2024) field experiment was conducted at Owo using a factorial randomized complete block design (RCBD) comprising three CPHB rates (0, 15, and 30 t ha⁻¹) and three PM rates (0, 10, and 20 t ha⁻¹), replicated three times. Soil physical and chemical properties, leaf nutrient concentrations, growth parameters, and tuber yield were evaluated following standard procedures.

Main Results: Results showed that CPHB and PM, applied singly or together, significantly ($P < 0.05$) improved soil properties compared with the control. The combined application of 30 t ha⁻¹ CPHB and 20 t ha⁻¹ PM resulted in the lowest bulk density (0.90 Mg m⁻³), highest total porosity (66.3%), moisture content (19.5%), organic matter (3.58%), total nitrogen (0.21%), available phosphorus (18.7 mg kg⁻¹), and exchangeable K (0.33 cmol kg⁻¹). Leaf N, P, K, Ca, and Mg concentrations, growth, and yield attributes also increased. Averaged over two years,

the highest tuber yield (46.1 t ha⁻¹) was recorded with 30 t ha⁻¹ CPHB + 20 t ha⁻¹ PM, representing 35–82% yield increases over other treatments.

Conclusions: CPHB and PM produced significant interaction effects on soil fertility, nutrient uptake, and yam yield on degraded Alfisols. Their combined application offers a sustainable approach for restoring soil productivity and improving yam production in tropical agroecosystems.

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INTRODUCTION

Yam (*Dioscorea rotundata* Poir) is one of the major root and tuber crops cultivated in tropical regions, ranking after cassava, potato, and sweet potato in terms of importance. The crop plays a vital role in food security, income generation, and rural livelihoods, particularly in West Africa. Global yam production is estimated at over 75 million tonnes annually, with Nigeria contributing nearly 70% of total production, thereby remaining the leading producer worldwide (FAO, 2023). Yam is a key staple food in tropical regions, providing a rich source of carbohydrates, dietary fiber, vitamins, and essential minerals. The tubers are widely consumed in various forms, including boiled, fried, roasted, and pounded preparations. In addition to its nutritional importance, yam contributes significantly to rural economies as a source of income and employment, and it also holds strong cultural and social significance in many West African communities, where it is associated with traditional ceremonies, festivals, and social status (Frossard *et al.*, 2017).

Despite its economic and food security importance, yam productivity under smallholder farming systems remains low. Average national yields in Nigeria and much of West Africa are about 10 t ha⁻¹

under farmers' conditions (Agbede *et al.*, 2013; Frossard *et al.*, 2017; Neina, 2021), which is far below the attainable yield potential of 50 t ha⁻¹ under improved management practices involving enhanced soil fertility, improved planting materials, and better agronomic practices (Frossard *et al.*, 2017; Neina, 2021). This wide yield gap has been largely attributed to declining soil fertility, continuous cultivation, shortened fallow periods, and inadequate nutrient inputs (Agbede *et al.*, 2013; Frossard *et al.*, 2017; Neina, 2021), particularly in tropical Alfisols characterized by low organic matter and poor nutrient retention capacity (Agbede *et al.*, 2013). These constraints underscore the need for sustainable soil fertility management strategies to enhance yam productivity.

Yam is a heavy feeder that requires fertile, loose, and well-drained soils for optimal growth and tuber expansion. However, continuous cultivation and erosion have depleted soil organic matter in many Alfisols, leading to acidity, low cation exchange capacity (CEC), high bulk density, and poor structure. These conditions restrict root penetration and water movement, resulting in reduced tuber yield (Agbede *et al.*, 2013). Restoring such degraded soils calls for sustainable management practices that enhance soil organic matter, nutrient availability, and soil physical

and biological quality. Organic amendments have proven to be effective and sustainable alternatives to inorganic fertilizers, which are often expensive and susceptible to nutrient losses in tropical environments. Poultry manure (PM), widely used in tropical agriculture, is rich in nitrogen, phosphorus, potassium, calcium, and magnesium. It improves soil fertility, promotes microbial activity, and enhances crop performance (Adekiya *et al.*, 2019; Adeyemo *et al.*, 2019). In practical field applications, PM is commonly applied at rates ranging from 5 to 20 t ha⁻¹, depending on crop type, soil condition, and management objectives, with higher rates often associated with improved soil organic matter and yield response in root and tuber crops (Agbede and Adekiya, 2012; Adekiya *et al.*, 2019; Agbede and Oyewumi, 2022). However, its rapid mineralization under high rainfall conditions often leads to volatilization and leaching losses, reducing its long-term effectiveness. Combining PM with a carbon-rich, stable material such as biochar can help retain nutrients and improve soil quality (Agegnehu *et al.*, 2017; Agbede and Oyewumi, 2022).

Biochar, a carbonaceous by-product of biomass pyrolysis under limited oxygen, has gained attention for its capacity to enhance soil fertility and mitigate degradation. It improves soil pH, water retention, CEC, and organic matter stabilization, while reducing nutrient leaching (Lehmann and Joseph, 2015; Adekiya *et al.*, 2019). In field conditions, biochar is typically applied at rates between 5 and 50 t ha⁻¹ (Major, 2010; Lehmann and Joseph, 2015; Raboin *et al.*, 2016), with moderate rates (e.g., 10–30 t ha⁻¹) often reported to significantly improve soil properties and crop performance in tropical soils (Agegnehu *et al.*, 2017; Adekiya *et al.*, 2020). When co-applied with PM, biochar may provide significant interaction effects by stabilizing organic nutrients and creating favorable conditions for root development.

The use of locally available feedstocks such as cocoa pod husk—a major agro-industrial waste in cocoa-producing areas—for biochar production offers an environmentally friendly approach to waste management and soil fertility restoration. Cocoa pod husk constitutes approximately 67–76% of the cocoa fruit weight, and about 10 tonnes of fresh husk are generated for every tonne of dry cocoa beans produced. With global cocoa production exceeding 4–5 million tonnes annually, this corresponds to an estimated 30–40 million tonnes of cocoa pod husk waste generated each year worldwide (Campos-Vega *et al.*, 2018). In major cocoa-producing nations such as Nigeria, Ghana, and Côte d'Ivoire, which collectively account for a large share of global production, substantial volumes of cocoa pod husk are often left on farms after pod breaking. For example, West Africa alone has been estimated to generate about 35 million tonnes of fresh cocoa pod husk annually, much of which remains underutilized and is typically left to decompose in situ (Hougni *et al.*, 2021). Cocoa pod husks are notably rich in potassium (K) and other exchangeable base cations such as calcium (Ca) and magnesium (Mg), making them a valuable nutrient source for soil amendment (Hougni *et al.*, 2021; Gopal *et al.*, 2025). Consequently, biochar derived from cocoa pod husks is particularly suitable for root and tuber crops such as yam, which have a high potassium requirement for tuber bulking and quality.

Recycling cocoa pod husk biochar (CPHB) offers considerable potential to enhance the mineral nutrition of cocoa. However, information on the nutrient composition and release dynamics of biochar produced from these husks remains limited. Cocoa pod husks, which are particularly rich in potassium, are often left to accumulate in heaps on plantations across Africa. The CPHB has been reported to increase soil pH,

available phosphorus, and moisture retention in acidic tropical soils (Ngalani *et al.*, 2023; Mwafurirwa *et al.*, 2024). The application of CPHB in yam-based systems remains largely underexplored, particularly on degraded Alfisols where soil erosion, compaction, and nutrient depletion severely constrain productivity. Previous studies have demonstrated that the combined use of biochar and poultry manure can improve soil fertility, structure, and crop performance in cereals and vegetable systems (Gunes *et al.*, 2014; Agegnehu *et al.*, 2017; Adekiya *et al.*, 2019; Liang *et al.*, 2024). However, these studies have largely focused on short-duration crops and have not adequately addressed root and tuber crops such as yam, which differ markedly in nutrient demand, growth duration, and soil interaction. More importantly, the mechanisms by which CPHB, alone or in combination with PM, influence soil physical and chemical properties, as well as leaf nutrient dynamics in yam production systems, remain poorly understood. This gap is significant both scientifically—due to the need to understand amendment–soil–crop interactions in tropical root cropping systems—and practically, because yam is a major staple crop in West Africa, and improving its productivity on degraded soils is essential for food security and sustainable land management. In addition, optimal application rates of CPHB combined with PM have not been clearly established, limiting the ability of smallholder farmers to adopt cost-effective and resource-efficient soil fertility management strategies.

This study is among the first field-based experiments to systematically evaluate the combined effects of CPHB and PM on soil properties, nutrient dynamics, and yam productivity in a degraded tropical Alfisol, with the aim of identifying optimal amendment rates for sustainable and economically viable production. It was hypothesized that the combined application of

CPHB and PM would exert significant interaction effects on soil physical and chemical properties, enhance nutrient uptake, and consequently improve the growth and tuber yield of yam on degraded tropical Alfisols compared with sole applications or the untreated control. Therefore, the objective of the present study was to evaluate the effects of CPHB and PM, applied alone and in combination, on soil properties, growth, and yield of yam cultivated on a degraded tropical Alfisol in southwestern Nigeria. The findings are expected to provide insight into the mechanisms of soil improvement and a sustainable, low-cost strategy for enhancing yam productivity in degraded tropical soils.

MATERIALS AND METHODS

Site Description and Treatments

Field experiments were carried out at Radiant International Nursery and Primary School, Owo, Ondo State, Nigeria (7°13'43.7"N, 5°36'08.5"E). Annual rainfall was 1,335 mm in 2023 and 1,424 mm in 2024. The rainy season typically begins in March and extends to October, while the dry season occurs between November and February, with mean temperatures of 24–32°C. The soil is classified as an Alfisol (USDA) or Luvisol (IUSS Working Group WRB, 2022). It is derived from quartzite, gneiss, and schist parent materials. Before the experiment, 0–20 cm composite soil samples were analyzed. The site had been continuously cultivated with cocoyam (*Xanthosoma sagittifolium* Crantz), cassava (*Manihot esculenta* Crantz), cowpea (*Vigna unguiculata* Walp), maize (*Zea mays* L.), and melon (*Citrullus colocynthis* L.) for over ten years without fertilizer application.

The experiment was laid out as a 3 × 3 factorial in a randomized complete block design (RCBD), comprising three rates of CPHB (0, 15, and 30 t ha⁻¹) and three rates of PM (0, 10, and 20 t ha⁻¹),

resulting in nine treatment combinations. The treatments were replicated three times, with each replication serving as a block to account for spatial variability across the experimental site. Within each block, the nine treatment combinations were randomly assigned to plots to ensure unbiased treatment distribution. Land preparation involved manual clearing, followed by the construction of mounds measuring 1 m × 1 m at the base and 0.75 m in height in April of each cropping season. Each plot measured 6 m × 6 m and contained 36 plants spaced at 1 m × 1 m. A 1-m buffer separated adjacent blocks, while plots within each block were separated by 0.5 m. The same experimental layout, blocking, randomization, and plot arrangement were maintained during the 2023 and 2024 cropping seasons.

Cocoa Pod Husk Biochar and Poultry Manure Preparation

Cocoa pod husks were collected from nearby cocoa farms, air-dried for three weeks, and pyrolyzed at 500°C for about four hours using a locally fabricated 200 L metal-drum kiln. The kiln had a bottom air inlet, side vents, and a chimney-fitted lid to regulate airflow and maintain limited oxygen conditions. Temperature was monitored with a probe thermometer, and the kiln was sealed after pyrolysis to cool the biochar slowly and prevent oxidation. The cooled biochar was then collected, crushed, and sieved through a 2-mm mesh to obtain uniform particle size suitable for soil incorporation and laboratory analysis.

Fresh poultry manure was obtained from a local farm, heaped under shade for three weeks to stabilize and reduce ammonia content. It was then air-dried, crushed, and sieved to ensure uniformity and minimize phytotoxicity. Both cocoa pod husk biochar and poultry manure are locally available, cost-effective, and sustainable resources for improving soil fertility and yam production.

Incorporation of Cocoa Pod Husk Biochar and Poultry Manure and Planting of Yam

Following land preparation and mound construction, the field was divided into 6 × 6 m plots. The CPHB and PM were applied at 0, 15, and 30 t ha⁻¹ and 0, 10, and 20 t ha⁻¹, respectively, with materials accurately weighed and uniformly distributed across each plot. The selected application rates were based on previous studies conducted on tropical soils and on established agronomic recommendations for the use of biochar and poultry manure. Specifically, the biochar application rates were within the agronomically recommended range of 5–50 t ha⁻¹ for improving soil properties without causing adverse effects (Major, 2010). Likewise, the poultry manure application rates (0–20 t ha⁻¹) represented moderate to high nutrient inputs suitable for nutrient-depleted Alfisols under yam cultivation (Agbede and Adekiya, 2012). The treatment combinations were structured according to an integrated plant nutrition approach, combining different levels of biochar with either partial or full rates of poultry manure, alongside their sole applications. No inorganic fertilizers were applied during the experiment to ensure that the observed effects on soil properties, growth, and yield responses were attributable solely to cocoa pod husk biochar and poultry manure treatments. All amendments were applied to the surface of each mound and incorporated uniformly into the top 10 cm of each mound using a hand hoe, targeting the actively cultivated zone rather than the inter-mound spaces. To ensure consistency, application rates were standardized per mound, and the same incorporation depth and procedure were maintained across all plots. Incorporation was carried out three weeks prior to planting to allow sufficient interaction between soil and amendments. The same treatments were reapplied to the respective plots at the start of each cropping season in 2023 and 2024.

Planting was carried out immediately after the construction of mounds. One seed yam sett (about 0.4 kg) of white yam (*Dioscorea rotundata* cv. Gambari) was planted on each mound on April 2, 2023, and April 3, 2024. Staking was done shortly after emergence to provide support for vine development. The experiment was conducted under rainfed conditions, and no supplementary irrigation was applied throughout the study period. Manual weeding using a hoe was performed at 3, 8, 12, and 16 weeks after planting (WAP).

Determination of Soil Physical and Chemical Properties

Soil physical properties, including bulk density, total porosity, and gravimetric moisture content, were assessed starting two months after yam planting and subsequently at two-month intervals, giving four sampling occasions per growing season (Agbede *et al.*, 2013). For each assessment, five undisturbed soil cores (4 cm diameter × 15 cm height) were collected from the 0–15 cm depth at the center of each plot, approximately 15 cm from the top of the mounds, using steel core samplers. The samples were oven-dried at 105°C for 24 hours to determine bulk density. Total porosity was estimated from bulk density and an assumed particle density of 2.65 Mg m⁻³. At each sampling time, five measurements per plot were taken, and their mean values were computed to obtain seasonal estimates for statistical analysis.

Before the start of the experiment in 2023, composite surface soil samples (0–20 cm depth) were collected from ten randomly selected locations across the field to establish baseline soil conditions. At harvest in both seasons, disturbed soil samples were taken from five random points within the center of each plot (0–20 cm depth), pooled, and homogenized to form a composite sample per plot. All soil samples

were air-dried, gently crushed, and passed through a 2-mm sieve prior to laboratory analyses, following standard procedures outlined by Carter and Gregorich (2007). Particle-size distribution was determined using the hydrometer method. Soil pH was measured in a 1:2 soil-to-water suspension using a digital pH meter. Soil organic carbon (OC) was determined directly using the Walkley–Black wet oxidation method, while soil organic matter (OM) content was calculated from OC using the conventional conversion factor ($OM = OC \times 1.724$). Total nitrogen (N) was analyzed using the micro-Kjeldahl digestion technique. Available phosphorus (P) was extracted using the Bray-1 method and quantified colorimetrically. Exchangeable potassium (K), calcium (Ca), and magnesium (Mg) were extracted using 1 M ammonium acetate (pH 7). Potassium was measured with a flame photometer, whereas Ca and Mg were determined by EDTA titration.

Analysis of Cocoa Pod Husk Biochar, Poultry Manure and Yam Leaves

The CPHB and PM used in this study were evaluated for selected physical and chemical properties using established analytical methods (Tel and Hagarty, 1984; International Biochar Initiative, 2015). Before analysis, the materials were air-dried to a constant weight, ground into fine particles, and passed through a 2-mm sieve to obtain uniform samples. Bulk density of both CPHB and PM was determined by carefully filling a container of known volume without applying pressure, followed by oven-drying to constant weight. Bulk density was then calculated as the ratio of oven-dry mass to the container volume (Mg m⁻³). Ash content was measured on a dry-weight basis by placing oven-dried subsamples in uncovered porcelain crucibles and igniting them in a muffle furnace at 750°C for 2 hours, after which the residues were cooled in a desiccator and weighed to obtain the remaining inorganic ash content. The specific surface

area of CPHB and PM was determined using the Brunauer–Emmett–Teller (BET) method based on N_2 adsorption–desorption isotherms at 77 K, following degassing of samples to remove moisture and volatile impurities. This method provides an estimate of the total surface area available for adsorption and nutrient retention. The pH and electrical conductivity (EC) of CPHB and PM were determined using a 1:10 solid-to-water extraction. Approximately 5 g of each prepared sample was mixed with 50 mL of deionized water, shaken for 30 minutes, and allowed to stand for 1 hour at $25 \pm 2^\circ\text{C}$. The mixture was filtered using Whatman No. 42 filter paper. The pH of the filtrate was measured with a calibrated digital pH meter using standard buffer solutions (pH 4 and 7), while EC was measured with a digital conductivity meter (Hanna Instruments HI 99301) calibrated with a 1.41 mS cm^{-1} KCl solution. EC values were used as an indicator of soluble salt content. In addition, CPHB and PM were analyzed for organic carbon (OC), total nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulphur (S), and micronutrients including iron (Fe), manganese (Mn), zinc (Zn), and copper (Cu) following standard procedures outlined by AOAC (2019).

During the 2023 and 2024 seasons, yam leaves were sampled five months after planting from the upper, middle, and lower canopy of five randomly selected plants per plot. Samples were oven-dried at 80°C for 24 hours and ground uniformly. Total nitrogen was determined by the micro-Kjeldahl method. Ground samples were dry-ashed at 450°C for six hours and digested with $\text{HNO}_3\text{--H}_2\text{SO}_4\text{--HClO}_4$ for nutrient analysis. Phosphorus was measured colorimetrically using the vanadomolybdate method, potassium by flame photometry, and calcium and magnesium by EDTA titration, following the procedures outlined by Tel and Hagarty (1984).

Determination of Growth Parameters and Tuber Yield

Growth and yield data were collected from ten randomly selected yam plants per plot. At five months after planting, vine length, leaf number, and leaf area were measured using a meter rule, leaf counts, and the graphical method, respectively. At harvest (eight months after planting), tuber yield was determined by weighing fresh tubers from ten plants per plot using a top-loading balance.

Statistical Analysis

Data collected from each experiment were subjected to a two-way analysis of variance (ANOVA) with the Genstat statistical software (VSN International, 2023). A combined ANOVA across the two cropping seasons was performed within a factorial randomized complete block design (RCBD). Year (2023 and 2024), cocoa pod husk biochar, and poultry manure were included as sources of variation in the model. Treatments were replicated three times in each experiment, with replications serving as blocks to account for experimental variability. The statistical model included the main effects of year (Y), CPHB, and PM, together with their interaction terms ($Y \times \text{CPHB}$, $Y \times \text{PM}$, $\text{CPHB} \times \text{PM}$, and $Y \times \text{CPHB} \times \text{PM}$) to evaluate treatment responses and their consistency across seasons. Mean separation was performed using Duncan's multiple range test (DMRT) at $P < 0.05$.

RESULTS AND DISCUSSION

Soil Physical and Chemical Properties before the Experiment

The pre-planting soil analysis (Table 1) showed that the site had a sandy loam texture dominated by sand (75.30%), with moderate silt (13.10%) and clay (11.60%) contents. The bulk density (1.54 Mg m^{-3}) and total porosity (41.89%) indicated moderate

compaction with sufficient aeration. The soil was slightly acidic (pH 5.62) and low in organic matter (1.57%), total N (0.11%), and available P (8.80 mg kg⁻¹). Exchangeable K, Ca, and Mg were below critical levels, confirming low fertility and the need for organic amendments to enhance yam productivity.

Properties of Cocoa Pod Husk Biochar and Poultry Manure

The physicochemical properties of CPHB and PM (Table 2) showed distinct differences. CPHB had lower bulk density (0.28 Mg m⁻³) and higher surface area (18.13 m² g⁻¹), indicating its lighter, porous nature. It was alkaline (pH 9.71) with higher electrical conductivity (13.40 mS cm⁻¹) and greater organic carbon (45.70%) but lower nitrogen (1.39%), giving a wide C:N ratio (32.88). PM was nearly neutral (pH 6.81), richer in nitrogen (2.94%) and micronutrients, with a narrower C:N ratio (9.74). CPHB improved soil structure and base cations, while PM supplied readily available nutrients, making their combination agronomically complementary.

Effects of Cocoa Pod Husk Biochar and Poultry Manure on Soil Physical Properties

Application of CPHB and PM significantly ($P < 0.05$) influenced soil bulk density, total porosity, and moisture content during the 2023 and 2024 cropping seasons (Table 3). Bulk density decreased progressively with increasing rates of both amendments, while total porosity and moisture content increased correspondingly. The untreated control exhibited the highest bulk density (1.56 and 1.61 Mg m⁻³) and the lowest total porosity (41.1% and 39.2%) and moisture content (11.4% and 10.9%) in 2023 and 2024, respectively. In contrast, the combined application of 30 t ha⁻¹ CPHB and 20 t ha⁻¹ PM produced the lowest bulk density (0.91 and 0.88 Mg m⁻³) and the highest total porosity (65.7% and 66.8%) and moisture content (19.2% and 19.7%). These changes represent a 42–45% reduction in compaction relative to the control.

The effects of year, CPHB, and PM were significant ($P < 0.05$), while the CPHB × PM interaction was also significant, demonstrating that the combined application of the amendments influenced soil physical

Table 1 Mean ± standard deviation of physical and chemical properties of soil (0–20 cm depth) before the experiment

Property	Value	Class
Sand (%)	75.30 ± 1.20	
Silt (%)	13.10 ± 0.32	
Clay (%)	11.60 ± 0.21	
Textural class	Sandy loam	
Bulk density (Mg m ⁻³)	1.54 ± 0.02	
Total porosity (%)	41.89 ± 0.05	
pH (water)	5.62 ± 0.03	Slightly acidic
Organic matter (%)	1.57 ± 0.02	Low
Total N (%)	0.11 ± 0.01	Low
Available P (mg kg ⁻¹)	8.80 ± 0.04	Low
Exchangeable K (cmol kg ⁻¹)	0.12 ± 0.01	Low
Exchangeable Ca (cmol kg ⁻¹)	1.75 ± 0.03	Low
Exchangeable Mg (cmol kg ⁻¹)	0.36 ± 0.02	Low

properties more effectively than their individual application. In contrast, year-related interactions ($Y \times \text{CPHB}$, $Y \times \text{PM}$, and $Y \times \text{CPHB} \times \text{PM}$) were not significant, indicating consistent treatment responses across seasons. The slight reduction in bulk density and corresponding increases in total porosity and moisture content observed in 2024 suggest residual effects of the amendments, while the low coefficients of variation (1.52–2.36%) indicate a high level of experimental precision.

The observed improvements reflect the complementary roles of both amendments. Biochar's low bulk density, porous structure, and stable carbon matrix enhance pore continuity, aeration, and aggregate stability (Blanco-Canqui, 2017; Zhu *et al.*, 2025). Poultry manure, on the other hand, contributes easily decomposable organic matter that fuels microbial activity and the production of binding agents such as extracellular polysaccharides and fungal hyphae, which promote stable aggregate formation.

The significant ($P < 0.05$) $\text{CPHB} \times \text{PM}$ interaction for all measured parameters demonstrates the complementary action of both amendments, with biochar enhancing the stabilization and retention of manure-derived organic matter and nutrients, thereby reducing structural degradation during mineralization (Blanco-Canqui, 2017; Guo *et al.*, 2025). Slightly better soil physical conditions in 2024 compared with 2023 suggest residual or cumulative effects of the amendments, particularly biochar's long-term persistence and continued improvement of soil aggregation and hydraulic conductivity (Blanco-Canqui, 2017). Enhanced soil moisture content under the combined treatment likely resulted from increased microporosity, organic matter content, and aggregate formation, which improved water-holding capacity and reduced rapid drainage losses. Similar outcomes have been reported by Chen *et al.* (2023) and Karki *et al.* (2025), who observed that biochar improves field capacity, soil water retention, and

Table 2 Mean $\pm$ standard deviation of physical and chemical properties of cocoa pod husk biochar and poultry manure used for the experiment

Property	Cocoa pod husk biochar	Poultry manure
Bulk density (Mg m^{-3})	0.28 ± 0.01	0.45 ± 0.02
Ash content (%)	30.72 ± 0.20	28.41 ± 0.10
Surface area ($\text{m}^2 \text{g}^{-1}$)	18.13 ± 0.06	4.32 ± 0.05
Electrical conductivity (mS cm^{-1})	13.40 ± 0.04	5.20 ± 0.06
pH (H_2O)	9.71 ± 0.03	6.81 ± 0.07
Organic C (%)	45.70 ± 0.20	28.63 ± 0.20
Nitrogen (%)	1.39 ± 0.02	2.94 ± 0.03
C:N	32.88 ± 0.20	9.74 ± 0.04
Phosphorus (%)	0.38 ± 0.01	1.35 ± 0.02
Potassium (%)	10.24 ± 0.04	2.16 ± 0.03
Calcium (%)	2.32 ± 0.03	1.12 ± 0.02
Magnesium (%)	1.37 ± 0.02	0.53 ± 0.01
Sulphur (%)	0.24 ± 0.01	0.52 ± 0.02
Iron (mg kg^{-1})	259.84 ± 9.27	$1,599.66 \pm 52.42$
Manganese (mg kg^{-1})	95.73 ± 5.68	230.17 ± 7.54
Zinc (mg kg^{-1})	189.57 ± 7.21	239.58 ± 8.95
Copper (mg kg^{-1})	62.81 ± 5.74	149.62 ± 4.96

Table 3 Effects of cocoa pod husk biochar and poultry manure on soil physical properties (0–15 cm depth), averaged over four sampling periods at 2, 4, 6, and 8 months after planting

CPHB (t ha ⁻¹)	PM (t ha ⁻¹)	Bulk density (Mg m ⁻³)		Total porosity (%)		Moisture content (%)	
		2023	2024	2023	2024	2023	2024
0	0	1.56 ± 0.02 ^a	1.61 ± 0.03 ^a	41.1 ± 0.6j	39.2 ± 0.5i	11.4 ± 0.3 ^f	10.9 ± 0.2 ^f
0	10	1.42 ± 0.03 ^b	1.40 ± 0.02 ^b	46.4 ± 0.7 ^h	47.2 ± 0.6 ^h	12.9 ± 0.3 ^e	13.4 ± 0.2 ^e
0	20	1.28 ± 0.02 ^d	1.26 ± 0.03 ^d	51.7 ± 0.8 ^f	52.5 ± 0.7 ^f	14.4 ± 0.3 ^d	14.9 ± 0.3 ^d
15	0	1.35 ± 0.03 ^c	1.33 ± 0.02 ^c	49.1 ± 0.6 ^g	49.8 ± 0.5 ^g	13.7 ± 0.3 ^d	14.2 ± 0.3 ^d
15	10	1.21 ± 0.02 ^e	1.19 ± 0.03 ^e	54.3 ± 0.7 ^e	55.1 ± 0.6 ^e	15.2 ± 0.3 ^c	15.7 ± 0.3 ^c
15	20	1.07 ± 0.02 ^g	1.05 ± 0.02 ^g	59.6 ± 0.8 ^c	60.4 ± 0.7 ^c	16.7 ± 0.3 ^b	17.2 ± 0.2 ^b
30	0	1.14 ± 0.03 ^f	1.12 ± 0.03 ^f	57.0 ± 0.8 ^d	57.7 ± 0.6 ^d	15.9 ± 0.3 ^c	16.4 ± 0.3 ^c
30	10	1.02 ± 0.02 ^h	1.00 ± 0.02 ^h	61.5 ± 0.7 ^b	62.3 ± 0.7 ^b	17.4 ± 0.3 ^b	17.9 ± 0.2 ^b
30	20	0.91 ± 0.02 ⁱ	0.88 ± 0.02 ⁱ	65.7 ± 0.6 ^a	66.8 ± 0.6 ^a	19.2 ± 0.3 ^a	19.7 ± 0.3 ^a
CV (%)		2.18	2.36	1.52	1.61	2.27	2.11
Source of variation							
Year		0.018	0.018	0.022	0.022	0.015	0.015
CPHB		0.001	0.001	0.001	0.001	0.001	0.001
PM		0.001	0.001	0.001	0.001	0.001	0.001
Y × CPHB		0.081 ^{ns}	0.081 ^{ns}	0.051 ^{ns}	0.051 ^{ns}	0.056 ^{ns}	0.056 ^{ns}
Y × PM		0.094 ^{ns}	0.094 ^{ns}	0.073 ^{ns}	0.073 ^{ns}	0.059 ^{ns}	0.059 ^{ns}
CPHB × PM		0.001	0.001	0.001	0.001	0.001	0.001
Y × CPHB × PM		0.112 ^{ns}	0.112 ^{ns}	0.105 ^{ns}	0.105 ^{ns}	0.098 ^{ns}	0.098 ^{ns}

Note: Means within the same column followed by different superscript letters (a–i) are significantly different at $P < 0.05$ according to Duncan's multiple range test. Values are presented as mean ± standard error. CPHB = cocoa pod husk biochar, PM = poultry manure, Y = year, CV = coefficient of variation, ns = not significant ($P > 0.05$).

plant-available water in coarse-textured and degraded soils. Overall, the integrated use of CPHB and PM significantly improved soil structure, porosity, and moisture retention, demonstrating a sustainable and eco-friendly approach for improving degraded tropical Alfisols, enhancing root development, and supporting long-term yam productivity under continuous cultivation.

Effects of Cocoa Pod Husk Biochar and Poultry Manure on Soil Chemical Properties

Application of CPHB and PM significantly ($P < 0.05$) influenced soil chemical properties during the 2023 and 2024 seasons (Table 4). Soil pH, organic matter, total N, available P, and exchangeable cations (K, Ca, and Mg) all increased with higher rates of CPHB and PM. The combined application of 30 t ha^{-1} CPHB and 20 t ha^{-1} PM produced the highest soil pH (6.87–6.91), organic matter (3.54–3.62%), total N (0.20–0.21%), available P (18.3–19.1 mg kg^{-1}), and exchangeable K, Ca, and Mg (0.32–0.34, 3.56–3.61, and 0.57–0.59 cmol kg^{-1} , respectively), while the control had the lowest nutrient levels. These improvements were more pronounced during the 2024 growing season.

The effects of year, CPHB, and PM significantly influenced soil chemical properties, while the CPHB $\times$ PM interaction was also significant ($P < 0.05$), indicating that their combined application enhanced soil fertility more effectively than either amendment alone. The non-significant year-related interactions ($Y \times \text{CPHB}$, $Y \times \text{PM}$, and $Y \times \text{CPHB} \times \text{PM}$) indicate stable treatment effects across seasons. Slightly greater values in 2024 suggest residual or cumulative effects of the amendments, and the low coefficients of variation (1.48–4.22%) indicate high experimental precision and reliable data.

The progressive rise in soil pH with increasing CPHB and PM rates reflects the liming potential of biochar and the release of base cations such as Ca^{2+} ,

Mg^{2+} , and K^{+} during decomposition (Wang *et al.*, 2014; Adekiya *et al.*, 2019). The alkaline nature of CPHB (Table 2; pH 9.71) likely neutralized soil acidity, increasing pH from 5.49 in the control to 6.91 under the highest combined treatment. This aligns with earlier findings that biochar from crop residues ameliorates soil acidity through cation exchange and hydroxyl ion release (Zubairu *et al.*, 2023; Zhu *et al.*, 2025). PM also contributed to pH improvement by releasing basic cations during organic matter mineralization (Agbede and Oyewumi, 2022).

The significant increase in soil organic matter and total N under CPHB and PM treatments demonstrates their complementary roles. Biochar provided stable carbon that enhanced long-term carbon sequestration and soil aggregation (Wang *et al.*, 2014; Premalatha *et al.*, 2023), while PM supplied labile organic matter that fueled microbial activity and nutrient mineralization. The combined use of both amendments resulted in higher organic matter than either alone, reflecting their complementary contributions to soil organic matter accumulation. Biochar's porous structure adsorbs labile nutrients and carbon from manure, reducing losses and improving organic matter stabilization (Agegnehu *et al.*, 2017; Adekiya *et al.*, 2019; Liang *et al.*, 2024). Similarly, total N and available P increased markedly under combined treatments. PM supplied mineral N and P through decomposition, whereas biochar retained these nutrients by adsorbing ammonium and phosphate ions (Madiba *et al.*, 2016). The highest available P values (18.3–19.1 mg kg^{-1}) under combined treatment suggest reduced P fixation, likely due to biochar complexation of Al and Fe ions that otherwise immobilize P in acidic soils (Bornø *et al.*, 2018). Exchangeable K, Ca, and Mg also increased significantly due to the high mineral content of CPHB and PM (Table 2), enhancing cation exchange capacity and base saturation. Overall, the significant

CPHB × PM interaction across all soil chemical properties demonstrates the synergistic relationship between the two amendments. Their co-application improved soil fertility indicators more effectively than individual use and exhibited residual effects in 2024, enhancing nutrient retention, base cation supply, and soil buffering capacity. Integrating CPHB with PM thus represents a sustainable and eco-friendly strategy for improving fertility and productivity in degraded tropical soils.

Effects of Cocoa Pod Husk Biochar and Poultry Manure on Leaf Nutrient Concentrations of Yam

Application of CPHB and PM, individually or combined, significantly ($P < 0.05$) influenced yam leaf nutrient concentrations in 2023 and 2024 (Table 5). Leaf N, P, K, Ca, and Mg concentrations increased consistently with increasing amendment rates. The combined application of 30 t ha⁻¹ CPHB and 20 t ha⁻¹ PM produced the highest values (4.29–4.32% N, 0.37–0.39% P, 2.94–2.96% K, 0.53–0.56% Ca, and 0.34–0.37% Mg), while the control recorded the lowest.

The main effects of year, CPHB, and PM significantly influenced leaf nutrient concentrations, while the significant CPHB × PM interaction showed that their combined application improved nutrient availability and uptake ($P < 0.05$). The non-significant Y × CPHB, Y × PM, and Y × CPHB × PM interactions indicate that treatment responses remained stable across both growing seasons. The low coefficients of variation (2.05–6.35%) further indicate good experimental precision and data reliability.

The increase in leaf N concentration reflects mineralization of organic N from PM and reduced N losses due to biochar's ammonium and nitrate adsorption capacity, which improves N retention and uptake (Agegnehu *et al.*, 2017). Biochar also promotes microbial immobilization and gradual N release

(Premalatha *et al.*, 2023). The increase in P concentration was attributed to biochar's capacity to adsorb and release phosphate ions, minimize P fixation by Al and Fe oxides, and stimulate microbial P solubilization, complemented by the soluble P fraction from PM (Madiba *et al.*, 2016; Bomø *et al.*, 2018). PM's phosphate content supports vigorous root and leaf growth, while biochar enhances P retention and availability.

The increased leaf K, Ca, and Mg concentrations can be attributed to the abundance of base cations in CPHB ash and its liming effect, which enhance soil cation exchange capacity and promote root nutrient uptake (Yan *et al.*, 2021; Premalatha *et al.*, 2023). In addition, PM improves nutrient mineralization and increases nutrient availability, thereby enhancing root absorption efficiency (Gunes *et al.*, 2014; Agbede, 2025). The significant CPHB × PM interactions highlight the complementary roles of biochar and PM, with biochar improving nutrient retention and PM supplying readily available nutrients. Slightly higher nutrient concentrations in 2024 reflect residual soil fertility from biochar's persistence and continued PM mineralization. Overall, combined CPHB and PM applications proved most effective in sustaining fertility and enhancing yam nutrition.

Effects of Cocoa Pod Husk Biochar and Poultry Manure on Growth Parameters and Tuber Yield of Yam

Application of CPHB and PM significantly ($P < 0.05$) enhanced yam growth and yield attributes in both 2023 and 2024 (Table 6). Vine length, leaf number, leaf area (Table 6), and tuber yield (Table 6, Figure 1) increased progressively with higher amendment rates. The highest values—4.68–4.72 m vine length, 455–468 leaves per plant, 2.89–2.92 m² leaf area, and 45.8–46.4 t ha⁻¹ tuber yield—were obtained with 30 t ha⁻¹ CPHB + 20 t ha⁻¹ PM, while the control recorded the lowest.

Table 4 Effects of cocoa pod husk biochar and poultry manure on soil chemical properties (0–20 cm depth)

CPHB (t ha ⁻¹)	PM (t ha ⁻¹)	pH (water)		Organic matter (%)		Total N (%)		Available P (mg kg ⁻¹)		Exchangeable K (cmol kg ⁻¹)		Exchangeable Ca (cmol kg ⁻¹)		Exchangeable Mg (cmol kg ⁻¹)	
		2023	2024	2023	2024	2023	2024	2023	2024	2023	2024	2023	2024	2023	2024
0	0	5.51 ± 0.03 ^g	5.49 ± 0.02 ^g	1.49 ± 0.06 ⁱ	1.35 ± 0.05 ⁱ	0.10 ± 0.01 ^g	0.09 ± 0.01 ^g	7.6 ± 0.2 ^h	7.1 ± 0.2 ^h	0.11 ± 0.01 ^h	0.10 ± 0.01 ^h	1.62 ± 0.06 ^h	1.45 ± 0.05 ^h	0.32 ± 0.02 ⁱ	0.30 ± 0.02 ⁱ
0	10	5.61 ± 0.02 ^f	5.68 ± 0.03 ^f	1.68 ± 0.04 ^h	1.73 ± 0.05 ^h	0.12 ± 0.01 ^e	0.13 ± 0.01 ^e	10.3 ± 0.3 ^e	10.9 ± 0.3 ^e	0.13 ± 0.01 ^h	0.14 ± 0.01 ^h	1.93 ± 0.04 ^h	1.98 ± 0.05 ^g	0.38 ± 0.02 ^f	0.39 ± 0.02 ^f
0	20	5.92 ± 0.03 ^f	5.97 ± 0.03 ^f	1.88 ± 0.05 ^g	1.94 ± 0.05 ^g	0.14 ± 0.01 ^d	0.15 ± 0.01 ^d	12.4 ± 0.3 ^d	13.0 ± 0.4 ^d	0.15 ± 0.01 ^f	0.16 ± 0.01 ^f	2.25 ± 0.06 ^e	2.31 ± 0.05 ^e	0.45 ± 0.02 ^d	0.47 ± 0.02 ^d
15	0	5.96 ± 0.03 ^f	6.01 ± 0.02 ^f	2.01 ± 0.06 ^f	2.06 ± 0.05 ^f	0.11 ± 0.01 ^f	0.12 ± 0.01 ^f	8.4 ± 0.3 ^g	8.8 ± 0.3 ^g	0.18 ± 0.01 ^e	0.19 ± 0.01 ^e	2.01 ± 0.05 ^f	2.07 ± 0.05 ^f	0.34 ± 0.02 ^h	0.36 ± 0.02 ^h
15	10	6.23 ± 0.03 ^e	6.29 ± 0.02 ^e	2.36 ± 0.05 ^e	2.41 ± 0.05 ^e	0.14 ± 0.01 ^d	0.15 ± 0.01 ^d	12.8 ± 0.3 ^d	13.3 ± 0.3 ^d	0.22 ± 0.01 ^d	0.23 ± 0.01 ^d	2.57 ± 0.05 ^d	2.63 ± 0.05 ^d	0.41 ± 0.02 ^e	0.43 ± 0.02 ^e
15	20	6.45 ± 0.03 ^{cd}	6.52 ± 0.03 ^{cd}	2.61 ± 0.06 ^d	2.68 ± 0.05 ^d	0.16 ± 0.01 ^c	0.17 ± 0.01 ^c	14.4 ± 0.4 ^{bc}	14.9 ± 0.4 ^{bc}	0.25 ± 0.01 ^c	0.26 ± 0.01 ^c	2.89 ± 0.05 ^c	2.94 ± 0.06 ^c	0.48 ± 0.02 ^c	0.50 ± 0.02 ^c
30	0	6.32 ± 0.02 ^{de}	6.38 ± 0.03 ^{de}	2.92 ± 0.05 ^c	2.99 ± 0.05 ^c	0.12 ± 0.01 ^e	0.13 ± 0.01 ^e	9.1 ± 0.3 ^f	9.8 ± 0.3 ^f	0.22 ± 0.01 ^d	0.23 ± 0.01 ^d	2.19 ± 0.05 ^e	2.26 ± 0.05 ^e	0.36 ± 0.02 ^g	0.38 ± 0.02 ^g
30	10	6.55 ± 0.02 ^{bc}	6.59 ± 0.03 ^{bc}	3.18 ± 0.06 ^b	3.23 ± 0.06 ^b	0.18 ± 0.01 ^b	0.19 ± 0.01 ^b	15.2 ± 0.4 ^b	15.7 ± 0.3 ^b	0.27 ± 0.01 ^b	0.29 ± 0.01 ^b	3.21 ± 0.06 ^b	3.28 ± 0.05 ^b	0.52 ± 0.02 ^b	0.54 ± 0.02 ^b
30	20	6.87 ± 0.02 ^a	6.91 ± 0.03 ^a	3.54 ± 0.06 ^a	3.62 ± 0.06 ^a	0.20 ± 0.01 ^a	0.21 ± 0.01 ^a	18.3 ± 0.5 ^a	19.1 ± 0.4 ^a	0.32 ± 0.01 ^a	0.34 ± 0.01 ^a	3.56 ± 0.05 ^a	3.61 ± 0.05 ^a	0.57 ± 0.02 ^a	0.59 ± 0.02 ^a
CV (%)		1.48	1.56	3.12	3.28	4.05	4.22	3.76	3.94	3.41	3.58	2.86	3.02	3.33	3.51
Source of variation															
Year		0.021	0.021	0.018	0.018	0.016	0.016	0.019	0.019	0.024	0.024	0.022	0.022	0.020	0.020
CPHB		0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
PM		0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Y × CPHB		0.072 ^{ns}	0.072 ^{ns}	0.058 ^{ns}	0.058 ^{ns}	0.061 ^{ns}	0.061 ^{ns}	0.052 ^{ns}	0.052 ^{ns}	0.063 ^{ns}	0.063 ^{ns}	0.058 ^{ns}	0.058 ^{ns}	0.056 ^{ns}	0.056 ^{ns}
Y × PM		0.085 ^{ns}	0.085 ^{ns}	0.061 ^{ns}	0.061 ^{ns}	0.059 ^{ns}	0.059 ^{ns}	0.064 ^{ns}	0.064 ^{ns}	0.051 ^{ns}	0.051 ^{ns}	0.066 ^{ns}	0.066 ^{ns}	0.053 ^{ns}	0.053 ^{ns}
CPHB × PM		0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Y × CPHB × PM		0.108 ^{ns}	0.108 ^{ns}	0.096 ^{ns}	0.096 ^{ns}	0.089 ^{ns}	0.089 ^{ns}	0.093 ^{ns}	0.093 ^{ns}	0.101 ^{ns}	0.101 ^{ns}	0.110 ^{ns}	0.110 ^{ns}	0.098 ^{ns}	0.098 ^{ns}

Note: Means within the same column followed by different superscript letters (a–i) are significantly different at P < 0.05 according to Duncan's multiple range test. Values are presented as mean ± standard error. CPHB = cocoa pod husk biochar, PM = poultry manure, Y = year, CV = coefficient of variation, ns = not significant (P > 0.05).

Table 5 Effects of cocoa pod husk biochar and poultry manure on leaf nutrient concentrations of yam at 5 months after planting

CPHB (t ha ⁻¹)	PM (t ha ⁻¹)	N (%)		P (%)		K (%)		Ca (%)		Mg (%)	
		2023	2024	2023	2024	2023	2024	2023	2024	2023	2024
0	0	1.86 ± 0.03 ⁱ	1.75 ± 0.04 ^j	0.17 ± 0.01 ^h	0.16 ± 0.01 ^h	1.78 ± 0.05 ^j	1.63 ± 0.04 ^j	0.19 ± 0.02 ^h	0.17 ± 0.01 ^h	0.08 ± 0.01 ^h	0.07 ± 0.01 ^h
0	10	2.58 ± 0.04 ^f	2.61 ± 0.05 ^f	0.22 ± 0.02 ^e	0.24 ± 0.02 ^e	2.25 ± 0.06 ^f	2.27 ± 0.05 ^f	0.25 ± 0.02 ^e	0.27 ± 0.02 ^f	0.13 ± 0.01 ^e	0.14 ± 0.01 ^e
0	20	3.31 ± 0.05 ^d	3.34 ± 0.05 ^d	0.26 ± 0.02 ^d	0.28 ± 0.02 ^d	2.53 ± 0.05 ^d	2.55 ± 0.04 ^d	0.30 ± 0.03 ^d	0.32 ± 0.02 ^d	0.16 ± 0.01 ^d	0.17 ± 0.01 ^d
15	0	1.88 ± 0.04 ^h	1.91 ± 0.03 ^h	0.18 ± 0.01 ^g	0.19 ± 0.01 ^g	1.85 ± 0.05 ^h	1.86 ± 0.05 ^h	0.21 ± 0.02 ^g	0.23 ± 0.02 ^g	0.10 ± 0.01 ^g	0.11 ± 0.01 ^g
15	10	3.05 ± 0.05 ^e	3.08 ± 0.05 ^e	0.25 ± 0.02 ^d	0.27 ± 0.02 ^d	2.34 ± 0.05 ^{ef}	2.36 ± 0.05 ^{ef}	0.29 ± 0.03 ^d	0.31 ± 0.02 ^d	0.16 ± 0.01 ^d	0.17 ± 0.01 ^d
15	20	3.47 ± 0.05 ^{cd}	3.50 ± 0.05 ^{cd}	0.29 ± 0.02 ^c	0.31 ± 0.02 ^c	2.59 ± 0.06 ^{cd}	2.60 ± 0.05 ^{cd}	0.39 ± 0.03 ^c	0.41 ± 0.03 ^c	0.21 ± 0.02 ^c	0.23 ± 0.02 ^c
30	0	2.08 ± 0.04 ^g	2.11 ± 0.04 ^g	0.20 ± 0.01 ^f	0.21 ± 0.01 ^f	1.99 ± 0.05 ^g	2.01 ± 0.05 ^g	0.23 ± 0.02 ^f	0.25 ± 0.02 ^f	0.12 ± 0.01 ^f	0.13 ± 0.01 ^f
30	10	3.82 ± 0.05 ^b	3.85 ± 0.06 ^b	0.32 ± 0.02 ^b	0.34 ± 0.02 ^b	2.67 ± 0.05 ^{bc}	2.68 ± 0.05 ^b	0.45 ± 0.03 ^b	0.47 ± 0.03 ^b	0.27 ± 0.02 ^b	0.29 ± 0.02 ^b
30	20	4.29 ± 0.06 ^a	4.32 ± 0.05 ^a	0.37 ± 0.03 ^a	0.39 ± 0.03 ^a	2.94 ± 0.06 ^a	2.96 ± 0.06 ^a	0.53 ± 0.04 ^a	0.56 ± 0.04 ^a	0.34 ± 0.03 ^a	0.37 ± 0.03 ^a
CV (%)		2.05	2.18	4.21	4.36	2.32	2.41	5.48	5.72	6.12	6.35
Source of variation											
Year		0.019	0.019	0.022	0.022	0.021	0.021	0.018	0.018	0.017	0.017
CPHB		0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
PM		0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Y × CPHB		0.064 ^{ns}	0.064 ^{ns}	0.058 ^{ns}	0.058 ^{ns}	0.052 ^{ns}	0.052 ^{ns}	0.051 ^{ns}	0.053 ^{ns}	0.059 ^{ns}	0.059 ^{ns}
Y × PM		0.071 ^{ns}	0.071 ^{ns}	0.059 ^{ns}	0.059 ^{ns}	0.053 ^{ns}	0.053 ^{ns}	0.063 ^{ns}	0.063 ^{ns}	0.056 ^{ns}	0.056 ^{ns}
CPHB × PM		0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Y × CPHB × PM		0.097 ^{ns}	0.097 ^{ns}	0.089 ^{ns}	0.089 ^{ns}	0.093 ^{ns}	0.093 ^{ns}	0.085 ^{ns}	0.085 ^{ns}	0.082 ^{ns}	0.082 ^{ns}

Note: Means within the same column followed by different superscript letters (a–i) are significantly different at $P < 0.05$ according to Duncan's multiple range test. Values are presented as mean ± standard error. CPHB = cocoa pod husk biochar, PM = poultry manure, Y = year, CV = coefficient of variation, ns = not significant ($P > 0.05$).

The main effects of year, CPHB, and PM significantly influenced yam growth and yield, while the significant CPHB $\times$ PM interaction showed that the combined treatments produced greater improvements than either amendment applied alone ($P < 0.05$). The non-significant year-related interactions suggest that treatment responses remained consistent across seasons. The relatively low coefficients of variation (2.38–3.62%) demonstrate good experimental precision and reliability of the results.

Although the biochar used in this study had a relatively high EC, no visible symptoms of salinity stress in yam—such as delayed sprouting, leaf scorching, or reduced vine growth—were observed in either growing season, even at the highest application rate of 30 t ha⁻¹. However, these observations alone are insufficient to rule out potential

salinity effects because post-treatment soil EC was not measured. Therefore, the absence of visible symptoms should be interpreted with caution, and no definitive conclusion regarding salinity safety can be made. The observed crop performance may suggest that soluble salts were moderated under field conditions through dilution, rainfall leaching, and soil buffering processes, as reported in comparable previous field studies (Agegnehu *et al.*, 2017; Ngalandi *et al.*, 2023; Mwafurirwa *et al.*, 2024) that soluble salts from high-EC organic amendments are often diluted or leached below the root zone in humid tropical environments, thereby minimizing the risk of salinity stress. Nevertheless, future studies should include post-application soil EC monitoring to assess potential salinity risks associated with long-term CPHB use.

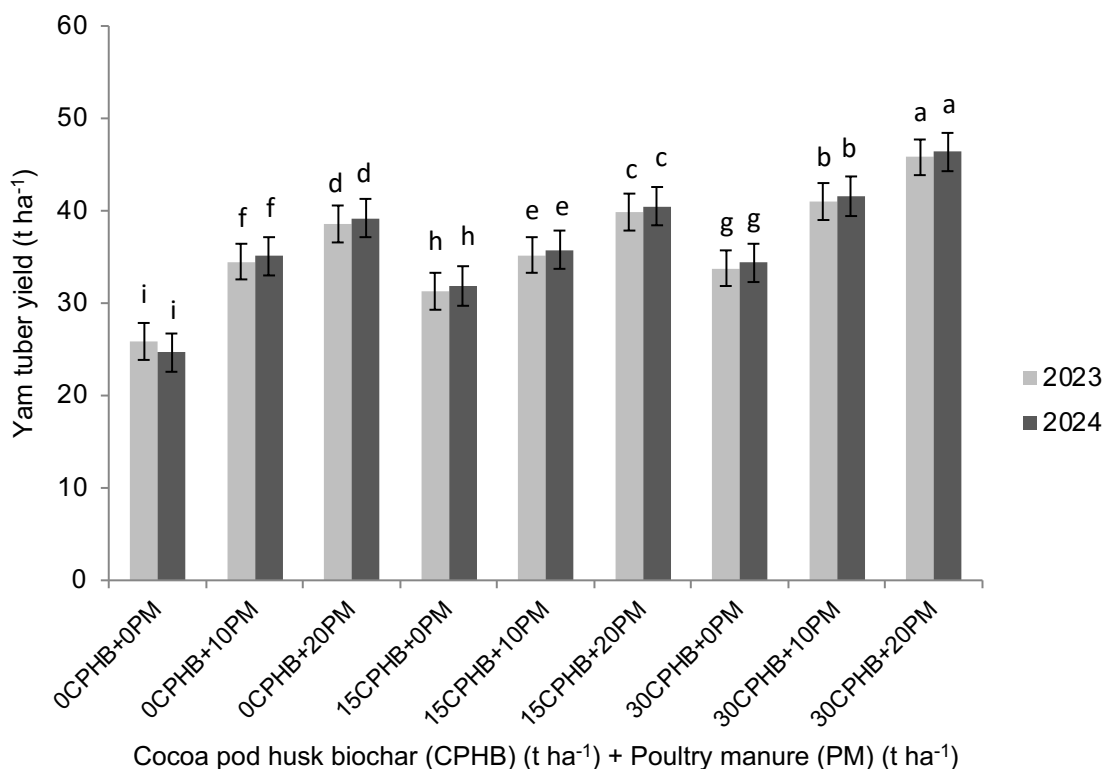


Figure 1 Effects of cocoa pod husk biochar (CPHB) and poultry manure (PM) on yam tuber yield at 8 months after planting for 2023 and 2024. Vertical bars show standard errors of comparisons. Bars marked with different letters (a–i) show means significantly different at $P < 0.05$ according to Duncan's multiple range test.

Table 6 Effects of cocoa pod husk biochar and poultry manure on growth parameters at 5 months after planting and yield of yam at 8 months after planting

CPHB (t ha ⁻¹)	PM (t ha ⁻¹)	Vine length (m)		Number of leaves per plant		Leaf area per plant (m ²)		Tuber yield (t ha ⁻¹)	
		2023	2024	2023	2024	2023	2024	2023	2024
0	0	2.68 ± 0.09 ^f	2.54 ± 0.07 ^f	185 ± 4.6 ⁱ	176 ± 3.8 ⁱ	1.53 ± 0.05 ^h	1.31 ± 0.04 ^h	25.9 ± 0.8 ^f	24.7 ± 0.7 ^f
0	10	3.07 ± 0.08 ^e	3.14 ± 0.10 ^e	212 ± 5.3 ^g	223 ± 5.7 ^g	1.99 ± 0.06 ^e	2.04 ± 0.06 ^e	34.5 ± 1.0 ^d	35.1 ± 1.1 ^d
0	20	3.26 ± 0.11 ^d	3.33 ± 0.09 ^d	239 ± 6.1 ^e	250 ± 6.4 ^e	2.25 ± 0.05 ^d	2.30 ± 0.06 ^d	38.6 ± 1.2 ^c	39.2 ± 1.3 ^c
15	0	2.98 ± 0.08 ^e	3.05 ± 0.10 ^e	196 ± 5.0 ^h	207 ± 5.2 ^h	1.75 ± 0.04 ^g	1.81 ± 0.05 ^g	31.3 ± 1.1 ^e	31.9 ± 1.1 ^e
15	10	3.14 ± 0.09 ^{de}	3.21 ± 0.08 ^{de}	301 ± 7.2 ^d	312 ± 7.4 ^d	2.04 ± 0.05 ^e	2.10 ± 0.05 ^e	35.2 ± 0.9 ^d	35.8 ± 1.0 ^d
15	20	3.56 ± 0.10 ^c	3.59 ± 0.09 ^c	354 ± 8.0 ^c	365 ± 8.2 ^c	2.37 ± 0.06 ^c	2.42 ± 0.06 ^c	39.9 ± 1.2 ^{bc}	40.5 ± 1.2 ^{bc}
30	0	3.08 ± 0.08 ^e	3.15 ± 0.09 ^e	229 ± 6.3 ^f	241 ± 7.0 ^f	1.89 ± 0.05 ^f	1.94 ± 0.05 ^f	33.8 ± 0.9 ^d	34.4 ± 1.0 ^d
30	10	4.12 ± 0.11 ^b	4.17 ± 0.10 ^b	402 ± 8.9 ^b	414 ± 9.1 ^b	2.63 ± 0.07 ^b	2.67 ± 0.07 ^b	41.0 ± 1.3 ^b	41.6 ± 1.4 ^b
30	20	4.68 ± 0.12 ^a	4.72 ± 0.11 ^a	455 ± 9.5 ^a	468 ± 9.8 ^a	2.89 ± 0.08 ^a	2.92 ± 0.08 ^a	45.8 ± 1.5 ^a	46.4 ± 1.6 ^a
CV (%)		2.78	2.64	2.45	2.38	3.12	3.05	3.48	3.62
Source of variation									
Year		0.024	0.024	0.021	0.021	0.019	0.019	0.017	0.017
CPHB		0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
PM		0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Y × CPHB		0.068 ^{ns}	0.068 ^{ns}	0.052 ^{ns}	0.052 ^{ns}	0.057 ^{ns}	0.057 ^{ns}	0.061 ^{ns}	0.061 ^{ns}
Y × PM		0.073 ^{ns}	0.073 ^{ns}	0.059 ^{ns}	0.059 ^{ns}	0.052 ^{ns}	0.052 ^{ns}	0.063 ^{ns}	0.063 ^{ns}
CPHB × PM		0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Y × CPHB × PM		0.094 ^{ns}	0.094 ^{ns}	0.088 ^{ns}	0.088 ^{ns}	0.082 ^{ns}	0.082 ^{ns}	0.079 ^{ns}	0.079 ^{ns}

Note: Means within the same column followed by different superscript letters (a–i) are significantly different at $P < 0.05$ according to Duncan's multiple range test. Values are presented as mean ± standard error. CPHB = cocoa pod husk biochar, PM = poultry manure, Y = year, CV = coefficient of variation, ns = not significant ($P > 0.05$).

The improvement in tuber yield could be attributed to complementary biological and agronomic mechanisms arising from enhanced soil physical and chemical conditions. Reduced bulk density and increased porosity improved aeration, moisture retention, and root penetration, while higher soil pH and exchangeable base cations (Ca^{2+} , Mg^{2+} , and K^{+}) minimized acidity and nutrient stress. Biochar increased cation exchange capacity and nutrient retention, especially potassium—essential for tuber development (Premalatha *et al.*, 2023; Zubairu *et al.*, 2023). Its porous structure adsorbed and slowly released nutrients from PM, reducing leaching and sustaining nutrient availability during tuber bulking (Liang *et al.*, 2024; Ali *et al.*, 2025). These improvements promoted vigorous canopy growth, greater photosynthetic activity, and higher dry matter accumulation. The significant CPHB $\times$ PM interaction indicates that their co-application enhances soil fertility, microbial activity, and crop productivity more effectively than the application of either amendment alone (Edussuriya *et al.*, 2023). From an agroecological standpoint, integrating biochar with manure promotes soil carbon sequestration, nutrient-use efficiency, and biological activity while reducing reliance on mineral fertilizers and mitigating nutrient losses. This integrated strategy aligns with climate-smart agriculture principles and offers a sustainable, low-cost soil fertility management option for smallholder farmers cultivating degraded Alfisols in tropical regions (Ali *et al.*, 2025). The 30 t ha⁻¹ CPHB + 20 t ha⁻¹ PM produced the optimum results in this experiment under the conditions of the present study and represents the best-performing treatment for sustainable adoption within smallholder farming

systems. Future studies should therefore focus on long-term field evaluations, cost–benefit analyses, and optimization of lower biochar rates.

CONCLUSIONS

This study demonstrated that integrating cocoa pod husk biochar (CPHB) with poultry manure (PM) significantly improved soil properties, growth, and yield of yam (*Dioscorea rotundata* Poir) on degraded tropical Alfisols. The highest agronomic performance was obtained at 30 t ha⁻¹ CPHB combined with 20 t ha⁻¹ PM, due to the complementary effects of biochar in enhancing nutrient retention and soil structure, and manure in supplying readily available nutrients. Therefore, the combination of 30 t ha⁻¹ CPHB and 20 t ha⁻¹ PM is the best-performing treatment under the experimental conditions of the present study. Overall, CPHB–PM integration shows strong potential as a sustainable soil improvement strategy and a viable complement to inorganic fertilizers. Further long-term studies are needed to evaluate residual effects, economic viability, optimization of lower biochar application rates, and performance across different agroecological zones.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest related to this research.

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