

Effect of Biochar Feedstock Types on Physical and Chemical Properties of Humic Nitisols in Kakamega County, Kenya

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ABSTRACT

In Kenya, inorganic fertilisers have been extensively promoted despite concerns regarding their high cost, limited farmer knowledge, and potential environmental risks. This study evaluated the potential of biochar as a soil amendment to enhance the physical and chemical properties of humic Nitisols in Kakamega County, Kenya. A field experiment was conducted in 2022 at the Kenya Agricultural and Livestock Research Organization (KALRO) Non-Ruminant Institute, Kakamega, using a randomized Complete Block Design with three replications. Biochar (5 t ha⁻¹), derived from sugarcane bagasse, coffee husk, coffee pulp, and timber offcut, was applied alone or in combination with NPK (23:23:0) at planting and calcium ammonium nitrate (200 kg ha⁻¹) as topdressing. Maize (Hybrid 624) was grown under field conditions. Soil physical properties (bulk density, porosity, and water holding capacity) and chemical properties were analyzed using standard laboratory procedures. Sugarcane bagasse biochar combined with fertiliser reduced bulk density from 1.215 g cm⁻³ to 0.776 g cm⁻³ and enhanced soil moisture from 21.78% to 30.13%. Coffee husk biochar with fertiliser significantly increased exchangeable potassium from 0.177 cmol kg⁻¹ to 1.708 cmol kg⁻¹, while timber offcut biochar applied alone increased total nitrogen from 0.454% to 1.307%. Coffee pulp and sugarcane bagasse biochars raised total organic carbon from 0.798% to 2.98% and soil pH from 5.6 to 6.38. Overall, integrating biochar with inorganic fertiliser consistently outperformed sole applications, demonstrating a climate-smart and sustainable strategy for restoring humic Nitisols and enhancing maize production in Western Kenya.

ARTICLE INFO

Keywords:

Climate resilience,
Fertiliser,
Humic Nitisols,
Soil chemical and physical properties.

Article History:

Received 25 August 2025
Received in revised form 9 December 2025
Accepted 17 December 2025
Available online 12 March 2026

1. Introduction

Nitisols are deep, well-structured, clay-rich tropical soils characterized by a stable granular structure, high consistency, and significant weathering. Globally, they occur predominantly in tropical and sub-tropical regions, especially in landscapes formed from volcanic and ferrallitic parent material. Their favorable physical characteristics, including good tilth, strong aggregation, and high rooting depth, make them inherently valuable for agricultural production (Deckers et al., 2025). In sub-Saharan Africa, Nitisols are widespread in highland and mid-altitude zones of countries such as Ethiopia, Kenya, Uganda, Burundi, and Rwanda. Although the soils are generally considered fertile due to their stable structure and deep profiles, they are also highly susceptible to nutrient depletion under continuous cultivation (Elias,

2017). Intensive cropping without adequate replenishment of soil organic matter has resulted in nutrient depletion and declining productivity in many Nitisols across the regions (Tully et al., 2015). Additionally, the sustainability of agricultural production in the SSA is threatened by a myriad of factors, including soil nutrient depletion, declining agricultural productivity, and climate change (Cassman & Grassini, 2020). In Kenya, Nitisols dominate central and western highlands, supporting key crops including maize, beans, coffee, and tea. Despite their agricultural benefits, many Nitisol-based farming systems experience persistent fertility constraints, especially deficiencies in nitrogen and phosphorus nutrients. These limitations are exacerbated by the high cost and limited accessibility of inorganic fertilisers for smallholder farmers (Series,

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Editor: Gershom Mutua, Masinde Muliro University of Science and Technology, Kenya.

Citation: Walekhwa S., Monjero K., Wanjala B., Akundabweni L., Wandahwa P., Otinga A., & Clarke L. (2026). Effect of Biochar Feedstock Types on Physical and Chemical Properties of Humic Nitisols in Kakamega County, Kenya. Journal of Advances in Science, Engineering and Technology 3(1), 26 – 33.

2015). In Western Kenya, particularly Kakamega County, farmers face chronic soil fertility decline driven by continuous cultivation, crop residue removal, and insufficient nutrient inputs. Low organic matter, limited fertiliser access, and increasing climate variability make it difficult for farmers to maintain yields and sustain soil health (Bhatt et al., 2019). This contest underscores the need for innovative and affordable soil-management strategies that enhance productivity while mitigating environmental risks. Approaches such as integrating organic amendments, including biochar, with judicious fertiliser use have emerged as promising interventions to enhance soil quality, build resilience, and support sustainable crop production for diverse groups of farmers (Hoque et al., 2025).

Biochar is a stable carbon product that is made by burning biomass from different sources in a process called pyrolysis (Pandian et al., 2024). Biochar serves as a soil amendment, enhancing nutrient retention, and serves as a carbon sequestration mechanism, offering a sustainable alternative to traditional fertilisers (Patel & Panwar, 2023). Recent meta-analyses and field studies have reported positive effects of biochar on soil quality and crop yield, although responses depend strongly on feedstock, pyrolysis conditions, soil type, and management (Jiang et al., 2024). However, site-specific evaluation of humic Nitisols in western Kenya is needed

to generate evidence-based, smallholder-relevant recommendations that can guide sustainable soil management and long-term productivity. Applying biochar in Kakamega County has the potential to help small-scale farmers improve soil productivity and enhance their well-being, including income security from commodity trading. Biochar contributes to increasing soil organic carbon, improving water holding capacity and soil aeration, enhancing base saturation, nutrient availability, and retention (Kabir et al., 2023). Furthermore, it decreases fertiliser needs and nutrient leaching; stimulates soil microbes, increases microbial biomass and activity (Nepal et al., 2023), enhances crop growth and yield, reduces anthropogenic greenhouse gas fluxes, and increases carbon sequestration (Patel & Panwar, 2023). Carbon sequestration in soil is favorable for enhancing soil fertility and achieving sustainable use of natural resources (Kalu et al., 2022). Incorporating biochar in soil is itself a carbon removal mechanism, but it can also deliver numerous other carbon reduction benefits, not only reducing the quantity of fertiliser required to deliver a given level of growth and yield and reducing the correspondingly high carbon emissions associated with the fertiliser, but also, for example, generating an ongoing increase in soil carbon stocks in subsequent years following the initial biochar application, due to its negative priming effects (Blanco-Canqui et al., 2020).

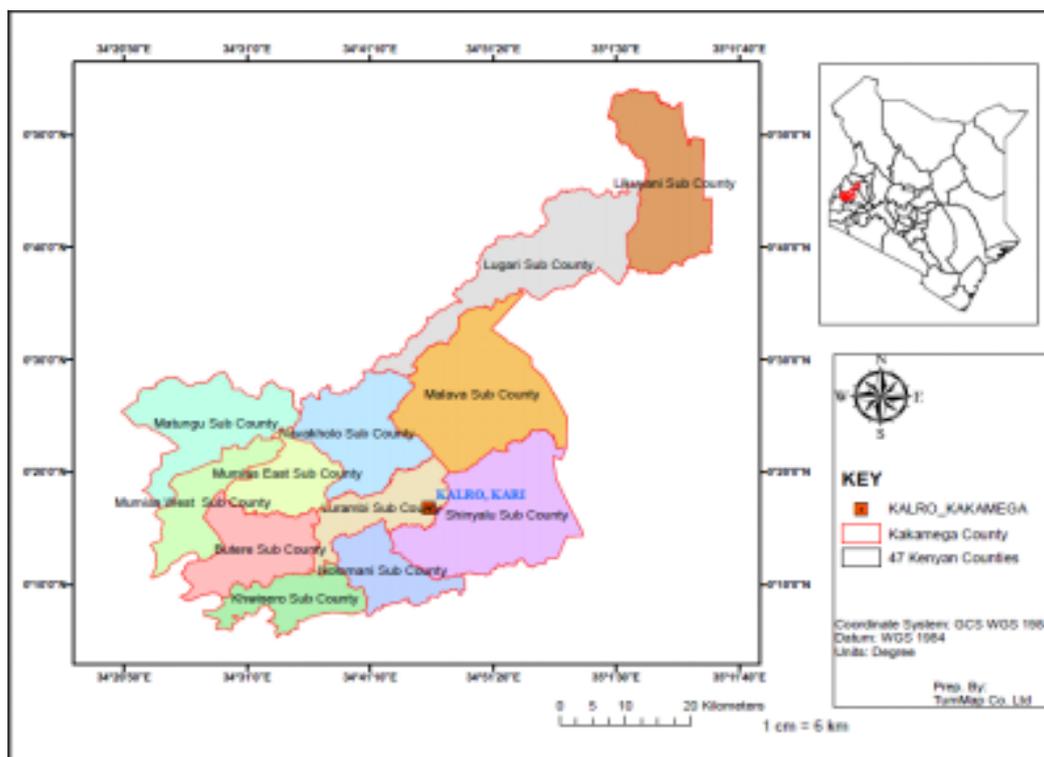


Fig. 1: Kenyan Map showing KALRO's location, Kakamega (GIS specialized, 2024).

Despite extensive global evidence demonstrating the positive effects of biochar on soil health, critical knowledge gaps persist for site-specific applications in Western Kenya, particularly for humic Nitisols. Various biomass resources, including sugarcane bagasse, coffee residues, and timber offcut are widely available in Kakamega County, few studies have been undertaken to

evaluate the effect of their derivatives under uniform field conditions. This limits the ability to provide evidence-based guidance on which feedstock offers the best agronomic value for smallholder systems. Furthermore, research exploring the synergistic effects of combining biochar with inorganic fertilisers on key soil physical and chemical properties remains scarce in

Kenya (Graef et al., 2018). Therefore, this study aimed to evaluate the effects of biochar produced from different feed stocks alone or in combination with inorganic fertilisers on the physical and chemical properties of a humic Nitisol. Understanding these interactions will provide valuable insights into biochar's role in sustainable soil management and climate-smart agriculture in the region.

2. Materials and Methods

2.1. Study Area

The study was conducted at the Kenya Agricultural and Livestock Research Organisation (KALRO), Non-Ruminant Institute (NRI) Research Station in Kakamega, located at latitude 0° 15'N and longitude 34° 46'E, with an elevation of 1530 m above sea level (Fig 1). This site falls within a moist transitional mid-altitude agro-ecological zone in western Kenya. Kakamega County exhibits diverse climatic and soil conditions. The region has an average annual temperature of 25 °C and receives bimodal rainfall, with an annual range of 1850-1916 mm. The long rains occur from March to June (Peaking in May), while the short rains fall between August and November. The county's mean annual rainfall ranges from 1,200 to 2,100 mm, with temperatures ranging from 18 to 25 °C (Burgin et al., 2018).

The site at which the study was conducted depicts features of a gentle slope with deep, well-drained clay-loam soil, comprising of 54% clay, 21% sand, and 25% silt, and a pH of 5.6, classified as humic Nitisol (FAO, 2005).

2.2. Treatments and experimental design

The study was conducted in 2022 as a factorial experiment laid out in a randomized complete block design (RCBD) with three replications. The experimental field measured 50 m × 30 m, and each sub-plot was 5 m × 3 m. Treatments comprised a negative control, fertiliser, and four sources of biochar (coffee husk, coffee pulp, timber offcut, and sugarcane bagasse) applied either alone or in combination with inorganic fertiliser at a rate of 5 t ha⁻¹, translating to 7.5 kg per sub-plot. NPK fertiliser (23:23:0) was applied at 200 kg ha⁻¹, followed by topdressing with calcium ammonium nitrate (CAN) at 200 kg ha⁻¹, supplying 46 kg ha⁻¹ N and 20 kg ha⁻¹ P from NPK and 54 kg ha⁻¹ N from CAN. Nutrient inputs were further supplemented by the different biochar sources, contributing to enhanced soil physiochemical properties. Biochar was evenly applied and incorporated into the topsoil at planting using a rake, while fertiliser was placed in planting holes and mixed with soil before seed placement.

2.3. Biochar production and characterization

The biochar kiln used in the experiment was designed by BionerG Ltd, UK, and fabricated at Sigalagala National Polytechnic. KALRO installed weight sensors and thermocouples connected to a data box for real-time data collection, following the BionerG C-Go system design guidelines. The kiln was specifically engineered to efficiently convert various feedstocks of sugarcane bagasse, coffee husks, coffee pulp, and timber offcuts into biochar. During the production

process, the weights of the feedstocks were recorded both before and after pyrolysis, along with the total processing time. The Kiln design allowed for precise monitoring and control of pyrolysis conditions, ensuring consistent and high-quality biochar production as presented in Table 1. After pyrolysis, the biochar was mechanically crushed, especially the biochar from timber offcuts, into a fine powder and packed into gunny bags, making it suitable for storage and use.

Biochars were produced under slow pyrolysis at the following temperatures under limited oxygen conditions: sugarcane bagasse at 350 °C, coffee husk at 400 °C, timber offcut at 400 °C, and coffee pulp at 400 °C for 60 min in a limited oxygen condition. The cooled biochars were ground and sieved separately through a <2 mm sieve, ready for analysis.

All analyses were conducted in triplicate. Biochar chemical analysis included pH, which was determined by weighing 20 g of biochar and dissolving it into 50 ml of distilled water at a ratio of 1:2.5 suspension (biochar: water), followed by pH measurement using a calibrated pH meter. Total nitrogen was determined using the colorimetric method by weighing 0.3 g of biochar, extracting it with 4.4 ml of extracting mixture, digested at 360 °C for 2 hours, and quantifying using UV-Vis Spectroscopy at 650 nm. Biochar organic carbon was determined using the Walkley-Black method, by weighing 0.3g of biochar, oxidized by sulfuric acid and aqueous dichromate, and heated at 155 °C for 30 minutes, and then quantified by titration with ferrous ammonium sulphate. Exchangeable potassium and calcium were determined by extracting 2.5 g of biochar with 50 ml of 1 M NH₄OAc solution, ensuring maximum exchange between NH₄⁺ and the biochar's exchange sites. The potassium and Calcium concentration was quantified using an Atomic Absorption Spectrophotometer (AAS). Available Phosphorus was analyzed using the Mehlich 1 method by extracting 5 g of biochar with 25 ml of 1 M HCl and 0.025 M H₂SO₄ solution, and quantified using a UV-Vis Spectroscopy at 430 nm. Biochar moisture content was determined gravimetrically by oven-drying at 105 °C for 24 hours. All analyses were performed and reported on a dry weight basis (Okalebo et al., 2002).

2.4. Soil Sampling Procedure

Soil samples were collected before and after the treatment application to assess changes in soil physical and chemical properties. Chemical properties were monitored at 30, 60, 90, and 120 days after treatment application. The physical properties, which respond more slowly than the chemical properties because of the complex interactions among the soil aggregates and their structural stability over time (Pyle et al., 2017), were evaluated at 60 and 260 days after treatment application. Samples were taken from 0-30 cm depth at the trial site using a soil auger. Six cores were collected in a randomized pattern per plot and homogenized in a clean plastic bucket to form a composite sample. A 500 g sub-sample was air dried, crushed with a mortar and pestle, and sieved through a <2 mm mesh for laboratory

analysis. For physical properties determination, three intact core samples were collected per plot using a specialized coring cylinder, weighed, and oven-dried at 105 °C for 24 hours, and used to compute bulk density, porosity, and moisture-related parameters.

2.5. Laboratory Analyses

The composite soil samples before and after the treatment application were analyzed in triplicate for chemical properties at KALRO-Kakamega, following the standard procedures outlined by Okalebo et al. (2002). All analytical instruments were calibrated before sample analyses.

2.5.1. Soil Chemical Analyses

Chemical analyses included soil pH, which was determined by dissolving 20 g of soil in 50 ml of distilled water, 1:2.5 suspension (soil: water), and reading the pH values using the pH meter. Total nitrogen was determined using the colorimetric method by weighing 0.3 g of soil, extracting it with 4.4 ml of extracting mixture, digesting it at 360 °C for 2 hours, and then quantifying using UV-Vis Spectroscopy at 650 nm. Available Phosphorus was analyzed using the Mehlich 1 method by extracting 5 g of soil with 25 ml of 1 M HCl and 0.025 M H₂SO₄ solution, followed by quantification using a UV-Vis Spectroscopy at 430 nm. Exchangeable potassium was determined by extracting 2.5 g of soil with 50 ml of 1 M NH₄OAc solution to ensure maximum exchange between NH₄⁺ and the soil's exchange sites. Potassium concentration was quantified using an Atomic Absorption Spectrophotometer (AAS). Iron was determined by extracting 5 g of soil with 25 ml of 0.1 N HCl, and its concentration was similarly quantified using an Atomic Absorption Spectrophotometer. Soil organic carbon was determined using the Walkley-Black method, by weighing 0.3 g of soil, oxidized by sulfuric acid and aqueous dichromate, and heated at 155 °C for 30 minutes, and then quantified by the titration method using ferrous ammonium sulphate.

2.5.2. Soil Physical Analyses

Physical properties, including bulk density, soil porosity, and moisture content, were determined using the core method. Their actual values in the soil were

calculated following the formulas described by Rashmi Jain & A.K. Shrivastava (2023). The initial baseline soil characteristics of the experiment site are presented in Table 2, while the average post-treatment physical and chemical properties are summarized in Tables 3 and 4, respectively.

2.6. Statistical analyses

The data collected were analyzed using R Statistical Software (Version 4.3.2). Descriptive statistics were calculated to summarize the trends in soil physical and chemical properties. Analysis of Variance (ANOVA) was performed to assess the effects of treatments, and significant differences among treatment means were separated using Tukey's Post-Hoc test at $P \leq 0.05$.

3. Results

3.1. Biochar Characterization

The biochar samples exhibited notable differences in their chemical and physical properties as per the feedstock type and the pyrolysis temperature. All biochar types underwent slow pyrolysis, with sugarcane bagasse biochar (SBB) produced at 350 °C, while the rest of the biochars were produced at 400 °C. pH levels of all biochar samples were consistently high (>10), highlighting their strong alkalinity nature with coffee husk biochar (11.6), being the most alkaline. Organic carbon content was also high for all the feedstock, ranging between 50.6% and 52.8%, with Coffee pulp biochar exhibiting the highest % OC. The % total nitrogen varied widely, with coffee pulp biochar (1.891%) and coffee husk biochar (1.732%) showing the highest nitrogen levels, while timber offcut biochar registered the lowest nitrogen levels at (0.106%). Exchangeable cations varied across the feedstock as well. Timber offcut registered the highest calcium level at 11.7 cmol kg⁻¹, while potassium was very high in coffee pulp biochar at 4.7 cmol kg⁻¹. Available phosphorus content increased from sugarcane bagasse to coffee pulp biochar, with coffee pulp biochar registering the highest Phosphorus value at 38.101 mg kg⁻¹. Sugarcane bagasse exhibited the highest biochar moisture retention capacity at 70.36%, followed by timber offcut at 38.91%, while coffee husk biochar recorded the lowest moisture retention at 29.778% (Table 1).

Table 1: Physical and chemical characterization of biochar.

Feedstock	Type of Pyrolysis	Pyrolysis temperature	Chemical properties (cmol kg ⁻¹)					Available P (mg kg ⁻¹)	Physical properties (% BM)
			pH	% TN	% OC	Ca	K		
SBB	Slow	350	10.6	0.409	51.8	7.7	3.6	20.014	70.357
CHB	Slow	400	11.6	1.732	52.3	7.0	3.0	17.012	29.778
TOB	Slow	400	11.28	0.106	50.6	11.7	2.9	31.104	38.906
CPB	Slow	400	11.1	1.891	52.8	7.8	4.7	38.101	37.082

% OC (Percent Organic Carbon), % TN (Percent Total Nitrogen), K (Potassium content), % BM (Percent Biochar Moisture), SBB (Sugarcane bagasse biochar), CHB (Coffee husk biochar), TOB (Timber offcut biochar), and CPB (Coffee pulp Biochar).

3.2. Pre-treatment of soil characteristics

Baseline soil samples were collected and analyzed to establish the initial nutrient content and structural conditions of the experimental site before the study. The analysis revealed that while certain properties, such as pH, potassium, and iron, soil moisture, porosity, and bulk density, were within optimal ranges, notable deficiencies were observed in available phosphorus and

total nitrogen (Table 2). The results indicated that available phosphorus was 10.3 mg kg⁻¹, below the optimal range of 15-25 mg kg⁻¹, total nitrogen was 0.731%, lower than the ideal 1.0-2.0%, and organic carbon was 2.101%, falling short of the optimal 3-5%. Physically, while soil moisture and bulk density were within optimal limits, soil porosity slightly exceeded the upper limit at 60.08%. Overall, while some soil properties

were satisfactory, the low levels of key nutrients, including available phosphorus, total nitrogen, and organic carbon, highlighted the need for soil

improvement through biochar application (Kenya Soil Survey Semi Detailed Soil Survey of the African Highland Produce Company I5814, 1996) (Table 2).

Table 2: Initial soil chemical and soil physical properties of a Humic Nitisol.

Soil Type	Soil Chemical Properties				Soil Physical Properties					
	pH	K (cmol kg ⁻¹)	Available P(mg kg ⁻¹)	Fe (cmol kg ⁻¹)	% TN	% SOC	% SM	% Porosity	Bulk density g cm ⁻³	
Humic Nitisol (FAO, 1998)	Result	5.5	0.50	10.3	6.301	0.731	2.101	20.56	60.08	1.00
Optimal range (Verde, 2018)	5.5-7.5	0.2-1.0	15-25	4.0-8.0	1.0-2.0%	3-5%	15-25%	50-60%	0.6-1.2	

% SOC (Percent Soil Organic Carbon Percentage); % TN (Percent Total Nitrogen); % SM (Percent Soil Moisture), Ca (Calcium content), Available P (Available phosphorus), Fe (Iron content), and Zn (Zinc content). These values represent the initial chemical and physical characteristics of the experimental site.

3.3. Effects of Biochar and Fertiliser Combination on the Physical Properties of Soil

The interaction between biochar and fertiliser significantly affected soil bulk density, porosity, and moisture content at 60 and 260 days after treatment application ($P \leq 0.05$), as shown in Table 3. The combined use of biochar and fertiliser resulted in greater changes in soil physical properties compared to when applied alone.

3.3.1. Soil Bulk Density (g cm⁻³)

The control treatment recorded the highest bulk density at 1.215 g cm⁻³. On the other hand, all biochar-amended treatments significantly reduced soil bulk density, with values ranging between 0.776 and 0.833 g cm⁻³. The lowest bulk density was recorded under the sugarcane bagasse biochar integrated with fertiliser at

0.776 g cm⁻³, followed closely by coffee husk biochar + Fertiliser.

3.3.2. % Soil Porosity

The control treatment recorded the lowest porosity of 56.173%, while biochar-amended soils showed a significant increase in porosity to 65%. The highest porosity was recorded under coffee husk biochar + Fertiliser at 68.298%, which was significantly different from the control.

3.3.3. % Soil Moisture

Biochar application enhanced soil moisture retention compared to the control (21.782%). The highest moisture content was recorded in sugarcane bagasse treatment (30.133%) and coffee husk biochar + Fertiliser treatment (29.708%), which were significantly higher than fertiliser treatment alone (27.248%) and coffee pulp biochar (26.885%).

Table 3: Effects of biochar and inorganic fertiliser combination on the average soil physical properties at 60 and 260 days

Treatment	Soil Bulk Density g cm ⁻³	% Soil Porosity	% Soil Moisture
Control	1.215b	56.173c	21.782d
Fertiliser	0.917a	59.388b	27.248bc
Coffee Pulp Biochar	0.833a	66.935a	26.885c
Coffee Husk Biochar	0.792a	67.088a	27.902abc
Sugarcane Bagasse Biochar	0.787a	67.477a	30.133a
Timber Offcut Biochar	0.795a	65.838a	25.847c
Coffee Pulp Biochar+ Fertiliser	0.82a	66.972a	27.313abc
Coffee Husk Biochar+ Fertiliser	0.817a	68.298a	29.708ab
Sugarcane Bagasse Biochar+ Fertiliser	0.776a	66.8a	27.238bc
Timber Offcut Biochar + Fertiliser	0.808a	68.163a	28.475abc
Significant Value	***	***	***
% CV	47.967	0.952	2.194

Numbers within the same column with the same letter are not statistically different at $p \leq 0.05$

%CV = Coefficient of Variance, *** Significance levels

3.4. Effects of Biochar and Fertiliser Combination on the Chemical Properties of Soil

Table 4 revealed that biochar, either alone or when integrated with inorganic fertiliser, significantly enhanced soil chemical characteristics compared to the control ($P \leq 0.05$). Soil pH values were consistently higher under biochar treatments, with the highest pH at 5.973 recorded in the timber offcut biochar + Fertiliser treatment, while the control remained low (5.134).

Exchangeable potassium K was enhanced remarkably with biochar application. The highest value (1.708 cmol kg⁻¹) was observed in sugarcane bagasse biochar + Fertiliser treatment, whereas the control remained very low (0.177 cmol kg⁻¹). All biochar-based treatments, with

or without fertiliser, recorded more than six-fold increases in K compared to the control.

Available phosphorus under biochar treatment followed a similar trend, with coffee pulp biochar registering the highest value (24.025 mg kg⁻¹). The control treatment had the lowest Phosphorus value (9.612 mg kg⁻¹). Generally, biochar alone and biochar + Fertiliser treatments provided sustained increases in Phosphorus availability compared to the sole fertiliser or the control.

Iron levels varied significantly across the treatments. The timber offcut biochar + Fertiliser treatment had the highest iron content (15.98 cmol kg⁻¹), while the control registered the lowest content (4.418 cmol kg⁻¹).

Soil % total Organic Carbon was consistently higher in biochar treatments, ranging between 2.69-2.98%, compared to 0.798% in the control. Similarly, % total nitrogen was very low in the control treatment (0.454%), and the highest value was recorded in timber offcut biochar (1.307%), indicating that biochar significantly improved soil organic carbon content and nitrogen level

as well. Overall, biochar treatments either alone or when combined with fertilisers, especially timber offcut, coffee pulp, and sugarcane bagasse biochars, produced significantly higher values for most soil chemical parameters compared to the control and sole fertiliser treatments.

Table 4: Effects of Biochar and inorganic fertiliser Combination on the Average soil Chemical properties at 30, 60, 90, and 260.

Treatment	Soil pH	Exchangeable K (cmol kg ⁻¹)	Available Phosphorus (mg kg ⁻¹)	Iron (cmol kg ⁻¹)	% Total organic Carbon	% Total Nitrogen
Control	5.134e	0.177c	9.612b	4.418d	0.798b	0.454d
Fertiliser	5.457d	0.744b	12.562ab	11.45b	2.84a	0.965abc
Coffee Pulp Biochar	5.909ab	1.234a	24.025a	11.973bc	2.663a	1.196ab
Coffee Husk Biochar	5.84abc	1.445a	13.148ab	11.98bc	2.653a	0.763bcd
Sugarcane Bagasse Biochar	5.78bc	1.484a	13.293ab	14.752ab	2.6a	1.146ab
Timber Offcut Biochar	5.894ab	1.401a	17.464ab	12.018bc	2.666a	1.307a
Coffee Pulp Biochar+ Fertiliser	5.732c	1.628a	12.324b	12.776bc	2.946a	0.624cd
Coffee Husk Biochar+ Fertiliser	5.839abc	1.645a	12.784ab	12.642bc	2.984a	0.638cd
Sugarcane Bagasse Biochar+ Fertiliser	5.882abc	1.708a	13.658ab	12.624bc	2.91a	0.908abc
Timber Offcut Biochar + Fertiliser	5.973a	1.678a	15.506ab	15.98a	2.873a	0.693cd
Significant Value	***	***	***	***	***	***
% CV	0.627	8.752	17.842	5.547	3.394	11.853

Numbers within the same column with the same letter are not statistically different at $p \leq 0.05$

%CV=Coefficient of Variance, *** Significance levels

4. Discussion

4.1. Effects of Biochar and Inorganic Fertiliser Combinations on the Soil Physical Properties

Biochar alone or in combination with fertiliser significantly enhanced soil physical properties. Notable improvements were observed between the two study times, especially in soils treated with coffee husk and sugarcane bagasse biochar in combination with fertiliser. These treatments significantly enhanced soil porosity, translating to enhanced microbial activity and water retention. This trend suggests that biochar's structural characteristics contribute to soil aeration and water-holding capacity over time, making it particularly relevant for water-scarce regions where soil moisture retention is a crucial factor for crop resilience (Pandian et al., 2024).

The superior moisture retention capacity of sugarcane bagasse (70%), timber offcut, and coffee pulp biochar translated into enhanced soil moisture retention of soils treated with these biochars as a result of increased soil pores. This underscores the importance of selecting biochar feedstocks based on their hydrophilic properties to maximize soil water retention.

Additionally, the study revealed a reduction in soil bulk density, particularly in sugarcane bagasse biochar, treated soils outperforming other treatments, followed by coffee pulp biochar- and timber offcut biochar-treated soils, which facilitated a decrease in soil compaction, allowing better root penetration. The reduced bulk density was a result of the incorporation of low-density biochar and highly porous biochar structures into the soil. These findings corroborate studies on disturbed humic Nitisols (Mantel, 2021; Khan et al.,

2024), which reported similar reductions in bulk density, enhanced porosity, and moisture content, reinforcing the benefits of biochar for soil health.

4.2. Effects of Biochar and Inorganic Fertiliser Combinations on the Soil Chemical Properties

In this study, biochar, which is known for its alkalinity, significantly enhanced the soil pH during the early stages after the application (Table 4) as a result of mineral residues (ash), including K, Mg, Ca, Na oxides, and carbonates released during the pyrolysis process. When incorporated in the soil, biochar reacts with water, oxides, and carbonates, which dissolve, releasing hydroxide (OH⁻) and carbonate (CO₃²⁻) ions, resulting in an increase in soil pH (Fidel et al., 2017). This was particularly the case for the coffee husk biochar + Fertiliser, sugarcane bagasse biochar + Fertiliser, and timber offcut biochar + Fertiliser treatments, in which the soil was ameliorated, leading to increased nutrient availability like Potassium, Phosphorus, etc. for crop uptake and, as a result, outperformed the other treatments.

The pH increase declined as the crop matured due to nutrient uptake, which required replenishment. This pattern is consistent with previous research showing the effectiveness of biochar in enhancing pH in acidic soils, but declines as a result of the crop utilizing the available nutrients for crop uptake (Zubairu et al., 2023). The available phosphorus and total nitrogen levels were highest in soils treated with timber offcut biochar + Fertiliser (Table 4). This is because the nutrients, especially phosphorus, are less mobile and can bind strongly to soil and biochar colloids, reducing losses through leaching during rainfall or irrigation. This results

in higher nutrient concentrations remaining accessible in the root zone (Hossain et al., 2020). These findings underscore the potential of biochar to enhance nutrient retention and availability, promoting sustainable agriculture.

Significant increases in Potassium levels (with soils treated with coffee husk biochar + Fertiliser) and Iron levels (with soils treated with timber offcut biochar + fertiliser) relative to both the control and fertiliser treatments were achieved on average across all four different sources of biochar. The increase in soil nutrients is a result of the pyrolysis process releasing stable and available forms of K and Fe ions in the soil. Fertiliser supplement further enhanced solubility, while biochar ensured less leaching, leading to their higher concentrations in the soil. Again, as biochar decomposes, nutrients are gradually released, ensuring both long term and sustained nutrient supply (Hossain et al., 2020).

5. Conclusions

The study demonstrated that biochar applied alone or in combination with inorganic fertilisers significantly enhanced the physical and chemical properties of humic Nitisols in Kakamega County. Sugarcane bagasse biochar co-applied with fertiliser reduced soil bulk density to 0.776 g cm^{-3} and increased moisture content above 30%, leading to enhanced soil structure. Chemically, biochar significantly raised soil pH, ameliorating soil acidity characteristics of Nitisol-dominated areas. Nutrient availability, including exchangeable potassium, iron, available phosphorus, total nitrogen, and total carbon, was strongly enhanced by 25-45%, with coffee husk and sugarcane bagasse biochar, particularly when combined with inorganic fertiliser. These findings highlight biochar's strong capacity to enhance nutrient retention, optimize fertiliser use efficiency, and reduce nutrient losses in acidic and highly weathered soils. This study therefore confirms that integrating biochar with moderate rates of inorganic fertiliser provides the most effective strategy for restoring degraded Nitisols, enhancing soil health, and contributing to climate-resilient agricultural systems. The results provide a robust scientific basis for promoting biochar as a nature-based, climate-smart soil amendment for smallholder farmers in Western Kenya and similar agro-ecological zones.

This study recommends the use of biochar from locally available biomass, particularly sugarcane bagasse, timber offcut and coffee residues, and integrates with fertiliser to enhance soil fertility, reduce input costs, and improve resilience. Policy makers should promote the adoption of biochar, particularly coffee husk and timber offcut biochars, by integrating it into soil health and climate-smart agriculture programs and by supporting farmers through targeted subsidies, extension training, and guidelines for its combined use with inorganic fertiliser. Future studies should conduct long-term, site-specific, and different cropping system studies on different biochar types, application rates, and socio-economic feasibility for wider adoption.

Conflict of Interests

The authors declare that they have no conflicts of interest.

Acknowledgments

The writing of this paper has been enabled through the Biochar Project developed by the UK-BionerG Ltd. and Kenya Agricultural & Livestock Research Organization (KALRO-Biotechnology Research Institute, Kabete and KALRO-Non-Ruminant Research Institute, Kakamega), funded through crowdfunding by the two organizations. Their support is highly acknowledged. We further acknowledge the management of KALRO-Non-Ruminant Research Institute, Kakamega, for donating land for researcher-managed trials and Masinde Muliro University of Science and Technology for the academic opportunity.

References

- Bhatt, M. K., Labanya, R., & Joshi, H. C. (2019). Influence of Long-term Chemical Fertilizers and Organic Manures on Soil Fertility - A Review. September. <https://doi.org/10.13189/ujar.2019.070502>.
- Blanco-Canqui, H., Laird, D. A., Heaton, E. A., Rathke, S., & Acharya, B. S. (2020). Soil carbon increased by twice the amount of biochar carbon applied after 6 years: Field evidence of negative priming. *GCB Bioenergy*, 12(4), 240-251. <https://doi.org/10.1111/gcbb.12665>.
- Burgin, L., George, G., & Richard, J. (2018). Climate Summary for Kakamega and Siaya Counties, Kenya. https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/business/international/wiser/wiser0085_climate_information_kakamega_siaya_counties.pdf.
- Cassman, K. G., & Grassini, P. (2020). A global perspective on sustainable intensification research. *Nature Sustainability*, 3(4), 262-268. <https://doi.org/10.1038/s41893-020-0507-8>.
- Deckers, J., Kimaro, D., Kimaro, O., Njore, R., Nachtergaele, F., & Ranst, E. Van. (2025). WRB Documentation Centre NITISOLS : Lecture Notes. 1-22.
- Elias, E. (2017). Characteristics of Nitisol profiles as affected by land use type and slope class in some Ethiopian highlands. *Environmental Systems Research*, 6(1). <https://doi.org/10.1186/s40068-017-0097-2>.
- FAO. (2005). FAO - Unesco. Soil Map of the World, Revised Legend, with corrections and updates. In *World Soil Resources Report 60* (pp. 1-140). http://www.fao.org/fileadmin/user_upload/soils/docs/isricu_i9264_001.pdf.
- Fidel, R. B., Laird, D. A., Thompson, M. L., & Lawrinenko, M. (2017). Characterization and quantification of biochar alkalinity. *Chemosphere*, 167, 367-373. <https://doi.org/10.1016/j.chemosphere.2016.09.151>.
- GIS Specialized. (2024). Map of Kenya showing the location of KALRO-Kakamega [Map].
- Graef, H., Kiobia, D., Saidia, P., Kahimba, F., Graef, F., &

- Eichler-Löbermann, B. (2018). Combined effects of biochar and fertilizer application on maize production in dependence on the cultivation method in a sub-humid climate. *Communications in Soil Science and Plant Analysis*, 49(22), 2905-2917. <https://doi.org/10.1080/00103624.2018.1547392>.
- Hoque, M., Saha, B. K., & Scopa, A. (2025). Biochar in Agriculture : A Review on Sources , Production , and Composites Related to Soil Fertility , Crop Productivity , and Environmental Sustainability. 1-18.
- Hossain, M. Z., Bahar, M. M., Sarkar, B., Donne, S. W., Ok, Y. S., Palansooriya, K. N., Kirkham, M. B., Chowdhury, S., & Bolan, N. (2020). Biochar and its importance on nutrient dynamics in soil and plant. *Biochar*, 2(4), 379-420. <https://doi.org/10.1007/s42773-020-00065-z>.
- Jiang, Y., Li, T., Xu, X., Sun, J., Pan, G., & Cheng, K. (2024). A global assessment of the long-term effects of biochar application on crop yield. *Current Research in Environmental Sustainability*, 7, 100247. <https://doi.org/10.1016/j.crsust.2024.100247>.
- Kabir, E., Kim, K.-H., & Kwon, E. E. (2023). Biochar as a tool for the improvement of soil and environment. *Frontiers in Environmental Science*, 11. <https://doi.org/10.3389/fenvs.2023.1324533>.
- Kalu, S., Kulmala, L., Zrim, J., Peltokangas, K., Tammeorg, P., Rasa, K., Kitzler, B., Pihlatie, M., & Karhu, K. (2022). Potential of Biochar to Reduce Greenhouse Gas Emissions and Increase Nitrogen Use Efficiency in Boreal Arable Soils in the Long-Term. *Frontiers in Environmental Science*, 10. <https://doi.org/10.3389/fenvs.2022.914766>.
- Kenya Soil Survey Semi Detailed Soil Survey of the African Highland Produce Company I5814. (1996).
- Khan, S., Irshad, S., Mehmood, K., Hasnain, Z., Nawaz, M., Rais, A., Gul, S., Wahid, M. A., Hashem, A., Abd_Allah, E. F., & Ibrar, D. (2024). Biochar Production and Characteristics, Its Impacts on Soil Health, Crop Production, and Yield Enhancement: A Review. *Plants*, 13(2), 166. <https://doi.org/10.3390/plants13020166>.
- Mantel, S. (2021). ISRIC World Soil Reference Collection management policy. <https://doi.org/10.17027/isric-wdc-2021-01>.
- Nepal, J., Ahmad, W., Munsif, F., Khan, A., & Zou, Z. (2023). Advances and prospects of biochar in improving soil fertility, biochemical quality, and environmental applications. *Frontiers in Environmental Science*, 11. <https://doi.org/10.3389/fenvs.2023.1114752>.
- Okalebo, J. R., Gathua, K. W., & Paul, L. W. (2002). *Laboratory Methods of Soil and Plant Analysis: A Working Manual The Second Edition*. SACRED Africa, Kenya Any, SECOND EDI, 1-131.
- Pandian, K., Vijayakumar, S., Mustaffa, M. R. A. F., Subramanian, P., & Chitraputhirapillai, S. (2024). Biochar - a sustainable soil conditioner for improving soil health, crop production and environment under changing climate: a review. *Frontiers in Soil Science*, 4. <https://doi.org/10.3389/fsoil.2024.1376159>.
- Patel, M. R., & Panwar, N. L. (2023). Biochar from agricultural crop residues: Environmental, production, and life cycle assessment overview. *Resources, Conservation & Recycling Advances*, 19, 200173. <https://doi.org/10.1016/j.rcradv.2023.200173>.
- Pyle, L. A., Magee, K. L., Gallagher, M. E., Hockaday, W. C., & Masiello, C. A. (2017). Short-Term Changes in Physical and Chemical Properties of Soil Charcoal Support Enhanced Landscape Mobility. *Journal of Geophysical Research: Biogeosciences*, 122(11), 3098-3107. <https://doi.org/10.1002/2017JG003938>.
- Rashmi Jain, & A.K. Shrivastava. (2023). Estimation of Soil Density, Porosity, Water Holding Capacity, and Moisture content of Arpa River Based Soil. *International Research Journal on Advanced Engineering Hub (IRJAEH)*, 1(01), 32-37. <https://doi.org/10.47392/IRJAEH.2023.005>.
- Series, R. P. (2015). *Climate Risk Profile Economic Review of Agriculture Intergovernmental Panel on Climate Change Society for International Development Kakamega*.
- Tully, K., Sullivan, C., Weil, R., & Sanchez, P. (2015). The State of Soil Degradation in Sub-Saharan Africa: Baselines, Trajectories, and Solutions. *Sustainability*, 7(6), 6523-6552. <https://doi.org/10.3390/su7066523>.
- Verde, B. (2018). Interactive effect of goat manure, phosphate fertilizer and lime on soil fertility in Embu County, Kenya. January.
- Zubairu, A. M., Kwari, S. J., & Buba, M. T. (2023). Exploring the effect of biochar on soil pH (A review) *Colloquia Series Available Online at www.ssn.ng*. November.