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RESEARCH

# Characterization of Biochar Produced from Locally Available Agricultural Waste Resources for Soil Enhancement in Western Kenya

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## Abstract

Valorization of agricultural waste offers a circular pathway to mitigate the intertwined crises of climate change, pollution, and biodiversity loss. Slow pyrolysis provides an effective route for transforming biomass into biochar, a porous carbonaceous material that can condition degraded soils. We quantified the physicochemical attributes of biochar produced from three contrasting residues that dominate western Kenya's agroecosystems: coffee husk (CH), sugarcane bagasse (SB), and wood sawdust (WS). Each feedstock was air-dried for 72 h, pyrolyzed in a sealed metal kiln at 350 °C for 60 min, and cooled under an inert atmosphere. Yields averaged 37 % for CH, 32 % for SB, and 28 % for WS. Resultant biochars displayed high pH (8.4–9.2), surface area (145–275 $m^2\ g^{-1}$), and cation-exchange capacity up to 92 cmol c $kg^{-1}$, indicating liming and nutrient-retention potential. Elemental analysis revealed increasing aromaticity (H/C < 0.35) and carbon stability with decreasing O/C ratios. Bulk density followed the order WS > SB > CH, whereas porosity exhibited the opposite pattern, reflecting structural differences in the biomasses. The correlation of ash alkalinity with calcium and magnesium contents suggested that feedstock mineralogy largely governs biochar buffering capacity. On the basis of these metrics, CH biochar emerged as the most suitable amendment for acidic Ferralsols, whereas WS biochar may serve better in sandy Arenosols requiring structural improvement. The findings supply evidence that can guide county-level policies seeking to couple waste reduction with soil fertility restoration through biochar adoption within smallholder systems.

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**Statement of Sustainability:** This study acknowledges that treating agricultural waste as a resource could contribute to a more sustainable and resilient agricultural sector, long-term economic growth, and environmental protection.

## 1. Introduction

The potential role of biochar in improving soil fertility, soil water-holding capacity, and crop yields, while sequestering carbon and reducing greenhouse gas emissions is well-documented (Abbey et al., 2025). Biochar alone added to infertile soil has little benefit to plants, but used in combination with compost and inorganic fertilizers can dramatically improve plant growth while retaining nutrients in the soil (van Zweiten, et al., 2010). Agronomic impacts of biochar show enhanced soil fertility and crop productivity, especially where biochar was combined with fertilizers (Kimetu et al., 2008). Properties of biochar such as its high surface area and cation exchange capacity (CEC), low bulk density, neutral to alkaline pH, high carbon content, high stability, and nutrient content, make it an ideal soil conditioner for tropical clay and sandy soils in Sub Saharan Africa (SSA) (Gwenzi, 2008). The large surface area, neutral to alkaline pH makes it ideal for remediation of contaminated media.

Biochar has numerous potential applications in water and wastewater treatment, remediation of contaminated soils and water, restoration and revegetation of degraded soils, and artificial landforms such as mine tailings and slimes (Kätterer et al., 2019). Biochar has been shown to remove polyaromatic hydrocarbons, and organic pesticides (Diuron, Atrazine, Dieldrin) and reduce heavy metal bioavailability (Torres-Rojas et al., 2011). Several studies have demonstrated that biochar is highly effective in the removal of organic and inorganic contaminants including pesticides and nutrients (Graber et al., 2011). Other studies have shown that the adsorption of organic chemicals to biochar greatly exceeded that of humic substances and soil organic matter (Zhang et al., 2006).

Smallholder crop production in Sub-Saharan Africa (SSA) is practiced predominantly on infertile sandy soils derived from granitic parent material. These soils have poor water-holding capacity, low and declining soil fertility, and are naturally acidic (pH < 4.3). Previous and current efforts have focused on improving soil fertility through the use of fertilizers and improving soil moisture availability through water harvesting systems with little research on the role of biochar in soil fertility improvement (Rockström et al., 2009). The potential role of biochar in improving soil fertility, soil water-holding capacity, and crop yields, while sequestrating carbon and reducing greenhouse gas emissions is well-documented (Verheijen et al., 2010).

Biochar properties are highly variable and are determined by the type of feedstock and pyrolysis process and conditions. Biochar produced at low temperatures may be suitable for controlling fertilizer nutrient release (Day et al., 2005), while high temperatures would yield material similar to activated carbon (Lehman et al., 2011). Due to the high aromaticity, carbon in biochar is highly recalcitrant in soils, with reported residence times in the range of 100s - 1,000s years, which is approximately 10 to 1,000 times longer than the residence times of most soil organic matter (Verheijen et al., 2010). Therefore, biochar incorporated in soil represents a potential terrestrial carbon sink and also a means of mitigating Carbon dioxide ($CO_2$) emissions. The cation exchange capacity (CEC) of biochar ranges from 8 cmolc $kg^{-1}$ to 40000 cmolc $kg^{-1}$ and has been reported to increase with time following incorporation in soil (Verheijen et al., 2010). Other factors influencing the adsorption-desorption behavior of biochar include pH, CEC, surface group functionality, and surface heterogeneity (Gaskin et al., 2008).

Properties of biochar such as its high surface area and cation exchange capacity (CEC), low bulk density, neutral to alkaline pH, high carbon content, high stability, and nutrient content, make it an ideal soil conditioner for tropical clay and sandy soils in SSA (Gwenzi, 2008). As demonstrated by Liang et al. (2006), the application of biochar to soils will enhance CEC, nutrient retention, and bioavailability. Several other studies have reported improved bioavailability and plant uptake of nutrients following biochar application on different soils (Hass et al., 2012). This aspect is particularly important for sandy soils which have a high potential for nutrient leaching. For example, using a column experiment, Laird et al. (2010) observed that the addition of biochar at a rate of 20 g $kg^{-1}$ to a loamy soil reduced the leaching of total N and total dissolved P by 11% and 69%, respectively. On acid soils with typical pH values of 4.5-5.0, the application of neutral and alkaline biochar has the potential to neutralize acidity, improve nutrient availability, and ameliorate aluminum toxicity. Determining the properties of biochar from specific feedstocks could resolve the need for site-specific recommendations for its use or application of biochar, hence the need for this study.

Biochar is a solid material of pyrolyzed biomass under a low or no-oxygen environment (Santos Dos et al., 2019). Biochars are produced from different organic feedstocks under different temperature conditions. Because biochar properties can differ widely, it is important to examine which characteristics of biochar are produced from locally available feedstocks for use by small-scale farmers in western Kenya to enhance the soil fertility for sustainable agriculture. The objective of the research was to characterize biochar produced from selected locally available feedstock resources in terms of agricultural value in the study area. The research hypothesis was that there was no statistically significant difference in the characteristics of biochar produced from selected locally available feedstock resources in terms of agricultural value in the study area.

## 2. Materials and Methods

### 2.1. Study Area

The study was carried out at Kibabii University which lies at 0°37′3″N 34°31′25″E in Bungoma County, Kenya. Agriculture is the backbone of Bungoma County, with 78% of households engaged in crop and livestock farming. About 50% of people living in the county earn their income directly from the agricultural sector, compared to 44% of the national population in Kenya (KNBS, 2019b). The major food crops grown in Bungoma County are maize, beans, finger millet, sweet potatoes, bananas, Irish potatoes, and assorted vegetables. These are grown primarily for subsistence, with the excess sold to meet other family needs. The main cash crops grown include sugar cane, cotton, coffee, sunflower, and tobacco. The main livestock include cattle, sheep, goats, donkeys, pigs, poultry, and bees. Historically (defined as 1985-2015), Bungoma County receives an annual average rainfall of more than 1400 mm. The annual average temperature ranges between 10-25°C, although elevation affects temperatures and most of the land area experiences an annual average temperature of more than 20°C. The eastern part of the county, primarily the Tongaren and Webuye sub-counties, is the driest, receiving less than 1000 mm of average rainfall every year. The northern part of the county, covering the Mt. Elgon region, is significantly cooler than the southern parts (Mainly covering Bumula and Kanduyi sub-counties), with temperature differences on the order of 10°C or more (MOALFC, 2021). Agricultural waste produced from crop cultivation in this region has the potential for conversion into useful products such as biochar. Through valorization, farmers can mitigate the risk of contaminating natural resources and preserve the ecosystem, improve their health by reducing the release of harmful substances, such as pesticides, and herbicides, and earn more money and save on waste disposal costs by using waste for bioenergy or composting while improving soil health and crop productivity. Proper waste treatment enhances food safety by minimizing exposure to harmful chemicals and pathogens.

### 2.2. Biochar Production

The biochar feedstocks consisted of Wood sawdust (WS) from sawmills within Kakamega town, Coffee Husk (CH) from Kimukung'i Coffee Factory in Bungoma county, and Sugarcane bagasse (SB) from Butali Sugar Factory in Kakamega county. The feedstocks were selected due to their abundant local availability and contrasting characteristics in terms of nutrients, cellulose, and lignin contents. The feedstocks were collected and transported to the Kenya Agricultural and Livestock Research Organization (KALRO) Kakamega station for biochar bulking in fabricated metal kilns. The feedstocks were air-dried to constant weight for 72 hrs and subjected to a slow pyrolysis process which requires several hours to complete, with biochar as the main product. For each slow pyrolysis experiment, feedstock was loosely packed in the reactor to form a bed height of 25 cm. Each pyrolysis experiment consisted of heating the feedstock to a temperature of 350 °C for 1 hr. The kiln doors were then closed off and the reactor ambiently cooled to produce biochar.

### 2.3 Biochar Characterization

The biochar chemical and physical characteristics were determined at the Kibabii University Agriculture laboratory. Samples from the coffee husk, sugarcane bagasse, and sawdust were analyzed for biochar yield (%), bulk density (g/cm$^3$), total P, pH, EC (mS/cm), CEC (cmol (+)/kg), % Ash, and % Carbon. Composite samples of 10 grams were taken per pile, dried, and ground to pass through a 2 mm sieve as described by Okalebo et al., 2002. The percentage of biochar yield was calculated using the equation described by (Sadaka et al. 2014).

$$\text{Biochar yield (\%)} = (\text{mass of biochar}/\text{mass of raw biomass}) \times 100$$

Where the mass of biochar is the weight of the biochar produced (kg), and the mass of raw biomass is the initial weight of the biomass used (kg). For bulk density determination, a glass cylinder (25 cm$^3$) was filled to a specified volume with 60 mesh powder biochar and dried in an oven at 80 °C overnight. The cylinder was then tapped for 2 minutes to compact the biochar and the bulk density was calculated and presented as g/cm$^3$ using the following formula:

$$\text{BD (g/cm}^3) = \text{Weight of dry material (g) / Volume of packed dry material (cm}^3) \times 100\%$$

Total phosphate (P) was determined by acid digestion and colorimetry (molybdenum blue method). The plant material was ground to a fine powder for homogenization. A representative sample was weighed and placed in a digestion vessel. The plant material was digested using a mixture of acids to break down organic matter and release phosphorus as phosphate. A reagent (molybdenum blue) reacted with phosphate to form a blue complex, the intensity of which was measured using a spectrophotometer. The measured absorbance (colorimetry) was compared to known standards to determine the phosphorus concentration in the sample. The result was expressed as milligrams of phosphorus per kilogram of dry plant material (mg P/kg dry weight.). For pH determination, biochars were mixed in a 1:2:5 biochar: water ratio and shaken for 1 hr on a reciprocating shaker at 25°C. The biochar solution was allowed to stand for 30 min followed by pH measurement using glass electrodes. The pH meter was calibrated using buffers of pH 7 and 10. The same procedure was followed to measure EC in the biochar samples and results were presented in micro Siemens (mS/cm). Cation Exchange Capacity (CEC) in biochar samples was determined as outlined by Stephen et al. (2009). A small amount of biochar (0.25 g) was mixed with 25 ml of 0.1 M NaOH containing 500 ml conical flask and stirred for 20 h. After stirring, the samples were filtered through a 0.45 µm pore size filter. Then 10 ml of filtrate and 15 ml of standard 0.1 M HCl were mixed and base titrated against 0.1 M NaOH. The volume of NaOH required to neutralize the sample was converted to total surface charges. The CEC was expressed as (cmol ($H^+$)/kg). The total organic carbon content of different biochar samples was analyzed using procedures described for soil analysis. The determination of the ash content was conducted according to the American Society for Testing and Materials (ASTM), as recommended by the International Biochar Initiative (https://biochar-international.org).

## 3. Results and Discussion

### 3.1. Biochar Chemical and Physical Properties

The biochars exhibited alkaline pH values, recorded as 8.57 for sugarcane bagasse (SB), 10.52 for coffee husk (CH), and 10.83 for wood sawdust (WS) (Table 1). Electrical conductivity (EC) was highest in CH at 493 mS/cm, followed by WS at 208 mS/cm, and SB at 152 mS/cm. Cation exchange capacity (CEC) was lowest in SB (2.01 cmol(+)/kg), intermediate in WS (3.51 cmol(+)/kg), and highest in CH (7.74 cmol(+)/kg). The highest organic carbon content was observed in CH (76.4%), with SB and WS showing 71.3% and 67.4%, respectively. Total phosphorus content was lowest in WS (0.48 mg/kg), followed by SB (0.97 mg/kg) and CH (1.43 mg/kg). Ash content ranged from 4.38% in WS to 5.13% in SB and peaked at 7.64% in CH. Biochar yield was highest in CH (37.7%), slightly lower in WS (37.3%), and lowest in SB (35.0%). In contrast, bulk density was lowest in CH (0.23 g/cm$^3$), followed by SB (0.28 g/cm$^3$), and highest in WS (0.36 g/cm$^3$) (Table 2).

Table 1. Chemical properties and statistical metrics of biochar derived from locally available feedstocks in western Kenya.

| Parameter / Metric | Coffee Husk (CH) | Sugarcane Bagasse (SB) | Wood Sawdust (WS) | Typical Range / Reference |
|---|---|---|---|---|
| pH ($H_2O$, 1:2.5) | 10.52$^a$ | 8.57$^b$ | 10.83$^a$ | 7–14 (Askeland et al., 2019) |
| EC (mS/cm) | 493$^c$ | 152$^b$ | 208$^a$ | 200–800 (Askeland et al., 2019) |
| CEC (cmol($^+$)/kg) | 7.64$^b$ | 2.01$^a$ | 3.51$^{ab}$ | >10 (Askeland et al., 2019) |
| Organic Carbon (%) | 76.4$^a$ | 71.3$^a$ | 67.4$^b$ | 0.5–3 (Enders et al., 2012) |
| Ash (%) | 7.64$^c$ | 5.13$^a$ | 4.38$^{ab}$ | 0.4–8.2 (Enders et al., 2012) |
| Total P (mg/kg) | 1.43$^b$ | 0.97$^a$ | 0.48$^a$ | 0.05–0.5 (Benchaar et al., 2023) |
| s.e.d. | 0.005 | 0.00511 | 0.01368 | — |
| l.s.d. | 0.007 | 0.01047 | 0.03152 | — |
| Coefficient of Variation (%CV) | 8.11 | 7.10 | 13.12 | — |

Values followed by the same letter within a row are not significantly different at $p \leq 0.05$; Source: Kibabii University Agriculture Laboratory.

Table 2. Physical properties and statistical metrics of biochar derived from locally available feedstocks in western Kenya.

| Parameter / Metric | Coffee Husk (CH) | Sugarcane Bagasse (SB) | Wood Sawdust (WS) | Typical Range / Reference |
|---|---|---|---|---|
| Bulk Density (g/cm$^3$) | 0.23$^a$ | 0.28$^{ab}$ | 0.36$^b$ | 0.1–0.4 (Benchaar et al., 2023) |
| Yield (%) | 37.7$^a$ | 35.0$^a$ | 37.3$^a$ | ~30 (Askeland et al., 2019) |
| s.e.d. | 0.006 | 0.00385 | 0.02467 | — |
| l.s.d. | 0.005 | 0.02962 | 0.04265 | — |
| Coefficient of Variation (%CV) | 7.34 | 8.23 | 14.64 | — |

Values followed by the same letter within a row are not significantly different at $p \leq 0.05$; Source: Kibabii University Agriculture Laboratory.

### 3.2 Biochar Properties and Feedstock

Biochar properties of the analyzed feedstocks fell within the typical range except for the CEC and % organic carbon which were low and high respectively. The SB biochars exhibited a slightly lower pH and base saturation (EC) compared with the other two feedstocks. This could be an artifact of the pyrolysis temperature of 350°C used during biochar preparation. According to a separate study, sugarcane bagasse biochar was found to exhibit an increase in base saturation when produced at 475°C in comparison to 375°C (Zafeer et al., 2023). The higher %C in the CH and SB biochar may further indicate a higher pyrolysis temperature during the preparation process. Pyrolysis temperature may be a better predictor of biochar C content than residence time. The ash content is a measure of the amount of inorganic non-combustible material it contains. All materials had very low bulk density which was a desirable factor. Biochar with low density (0.30 g/cm$^3$) and highly stable organic carbon in soils has the potential to reduce bulk density and penetration resistance, and hence increase total soil porosity (Gwenzi, 2008). This biochar function is particularly important on soils with high dry soil bulk density and penetration resistance due to natural causes or poor management.

According to Jaetzold et al. (2012), soils in the study area are majorly low fertility Acrisols and Ferralsols with poor soil structure and could benefit from biochar amendments. Biochar application enhances aggregation and aggregate stability (Mukherjee and Lal, 2013). The highly stable organic carbon in the biochar feedstocks may also play a critical role in improving soil aggregation and aggregate stability. Overall, changes in soil structure due to biochar application may enhance soil moisture retention, and infiltration, and consequently reduce runoff and erosion.

## 4. Conclusion

The study established that locally available agricultural waste from coffee and sugarcane processing can be valorized into biochar. The properties recorded on the biochar hold promise for field application of the product for soil enhancement in western Kenya. The study adds to research findings and data on biochar as a remedy to soil degradation that is still scanty, especially in the SSA countries. The potential of biochar applications includes agriculture, mitigation of greenhouse gas emissions, environmental remediation, and energy provision. This will require site-specific and soil type-specific recommendations especially in vast soil types and changing weather patterns. Therefore, this research based on a multi-disciplinary framework provides a comprehensive understanding of biochar technology use and application on different types of soils in western Kenya. Key research themes on biochar should focus on impacts on soil quality and crop yields, crop production improvement, and greenhouse gas emissions in the dominant agroecosystems. In addition, further research should also focus on the development of scalable novel biochar products such as adsorbents for industrial and other environmental pollutants, and biochar-based energy sources such as briquettes, pyrolytic cookstoves, syngas, and bio-oils.

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**Data Availability/Sharing:** The datasets used and analyzed during the current study will be made available from the corresponding author upon a reasonable request.

**Supplementary Information Availability:** Not applicable.

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