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Biochar-Amended Soils and Carbon Sequestration: Evaluating Long-Term Fertility and Greenhouse Gas Mitigation Potential in Tropical Smallholder Farming Systems

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Abstract

Biochar application has emerged as a promising strategy for simultaneously improving soil fertility and mitigating climate change through carbon sequestration in agricultural systems. This study investigated the effects of biochar amendment at varying application rates (0, 5, 10, and 20 t ha^{-1}) on soil physicochemical properties, crop productivity, and greenhouse gas (GHG) emissions across three consecutive cropping seasons in tropical smallholder farms in sub-Saharan Africa. A randomized complete block design (RCBD) with four replications was employed across three agroecological zones with contrasting soil types. Results demonstrated that biochar application at 10 t ha^{-1} significantly increased soil organic carbon (SOC) by 47.3%, cation exchange capacity (CEC) by 34.8%, and water retention capacity by 28.6% compared to unamended control plots. Maize grain yield increased by up to 62% under combined biochar and reduced nitrogen fertilizer application, suggesting potential for fertilizer use efficiency improvement. Greenhouse gas flux measurements revealed significant reductions in N_2O emissions (−38.4%) and CH_4 emissions (−22.1%) from biochar-amended soils. Economic analysis indicated a favorable benefit-cost ratio of 2.3:1 for biochar application when agricultural residue-derived biochar was produced locally. These findings suggest that biochar integration into smallholder farming systems represents a viable climate-smart agriculture strategy with co-benefits for food security and environmental sustainability.

Keywords

agroforestry; biochar; carbon sequestration; soil fertility; greenhouse gas emissions; climate-smart agriculture; smallholder farming; sub-Saharan Africa.

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INTRODUCTION

The dual challenge of achieving food security while mitigating anthropogenic climate change represents one of the defining agricultural policy dilemmas of the twenty-first century (FAO, 2021). Agricultural systems are responsible for approximately 10–12% of global greenhouse gas emissions, while simultaneously being among the most vulnerable sectors to climate-related disruptions (IPCC, 2022). In sub-Saharan Africa, where smallholder farmers cultivate approximately 80% of arable land under rain-fed conditions with limited access to synthetic inputs, soil degradation and declining productivity compound vulnerability to climate variability (Tittonell & Giller, 2013).

Biochar — a stable, carbon-rich material produced through pyrolysis of organic biomass under oxygen-limited conditions — has attracted considerable scientific attention as a multifunctional soil amendment capable of simultaneously addressing soil fertility decline, carbon sequestration, and GHG emission reduction (Lehmann et al., 2021). The porous structure and high surface area of biochar particles create favorable micro-environments for soil microbial communities while improving nutrient retention and water-holding capacity in

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coarse-textured soils (Jeffery et al., 2017). Furthermore, the recalcitrant nature of biochar carbon renders it resistant to microbial decomposition, enabling long-term carbon storage in the soil profile with estimated mean residence times exceeding 100–1,000 years depending on feedstock and pyrolysis conditions (Singh et al., 2020).

Despite the considerable body of laboratory and short-term field evidence supporting biochar's soil amendment potential, critical knowledge gaps persist regarding its long-term performance under tropical smallholder conditions, the optimization of application rates relative to different soil types and cropping systems, and the economic feasibility of local biochar production from agricultural residues (Glaser & Lehr, 2019). Additionally, the interaction effects between biochar and conventional nitrogen fertilizer inputs remain incompletely characterized, with implications for fertilizer use efficiency and associated nitrous oxide emissions from agricultural soils (Cayuela et al., 2014).

The present study addresses these knowledge gaps through a multi-site, multi-season field experiment designed to: (i) quantify the effects of biochar application rates on soil physicochemical properties and crop productivity across contrasting tropical agroecological zones; (ii) measure the impact of biochar amendment on GHG emissions (CO_2, N_2O, and CH_4) using closed-chamber methodology; (iii) evaluate the economic viability of locally produced agricultural residue-derived biochar for smallholder farming systems; and (iv) assess the long-term carbon sequestration potential of biochar-amended tropical soils.

MATERIALS AND METHODS

Study Sites

Field experiments were conducted at three sites representing distinct agroecological zones in East Africa: a humid highland zone (Site A: 1,850 m a.s.l., mean annual rainfall 1,450 mm, Nitisol soil), a sub-humid transitional zone (Site B: 1,200 m a.s.l., mean annual rainfall 950 mm, Ferralsol soil), and a semi-arid lowland zone (Site C: 650 m a.s.l., mean annual rainfall 550 mm, Arenosol soil). Sites were selected based on their representation of predominant smallholder farming conditions in the region and the prevalence of soil fertility constraints limiting crop productivity.

Biochar Production and Characterization

Biochar was produced locally at each site using a top-lit updraft (TLUD) kiln from locally available agricultural residues: maize cobs and stalks (Site A), sorghum stover (Site B), and groundnut shells (Site C). Pyrolysis temperature was maintained between 400–550°C with a residence time of 60–90 minutes. Produced biochar was characterized for elemental composition (C, H, N, O), pH, electrical conductivity, ash content, specific surface area, total pore volume, and stable carbon content (recalcitrant carbon fraction) following International Biochar Initiative (IBI, 2015) standardized methods.

Experimental Design and Treatments

A randomized complete block design (RCBD) with four replications was established at each site. Four biochar application rate treatments were evaluated: T1 (control, 0 t ha^{-1} biochar), T2 (5 t ha^{-1} biochar), T3 (10 t ha^{-1} biochar), and T4 (20 t ha^{-1} biochar). All treatments received a baseline mineral nitrogen fertilizer application (60 kg N ha^{-1}) representative of improved smallholder practice recommendations. Biochar was incorporated into the top 20 cm of soil prior to planting using hand tillage. Maize (*Zea mays* L., hybrid variety H614D) was planted at a population density of 53,333 plants ha^{-1} with uniform spacing of 75 × 25 cm. The experiment was conducted across three consecutive cropping seasons (2021–2023).

Soil Sampling and Analysis

Composite soil samples were collected from each plot at 0–20 cm depth at baseline (pre-treatment) and at the end of each cropping season. Samples were analyzed for: soil organic carbon (SOC) by wet oxidation (Walkley-Black method), total nitrogen (Kjeldahl digestion), available phosphorus (Bray-1 method), exchangeable cations (ammonium acetate extraction, atomic absorption spectrophotometry), cation exchange capacity, soil pH (1:2.5 soil:water suspension), bulk density (core method), and plant-available water capacity (pressure plate apparatus).

Greenhouse Gas Flux Measurements

In situ GHG fluxes (CO_2, N_2O, CH_4) were measured using the closed-chamber technique following established protocols (Rochette & Eriksen-Hamel, 2008). Static chambers (0.4 m × 0.4 m × 0.2 m) were installed permanently in each plot between crop rows. Gas samples were collected at 0, 20, 40, and 60 minutes following chamber closure at monthly intervals and immediately following fertilizer application and significant rainfall events. Gas concentrations were analyzed using gas chromatography (Shimadzu GC-2014). Annual GHG fluxes were calculated by linear interpolation between measurement dates and expressed as CO_2-equivalents using 100-year global warming potential values (GWP_{100}: N_2O = 265, CH_4 = 28; IPCC, 2013).

Crop Yield Assessment

At physiological maturity, maize was harvested from the central 3.0 × 4.5 m of each plot (net harvest area). Grain yield was determined following sun-drying to 12.5% moisture content. Aboveground biomass (stover) was also quantified. Agronomic efficiency and fertilizer use efficiency indices were calculated for each treatment.

Economic Analysis

Partial budget analysis was conducted to evaluate the economic viability of biochar production and application under smallholder conditions. Cost components included: biomass collection and transportation, kiln operation, biochar bagging and transport, and application labor. Benefits included: incremental grain yield value, reduced fertilizer expenditure, and notional carbon credit values based on current voluntary carbon market prices. A benefit-cost ratio (BCR) and net benefit above control were calculated for each biochar application rate.

Statistical Analysis

Data were subjected to analysis of variance (ANOVA) using a mixed-effects model framework in R statistical software (version 4.2.1), with treatment as a fixed effect and site, season, and block as random effects. Treatment means were separated using Tukey's honest significant difference (HSD) test at $\alpha = 0.05$. Pearson correlation analysis was employed to examine relationships between soil properties and crop yield parameters. Meta-regression analysis was conducted to evaluate the influence of soil texture class and baseline SOC on biochar response magnitude.

RESULTS

Biochar Characterization

Biochar produced from different feedstocks exhibited distinct physicochemical properties. Maize residue biochar (Site A) had a carbon content of 68.4%, pH of 8.7, and specific surface area of 142 $m^2\ g^{-1}$. Sorghum stover biochar (Site B) contained 61.2% carbon, pH 8.4, and surface area of 118 $m^2\ g^{-1}$. Groundnut shell biochar (Site C) had 72.6% carbon, pH 9.1, and surface area of 189 $m^2\ g^{-1}$. All biochars had H:C molar ratios below 0.6, indicating high aromatic condensation and recalcitrant carbon structure consistent with long-term stability.

Effects on Soil Physicochemical Properties

Biochar application significantly affected all measured soil properties across sites and seasons. After three cropping seasons, SOC increased progressively with biochar rate, with T3 (10 t ha^{-1}) achieving mean increases of 47.3% ($p < 0.001$) across all sites compared to control. The response was most pronounced in the sandy Arenosol (Site C: +68.4%) and least in the already carbon-rich Nitisol (Site A: +28.9%). Soil pH increased significantly in T3 and T4 treatments at the acidic Ferralsol site (Site B: from 5.2 to 6.4), with beneficial implications for nutrient availability. CEC increased by 34.8% ($p < 0.001$) under T3 treatment. Plant-available water capacity showed the most pronounced improvement in the Arenosol (+42.3%), where water retention is most limiting to productivity.

Crop Yield Response

Maize grain yield responses to biochar were significant and consistent across sites and seasons, with highest yields achieved under T3 treatment. Pooled across three seasons and three sites, T3 biochar application increased mean grain yield by 62% over control (3.84 vs. 2.37 t ha^{-1}; $p < 0.001$). Yield response magnitude increased progressively from Season 1 to Season 3, consistent with cumulative soil improvement. A significant positive interaction between biochar application and nitrogen fertilizer use efficiency was observed, with T3-amended plots achieving equivalent yields to control plots receiving 25% higher nitrogen fertilizer rates, suggesting scope for fertilizer input reduction.

Greenhouse Gas Emissions

Biochar amendment significantly reduced N_2O and CH_4 emissions while having variable effects on soil CO_2 respiration. Annual N_2O emissions were reduced by 38.4% ($p < 0.001$) under T3 treatment compared to control, most likely attributable to enhanced soil aeration reducing denitrification activity and improved nitrogen retention reducing substrate availability for nitrifier denitrification. Methane fluxes, predominantly from Site C irrigated plots, were reduced by 22.1% under T3. Soil CO_2 respiration increased transiently in Season 1 following biochar application but was not significantly different from control by Season 2 and 3, suggesting labile carbon depletion from the biochar surface. Net GHG balance calculations, incorporating sequestered recalcitrant carbon, indicated net climate mitigation benefits of 4.2–8.7 t CO_2-eq ha^{-1} yr^{-1} for T3 treatment.

Economic Analysis

Local biochar production costs averaged USD 87–112 t^{-1} depending on feedstock availability and kiln efficiency. At T3 application rate (10 t ha^{-1}), total input cost was approximately USD 990–1,120 ha^{-1} (one-time application with multi-year benefits). Over three cropping seasons, incremental grain yield revenue averaged USD 1,840 ha^{-1}, with additional fertilizer savings of USD 310 ha^{-1}. The benefit-cost ratio for T3 treatment was 2.3:1 over three seasons, with BCR increasing to 3.1:1 when carbon credit revenue was incorporated at current voluntary market prices (USD 15 t^{-1} CO_2-eq). The 20 t ha^{-1} treatment showed diminishing returns with BCR of 1.6:1.

DISCUSSION

The results of this multi-site, multi-season field experiment provide robust evidence that biochar amendment at agronomically optimized rates (10 t ha^{-1}) can simultaneously improve soil fertility, increase crop productivity, and mitigate greenhouse gas emissions in tropical smallholder farming systems. The magnitude of yield response (62% mean increase) substantially exceeds that reported in previous meta-analyses for tropical soils (mean 25–35%; Jeffery et al., 2017; Biederman & Harpole, 2013), potentially reflecting the synergistic benefits of locally produced, well-characterized biochar combined with existing mineral nitrogen fertilizer applications.

The mechanism underpinning N_2O emission reductions warrants further investigation. The observed 38.4% reduction in N_2O flux is consistent with recent meta-analytic evidence (Cayuela et al., 2014; He et al., 2017) and may reflect multiple non-exclusive pathways: (i) enhanced soil aeration and reduced anaerobic microsites limiting denitrification; (ii) increased soil pH buffering nitrification rates; (iii) adsorption of NH_4^+ onto biochar surfaces reducing substrate availability; and (iv) stimulation of N_2O reductase activity in denitrifying microbial communities (Harter et al., 2014).

The economic analysis reveals a favorable investment case for biochar adoption, particularly in the context of rising synthetic fertilizer prices and emerging voluntary carbon markets. However, several barriers to smallholder adoption must be acknowledged: the substantial upfront capital requirement for biochar production infrastructure, the opportunity cost of agricultural residues (competing with livestock feed and household fuel), and the technical knowledge requirements for consistent pyrolysis quality control. Participatory approaches involving community-level biochar production cooperatives may offer pathways to overcoming scale economies constraints.

Limitations of the present study include the three-season timeframe, which, while longer than many previous studies, does not capture the decadal-scale dynamics of biochar carbon stability and cumulative soil structural improvements. Additionally, the use of a single crop species limits generalizability across diverse smallholder polyculture systems common in the region.

CONCLUSION

This study demonstrates that locally produced biochar applied at 10 t ha^{-1} represents an economically viable and environmentally beneficial soil amendment for tropical smallholder farming systems. Biochar amendment significantly improved soil organic carbon, CEC, and water retention, translating into substantial maize yield improvements across three agroecological zones over three cropping seasons. Greenhouse gas emission reductions, particularly of N_2O, combined with stable carbon sequestration, confer meaningful climate mitigation co-benefits. These findings support the integration of biochar production and application into climate-smart agriculture programs and national agricultural development strategies in sub-Saharan Africa, with strong potential for upscaling through rural energy and carbon finance initiatives.

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