Research article

An investigation of the effect of biochar application rates on CO2 emissions in soils under upland rice production in southern Guinea Savannah of Nigeria

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ABSTRACT

Biochar is a chemically recalcitrant carbon-rich solid material used in soil for its potential to improve soil quality and sequester carbon. While the rate of application has implications for soil carbon dioxide (CO2) emission and the overall benefits of biochar, its effects are yet to be fully understood. To evaluate the effect of application rates of rice husk biochar on CO2 emissions, 91-day field experiments were conducted on three soil types (Anthraquic Ustorthent, Grossarenic Kandiustalf, and Ustic Quartzipsamment) in the southern Guinea Savannah of Nigeria, using three biochar application rates of 5, 15 and 25 t ha\(^{-1}\), and control.

A two-way ANOVA showed that cumulative CO2 emissions were significantly (\(p < 0.01\)) different between soil types and treatments, and soil type/treatment interactions were also significant at \(p = 0.05\). The highest cumulative CO2-C emission of 2.77 g/m\(^2\) was recorded in the Grossarenic Kandiustalf, while the least value of 2.11 g/m\(^2\) was recorded in the Ustic Quartzipsamment. CO2 emission increased with increasing biochar application rates, with the highest (3.06 CO2-C g/m\(^2\)) value recorded at 25 t/ha compared to 2.78 g/m\(^2\) and 1.52 g/m\(^2\) values recorded for 5 t/ha and control treatments respectively. While CO2 emissions increased with biochar application rate however, the percentage of biochar-C mineralized was higher at lower biochar rates, and differences were significant at \(p = 0.01\). While 0.63 % of biochar C was mineralized under 5 t/ha biochar treatment, 0.15 % was recorded for 25 t/ha treatment. Factors that had significant correlation with CO2-C emission in the soils were biochar addition rate, soil pH, N, P, Ca, Mg and K. At day 91, there were no significant differences in CO2 emissions between amended treatments and control, and only a small percentage (<1) of biochar C had been mineralized.

1. Introduction

Biochar is a chemically recalcitrant carbon-rich solid material produced by heating biomass in an oxygen-limited environment (Ok et al., 2015). It has been widely promoted as a sustainable strategy for improving soil quality and fertility (El-Naggar et al., 2018), carbon sequestration and climate change mitigation (Paustian et al., 2016; El-Naggar et al., 2018) reduction of greenhouse gas (GHG) emissions (Kuzyakov et al., 2014), and numerous other environmental applications (El-Naggar et al., 2019; Huang et al., 2019).

In a meta-analysis, Wang et al. (2016) showed that biochar application could stimulate soil CO2 emissions by as much as 28–32 %, but this effect is generally not direct due to varied soil and biochar types. Wide varying GHGs emission responses have been reported in soils, following biochar amendment in previous research both under laboratory and field conditions. This include increase, decrease and neutral effects (Novak et al., 2010; Scheer et al., 2011; Wang et al., 2014). As biochar is a complex material with wide varying properties resulting from many possible feedstock types, production conditions (Solaiman and Anawar, 2015; Shaheen et al., 2018), and the environment it is applied to, which all influence its action in soil (Butnan et al., 2015; Lehmann and Joseph, 2015), no generalized application rates are applicable for its use in soils, and suitable biochar types are recommended in consideration of site-specific conditions Abiven et al. (2014). Due to this, wide varying rates have been used in research ranging from <5 t/ha to >100 t/ha.

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While the effect of biochar and soil properties on its actions in soils (including GHGs emissions) such as feedstock type, biochar aging, soil mineralogy and texture have been extensively studied (Kloss et al., 2014; Butnan et al., 2015), there is still a lack of full understanding on the effect of its application rates on CO2 emission responses in soils. The effective use of biochar as a C sequestration tool to offset rising atmospheric CO2 concentrations depends on all influential factors relating to its reaction in soil, and makes research on the effect of application rates vital. This is especially important before biochar use in soil can be applied on a wide scale, as indications from its promotion worldwide suggest (Park et al., 2017; Rizwan et al., 2016).

This study hypothesizes that biochar-C short-term degradation and resultant CO2 emission will differ in different soil types, and more emissions is expected at higher application rates. The objectives of this study therefore were to evaluate the effect of rice husk biochar application rates on CO2 emissions in three soil types in southern Guinea Savanna of Nigeria, and determine what soil factors contribute to the immediate (short term) degradation of biochar-C in the 90-day field study.

2. Materials and methods

2.1. The study area and soils

The research was conducted in the southern Guinea Savannah axis of Kwara State in Nigeria. Geographically, the state is located between latitudes 7° 55’ and 10° 05’ North of the Equator, and longitudes 2° 45’ and 6° 15’ East of the Greenwich Meridian. The climate is tropical, with double rainfall maxima (tropical wet and dry climate). The rainy season lasts for about 6 months between May and November, with a short break in August. The other part of the year represents the dry season.

Atmospheric temperature is uniformly high, and range between 25 and 30 °C throughout the wet season except in July and August when cloudy skies prevents direct insolation. According to the Federal Department of Agricultural Land Resources (FDALR) (1990) soil map of Nigeria, Kwara state soils are predominantly formed from metamorphic and igneous basement complex rocks (95 %). The other 5 % are formed from sedimentary rocks and recent alluvium majorly along the Niger River bank. Major metamorphic rocks found in the state are granitic gneiss, biotite gneiss, quartzite, augite gneiss and banded gneiss (Olaniyan, 2003).

2.2. Soil survey and soil characterization

Free survey aided by aerial photographs and ground evidence were carried out in three locations (Ilorin, Shonga and Patigi) within Kwara state. Soil examination was done at each location using an orchard auger, and soil samples were described morphologically in situ following United States Department of Agriculture (USDA) Soil Survey Staff Guidelines (2017). Profile pits were dug on selected soils, characterized, and classified according to USDA Soil Survey Staff (2014) guidelines.

Soils were labelled IS (Ilorin), SS (Shonga) and PS (Patigi). The experimental site at Ilorin was located at approximately 8° 27′ 3.43″N, 4° 39′ 30.45″E; Shonga at 9° 0′ 45.37″N, 5° 10′ 21.61″E; and Patigi site at 8° 43′ 3.31″N, 5° 47′ 48.01″E as shown in Figure 1. The morphological, physical and chemical properties of test soils are presented in Tables 1, 2, and 3 respectively. Based on the measured soil properties, soils IS, SS and PS were classified at the sub-Group level as Anthraquic Ustorthent, Grossarenic Kandiustalf, and Ustic Quartzipsamment respectively.

2.3. Biochar production and analysis

Biochar used in the study was produced from rice husk sourced from a local rice mill in Ilorin, and pyrolyzed at ~ 350 °C using a biomass-powered stainless-steel mini reactor at the Mechanical Engineering Department of University of Ibadan, Nigeria. The process occurred at an estimated heating rate of 10 °C/min, and a minimum resident time of three hours to allow sufficient time for complete pyrolysis. Biochar was air-dried, pulverized and sieved using a <2 mm mesh sieve before it was subjected to laboratory analysis in triplicate samples. Proximate analysis of biochar was conducted according to ASTM standards (moisture content: ASTM E871-82, volatile matter: ASTM E872-82, ash: ASTM D1102-84 and fixed carbon: calculated by difference). Ultimate analysis for C, H, and N contents was done using an elemental analyzer (EA-1108 CHNS-O Element Analyzer), and O content determined by difference. Total P, Na, K, Ca and Mg were determined using the modified dry-ash method following a wet digestion according to Enders and Lehmann (2012). Analyses results are presented in Table 4.

2.4. Experimental set-up

Field experiments were conducted between July and October, 2017 using three (3) biochar treatment rates of 5, 15 and 25 t/ha denoted as B5, B15 and B25 respectively, while the control (B0) treatment had no...
### Table 1. Morphological properties of modal Soil profiles.

| Pedon Design. | Horizon Depth (cm) | Colour (moist) | Texture + | Structure ++ | Mottles +++ | Drainage *** | Boundary ** | Consistence * | Artifacts | Roots* | Landform/topography (elevation (m ASL)) |
|---------------|-------------------|---------------|-----------|--------------|------------|--------------|-------------|--------------|-----------|-------|---------------------------------------|
| IS            | IS A1 0-8 10 YR 2/2 (very dark brown) | Sandy Mo,fr,ct | F,md,cl | II | d,g | m,fr;w,nt,npl | A | C, vfi | Plain (314) |
|               | IS A2 8-22 10 YR 3/2 (dark brown) | Sandy Mo,f,pl | N | III | d,s | m,fr;w,nt,npl | A | F, fi |
|               | IS A3 22-30 10 YR 3/6 (dark yellowish brown) | Fine sandy Mo,f,pl | N | III | s,c | m,fi;w,nt,npl | A | Vf,md |
|               | IS Bw1 30-45 10 YR 3/6 (dark yellowish brown) | Fine sandy Mo,m,sab | A,md,cl | II | d,c | m,fr;w,nt,npl | A | Vf,md |
|               | IS Bw2 45-60 10 YR 3/4 (dark yellowish brown) | Loamy Mo,m,sab | m,md,D | II | s,c | m,fr;w,nt,npl | A | Vf,co |
|               | IS Bw3 60-100 10 YR 4/4 (dark yellowish brown) | Clayey Mo, s, sab | c,co,D | II | d,c | m,fr;w,nt,npl | A | Vf,co |
|               | IS Bw4 100-140 10 YR 3/4 (dark yellowish brown) | Loamy Mo,c,sab | f,co,D | II | m,c | m,fr;w,nt,npl | A | A |
|               | SS Apu 0-40 5 YR 5/3 (reddish brown) | Fine sandy We,f,sab | N | III | c,g | m,fi;w,nst,npl | A | M, vfi/co |
|               | SS Bw1 40-100 7.5 YR 7/4 (pink) | Fine sandy We,f,sab | F,md,cl | II | c,g | m,fi;w,nst,npl | A | M,fi/co |
|               | SS Bw2 100-150 7.5 YR 7/4 (pink) | Fine sandy We,f,sab | F,md,cl | II | c,g | m,fi;w,nst,npl | A | F,co |
|               | PS Ap 0-25 5YR 3/1 (very dark grey) | Loamy We,f,sab | N | III | c,w | m,fr;w,nst,npl | A | C, vfi |
|               | PS Bw1 25-60 5 YR 6/4 (light reddish brown) | Fine sandy We,f,sab | N | III | s,g | m,fi;w,nst,npl | A | Vf,fi |
|               | PS Bw2 60-165 5 YR 6/8 (reddish yellow) | Silty We,f,sab | N | III | s,g | m,fr;w,sst,npl | A | Vf,fi |

**DESCRIPTION KEYS:** Texture +: b = boulder; s = stony; g = gravelly; cs = coarse sandy; fs = fine sandy; sl = silty; cl = clayey; l = loamy; Structure ++: we = weak; st = strong; mo = moderate; ms = medium to strong; wm = weak to moderate; c = coarse; f = fine; g = granular; cr = crumbs; sg = single grained; pl = platy; sab = sub-angular blocky; ab = angular blocky. Mottles +++: n = none; f = few; v = very few; c = common; a = abundant; m = many; vfi = very fine; fi = fine; md = medium; co = coarse; fa = faint; d = distinct; p = prominent; s = sharp; cl = clear; d = diffuse. Consistence *: m = moist; w = wet; l = loose; fr = friable; f = firm; c = crumbly; st = strong; stt = slightly sticky; spt = slightly plastic; s = sticky; p = plastic; nst = non-sticky; npl = non plastic; Boundary **: c = clear; d = diffuse; s = smooth; g = gradual; w = wavy; di = breakage (Discontinuous); Drainage ***: I = swamp; II = poorly drained; III = well drained. Artifacts *: P = Present; A = Absent; Roots*: F = Few; Vf = Very few; C = Common, M = Many; vfi = Very fine; fi = Fine; md = Medium; co = Coarse, A = Absent.

### Table 2. Physical properties of modal soil profiles.

| Pedon designation | Horizon Depth (cm) | Gravel % | Sand % | Silt % | Clay % | Textural Class | Bulk Density (g/cm³) | Total Porosity | Water Holding Capacity (%) |
|-------------------|-------------------|----------|--------|--------|--------|----------------|----------------------|----------------|-----------------------------|
| IS                | IS A1 0-8         | 2.12     | 66.24  | 26.00  | 7.760  | Sandy loam     | 1.51                 | 0.09           | 27.23                       |
|                   | IS A2 8-22        | 3.17     | 64.24  | 28.00  | 7.760  | Sandy loam     | 1.50                 | 0.12           | ND                          |
|                   | IS A3 22-30       | 1.02     | 70.24  | 22.00  | 7.760  | Sandy loam     | 1.56                 | 0.13           | ND                          |
|                   | IS Bw1 30-45      | 6.46     | 64.24  | 24.00  | 11.76  | Sandy loam     | 1.60                 | 0.17           | ND                          |
|                   | IS Bw2 45-60      | 13.7     | 62.24  | 15.84  | 21.92  | Sandy clay loam| 1.62                 | 0.04           | ND                          |
|                   | IS Bw3 60-100     | 17.2     | 56.48  | 17.76  | 25.76  | Sandy clay loam| 1.61                 | 0.61           | ND                          |
|                   | IS Bw4 100-140    | 10.2     | 64.08  | 15.16  | 20.76  | Sandy clay loam| 1.61                 | 0.52           | ND                          |
| SS                | SS Apu 0-40       | 2.15     | 84.24  | 5.00   | 10.76  | Loamy sand     | 1.13                 | 0.15           | 25.0                        |
|                   | SS Bw1 40-100     | 3.08     | 72.24  | 8.00   | 19.76  | Sandy loam     | 1.06                 | 0.17           | ND                          |
|                   | SS Bw2 100-150    | 1.85     | 58.24  | 6.00   | 35.76  | Sandy clay loam| 1.28                 | 0.06           | ND                          |
| PS                | PS Ap 0-25        | 6.11     | 75.24  | 17.0   | 7.760  | Sandy loam     | 0.46                 | 0.12           | 28.79                       |
|                   | PS Bw1 25-60      | 4.22     | 73.28  | 16.0   | 10.76  | Sandy loam     | 0.68                 | 0.61           | ND                          |
|                   | PS Bw2 60-165     | 3.24     | 51.44  | 14.0   | 34.76  | Sandy clay loam| 1.32                 | 0.04           | ND                          |

ND = not determined.
biochar amendment. Treatments were replicated thrice. Treatment plots of 5 × 5 m separated by a 1 m alley were laid out in completely randomized design (CRD) at each location. NPK 15:15:15 fertilizer was applied to all treatments, pre-emergence at 200 kg/ha by broadcasting followed incorporation into the soil using a hoe. Biochar was also applied pre-planting to a depth of ∼20 cm. Urea (NH₄)₂CO) was applied at 108.69 kg/ha in 2 equal splits at 21 and 45 days after planting (DAP). NERICA 8 upland rice was planted by dibbling 4 seeds/hill, to a depth of 2–3 cm at 20 × 20 cm spacing, and stands were thinned to 2 plants/stand at 14 DAP. Pre-emergence herbicide Butachlor was applied after planting, and hand hoe weeding were done at 30 and 55 DAP.

2.5. Carbon mineralization and CO₂ emissions measurement

Soil respiration was measured in situ by alkali absorption method, using the non-flow-through steady-state (static chamber) system. Permanent chambers made of 10.6 cm diameter Polyvinyl Chloride (PVC) pipes of equal heights measuring 30 cm and installed to 20 cm depth giving a trapping head space of about 1/3 of the chamber volume were installed at the center of each treatment plot at spots cleared of all organic residue, and covered with thick aluminum foils. Carbon dioxide emission was trapped in 60 mL vials containing 40 mL 0.25 M NaOH. Five milliliter (5 mL) aliquots of the trapping solution (0.25 M NaOH) were back-titrated to a colourless end-point with 0.15 M HCl after precipitation of carbonates by adding 8 mL 3 M BaCl₂ using phenolphthalein as an indicator according to Haber (1958). Readings were taken on day 1, 3, 7, 14, 21, 28, 35, 42, 49, 56, 63, 77, and 91. CO₂⁻C was evaluated using equation i below:

\[ \text{CO}_2^-\text{C} = \frac{(B - V) \times M \times E}{A} \]  

where; \( \text{CO}_2^-\text{C} \) = C emission as CO₂-C (mg/m²/d); \( B \) = HCl volume used to titrate treatment samples (mL); \( V \) = HCl volume used to titrate blank samples (mL); \( M \) = molarity (mol L⁻¹) HCl; \( E \) = gram-equivalent of C (6 g); \( A \) = trapping soil surface area (m²).

The percentage of biochar C mineralized was evaluated using equation ii:

\[ \text{BCM} (%) = \frac{\text{CMCtreatment} - \text{CMControl}}{\text{biochar C applied}} \times 100 \]  

where \( \text{BCM} \) (%) = C mineralized in amended treatments; \( \text{CMC} \) = C emission trend, the incubation experiment was segmented into two stages. The initial high emission and rapid decrease stage (days 1–21 (1-21d)) and the slow emission/slow decrease stage (days 21–91 (21-91d)).

2.6. Data analysis

Carbon mineralization data was subjected to analysis of variance (ANOVA), and significant means were separated by Standard Error of Difference of Means (SED) at \( p = 0.05 \) using General Statistics (GenStat) 5.32. correlation analysis was done to determine relationships between soil properties and CO₂ emission. Graphs were plotted using Microsoft Excel (2016).

3. Results

3.1. CO₂-C emission rate and cumulative emissions

Figure 2 shows the trends of CO₂⁻C emission in soils under all treatments and control. Temporal variation in CO₂ emissions in all treatments was similar, and values were highest at the initial stage of incubation before they decreased rapidly, and then slowly through the experiment duration in all three soils and treatment, including control. Based on the CO₂-C emission trend, the incubation experiment was segmented into two stages. The initial high emission and rapid decrease stage (days 1–21 (1-21d)) and the slow emission/slow decrease stage (days 21–91 (21-91d)). CO₂ emissions in amended treatments were consistently significantly (\( p < 0.01 \)) higher than in control treatments (Figure 2), and just as higher emissions were recorded at higher biochar application rates. Biochar
application at 25 t/ha resulted in cumulative emission of 3.06 g/m² CO₂-C, and this value was significantly higher than 2.82 g/m² and 2.78 g/m² recorded in B15 and B5 respectively (Table 5).

The difference in cumulative emission values for B15 and B5 is however not significant (p < 0.05). Mean 1-21d emission evaluation was similar to cumulative emission trends, but there was no significant difference in emissions in the last stage (21-91d) of measurement where CO₂ release in all treatments had almost equaled. Although difference in emission rates between soils remained significant (p < 0.05) till the end of the field experiment (Table 5). Cumulative CO₂–C emissions increased with increasing biochar application rates in all three soils (Table 5). An analysis of the percentage of biochar-C mineralized in each treatment however showed that higher biochar application rates resulted in lower biochar-C mineralization, and the differences recorded were significant at p = 0.01. At 91d, the percentages of biochar-C mineralized in treatments were 0.15, 0.22 and 0.63 % for B25, B15 and B5 respectively (see Table 6).

3.2. Effect of soil properties on biochar mineralization and CO₂ emissions

Table 7 shows the results of the Pearson’s product moment correlation analysis of soil properties, cumulative CO₂-C emissions and biochar carbon mineralized (BCM) in this study. Result shows that measured soil textural properties had no significant (p < 0.05) relationships with cumulative CO₂-C emissions nor the amount of biochar-C mineralized. On the other hand, soil pH, total N, Ca²⁺, Mg²⁺, K and available P all had strong significant (p < 0.05) negative relationships with cumulative CO₂-C emissions in test soils. Biochar C mineralization had significant (p < 0.05) positive relationships with soil OC (r = 0.683; p = 0.01), and Fe (r = 0.808; p = 0.001) contents.

3.3. Effect of soil type and biochar treatment interactions on biochar mineralization and CO₂ emissions

Soils exerted significant effects on CO₂-C emissions. In soil IS, in which the second highest cumulative emission and highest biochar mineralization percentage was recorded, CO₂-C emission rates generally reduced with increasing biochar addition. This relationship was otherwise in soil PS which had the lowest cumulative CO₂-C emission and a lower biochar C mineralization percentage. In soil SS which had the least biochar C mineralization percentage but the most cumulative emissions, the relationship between biochar addition rate and CO₂-C emission was less direct.

4. Discussion

The initial high CO₂-C release in all treatments at the start of incubation conforms with findings from previous studies that biochar addition to soil results in an initial flush of CO₂-C emission (Luo et al., 2011; Zimmerman et al., 2011), following which amended biochar becomes more stable, leading to decreased CO₂-C emission. In our study, both control and biochar treatments exhibited this immediate flush of CO₂-C release, which may have resulted from soil carbonate dissociation or labile biochar C breakdown, as El-Naggar et al. (2015) and Bruun et al. (2012) among other authors have reported. Carbonate dissociation is probable, and may have resulted from soil disturbance effect of tillage at the start of the experiment. The fact that control treatments which were not amended with biochar also had heightened emissions at the initial stage of incubation buttress this point. According to Smith et al. (2010), after the depletion of the labile pool of biochar C, biochar is expected to remain stable in soil for decades and centennials as a result of leftover more recalcitrant C. Biochar treatments consistently had higher emissions than control, with the highest biochar application rate of 25 t/ha having about 101.3% more (total) emissions than the control. While emission rates increased with increasing biochar levels however, resultant increments in emissions were not proportional to the amount of biochar applied. Analysis of the percentage of biochar C mineralized in each treatment showed that its values decreased with increasing biochar application rates, and was highest for the lowest application rate of 5 t/ha at 0.63 %. This observation implies a general reduction in CO₂ emissions with increasing biochar addition rate, in conformity with Keith and Singh. (2011), Prayogo et al. (2014) among other earlier studies. The application rates and thresholds reported in majority of previous research however differ from those of this study. For example, while Zhang et al. (2012) reported reduced emissions of CH₄, N₂O and CO₂ following biochar application, they found no differences between biochar application rates of 10 and 40 t/ha. The trend of C mineralization and CO₂-C emission observed in this study may have been
influenced by any of the mechanisms of soil C protection highlighted by Prayogo et al. (2014); through greater aggregation and protection of biochar and SOM from degradation, effect of biochar components (e.g. dioxins and polyaromatic hydrocarbons) toxicity on soil microbiota which could reduce microbial activity, and changes in microbial enzyme activity resulting from enzyme sorption to biochar.

While CO₂–C emission trend was generally the same in all soil types, the magnitude and direction differed. Cumulative CO₂–C emission under control treatment was highest in soil SS, and biochar C mineralization was lowest in the same soil. On the other hand, while CO₂–C emission generally increased with increasing levels of biochar in soil PS, a reduction in emissions was observed in soil IS. This is an indication of a complex soil-biochar relationship leading to marked differences in C degradation mechanisms in the soils, attributable to soil physicochemical properties. The general reduction in CO₂–C emission as incubation progressed supports the notion of biochar recalcitrance to degradation, reported by many previous authors including Smith et al. (2010). The trend suggests that as more of the labile forms of C in the biochar material became depleted, more recalcitrant C forms become less available for microbial degradation.

As CO₂–C emissions increased with increasing application rates of biochar, one could attribute the observation to possible higher levels of microbial activity resulting from higher OC (substrate) availability. Earlier studies such as Zhu et al. (2017) have reported such effects of biochar in soil. Inferences from the correlation analysis of soil properties and CO₂–C emission however showed that soil N, P, pH and exchangeable bases (Ca²⁺, Mg²⁺ and K⁺) were most correlated with CO₂–C, and suggests other more probable mechanisms to explain the emission trend observed. One is possible increased biotoxicity resulting from biochar components, which is expected to increase as application rates increase.
Table 7. Correlation analysis of CO₂-C emissions and soil properties in the three soil types.

| Soil property | Pearson’s r (n = 11) | p-value (p < 0.05) | % BCM | Pearson’s r (n = 11) | p-value (p < 0.05) |
|---------------|----------------------|---------------------|-------|----------------------|---------------------|
| Gravel (%)    | -0.353               | 0.237               | 0.25  | 0.41                 |
| Sand (%)      | 0.027                | 0.929               | 0.096 | 0.756                |
| Silt (%)      | -0.433               | 0.139               | -0.161| 0.6                  |
| Clay (%)      | -0.432               | 0.14                | -0.163| 0.594                |
| pH 1:1 H₂O    | -0.906               | 0.001               | -0.461| 0.112                |
| Total N       | -0.845               | 0.001               | -0.509| 0.076                |
| OC (%)        | 0.331                | 0.269               | 0.683 | 0.01                 |
| OM (%)        | -0.087               | 0.776               | 0.106 | 0.73                 |
| Ca²⁺ (cmol(+)kg⁻¹) | -0.77             | 0.062               | -0.173| 0.571                |
| Mg²⁺ (cmol(+)kg⁻¹) | 0.889            | 0.001               | -0.367| 0.217                |
| Na⁺ (cmol(+)kg⁻¹) | 0.242            | 0.425               | 0.177 | 0.564                |
| K⁺ (cmol(+)kg⁻¹) | 0.575              | 0.04                | -0.308| 0.305                |
| Av. P (mg/kg) | -0.761               | 0.003               | 0.048 | 0.877                |
| ECEC (cmol(+)kg⁻¹) | 0.169           | 0.581               | 0.175 | 0.01                 |
| BS (%)        | 0.157                | 0.609               | -0.32 | 0.287                |
| Fe (mg/kg)    | 0.104                | 0.734               | 0.808 | 0.001                |
| Zn²⁺ (mg/kg)  | -0.213               | 0.484               | -0.306| 0.31                 |

BCM: biochar carbon mineralized; BS: base saturation; Av.: available.

Soil pH, P and N were also negatively correlated with CO₂-C emission, and soils SS and PS which had the lowest percentage of biochar-C mineralized and cumulative emissions had higher inherent N amounts. Although earlier research by Kimetu et al. (2009) suggest that soils with lower N and C content may adsorb more labile biochar C before adsorption saturation is reached in clay and mineral adsorption surfaces, after which extra free C is available for microbial utilization and as source of CO₂, lower biochar VM toxicity is expected in soils of lower C and N, which may translate into higher microbial C degradation activities in lower N soil environment. Previous authors such as Spokas and Reicosky (2010) and Cayuela et al. (2014) have also reported similar findings.

Applied biochar material could also act as a sorbent for soil nutrient, thereby limiting microbial access and activity, and leading to less C mineralization at higher biochar application rates. According to Kazosi et al. (2010) and Herath et al. (2015), biochar has a porous structure and high affinity for organic materials which enhances the adsorption of SOC onto its surface and retention in pores, hindering the accessibility of microbial decomposers. Results of correlation analysis show that there were no significant relationships between the textural properties of soils and CO₂-C emissions in this study. This is opposed to previous findings by authors such as Sissoko and Kpomblekou-A (2010) which attribute finer soil textural components (clay and silt) with higher sorption capacity for soil and biochar-C, and lowered CO₂ emissions due to large surface area of their particles.

5. Conclusion

In examining CO₂ emissions in soils amended with rice husk biochar in this study, it was found that biochar application rates and soils had significant effects on emissions. Although higher application rates resulted in significantly higher CO₂-C emissions, the magnitude was not proportional to the level of addition, as lower percentages of biochar C were mineralized at higher application rates. The magnitude and direction of emission also differed in the different soils examined, and emission trends were generally correlated with soil N, P, pH and exchangeable bases (Ca²⁺, Mg²⁺ and K⁺), and biochar mineralization had significant positive correlation with SOC and Fe content.

The lower C mineralization observed in higher biochar application treatments may have resulted from increased biochar material bio-toxicity inhibiting microbial degradation activities, or higher protection of soil and biochar C from biochar surface adsorption or occlusion. While the emission trend in this study does not indicate that biochar addition can suppress CO₂ emissions in soils, the recalcitrance of biochar which led to lower emissions as incubation progressed was demonstrated. Also, only a minimal amount of biochar C was mineralized by the end of the experiment. The cumulative C loss as such is very small in comparison to the C value of the biochar material, and suggests that biochar is a viable option for C sequestration and climate change mitigation.

Declarations

Author contribution statement

John Olajide Olaniyan; Bashiru Ademola Raji: Conceived and designed the experiments.

Theophilus Olufemi Isimikalu: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Kehinde Olayemi Affinini: Analyzed and interpreted the data.

Olusegun Nathaniel Ajala; Sikiru Yusuf Alasinrin: Contributed reagents, materials, analysis tools or data.

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Data availability statement

Data included in article.

Declaration of interests statement

The authors declare no conflict of interest.


Additional information

No additional information is available for this paper.

References

Abiven, S., Schmidt, M.W.I., Lehmann, J., 2014. Biochar by design. Nat. Geosci. 7, 326–327.

Bruun, E.W., Ambus, P., Egeberg, H., Hauggaard-Nielsen, H., 2012. Effects of slow and fast pyrolysis biochar on soil C and N turnover dynamics. Soil Biol. Biochem. 46, 73-79.

Butnain, S., Deenik, J.J., Toomsan, B., Antal, M.J., Vityakon, P., 2015. Biochar characteristics and application rates affecting crop growth and properties of soils contrasting in texture and mineralogy. Geoderma 237, 105–116.

Cayuela, M.L., van Zwieten, L., Singh, B.P., Jeffery, S., Roig, A., Sanchez-Moncada, M.A., 2014. Biochar's role in mitigating soil nitrous oxide emissions: a review and meta-analysis. Agric. Ecosyst. Environ. 191, 5–16.

El-Naggar, A., Awad, Y.M., Tang, X.Y., Liu, C., Niazi, N.K., Jien, S.H., Tsang, D.C., Song, H., Ok, Y.S., Lee, S.S., 2018. Biochar influences soil carbon pools and facilitates interactions with soil: a field investigation. Land Degrad. Dev.

El-Naggar, A., Shaheen, S.M., Hur, Z.Y., Wang, S.L., Ok, Y.S., Rinklebe, J., 2019. Release dynamics of As, Co, and Mo in a biochar treated soil under pre-definite redox conditions. Sci. Total Environ. 657, 686–695.

El-Naggar, A.H., Usman, A.R., Al-Omran, A., Ok, Y.S., Ahmad, M., Al-Wabel, M.I., 2015. Carbon mineralization and nutrient availability in calcareous sandy soils amended with woody waste biochar. Chemosphere 138, 67–73.

Enders, A., Lehmann, J., 2012. Comparison of wet digestion and dry-ashing methods for total elemental analysis of biochar. Commun. Soil Sci. Plant Anal. 43, 1042–1052.

FDALAR (Federal Department of Agricultural Land Resources), 1990. Reconnaissance Soil Survey Report of Nigeria, Vols 1–4. FDALAR, Jos.

Haber, W., 1958. Ökologische Untersuchungen der Bodenatmung. [Ecolological analysis of soil respiration (review of methods)]. Flora 146, 109–157.

Herath, H.M.S.K., Camps-Arbestain, M., Hedley, M.J., Kirschbaum, M.U.F., Wang, T., van Haile, R., 2015. Experimental evidence for sequestering C with biochar by avoidance of CO2 emissions from original feedstock and protection of native soil organic matter. GCB Bioenergy 7, 512–526.

Huang, D., Luo, H., Zhang, C., Zeng, G., Lai, C., Cheng, M., Wang, R., Deng, R., Xue, W., Gong, X., Guo, X., Li, T., 2019. Nonnegligible role of biomass types and its compositions on the formation of persistent free radicals in biochar: insight into the influences on Fenton-like process. Chem. Eng. J. 361, 353–363.

Kazosi, G.N., Zimmerman, A.R., Nkedi-Kizza, P., Gao, B., 2010. Catechol and humic acid mineralization in a smectite-rich soil. Environ. Sci. Technol. 45, 9611–9618.

Kloss, S., Zehetner, F., Wimmer, B., Ruecker, J., Rempt, F., Soja, G., 2014. Biochar application to temperate soils: effects on soil fertility and crop growth under contrasting conditions. J. Plant Nutr. Sci. 177, 3–15.

Kuzyakov, Y., Bogomolova, I., Glaser, B., 2014. Biochar stability in soil: decomposition during eight years and transformation as assessed by compound-specific 14C analysis. Soil Biol. Biochem. 70, 229–236.

Lehmann, J., Joseph, S., 2015. Biochar for environmental management: an introduction. In: Lehmann, J., Joseph, S. (Eds.), Biochar for Environmental Management: Science, Technology and Implementation, second ed. Earthscan from Routledge, London, pp. 1–1214.

Luo, Y., Durenkamp, M., Nobili, M.D., Lin, Q., 2011. Brookes, P.C. Short term soil priming effects and the mineralisation of biochar following its incorporation to soils of different pH. Soil Biol. Biochem. 43, 2304–2314.

Novak, J.M., Busscher, W.J., Watts, D.W., Laird, D.A., Ahmeda, M.A., Niandou, M.A.S., 2010. Short-term CO2 mineralization after additions of biochar and switchgrass to a Typic Kandudult. Geoderma 154, 281–288.

Ok, Y.S., Uchimiya, S.M., Chang, S.K., Bolan, N., 2015. Biochar—Production, Characterization and Applications. CRC Press, Taylor and Francis, London.

Olaniyi, J.O., Olaniyan, J.O., 2003. Evaluation of the Soil Map of Nigeria for Land Use Planning in Kwara State. Ph.D. Thesis. University of Ilorin, Unpublished. Ilorin.

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G.P., Smith, P., 2016. Characteristics of biochars derived from fruit tree pruning wastes and their effects on lead adsorption. J. Korean Soc. Appl. Biol. Chem. 58, 751–760.

Prayogo, C., Jones, J.E., Baejens, J., Bending, G.D., 2014. Impact of biochar on mineralization of C and N from soil and willow litter and its relationship with microbial community biomass and structure. Biol. Fertil. Soils 50, 695-702.

Rizwan, M., Ali, S., Qayyum, M.F., Ibrahim, M., Zia-ar-Rehman, M., Abbas, T., Ok, Y.S., 2016. Mechanisms of biochar-mediated alleviation of toxicity of trace elements in plants: a critical review. Environ. Sci. Pollut. Res. 23, 2280–2284.

Schreer, C., Grace, P.R., Rowlings, D.W., Kimber, S., Zwieten, L.V., 2011. Effect of biochar amendment on the soil-atmosphere exchange of greenhouse gases from an intensive subtropical pasture in northern New South Wales, Australia. Plant Soil 345, 47–58.

Shaheen, S.M., Niazi, N.K., Hassan, N.E., Bibi, I., Wang, H., Tsang, D.C., Ok, Y.S., Bolan, N., Rinklebe, J., 2018. Wood-based biochar for the removal of potentially toxic elements in water and wastewater: a critical review. Int. Mater. Rev. 22, 1–32.

Sisoko, A., Kpomblekou-A, K., 2010. Carbon decomposition in broiler litter-amended soils. Soil Biol. Biochem. 42, 543–550.

Smith, J.L., Collins, H.P., Bailey, V.L., 2010. The effect of young biochar on soil respiration. Soil Biol. Biochem. 42, 2345–2347.

Solaiman, Z.M., Anwar, H.M., 2015. Application of biochars for soil constraints: challenges and solutions. Pedsophere 25, 631–638.

Spokas, K.A., Reicosky, D.C., 2010. Impacts of sixteen different biochars on soil greenhouse gas production. Ann. Environ. Sci. 3, 179–193.

United States Agency for International Development USDA, 2014. Soil Survey Field and Laboratory Methods Manual. Soil Survey Investigations Report No 51 Version 2. United States Agency for International Development USDA, 2017. Soil Survey Manual. Soil Science Division Staff. United States Department of Agriculture. Handbook No. 18. Issued March 2017.

Wang, J., Dokohely, M.E., Xiong, Z., Kuzyakov, Y., 2016. Contrasting effects of aged and fresh biochars on glucose-induced priming and microbial activities in paddy soil. J. Soils Sediments 16, 191–203.

Wang, Z., Li, Y., Chang, S.X., Zhang, J., Jiang, P., Zhou, G., Shen, Z., 2014. Contrasting effects of bamboo leaf and its biochar on soil CO2 efflux and labile organic carbon in an intensively managed Chinese chestnut plantation. Biol. Fertil. Soils 50, 1109–1119.

Zhang, A.F., Liu, Y.M., Pan, G.X., Hussain, Q., Li, L.Q., Zheng, J.W., Zhang, X.H., 2012. Effect of biochar amendment on maize yield and greenhouse gas emissions from a soil organic carbon poor calcareous loamy soil from Central China Plain. Plant Soil 351, 263–275.

Zhu, X., Chen, B., Zhou, L., Xing, B., 2017. Effects and mechanisms of biochar-microwave interactions in soil improvement and pollution remediation: a review. Environ. Pollut. 227, 98–115.

Zimmerman, A.R., Gao, B., Ahn, M.Y., 2011. Positive and negative carbon mineralization priming effects among a variety of biochar-amended soils. Soil Biol. Biochem. 43, 1169–1179.

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