Nutrient Characteristics of Biochar Derived from Cocoa Husk, Rice Straw and Corn Cob and Their Effects on Maize Yield in Ghana

Bernice Amoafoa[1]*, Collins Agyei Menka[2], and Iddrisu Sumaila[3]

[1]Kibi Presbyterian College of Education, Science Department, Private Mail Bag, Kibi- Ghana.
[2]Wiawso College of Education, Vocational and Technical Department, Ghana.
[3]Atebubu College of Education, Science Department P.O.Box 29, Atebubu- Ghana.
*Corresponding author's email: berniceamoafoa@gmail.com

Received 10 December 2025, Accepted 9 January 2026, Published 15 January 2026

Direct Research Journal of Agriculture and Food Science

Direct RESEARCH JOURNALS

Vol. 14(1), Pp. 40-49, January 2026

https://journals.directresearchpublisher.org/index.php/drjafs; https://www.ajol.info/index.php/drjafs

Research Article
ISSN: 2354-4147

ABSTRACT

The Inadequate soil fertility remains a major constraint to maize production in Ghana and large areas of sub-Saharan Africa, especially in regions having weathered Ultisols with low organic matter and nutrient-holding capacity. The present study investigated the impact of locally produced agricultural residue-derived biochar on maize yield under field conditions in Ghana. Biochar was obtained from cocoa pod husk, rice straw and corn cob by pyrolysis at 500°C for 45 minutes in the total absence of oxygen and chemically characterised. The field study was carried out at Kwadaso, Ghana, in a split-split plot design with three replications over the principal and minor crop seasons. Treatment included biochar type and application rate (2.5 t ha^{-1}, 5 t ha^{-1}) in comparison with fertilizer. The pH of all the biochars was strongly alkaline (pH 10.3–10.4). Soil amendment Biochars made of rice straw showed the highest organic C (41.0%) and available P (343.6 mg kg^{-1}), whereas those derived from cocoa husk had the highest exchangeable base cations. Application of biochar significantly enhanced the growth and yield of maize as compared to the control. At 5 t ha^{-1}, application led to a 32.9% and 58% increase in grain and cob yields, respectively. Response in yield was not dramatically different among the biochar types. These findings confirm that indigenous biochar feedstocks increase the productivity of maize and the sustainable management of soil fertility in Ghana.

Keywords: *Biochar; Agricultural residues; Soil fertility; Maize yield; Ghana; Pyrolysis*

Citation: Amoafoa, B., Menka, C. A., & Sumaila, I. (2026). Nutrient Characteristics of Biochar Derived from Cocoa Husk, Rice Straw and Corn Cob and Their Effects on Maize Yield in Ghana. *Direct Research Journal of Agriculture and Food Science*. Vol. 14(1), Pp. 40-49: .https://doi.org/10.26765/DRJAFS17284877

INTRODUCTION

The declining fertility of soils is a major limitation to the sustainable production of crops in Ghana and large parts of sub-Saharan Africa (Raimi *et al.*, 2017). The continuous cultivation without adequate nutrient replenishment, as well as problems like soil erosion, nutrient leaching, and gas losses, has caused soil degradation, especially in developing countries where rapid population growth is increasing the need for food production on already fragile soils (Zhu *et al.,* 2020; Telo da Gama, 2023). Therefore, the efficient management of soil fertility is a very important way to improve crop yield and make agriculture sustainable in the long run (Batabyal, 2017).

In Ghana, compost and poultry manure, among other organic amendments, have been practically accepted as the main way of restoring soil fertility (Shu *et al.,* 2022). However, farmers on a small scale often face difficulties when trying to make use of organic amendments because of the limited supply plus fast decay of the materials in tropical conditions. Besides, they get affected by the product size (Lehmann & Joseph, 2015; Paul, 2016). Moreover, the composting of the organic matter not only emits CO_2 but also releases methane (CH_4) and nitrous oxide (N_2O) into the atmosphere, which are among the most powerful greenhouse gases that contribute to the Earth's warming, hence the analogy (Policastro & Cesaro, 2022). Such negative aspects have pointed out the importance of creating soil amendments that are able to keep the nutrients in the soil while at the same time supporting the implementation of climate-smart farming practices. These difficulties are widely encountered in sub-Saharan Africa, especially in the regions where smallholder farming systems prevail, and the availability of affordable soil amendments is still a major issue.

Pyrolysis of biomass under conditions of low oxygen results in a biochar rich in carbon. This biochar has been acknowledged as a safe and environmentally friendly option for soil enhancement, exhibiting significant potential for agricultural applications (Afshar & Mofatteh, 2024). The characteristics of biochar, including its porosity and stability, along with soil water-holding capacity, cation exchange capacity, microbial activity, and nutrient retention, make soil more effective and also reduce the amount of nutrients lost through leaching (Chan *et al.,* 2007; Niraj & Bhimsen, 2024; Antonangelo, 2021). Consequently, biochar can be seen as a component of the ISFM (Integrated Soil Fertility Management) system, where the application of organic and inorganic fertilizers together results in improved nutrient use and increased crop production (Mugwe *et al.,* 2019; Kumar & Bhattacharya, 2021).

The production of biochar from agricultural waste entails various benefits, and among them are environmental protection and the generation of eco-friendly energy through this process, good waste management and the use of less harmful methods than open burning and also better carbon absorption in soil (Patel & Panwar, 2023; Matsagar & Wu, 2022). (Patel & Panwar, 2023; Matsagar & Wu, 2022). Ghana's agricultural market is massive; for instance, the country has been able to generate more than 3.52 million tonnes of maize and about 1.72 million tonnes of rice during the last couple of years, signalling that the cereal production is flourishing (NDPC, 2024). Apart from being the second-largest cocoa producer globally, Ghana also has to manage a lot of cocoa waste every year (USDA estimates, 2024). All these leads to the generation of huge amounts of biomass waste like cocoa husk, rice straw, and corn cobs, which are never utilized fully and are sometimes just thrown away, while they carry the potential to be biochar feedstocks. On the other hand, the nutrient content and agricultural fitness of biochar derived from these regions' residues are not well recorded in the case of Ghana (Rafqu *et al.,* 2020). Thus, the current study explores the nutrient characteristics of biochar produced from cocoa husk, rice straw, and corn cob to judge their applicability as soil amendments for the enhancement of soil fertility and sustainable crop production support. The study objectives were: to characterize the chemical properties of biochar from three agricultural residues and to evaluate the effects of biochar type and application rate on maize growth and yield.

MATERIALS AND METHODS

Study Site Description

The Soil Research Institute (SRI), Kwadaso, was the location for the field and laboratory experiments and is within the Kumasi Metropolis of Ghana. The region is in the humid semi-deciduous rainforest zone at about 252 m above sea level. The soils of the experimental site are components of the Nzima series and are considered Ultisols with a loamy texture. The region has a bimodal rainfall pattern, with annual precipitation between 1,250 and 1,500 mm and temperatures ranging from 21.5 to 30.7°C on average per year (Ghana Meteorological Agency, 2021).

Biochar Production

The biochar feedstocks used in the study were corn cob, rice straw, and cocoa pod husk, which were collected from various farming communities in the Ashanti Region. The materials were air-dried, ground, and pyrolysis in a reactor at 500°C for 45 minutes in a limited oxygen environment. The selected pyrolysis temperature was aimed at providing proper carbonization while retaining crucial nutrients for soil amendment.

Experimental Design and Field Management

The field experiment was conducted as a split-split plot design with three replications. The main plot factor was biochar type, and biochar application rate was assigned to the subplots, and the fertilizer rate created the sub-subplots. The three types of biochar were corn cob biochar, rice straw biochar, and cocoa pod husk biochar. Two rates of biochar application (2.5 and 5.0 t ha^{-1}) were given. These rates were chosen to indicate moderate and ideal levels for agronomy in smallholder farming systems, as studies have indicated that application rates ≤5 t ha^{-1} are sufficient for enhancing soil properties without causing nutrient imbalance or yield suppression in the long run. Three application rates of N-P-K as inorganic fertilizer (90-60-60, 45-30-30 and 0-0-0) were used. The sources of N-P-K used were Urea, Triple superphosphate and Muriate of Potash respectively. The experimental units of the main plots were 9.4 m × 12.8 m with a 2 m buffer in between. The sub-subplots measured 4.2 m × 3.6 m, with 1 m alleys between plots. The net plot size employed for yield determination was 2.4 m × 2.4 m (5.76 m^2) after the border rows were excluded. The treatments were assigned randomly within each level of the split-split plot structure in each replication. The control treatment consisted of plots that did not receive any biochar or inorganic fertilizer, specifically 0 t ha^{-1} biochar and 0–0–0 NPK. The hybrid maize (Mamaba) was chosen as the experimental crop, and a spacing of 80 cm × 40 cm was used for sowing, thus giving a plant density of 62,500 per hectare. Manual weeding was performed at the intervals of two, five, and eight weeks post-planting.

Data Collection

Plant height and stem girth were recorded from three weeks after planting to six weeks after planting, while the harvest took place fifteen weeks after planting. The yield parameters measured were the grain yield, stover yield, and cob yield.

Soil Sampling and Laboratory Analysis

Before the application of biochar, composite soil samples were collected from the 0-15 cm depth, which corresponds to the plough layer, for initial soil characterization. Subsequently, additional soil samples were gathered from this same depth for a more detailed soil analysis. The soil chemical properties tested included pH, organic C, total N, available P, and exchangeable K, Na, Mg, and Ca. A microprocessor pH meter was used to determine soil pH. Soil organic carbon content was estimated by using the Walkley-Black method, whereas total nitrogen was determined by the Kjeldahl method, and the Bray No. 1 extraction method was used for available phosphorus determination. Ammonium acetate was employed for the extraction of exchangeable cations, and effective cation exchange capacity (ECEC) was derived as the combination of exchangeable bases and exchangeable acidity.

Statistical Analysis

The statistical analysis of the data was performed by means of the General Linear Model (GLM) procedure in SAS (Version 2012). The treatments were regarded as random effects, whereas the biochar type, biochar rate, fertilizer rate, and their interactions were classified as fixed effects. The appropriate split–split plot error structure was applied in the analysis. Residual plots and Shapiro–Wilk tests were used to check for normality and homogeneity of variances before proceeding with the analysis. Where the assumptions were met, the untransformed data were used. All two-way and three-way interaction effects were tested, and treatment means were separated using the least significant difference (LSD) test at $p \leq 0.05$.

RESULTS AND DISCUSSION

Chemical analysis of biochar

Results of the characterization of conventional biochar (Table 1) showed an alkaline pH of 10.3–10.4, with rice straw biochar having the highest content of organic carbon (41.00%) and C/N ratio (56.16), and the content of total nitrogen from the highest (0.84%) was in cocoa husk biochar. Also, except for Mg and K, where rice straw biochar showed higher values, cocoa husk biochar reached the highest concentration of exchangeable cations. The biochar produced from rice straw had the highest available phosphorus (343.62 mg/kg), followed by biochars from corn and cocoa husk. The nutrient profiles of the agricultural wastes utilized for biochar production possess fertility-enhancing features, and consequently, they could be improved. Biochar made from rice straw had more organic carbon and available phosphorus than the other two feedstocks, while the biochar from cocoa husks had the highest amount of cations that could be exchanged. Therefore, such results made it possible to consider biochar as a sustainable soil fertility and productivity-improving amendment in Ghanaian agriculture.

The study indicated that all the biochars had a very high range of pH values from 10.3 to 10.4, which means they were very alkaline. This was interpreted as having a strong potential for improving the acidic soils that are typical in Ghana's humid forest regions. As per Tomczyk *et al.* (2020) and Pariyar *et al.* (2020), the pH values for biochars derived from alkaline crop residues were similar, and the reason was the build-up of basic cations during the pyrolysis process. The variation in the nutrient composition of the biochars is in accordance with the fact that the feedstock type is the prime factor in determining the quality of biochar. Rice straw biochar, among the various types of biochar, was characterised by the highest concentrations of both organic carbon and available phosphorus, whereas cocoa husk biochar was found to contain the highest levels of exchangeable base cations. These observations are in line with the findings of Alghamdi (2018) and Hale et al. (2020), who noted that nutrient-rich feedstocks yield biochars with significant fertility-enhancing properties. The findings of C/N ratios of biochars, especially in the case of rice straw biochar, were quite high, and they suggested a more stable structure and slower decomposition; hence, the potential for long-term carbon sequestration instead of an immediate nitrogen supply.

Table 1: Chemical composition of biochar prepared from three feedstocks.

Feedstock type	pH (H2O)	%Org. C	% N	C/N ratio	Ca	Mg	K	Na	Avail. P	Exch K
					Cmol kg-l				mg/kg	
Cocoa husk	10.4	36.50	0.84	43.45	18.6	17.09	13.5	4.5	263.31	6431.66
Corn cob	10.3	40.50	0.82	45.40	2.67	7.34	6.75	1.35	300.57	2890.21
Rice straw	10.4	41.00	0.73	56.16	2.14	18.69	16.88	3.15	343.62	3477.58

Table 2: Soil physical and chemical properties of the study site at the Soil Research Institute.

Soil parameter	Value
pH (1:1) (H_2O)	6.10
Organic carbon (%)	0.78
Nitrogen (%)	0.11
Calcium (Cmol Kg^{-l})	5.87
Magnesium (Cmol Kg^{-l})	0.53
Potassium (Cmol Kg^{-l})	0.17
Sodium (Cmol Kg^{-l})	0.10
Total Exchangeable bases (cmol kg-l)	6.67
Exchangeable acidity (Cmol Kg^{-l})	0.15
Effective cation exchange capacity (cmol kg^{-l})	6.82
Base saturation (%)	97.80
Available Bray 1 Phosphorus (mg Kg^{-l})	30.62
Exchangeable Potassium (mg Kg^{-l})	79.02
Zinc (mg Kg^{-l})	41.60
Manganese (mg Kg^{-l})	37.20
Copper (mg Kg^{-l})	101.60
Iron (mg Kg^{-l})	464.20
Textural class	Loam

This correlates with previous studies that recommended the use of biochars produced at high temperatures for aesthetic, recalcitrant, and thus long-term soil conditioning rather than short-term nutrient release (Tomczyk *et al.,* 2020). Consequently, the chemical properties of this study indicate that the agricultural waste locally available in Ghana can be transformed into biochars with different nutrient functions, which will help both the objectives of soil fertility improvement and carbon sequestration.

Initial soil analysis

The initial soil investigation (Table 2) showed that the soil at the study site was loamy in texture, which is a physical condition that can support crop growth because of its water-holding capacity, aeration, and root penetration being in balance. The soil, however, was still a chemically constrained one, having very low organic carbon (0.78%) and total nitrogen (0.11%) contents, plus low levels of exchangeable base cations present. These features denote a low fertility status naturally, and yet the base saturation was high; it was pointing to the prevalence of basic cations over exchangeable acidity rather than an adequate nutrient reserve.

The slightly acid soil pH (6.10) is acceptable for maize production, but under such conditions, the key nutrient availability, mainly phosphorus, may be restricted due to fixation by iron and aluminium oxides, which are prevalent in the tropics with highly weathered soils. This is evidenced by the high concentration of iron that was recorded at the site, which can lead to low phosphorus availability despite moderate Bray-1 levels. The cation exchange capacity (6.82 cmol kg^{-1}) being low means that the soil can hardly hold nutrients; therefore, it gets leached during the wet season, which is characteristic of the humid forest zone.

The limitations in fertility that are seen in these cases are typical of the Ultisols, which are heavily weathered and found in large areas of sub-Saharan Africa. The rainy season, combined with continuous cropping, hastens the nutrient loss and leaching (Batabyal, 2017). As a result, the initial soil conditions, which are poor in nutrients, require the introduction of soil amendments that not only provide the required nutrients but also improve the physical and chemical properties of the soil in such a way that its overall nutrient retention capacity is doubled or even more enhanced. On the other hand, the low initial fertility status sets a perfect ground for the biochar and fertilizer treatments to be evaluated in terms of their impact on maize growth and yield, thus making it easier to tell the agronomic advantages of the interventions that were tested in this study.

Plant height at the 6th week after planting as affected by biochar application rate

There was a significant ($P < 0.0112$) effect of biochar rates on plant height at 6th WAP (Table 3), and increasing biochar rate resulted in corresponding increases in plant height. The 5 t/ha biochar rate recorded the tallest maize height with a 23% increase in plant height, followed by the

Table 3. Effects of biochar rate on maize height at the 6th week.

Br	Height(cm)
0.0t/ha	114.01^{c}
2.5t/ha	125.71^{b}
5t/ha	140.76^{a}
P v	0.0112

Letter superscripts in a column followed by the same letters are not significantly different at p≤0.05.

2.5 t/ha rate with a 10.3% increase in plant height compared to the control. A significant effect of the biochar application rate on the height of maize plants was noticed six weeks after planting (Tables 3). The increase of the biochar rate from 2.5 to 5.0 t ha^{-1} resulted in the same increases in plant height, with 5 t ha^{-1} producing plants 23% taller than the control. Such results closely match the previous findings of Edmunds (2012) and Hale *et al.* (2020), who noticed better early crop development with moderate biochar application rates. The lack of any considerable variation in plant height among the biochar types implies that at early growth stages, application rate is more important than the feedstock source.

Effect of fertilizer rate on plant height and stem girth six weeks after planting

Fertilizer application had a very strong statistically significant effect ($p < 0.0001$) on the height and girth of maize plants six weeks after planting (Table 4). The height of the plants showed a steady increase as the fertilizer rate increased, and the full recommended rate gave the tallest plants (151.06 cm), which is a 26% rise above the unfertilized control. The half rate also marked an 18% increase in height, thus indicating that the supply of nutrients is a major factor in determining early vegetative growth. The increased nitrogen and phosphorus supply were clearly the main reasons for the substantial increase of the response, since one of the main roles that these two nutrients together play in young plants is for the early cell division in the root and shoot plus their photogenic main role of leaf and stem extension and introduction of light capture (Essilfie *et al*., 2024; Chen *et al.,* 2020). In the same way as the plant height, the girth of the stem was also affected by the fertilizers; nevertheless, no considerable difference was observed between the full and half rates. This implies that a moderate application of fertilizers might be just enough to stimulate the growth of the stem during the early stages. The plant with increased girth is more resistant to lodging and can withstand disasters such as strong winds; thus, one of the factors yielding stability (Wang *et al.,* 2025). The results support other recent studies that also observed the height and diameter of maize plants getting significantly better with higher fertilizer rates and that this trend was particularly seen in nutrient-poor tropical soils (Pasley *et al.,* 2020). The equal stem girth of full and half rates indicates the possibility of cutting back on fertilizer use without losing early plant vigour. This situation is very important for smallholder farmers, as they can optimize their fertilizer rates to get the same production with lower costs and at the same time reduce the environmental risks which are associated with the overuse of fertilizer.

Maize yield in the major and minor cropping seasons

The cropping season had a very strong effect on the maize yield components, and the yields of grain, stover, cob, and biomass were all considerably greater during the main season than in the minor season ($P < 0.0001$). Grain yield experienced an upsurge from 0.55 Mg ha^{-1} in the minor season to 5.02 Mg ha^{-1} in the major season, which was a rise of almost tenfold. Stover yield also showed a similar pattern, increasing from 0.70 Mg ha^{-1} in the non-major season up to 5.41 Mg ha^{-1} in the main season (Table 5). Moreover, the major season yield of cobs was 1.20 Mg ha^{-1}, whereas that of the minor season was only 0.20 Mg ha^{-1}; this translated to an increase of 83%. Thus, the total yield of biomass in the major season (11.62 Mg ha^{-1}) was more than eight times that of the minor season (1.45 Mg ha^{-1}).

The major season's harvest index (HI) was significantly higher at 0.42 compared to the minor season's 0.33, indicating that more assimilates were being partitioned towards the production of grain during the good seasonal conditions. The 21% increase in harvest index during the major season suggests that environmental conditions during this time period not only allowed for greater accumulation of biomass but also better reproductive efficiency.

Table 4: Effect of fertilizer rate on plant height and stem girth six weeks after planting.

Fertilizer rate	Height(cm)	Girth(cm)
Full	151.06^{a}	6.1208^{a}
Half	136.78^{b}	5.8667^{a}
No	111.87^{c}	5.3187^{b}
Pv	<.0001	<.0001

Letter superscripts in a column followed by the same letters are not significantly different at p≤0.05.

Table 5: Maize yield in the major and minor cropping seasons.

Season	Grain	Stover	Cob	Total yield	HI
			$Mgha^{-1}$		
Major	5.0205^{a}	5.4070^{a}	1.1954^{a}	11.6229^{a}	0.4213^{a}
Minor	0.5499^{b}	0.6970^{b}	0.2030^{b}	1.4499^{b}	0.3326^{b}
P v	<.0001	<.0001	<.0001	<.0001	0.0001

Letter superscripts in a column followed by the same letters are not significantly different at p≤0.05

The marked seasonal differences in maize yield can basically be attributed to the differences in precipitation pattern, soil moisture availability and temperature, which were characteristic of the two cropping seasons. The major season usually happens to be the period with rain that is not only more but also better distributed in the humid forest zone of Ghana, and this is the area where the nutrients are easily taken in, photosynthesis is very efficient, and grains are also full. In maize-based systems in West Africa, similar seasonal yield patterns have been observed and reported quite extensively. This is because rainfall variability is the primary factor that affects the performance of these crops (Oguntunde *et al.,* 2004; Zhang *et al*., 2024). One of the main points of the current research is that it has quantified the extent of seasonal yield variation very clearly under field conditions. Even with soil amendments, the growing of maize is still very much dependent on seasonal climatic factors; that is what has been proved. Yield, biomass production, and harvest index have been interrelated across major and minor seasons; the research can thus explain the interaction between soil fertility management and seasonal rainfall patterns by making it clear. These results emphasize the need to coordinate the timing of biochar and fertilizer application in such a way that agronomic benefits are maximized. The outcomes also indicate that soil amendments such as biochar might stabilize the yield better during the good seasons, while during the poor minor seasons, additional management interventions might be needed to reduce the yield drop. Taking this seasonal view is particularly relevant as it fills a gap in previous studies on biochar effects, which often ignore the temporal variability in crop response, thus making the current study more credible in the context of climate-resilient maize production in sub-Saharan Africa.

Effect of fertilizer **application on maize yield**

The results showed that the full fertilizer rate produced grain, stover, cob and total yields which were significantly higher than the control but are statistically similar to the half fertilizer rate (Table 6). The grain yield obtained for the full fertilizer rate was not significantly different from the grain yield produced by the half fertilizer rate, although there was a 15% drop in grain yield when fertilizer was reduced by half. There was a significant increase in grain yield due to fertilizer application (both full and half rates) over the control, with the full fertilizer rate increasing grain yield by more than 46% and the half fertilizer rate by 37%. A similar trend was observed with cob yield, with full fertilizer rate producing 42% and half fertilizer rate producing 30% cob yield, more than the control. Reduction in fertilizer application by half reduced stover yield by about 18%, which was not significantly different from the stover yield produced by the full fertilizer rate. However, full fertilizer application increased stover yield by 34% compared with the control. There was a significant influence of fertilizer application at all levels on total biomass yield, with the full fertilizer rate producing more than 16% total biomass yield higher than the half rate. Full fertilizer and half fertilizer rates total biomass yield were increased by 40% and 28%, respectively, compared to the control. Half-rate fertilizer application gave the highest harvest index, which falls within the normal range of 0.4 to 0.6, with about 5.7% higher compared to the full rate and 16% higher compared to the control. Full fertilizer application rate and control had harvest index not statistically different, which were below the recommended range, although the full fertilizer rate gave a harvest index higher than the control.

Table 6: Effect of fertilizer application on maize yield.

F rate	Grain	Stover $Mgha^{-1}$	Cob	Total yield	HI
Full	3.5045^{a}	3.7014^{a}	0.8692^{a}	8.0752^{a}	0.3838^{ab}
Half	2.9799^{a}	3.0059^{ab}	0.7253^{a}	6.7111^{b}	0.4071^{a}
No	1.8713^{b}	2.4486^{b}	0.5030^{b}	4.8229^{c}	0.3400^{b}
P v	<.0001	0.0025	<.0001	<.0001	0.0457

Letter superscripts in a column followed by the same letters are not significantly different at p≤0.05

Fertilizer application was a decisive factor in increasing maize yield components compared to the control (Table 6). The full fertilizer rate gave the highest volumes of grains and total biomass, but these were not statistically different from the yields produced with the half fertilizer rate. This suggests that if fertilizer usage is reduced to half, one can still achieve good yields, especially if the soil has been improved through the use of organic amendments.

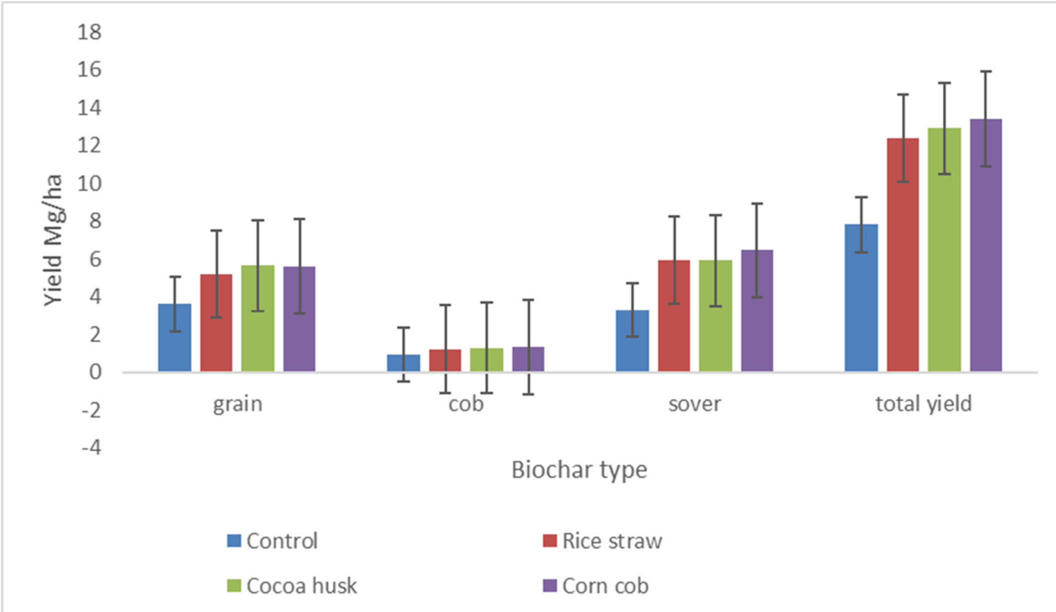

Figure 1: *Effect of biochar types on grain, stover, cob and total yields. Error bars represent the standard error of the mean.*

Similar results have been reported by Calys-Tagoe *et al.* (2019), who pointed out that integrated soil fertility management strategies can parametrise dependence on high fertilizer inputs and at the same time sustain yield.

Effect of biochar type on maize yield

Application of biochar significantly increased the yields of maize grain, stover, cob, and total biomass compared to the control treatment (Figure 1), which indicates that the biochar amendment improved the overall productivity of the crop under the low-fertility soil conditions of the study site. The increase in yield is an indication that the application of biochar has lifted soil chemical conditions and nutrient availability, and possibly also enhanced soil physical properties such as water retention and aeration, which are essential for maize in the highly weathered tropical soils. Even though the control treatment was outperformed by all the treatments with biochar, the yields obtained with the various biochar types corn cob, rice straw, and cocoa pod husk were not statistically different from each other. This means that, although there were differences in chemical composition among the biochars, their short-term effects on the maize yield were functionally similar. Similar yield responses among the different feedstocks used for biochar production were reported by Chan *et al.* (2008) and Edmunds (2012). They said the different organic residues resulted in similar crop yield responses when applied at moderate rates under field conditions; thus, the main contributor to the yield increase observed was not nutrient addition from specific feedstocks but rather the improvement in soil conditions. The short period of the experiment could be one of the factors contributing to the minor difference in yield between the different types of biochar. Nutrient differences among the feedstocks were revealed in the chemical analysis, where rice straw biochar had the highest phosphorus content and cocoa husk biochar had the highest exchangeable cations content. However, such differences in nutrient availability may have a greater impact when higher application rates typical of longer time periods are used or when nutrient availability in the soil is low. This is consistent with the observations made by Hale *et al.* (2020), who stated that climate conditions and feedstock effects on crop performance become more evident in multi-season or long-term trials as the biochar interacts with the soil processes over time.
One of the major outcomes of the current research is that it has shown that the agricultural wastes that are ecologically very friendly in Ghana, such as corn cobs, rice straws, and cocoa pods, can be used to produce biochar to the same extent and make the same positive impacts on maize yield. This assertion is new and fresh in the Ghanaian environment, where comparative studies done in multi-field areas about biochar feedstock are rare. The implications of the study are quite favourable, as the sellers of biochar and farmers do not have to depend on one specific feedstock but can go for the most accessible residue, thus making biochar more adoptable through its practicality and scalability. Additionally, the comparability

of biochar types found in this research work is a strong reason for the adoption of biochar in the Integrated Soil Fertility Management systems as a local and flexible soil amendment. Through the output of this research, which shows the yield benefits regardless of the type of feedstock, a large gap that was made by earlier studies, which were mostly focused on a single biochar source or laboratory experiments, has been bridged and provided field-level evidence that applies to smallholder farming systems in sub-Saharan Africa.

Effect of biochar rate on grain and cob yields

The response of maize grain and cob yields to biochar application rate was significant at $P < 0.05$; the higher the biochar rates, the higher the yields in general (Figure 2). When the biochar was not applied, the grain yield was up by 32.89%, and the cob yield was up by 58% at 5 t ha^{-1}, thus showing a strong positive yield response to biochar application. The 2.5 t ha^{-1} rate also resulted in higher yields compared to the control, but this was less pronounced, indicating that the response of the maize yield to biochar addition is indeed dose-dependent. The increase in yield that was associated with higher biochar rates was an indication that the largest biochar amounts had the effect of soil nutrient retention enhancement, cation exchange capacity, and water-holding capacity, thereby making nutrients available to maize during the critical growth stages. Chan *et al.* (2008) and Major *et al.* (2010) also provided similar reports about the yield

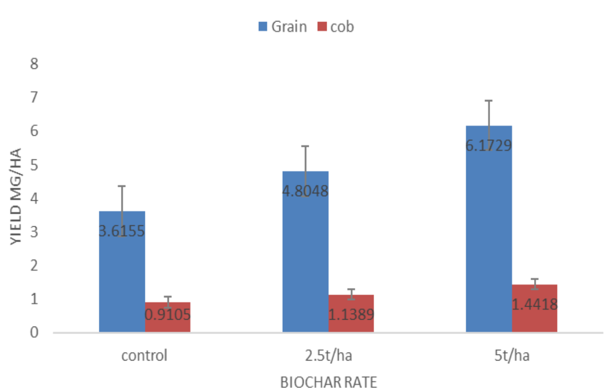

Figure 2: *Effect of different biochar rates on grain and cob yields. Error bars represent the standard error of the mean.*

responses to biochar being dependent on its dosages. They indicated application rates of 2-10 t ha^{-1} with major yield increases in tropical soils for maize and other cereals. The pronounced effect of the yield of cob over that of grain indicates that biochar treatment could have boosted the partitioning of the assimilates and the development of the reproductive organs, most likely through the improved nutrient and moisture availability. The absence of yield saturation at 5 t ha^{-1} implies that the rate was still within the optimum threshold for the maize crop under the soil and climatic conditions of the study area. On the other hand, some studies have reported a decrease or neutral yield responses even at much higher biochar rates (>20 t ha^{-1}), which has been explained by nutrient immobilization or changes in soil physical conditions (Hale *et al.,* 2020). The findings of this study, therefore, favour the use of moderate biochar rates that would be agronomically effective and economically viable for smallholder farmers. One of the most important aspects of this study is the measurement of the yield increases due to the biochar application rates that are legitimate under field conditions in Ghana. The paper, by showing 5 t ha^{-1}, gives a very practical argument that moderate biochar rates will considerably increase the maize production with no need to use high biomass inputs. Moreover, such a strong dose-response relationship allows researchers to consider biochar as a component of integrated soil fertility management practices, thus helping them to improve nutrient use efficiency and crop performance in low-fertility tropical soils.

Contribution to knowledge

The contribution of the present study is to systematically evaluate the nutrient characteristics of biochar produced from locally available agricultural wastes and their effects on maize growth and yield under field conditions in Ghana. The study generates comparative field-based evidence on different biochar feedstocks and their application rates, whereas most of the earlier studies restricted themselves to either a single feedstock or laboratory-scale trials. The study, by linking biochar chemical properties (Table 1) to soil fertility status (Table 2), crop growth responses (Tables 3-4), and yield outcomes across seasons (Tables 5–6, Figures 1–2), has filled up a significant gap in the literature concerning the agronomic performance of locally produced biochars in Ghanaian farming systems.

Key findings and implications

Overall, the findings suggest that the biochar produced from corn cobs, rice straw, and cocoa pod husks are effective soil amendment and, as such, can be used in low-fertility plantations of maize for better growth and yield. The application rate turned out to be of greater influence on crop response than the type of feedstock in the short run. Besides, it was found that if the fertilizers are optimized and moderate amounts of biochar are applied, it will result in greater nutrient use efficiency and eventually support sustainable maize production. Thus, these results add to the already large cross-section of evidence that is increasingly backing biochar-based integrated soil fertility management as a climate-smart option for sub-Saharan African smallholder farming.

Conclusion

The study reveals that biochars made from agricultural waste have different and beneficial chemical properties that can be used for soil amendment in Ghana. The biochars from all sources were very alkaline (pH 10.3–10.4). That meant that these biochars were capable of ameliorating the acidic Ultisols. On the other hand, rice straw biochar had the largest amount of organic carbon and available phosphorus among the three sources, while cocoa husk biochar had the highest exchangeable base cations. These attributes characterise the biochars in question as having the potential to enhance nutrient availability and soil quality chemically.

Soil analysis at the start of the project indicated very small quantities of organic carbon, total nitrogen and exchangeable cations. This confirmed the study area's very low fertility status. Under the given conditions, the application of biochar resulted in a significant increase in the growth and yields of maize. On the other hand, the application rate of biochar had a stronger impact on crop performance than the type of feedstock used in the short term. Application of biochar at 5 t ha^{-1} led to the rise of heights and yields of grains and cobs, and also to the increase of grain and cob yields by 32.9% and 58%, respectively, when compared to the control. All types of biochar gave a similar response in terms of yields, indicating that they are functionally equivalent even though they differ in nutrient composition.

Seasonal factors played a major role in determining the productivity of maize, and the major cropping season gave rise to considerably greater values of grain, biomass, and harvest index as compared to the minor season. This underscores the basic dependence of the climatic factors, specifically the distribution of rainfall, in determining the yield of maize even under the conditions of soil amendments. The use of fertilizers did improve the yield, but the yield obtained with half of the recommended fertilizer was the same as that of the full rate statistically, indicating better nutrient use efficiency under integrated management. The study achieved its aims, as it characterized the properties of biochar nutrients, quantified their effects on maize growth and yield, and proved that moderate rates of biochar application can boost production in the low-fertility tropical soils. The results offer evidence based on the field that the biochars produced locally can be effective components of Integrated Soil Fertility Management Systems in Ghana.

Recommendations

(i) It is recommended that the agricultural extension officers should encourage the adoption of biochar from locally available residues (cocoa pod husk, rice straw and corn cob) at an application rate of around 5 tonnes per hectare for maize cultivation on low-fertility soils.

(ii) Biochar should be a part of Integrated Soil Fertility Management (ISFM) schemes, and thus its use should be considered along with the inorganic one. On the other hand, fertilizer recommendations should be modified in such a way that lower rates of fertilizer will be allowed when biochar is applied, especially in the case of small-scale farmers who lack resources.

(iii) Training programmes should be organized for personnel on safe pyrolysis methods and quality control to make sure that the biochar produced is effective in agriculture.

REFERENCES

Abbas A, Naveed M, Shehzad Khan K, Ashraf M, Siddiqui MH, Abbas N, Mustafa A and Ali L (2024) The Efficacy of Organic Amendments on Maize Productivity, Soil Properties and Active Fractions of Soil Carbon in Organic-Matter Deficient Soil. Span. *J. Soil Sci. 14*:12814. doi: 10.3389/sjss.2024.12814

Adjei, V., & Kwantwi, L. (2019). Maize and cashew farming in the face of climate change variability in the transitional zone of Ghana: A case study of Nkoranza South Municipality. *American Journal of Environmental Sciences, 15*, 82–89. https://doi.org/10.3844/ajessp.2019.82.89

Afshar, M., & Mofatteh, S. (2024). Biochar for a sustainable future: Environmentally friendly production and diverse applications. *Results in Engineering, 23*, 102433. https://doi.org/10.1016/j.rineng.2024.102433

Alghamdi, A.G. (2018). Biochar as a potential soil additive for improving soil physical properties—a review. *Arab J Geosci* 11, 766 https://doi.org/10.1007/s12517-018-4056-7

Antonangelo, J. A., Sun, X., & Zhang, H. (2021). The roles of co-composted biochar (COMBI) in improving soil quality, crop productivity, and toxic metal amelioration. *Journal of Environmental Management, 277*, 111443. https://doi.org/10.1016/j.jenvman.2020.111443

Batabyal, K. (2017). Nutrient Management for Improving Crop, Soil, and Environmental Quality. In: Naeem, M., Ansari, A., Gill, S. (eds) Essential Plant Nutrients. Springer, Cham. https://doi.org/10.1007/978-3-319-58841-4_18

Braimoh, A. K., & Vlek, P. LpG (2006) Soil quality and other factors influencing maize yield in northern Ghana. Soil Use Manage 22:165–171.

Calys-Tagoe, E., Sadick, A., Yeboah, E., and Amoah, B. (2019). Biochar effect on maize yield in selected farmers' fields in the northern and upper east regions of Ghana. *J. Exp. Agric. Int.* 30, 1–9. doi:10.9734/jeai/2019/44168

Chan K., Van Zwieten L., Meszaros I., Downie A. and Joseph S. (2008) Using poultry litter biochars as soil amendments. *Soil Research* 46(5), 437-444.

Chen, Y. L., Zhang, P. P., Wang, L. F., Ma, G., Li, Z., Wang, C. Y. (2020). Interaction of nitrogen and phosphorus on wheat yield, N use efficiency and soil nitrate nitrogen distribution in the North China plain. *Int. J. Plant Prod. 14,* 415–426. doi: 10.1007/s42106-020-00093-6

Edmunds C.W. (2012) The effects of biochar amendment to soil on bioenergy crop yield and biomass composition.

Essilfie ME, Darkwa K, Asamoah V. (2024) Growth and yield response of maize to integrated nutrient management of chicken manure and inorganic fertilizer in different agroecological zones. *Heliyon.* Jul 18;1*0(*14):e34830. doi: 10.1016/j.heliyon.2024.e34830. PMID: 39149013; PMCID: PMC11325770.

Hale, S. E., Nurida, N. L., Jubaedah, J., Mulder, J., Sørmo, E., Silvani, L., Abiven, S., Joseph, S., Taherymoosavi, S., & Cornelissen, G. (2020). The effect of biochar, lime, and ash on maize yield in a long-term field trial in an Ultisol in the humid tropics. *Science of The Total Environment, 719*, 137455. https://doi.org/10.1016/j.scitotenv.2020.137455

Hossain, M.Z., Bahar, M.M., Sarkar, B. *et al.* (2020). Biochar and its importance on nutrient dynamics in soil and plant. *Biochar* 2, 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

Jin, X., Zhang, T., Hou, Y. *et al.* (2024). Review on the effects of biochar amendment on soil microorganisms and enzyme activity. *J Soils Sediments* 24, 2599–2612 https://doi.org/10.1007/s11368-024-03841-7

Karer J., Wimmer B., Zehetner F., Kloss S. and Soja G. (2013) Biochar application to temperate soils: effects on nutrient uptake and crop yield under field conditions. *Agricultural and Food Science* 22(4), 390-403.

Kugedera, A. T., Badza, T., & Odindo, A. O. (2023). Integrated soil fertility management practices for improved crop production in smallholder farming systems of semi-arid areas: A synthetic review. *Cogent Food & Agriculture*, *9*(1). https://doi.org/10.1080/23311932.2023.2256137

Kumar, A., & Bhattacharya, T. (2021). Biochar: a sustainable solution. *Environ Dev Sustain* 23, 6642–6680. https://doi.org/10.1007/s10668-020-00970-0

Lehmann, J., & Joseph, S. (Eds.). (2015). *Biochar for environmental management: Science, technology and implementation* (2nd ed.). Routledge..

Liang F., LI G.-t., LIN Q.-m. and ZHAO X.-r. (2014) Crop yield and soil properties in the first 3 years after biochar application to a calcareous soil. *Journal of Integrative Agriculture* 13(3), 525-532.

Major J., Rondon M., Molina D., Riha S.J. and Lehmann J. (2010b) Maize yield and nutrition during 4 years after biochar application to a Colombian savanna oxisol. *Plant and Soil* 333(1-2), 117-128.

Matsagar, B. M., & Wu, K. C.-W. (2022). Agricultural waste-derived biochar for environmental management. In D. C. W. Tsang & Y. S. Ok (Eds.), *Biochar in agriculture for achieving sustainable development goals* (pp. 3–13). Academic Press. https://doi.org/10.1016/B978-0-323-85343-9.00026-4.

Mugwe, J., Ngetich, F., Otieno, E.O. (2019). Integrated Soil Fertility Management in Sub-Saharan Africa: Evolving Paradigms Toward Integration. In: Leal Filho, W., Azul, A., Brandli, L., Özuyar, P., Wall, T. (eds) Zero Hunger. Encyclopedia of the UN Sustainable Development Goals. Springer, Cham. https://doi.org/10.1007/978-3-319-69626-3_71-1

National Development Planning Commission. (2024). 2024 *National Annual Progress Report.* Accra, Ghana: NDPC.

Ngo Ndoung, O. C., de Figueiredo, C. C., & Ramos, M. L. G. (2021). A scoping review on biochar-based fertilizers: Enrichment techniques and agro-environmental application. *Heliyon, 7(12)*, e08473. https://doi.org/10.1016/j.heliyon.2021.e08473

Niraj K.C. and Bhimsen Mahat (2024). A Review Article on The Effect of Biochar on Soil Properties. Journal of Wastes and Biomass Management, 6(2): 77-81.

Oguntunde P.G., Fosu M., Ajayi A.E. and Van De Giesen N. (2004) Effects of charcoal production on maize yield, chemical properties and texture of soil. *Biology and fertility of soils* 39(4), 295-299.

Pariyar, P., Kumari, K., Jain, M. K., & Jadhao, P. S. (2020). Evaluation of change in biochar properties derived from different feedstock and pyrolysis temperatures for environmental and agricultural applications. *Science of The Total Environment, 713*, 136433. https://doi.org/10.1016/j.scitotenv.2019.136433

Pasley, H.R., Camberato, J.J., Cairns, J.E. (2020). Nitrogen rate impacts on tropical maize nitrogen use efficiency and soil nitrogen depletion in eastern and southern Africa. *Nutr Cycl Agroecosyst* 116, 397–408 . https://doi.org/10.1007/s10705-020-10049-x

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

Paul, E. A. (2016). The nature and dynamics of soil organic matter: Plant inputs, microbial transformations, and organic matter stabilization. *Soil Biology and Biochemistry, 98*, 109–126. https://doi.org/10.1016/j.soilbio.2016.04.001

Policastro, G., & Cesaro, A. (2022). Composting of Organic Solid Waste of Municipal Origin: The Role of Research in Enhancing Its Sustainability. *International journal of environmental research and public health*, *20*(1), 312. https://doi.org/10.3390/ijerph20010312

Rafique M, Ortas I, Rizwan M, Chaudhary HJ, Gurmani AR, Munis MFH (2020), Residual effects of biochar and phosphorus on growth and nutrient accumulation by maize (Zea mays. L) amended with microbes in texturally different soils. Chemosphere. https://doi.org/10.1016/j.chemosphere.2019.124

Raimi, A., Adeleke, R., & Roopnarain, A. (2017). Soil fertility challenges and Biofertilizer as a viable alternative for increasing smallholder farmer crop productivity in sub-Saharan Africa. *Cogent Food & Agriculture*, *3*(1). https://doi.org/10.1080/23311932.2017.1400933

Schulz, H., Dunst, G., & Glaser, B. (2014). No effect level of co-composted biochar on plant growth and soil properties in a greenhouse experiment. Agronomy, 4(1), 34-51.

Shu, X., He, J., Zhou, Z., Xia, L., Hu, Y., Zhang, Y., Zhang, Y., Luo, Y., Chu, H., Liu, W., Yuan, S., Gao, X., & Wang, C. (2022). Organic amendments enhance soil microbial diversity, microbial functionality, and crop yields: A meta-analysis. *Science of The Total Environment, 829*, 154627. https://doi.org/10.1016/j.scitotenv.2022.154627

Telo da Gama, J. (2023). The Role of Soils in Sustainability, Climate Change, and Ecosystem Services: Challenges and Opportunities. *Ecologies*, *4*(3), 552-567. https://doi.org/10.3390/ecologies4030036

Teressa, D., Kibret, K., Dechasa, N., & Wogi, L. (2024). *Soil properties and nutrient uptake of maize (Zea mays) as influenced by mixed manure and blended inorganic fertilizer in Haramaya district, eastern Ethiopia*. *Heliyon, 10*(16), e35784. https://doi.org/10.1016/j.heliyon.2024.e35784

Tomczyk, A., Sokołowska, Z. & Boguta, P. (2020). Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects. *Rev Environ Sci Biotechnol* 19, 191–215 https://doi.org/10.1007/s11157-020-09523-3

United States Department of Agriculture (USDA). (2024). *Ghana cocoa sector overview*. *Foreign Agricultural Service.* Available at: https://www.fas.usda.gov

Wang, N., Zhang, T., Li, Y., Cong, A., Lian, J., & Feng, K. (2025). *Integrated application of fertilization increased maize (Zea mays L.) yield by improving soil quality, particularly under limited water conditions in a semi-arid sandy area*. *Agricultural Water Management, 309*, 109334. https://doi.org/10.1016/j.agwat.2025.109334

Yuan, X., Li, S., Chen, J., Yu, H., Yang, T., Wang, C., Huang, S., Chen, H., & Ao, X. (2024). Impacts of Global Climate Change on Agricultural Production: A Comprehensive Review. *Agronomy*, *14*(7), 1360. https://doi.org/10.3390/agronomy14071360

Zhang, X.G., Abdul Raman, A.A., Jewaratnam, J. (2024). Sustainable carbon dioxide capture, storage, and utilization: review of current status and future direction. *Int. J. Environ. Sci. Technol.* https://doi.org/10.1007/s13762-024-05908-x

Zhu, X., Liu, W., Chen, J. *et al.* (2020). Reductions in water, soil and nutrient losses and pesticide pollution in agroforestry practices: a review of evidence and processes. *Plant Soil* 453, 45–86 https://doi.org/10.1007/s11104-019-04377-3.