

Soil Fertility Improvement, Heavy Metal Safety and Carbon Benefits of Green Charcoal Briquettes in Maize and Cucumber Production

Bassam Lawan Abdulrahman ¹; Basiru Labaran Jazuli ²; and Adnan Aminu Adnan³

¹Department of Soil Science, Bayero University, Kano, Nigeria. ²Department of Soil Science, Federal University Dutsin-Ma, Katsina, Nigeria. ³Department of Agronomy, Bayero University, Kano, Nigeria.

Corresponding author: basirulabs@gmail.com

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Abstract

Declining soil fertility and the rising cost of synthetic fertilizers are major constraints to agricultural productivity in Nigeria. Green charcoal briquettes, produced from compressed organic residues, are primarily promoted as renewable energy sources, yet their potential as safe and effective soil amendments remain underexplored. This study evaluates the chemical composition, heavy metal content and fertilizer potential of green charcoal briquettes on maize (*Zea mays* L.) and cucumber (*Cucumis sativus* L.) under screen house conditions. Laboratory analyses revealed that the briquettes contained appreciable amounts of nitrogen (1.5%), phosphorus (0.8%), potassium (1.2%) and essential micronutrients, while Pb, Cd, Cr and Hg concentrations were all below WHO/FAO permissible limits, confirming environmental safety. Application of green charcoal briquettes significantly increased maize and cucumber yields compared with the control treatment ($p < 0.05$), with maize biomass increasing by 25% at 4.5t ha⁻¹ and cucumber fruit yield rising by approximately 26% at 6.0t ha⁻¹, indicating a positive agronomic response to the amendment. Soil organic carbon improved by up to 18%, and water holding capacity increased by 15%. Estimated carbon sequestration potential ranged from 1.5 to 2.3t C ha⁻¹, indicating notable long-term environmental benefits. These results demonstrate the dual functionality of green charcoal briquettes as both nutrient sources and carbon sinks. The study recommends their integration into sustainable farming systems, with further field trials required to validate long-term agronomic, environmental and economic benefits.

Keywords: Biochar, Soil Organic Carbon, Water Holding Capacity, Sustainable Agriculture, Carbon Sequestration, Screen House Experiment.

Introduction

Soil fertility decline is widely recognized as a major constraint to food security in sub-Saharan Africa, where continuous cultivation, low organic matter input and nutrient mining severely limit crop productivity (Sanchez, 2002; FAO, 2015). In Nigeria, the depletion of soil organic carbon and essential nutrients particularly pronounced in intensively cultivated areas, leading to reduced crop yields, land degradation and increased vulnerability of smallholder farming systems (Nkonya *et al.*, 2016). Addressing soil fertility constraints is

therefore critical to achieving sustainable agricultural intensification and ensuring food security in the region.

Mineral fertilizers remain the dominant strategy for replenishing soil nutrients, yet their widespread use is constrained by high cost, limited availability and environmental concerns, including soil acidification, nutrient leaching and greenhouse gas emissions (Sanginga and Woomer, 2009; Vanlauwe, Sanginga and Woomer, 2013). These challenges underscore the need for affordable, sustainable and environmentally safe alternatives that can enhance soil fertility while minimizing ecological risks.

Organic and carbon-based soil amendments, particularly biochar, have received considerable attention for their ability to improve soil chemical and physical properties, enhanced water retention and contribute to long-term carbon sequestration (Lehmann and Joseph, 2009; Jeffery *et al.*, 2011). Biochar application has been shown to increase crop yields, reduce nutrient losses and provide a sink providing both agronomic and climate change mitigation benefit (Glaser *et al.*, 2002; Biederman and Harpole, 2013; Woolf *et al.*, 2010). Recent meta-analyses indicate that biochar consistently improves crop productivity across diverse soils and climatic conditions, with average yield gains of 10-20% (Agegnehu *et al.*, 2017; Xiang *et al.*, 2017), highlighting its potential a sustainable soil management tool. Green charcoal briquettes, produced from compacted agricultural and forestry residues, have been primarily developed as renewable energy sources for cooking and heating in low-income regions (Philip, Mia and Kenneth, 2022; Hoque *et al.*, 2025). Despite their widespread use as fuel, the potential of green charcoal briquettes as dual-purpose materials serving both as an energy source and a soil amendment remains largely unexplored. Similar to biochar, briquettes may supply essential nutrients and organic matter, enhancing soil fertility, water retention and crop productivity. However, concerns persist regarding their safety, particularly the potential accumulation of heavy metals such as lead (Pb), Cadmium (Cd), Chromium (Cr) and Mercury (Hg), which could contaminate soils and enter the food chain if concentrations exceed permissible limits (Alloway, 2013; Rashid *et al.*, 2023).

Although biochar research has advanced substantially, limited information exists on the agronomic performance, soil fertility impacts, heavy metal safety and carbon sequestration potential of green charcoal briquettes under controlled crop systems. Recent studies have reported growing interest in compacted biochar and briquette-based organic amendment and carbon sequestration. Briquette-based amendments derived from organic waste have been shown to improve soil pH, cation exchange capacity and crop productivity under tropical conditions (Oyebamiji *et al.*, 2025; Sharma *et al.*, 2025). Similarly, biochar-based materials enhance soil moisture retention, nutrient use efficiency and microbial activity, particularly in degraded and sandy soils common in sub-Saharan Africa (Pokharel *et al.*, 2025; Ali *et al.*, 2025). Long-term field studies further indicated that biochar application contributes to sustained increases in soil organic carbon stock and improved resilience to climate change-induced soil degradation (Pei *et al.*, 2025).

Despite these advances, the agronomic value, heavy metal safety and carbon benefits of green charcoal briquettes especially those traditionally produced for household energy use remain poorly understood. Compared with loose biochar, briquettes are denser, easier to

transport and apply, and increasingly produced from agricultural and organic wastes, positioning them as promising waste-to-wealth materials. However, empirical evidence supporting their integration in to sustainable soil management systems is limited.

Therefore, this study evaluated the chemical composition and heavy metal concentration of green charcoal briquettes, assessed their effects on maize (*Zea mays* L.) and cucumber (*Cucumis sativus* L.) growth and yield under screen house conditions and determine their contribution to soil fertility and carbon sequestration potential.

Materials and Methods

Study Area

The study was conducted at the Center for Dryland Agriculture, Bayero University Kano, Nigeria. A completely randomized design (CRD) was adopted to evaluate the effects of green charcoal briquettes on soil properties, crop growth and nutrient dynamics. Six fertilizer treatments, each replicated three times, were tested. Treatments included a control with no input, green charcoal briquette applied at 1.5, 3.0, 4.5 and 6.0 t ha⁻¹, and a generic organic fertilizer used as a standard check.

Laboratory Analysis

The physical and chemical properties of the green charcoal briquettes were determined in the laboratory. The pH was measured in a 1:2.5 sample-to-water suspension using a glass electrode pH meter, while electrical conductivity (EC) was determined in a 1:5 suspension using an EC meter. Moisture content was determined by oven-drying at 105°C for 24 h and ash content was measured by ignition at 550°C for six hours in a muffle furnace. Total nitrogen was determined using the Kjeldahl digestion method, available phosphorous was analyzed using the Olsen method and exchangeable potassium was measured with a spectrophotometer following extraction with ammonium acetate. Micronutrients (Zn, Cu, Fe) were extracted with 0.1 M HCl and measured using an atomic absorption spectrophotometer (AAS). Heavy metals (Pb, Cd, Cr, Hg) were digested with aqua regia and quantified using AAS, with concentration compared against WHO/FAO permissible limits for organic fertilizers.

Screen House Trial

Loamy sand soil was collected from the top 0-20 cm air dried and placed in plastic pots. One maize (*Zea mays* L.) and cucumber (*Cucumis sativus* L.) seedling was maintained per pot after thinning. Green Charcoal briquettes were incorporated into the soil at planting according to designated treatment rates, and pots were irrigated regularly to maintain soil moisture at approximately field capacity.

Although the present study did not include a full-rate inorganic fertilizer or commercial organic fertilizer as a comparative control, several recent studies have reported comparable improvements in crop yield and soil quality when carbon-based amendments are applied as standalone treatments or integrated into nutrient management systems. For instance,

biochar and biochar-based amendments have been shown to enhance nutrient use efficiency and improve crop performance when compared with or combined with mineral fertilizers (Gross *et al.*, 2021; Zubairu *et al.*, 2023; Oduro *et al.*, 2024). The focus of the present study was therefore to evaluate the agronomic potential, safety and soil fertility effects of green charcoal briquettes as a stand-alone amendment, while future studies may integrate direct comparisons with full-rate inorganic and commercial organic fertilizers.

Data Collection

Data collected included maize aboveground biomass (oven-dried at 70°C for 48 h), cucumber fruit yield and nutrient uptake. Soil samples were collected before planting and after harvesting to assess changes in soil organic carbon (SOC) using the Walkley-Black method and water holding capacity (WHC) using the Keen-Raczowski method. Carbon sequestration was estimated from biomass and SOC changes using IPCC (2006) guidelines, assuming a default carbon fraction of 0.47 for plant biomass.

Statistical Analysis

Data collected were subjected to analysis of variance (ANOVA) using JMP software, and treatment means were separated with Tukey's (HSD) test at a significant level of $p \leq 0.05$.

Results and Discussion

Briquette Properties and Heavy Metals Concentration

The green charcoal briquettes used in this study exhibited favourable chemical and physical properties that support their suitability as soil amendments. The briquettes were slightly alkaline, with a pH of 7.2 ± 0.3 , indicating that their application is unlikely to induce soil acidity and may contribute to buffering acidic soils. Electrical conductivity was low ($1.8 \pm 0.2 \text{ dS m}^{-1}$), confirming that the briquettes pose minimal risk of increasing soil salinity. The nutrient composition revealed appreciable levels of total nitrogen (1.5%), available phosphorous (0.8%) and exchangeable potassium (1.2%), along with beneficial concentrations of micronutrients such as zinc (45 mg kg^{-1}), copper (12 mg kg^{-1}) and iron (320 mg kg^{-1}). These nutrient levels indicate that carbonized organic materials can contribute meaningful nutrient input to soil, consistent with earlier reports in the literature (Chan *et al.*, 2007; Agegnehu *et al.*, 2017).

Heavy metal concentrations in the briquettes were well below WHO/FAO permissible limits, indicating a low risk of soil contamination or food-chain transfer. Lead (2.1 mg kg^{-1}), cadmium (0.5 mg kg^{-1}), chromium (3.2 mg kg^{-1}) and mercury (0.02 mg kg^{-1}) were all within internationally accepted safety thresholds. These findings corroborate previous studies demonstrating that properly carbonized biomass-derived amendments typically contain low concentrations of heavy metals and are safe for agricultural application (Rashid *et al.*, 2023; Wang *et al.*, 2021). In addition, the high organic carbon content (753 g kg^{-1}) and low bulk density (0.21 g cm^{-3}) suggest a strong potential for improving soil physical properties by increasing porosity and reducing compaction. Such improvements align with established

biochar mechanisms, whereby carbon-rich materials enhance soil aeration, water retention and structural stability (Glaser *et al.*, 2002; Lehmann and Joseph, 2009).

Table 1: *Physical and chemical properties and nutrient composition of green charcoal Briquettes*

Parameter	Unit	Concentration (Mean $\pm$ SD)
Organic Carbon	g kg ⁻¹	753 $\pm$ 20
pH	-	7.3 $\pm$ 0.1
Total Nitrogen (N)	%	1.5 $\pm$ 0.1
Available Phosphorus (P)	%	0.8 $\pm$ 0.05
Exchangeable Potassium (K)	%	1.2 $\pm$ 0.1
Zinc (Zn)	mg kg ⁻¹	45 $\pm$ 3
Copper (Cu)	mg kg ⁻¹	12 $\pm$ 1
Iron (Fe)	mg kg ⁻¹	320 $\pm$ 15
Bulk Density (BD)	g cm ⁻³	0.21
Particle Density (PD)	g cm ⁻³	0.67
Porosity	%	85.82
Moisture Content (MC)	%	1.01
Electrical Conductivity (EC)	dS m ⁻¹	0.38

Note: Values represent mean concentrations of green charcoal briquettes determined under laboratory conditions. SD = Standard deviation.

Table 2: *Heavy metal concentrations in green charcoal briquettes relative to WHO/FAO permissible limits*

Heavy Metal	Concentration (Mean $\pm$ SD)	Permissible Limit (WHO/FAO)
Lead (Pb) (mg/kg)	2.1 $\pm$ 0.3	5
Cadmium (Cd) (mg/kg)	0.5 $\pm$ 0.1	1
Chromium (Cr) (mg/kg)	3.2 $\pm$ 0.4	10
Mercury (Hg) (mg/kg)	0.1 0.02*	0.5

SD = Standard deviation

*Very low variability observed for Hg concentration

Crop Performance and Yield Response

Application of green charcoal briquettes significantly enhanced both maize biomass and cucumber fruit yield. Maize above-ground biomass increased progressively with higher application rates, reaching 3,750 $\pm$ 50 g at 4.5 t ha⁻¹, representing a 25% increase over the control treatment. This response indicates that the briquettes supplied adequate nutrients while simultaneously improving soil physical conditions that support root development and nutrient uptake. Similar yield improvements following biochar application have been reported, with increases attributed to enhanced nutrient retention, reduced leaching and improved soil structure (Jeffery *et al.*, 2011; Beiderman and Harpole, 2013).

Cucumber exhibited an even stronger yield response, with the highest fruit yield recorded at 6.0 t ha^{-1} , representing a 30% increase relative to the control. The greater responsiveness of cucumber compared with maize suggests a higher sensitivity to improvements in soil nutrient availability and moisture retention. Previous studies have demonstrated that horticultural crops often benefit more from organic and carbon-based amendments due to their relative high nutrient and water requirements (Xiang *et al.*, 2017; Joseph *et al.*, 2021). The observed yield increases therefore indicate that green charcoal briquettes effectively improve soil hydro-physical conditions sufficient to meet the demands of high-value vegetable crops.

The enhancement of maize biomass and cucumber yield following briquette application can be attributed to the gradual release of nutrients and improvement in soil physicochemical properties. Carbon-rich amendments such as green charcoal briquettes increase soil cation exchange capacity, water holding capacity and microbial activity, thereby enhancing nutrient availability over time (Gross *et al.*, 2021; Ashraf *et al.*, 2025). The approximately 25% increase in maize biomass observed in this study is comparable to yield improvements ranging from 20-35% reported in recent biochar-based studies under similar agro-ecological conditions (Zubairu *et al.*, 2023). This comparison suggests that green charcoal briquettes perform within the expected efficacy range of carbonized organic soil amendments.

Beyond short-term yield effects, the stability of carbon in green charcoal briquettes is of particular significance. Owing to their densified structure and relatively high aromatic carbon content, briquettes are less susceptible to rapid decomposition than raw organic residues, thereby contributing to longer-term soil carbon sequestration (Koutika *et al.*, 2025). This enhanced carbon stability supports sustained soil organic matter improvement and aligns with climate-smart agriculture objectives, particularly in tropical systems where organic carbon losses are typically rapid.

Table 3: *Effect of Green Charcoal Briquette Application on Maize Biomass*

Treatment	Application rate (t ha^{-1})	Mean $\pm$ SD (g)
Control	0.0	3000 ± 100
Recommended Rate	3.0	3172 ± 100
Low Rate	1.5	3300 ± 100
Medium Rate	4.5	3750 ± 50
High Rate	6.0	3600 ± 100
Generic check	-	3450 ± 50

SD = Standard deviation

Table 4: *Effect of Green Charcoal Briquette Application on Cucumber fruit yield*

Treatment	Application rate (t ha^{-1})	Mean $\pm$ SD (g)
Control	0.0	5180 ± 103
Recommended Rate	3.0	6023 ± 102
Low Rate	1.5	5504 ± 100

Treatment	Application rate (t ha ⁻¹)	Mean ± SD (g)
Medium Rate	4.5	6023 ± 105
High Rate	6.0	6512 ± 100
Generic Check	-	5807 ± 100

Cucumber fruit yield increased numerically with increasing green charcoal briquette application rate, with the highest yield observed at 6.0 t ha⁻¹, indicating a strong positive crop response to the amendment

SD = Standard deviation

Nutrient Uptake in Cucumber

Nutrient uptake in cucumber increases markedly with briquette application. The highest application rate (6.0 t ha⁻¹) resulted in a 20% increase in nitrogen uptake, 18% increase in phosphorous uptake and 19% increase in potassium uptake relative to the control. These improvements reflect increased nutrient availability and retention within the soil-plant system, likely due to the briquettes' high cation exchange capacity, porous structure and slow nutrient release characteristics. Similar trends have been reported in studies where biochar enhanced nutrient use efficiency by reducing leaching losses and improving soil-root interactions (Lehmann *et al.*, 2006; Agegnehu *et al.*, 2017).

The steady increases in nutrient uptake across the treatment rate also indicate that briquettes provide a gradual, sustained supply of nutrients, unlike some mineral fertilizers that release nutrients rapidly and are prone to losses. Enhanced nutrient uptake directly explains the observed increases in cucumber yield and biomass, reinforcing the agronomic potential of green charcoal briquettes as a fertilizer substitute or complement.

Table 5: Effect of green charcoal briquette application rates on nutrient uptake in cucumber

Treatment	Application rate (t ha ⁻¹)	N Uptake (%)	P uptake (%)	K Uptake (%)
Control	0.0	0.52	0.5	0.1
Recommended Rate	3.0	12	7	11
Low Rate	1.5	10	8	9
Medium Rate	4.5	15	12	14
High Rate	6.0	20	18	19
Generic Check	-	12	10	11

Note: Nutrient uptake values represent percentage increases relative to the control treatment

Improvements in Soil Fertility Indicators

Soil organic carbon (SOC) increased significantly following briquette application, with the highest improvement of 18% recorded at 4.5 t ha⁻¹. This rise reflects the high carbon content and stability of the briquettes, which contribute to long-term soil carbon storage. Improved SOC enhances soil structure, nutrient cycling and microbial activity, all of which support

sustainable crop production. These results align with findings by Glaser *et al.* (2002) and Lehmann *et al.* (2006), who reported that carbonized biomass amendments increase soil organic carbon by introducing stable aromatic carbon compounds into the soil matrix. Water-holding capacity (WHC) also improved substantially. The maximum improvement (15%) occurred at 4.5 t ha⁻¹, indicating that medium application rates produce the most beneficial effects on soil moisture retention. Increased WHC is attributable to the porous nature of the briquettes, which enhances the soil's ability to retain and supply water to plants. This property is particularly important in dryland and drought-prone regions, where soil moisture is a major limiting factor for crop productivity. The results of this study corroborate the work of Kammann *et al.* (2017) and Woolf *et al.* (2010), who observed similar improvements in soil moisture dynamics following biochar application.

Table 6: Changes in SOC and WHC following green charcoal briquette application in the maize experiment

Treatment	Application rate (t ha ⁻¹)	SOC Increase (%)	WHC Improvement (%)
Control	0.0	0	0
Recommended Rate	3.0	6	7
Low Rate	1.5	10	8
Medium Rate	4.5	18	15
High Rate	6.0	12	10
Generic Check	-	8	6

Note: SOC = soil organic carbon; WHC = water-holding capacity. Values represent percentage changes relative to the control treatment.

Carbon Sequestration and Environmental Impact

Green charcoal briquettes demonstrated substantial potential for carbon sequestration. Total carbon stocks, incorporating above-ground biomass, below-ground biomass and changes in soil organic carbon, ranged from 1.5 to 2.3 t C ha⁻¹ across treatments. The highest carbon sequestration was observed in cucumber under the 6.0 t ha⁻¹ application rate. These findings indicate the dual functionality of green charcoal briquettes as both agronomic inputs and climate change mitigation tools. Carbonized biomass is characterized by chemically stable carbon fractions that persist in soil decades to centuries, thereby contributing to long-term reductions in atmospheric carbon dioxide concentrations (Woolf *et al.*, 2010; Lehmann and Joseph, 2009).

Moderate application rates appeared to provide an optimal balance between crop productivity and carbon sequestration. Excessively high application rates did not consistently improve carbon stocks, potentially due to nutrient imbalances or reduced microbial mineralization efficiency. Similar response patterns have been reported in biochar-based studies, where agronomic and environmental benefits peak at intermediate application level (Jeffery *et al.*, 2011; Agegnehu *et al.*, 2017). The results therefore suggest

that green charcoal briquettes function as effective carbon-enhancing amendments capable of supporting climate-smart agricultural systems.

Table 7: Total carbon stock in maize and cucumber following green charcoal briquette application

Treatment	Application rate (t ha ⁻¹)	Maize (t C ha ⁻¹)	Cucumber (t C ha ⁻¹)
Control	0.0	0.8	0.9
Recommended Rate	3.0	1.2	1.3
Low Rate	1.5	1.3	1.4
Medium Rate	4.5	1.5	1.8
High Rate	6.0	1.3	2.3
Generic Check	-	1.0	1.2

Note: total carbon stock includes above-ground biomass, below-ground biomass and changes in soil organic carbon. Values represent treatment-based estimates relative to the control

Table 8: Net change in soil organic carbon (SOC) across green charcoal briquette treatments

Treatment	Application rate (t ha ⁻¹)	Net Change in SOC (%)
Control	0.0	0.0
Recommended Rate	3.0	11.0
Low Rate	1.5	10.0
Medium Rate	4.5	18.0
High Rate	6.0	12.0
Generic Check	-	8.0

Note: Net change in SOC represents the percentage increase relative to the control treatment following green charcoal application

Conclusion

This study demonstrated that green charcoal briquettes possess favourable chemical and physical properties that support their use as soil amendments for improving crop productivity. The briquettes contained appreciable concentrations of essential macronutrients, including nitrogen, phosphorous and potassium, as well as beneficial micronutrients, while heavy metal concentrations remained well below WHO/FAO permissible limits, confirming their environmental safety. Application of green charcoal briquettes to maize and cucumber under screen house conditions resulted in improved crop performance, as evidenced by increased biomass production, fruit yield and nutrient uptake. These agronomic responses were accompanied by notable improvements in soil quality indicators, particularly soil organic carbon and water-holding capacity, which are critical for sustainable soil fertility management in intensively cultivated system. In addition, the briquettes contributed to enhanced carbon sequestration, with total carbon stocks ranging from 1.5 to 2.3 t C ha⁻¹ across treatments, highlighting their potential role in

climate-smart agriculture through simultaneous yield improvement and soil carbon storage. Medium application rates, particularly 4.5 t ha⁻¹ for maize and 6.0 t ha⁻¹ for cucumber, provided the most balanced outcomes in terms of nutrient supply, soil quality enhancement and carbon benefits.

Overall, green charcoal briquettes function as dual-purpose materials capable of improving soil fertility while contributing to long-term environmental sustainability. Their use as soil amendments presents a promising opportunity to reduce reliance on costly synthetic fertilizers while promoting waste recycling and resource efficiency. However, further research under field conditions across diverse agroecological zones is required to validate these findings, assess long-term impacts, evaluate economic feasibility and explore integration with existing soil fertility management practices. Such studies will strengthen the evidence base needed to support the adoption of green charcoal briquettes as a viable component of sustainable agricultural systems.

Data Availability

The datasets generated during the current study are not publicly available and will not be shared in order to protect the authors' intellectual property and research integrity.

Conflict of Interest

There is no conflict of interest associated with study.

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