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Application of Rice-Husk Biochar to Coarse-Textured Ultisols and the Effects on Soil Fertility Indicators at Different Amendment-to-Sampling Intervals

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ABSTRACT

The low fertility status of the highly weathered tropical soils offers the opportunity to study the potential and optimum application rate of biochar as an organic soil amendment, especially for the dominant coarse-textured Ultisols. Despite the relatively fast mineralisation of organics in these soils and the need to synchronise nutrient release crops critical stages of nutrient requirement, the time corresponding to peak effects of biochar remains unclear. The effects of rice-husk biochar (RHB) on the soil fertility of sandy-loam Ultisols at 0, 7.5, 15, 30, and 60 Mg ha^{-1} equivalents in 2-kg soils were assessed at 0, 2, 4, 8, and 12 weeks of incubation (WOI). Treatments were prepared in batches to enable concurrent sampling for all five incubation intervals. The RHB enhanced soil fertility across the incubation intervals, with optimal rates as 15 Mg ha^{-1} for soil pH and 30 - 60 Mg ha^{-1} for macronutrients availability. Relative to the its non-application, RHB increased soil pH-H_2O, total N, available P, exchangeable bases, exchangeable acidity, apparent CEC and base saturation by 4-30%, 43-100%, 30-202%, 13-240%, 14-675%, 21-126% and 7-82%, respectively. Soil pH tended to decrease after, while available P progressively decreased before 8 WOI, when treatment effects were generally most pronounced. At an all-encompassing optimal rate range of 30-60 Mg ha^{-1}, RHB could reduce soil acidity and enhance the macronutrient status of coarse-textured Ultisols over at least 12 weeks, soil fertility restoration effects of which are likely to be most pronounced around 8 weeks.

Keywords: Incubation intervals, organic amendment, rice-husk biochar, soil nutrients, ultisols

INTRODUCTION

In recent years, the transformation of agro-wastes into biochar to improve soil quality and carbon sequestration has gained attention (Billa et al., 2018). Biochar addition to soils can improve their structure stability and hydraulic properties (Adekiya et al., 2019; Ebido et al., 2021). Biochar has hygroscopic properties, and its highly porous nature is desired to attract and retain water and beneficial plant nutrients in the soil. Adding biochar to acidic soils increases soil pH (Glaser et al., 2002; Frimpong Manso et al., 2019), making it a good liming material. Thus, biochar addition can ameliorate soil acidity and improve soil fertility (Liang et al., 2006; Chan & Xu, 2009; Van Zwieten et al., 2010; Jien & Wang, 2013). By increasing soil CEC, biochar reduces leaching of nutrients (Liu et al., 2017; Mehmood et al., 2018). This ability of biochar to ameliorate soil acidity and increase soil CEC suggests that it could be a promising soil amendment for highly weathered acid, low-fertility tropical soils (Obalum et al., 2024).

Biochars vary in their physicochemical properties, influencing their contents and availability of nutrients to plants when applied to the soil (Downie et al., 2009). Such variations in biochar quality are driven mainly by the nature of the organic material selected as feedstock for the biochar (Ippolito et al., 2020). Rice husk, the main by-product of rice processing industries, is superior to most other biochar feedstocks in terms of nutrient content of the biochar produced (Alburquerque et al., 2014; Nwajiaku et al., 2018). In Nigeria, a considerable amount of rice husk is generated from rice mills and heaped daily (Nwite et al., 2012a, b; Njoku et al., 2015). Because rice husk is not readily mineralisable (Ezenne et al., 2019), its steadily enlarging heaps could constitute both environmental nuisance and hazards (Baiyeri et al., 2020). They must, therefore, be rationally disposed of.

Though rice husk can serve as an organic soil conditioner and amendment (Igwe et al., 2013; Njoku et al., 2015; Ezenne et al., 2019) or as an organic aerator in soil-based nursery media (Adubasim et al., 2018; Ugwu et al., 2020), converting it to biochar before use could be a better way to enhance its agricultural value while further reducing its heaps. Soil application of rice-husk biochar (RHB) has been reported to improve soil quality (including nutrient release) not only in temperate environments (Ghorbani et al., 2019; Oraegbunam et al., 2022) but also in tropical climates (Masulili et al., 2010; Adejumo et al., 2016; Persaud et al., 2018). However, the relatively more fertile soils of the temperate region may generally require lower application rates to produce similar effects as would do bay higher rates in tropical soils.

Research has shown RHB to have a high sorption capacity due to its high charge density and surface area (Liang et al., 2006). Also, RHB has high resistance to microbial decomposition, implying a low mineralisation rate in soils (Zheng et al., 2010), suggesting that nutrient release in RHB-amended soils could proceed rather slowly. The potential for RHB to exhibit sorption behaviour when added to the soil has been suggested to increase over time (Huang et al., 2020). However, the exact nature of this phenomenon is expected to depend on a range of soil-related factors, thus calling for research to better understand the extent of such persistence in soils (Huang et al., 2020). Oraegbunam et al. (2022) reported that the respiration of a sandy Japanese soil in response to biochar (including RHB) increased between treatments and four weeks after planting and, thereafter, increased every week for the next four weeks. The duration of soil-biochar incubation may have an underlying influence on the effects of varying application rates of RHB on soil fertility and release of nutrients in the soil.

The coarse-textured Ultisols dominating the soil resources of southeastern Nigeria typify the acidic, low-fertility tropical soils. In an earlier paper, RHB effects on aggregate stability and total N status of these soils, as well as growth of short-duration leafy vegetables, were reported to vary according to soil-biochar incubation duration (Ebido et al., 2021). However, there is scant information regarding such effects more generally on the physicochemical fertility indices of the soils. This present paper thus reports the contributions of RHB to the fertility status of these Ultisols, whereby the RHB was applied at different rates and the assessment was done under different soil-biochar incubation intervals.

MATERIALS AND METHODS

Soil of the Study and Its Procurement/Preparation

Under glasshouse conditions, the experiment was conducted with homogeneous potted soils at the University of Nigeria, Nsukka, Nigeria. Soil for the experiment was collected from the University of Nigeria Teaching & Research Farm (6°521'N, 7°241'E; 447 m above sea level). The soil is a deeply weathered brownish red coarse-textured (sandy-loam) Ultisols, underlain by false-bedded sandstone. The soil is of low fertility status and is often described as ‘degraded’ (Obalum et al., 2011). Soil samples were collected randomly at a depth of 0-15 cm (topsoil) and bulked to form a representative composite sample. The soil samples were air-dried in the glasshouse for one week and, thereafter, crushed and passed through a 2-mm sieve.

Biochar Production from Rice Husk

The rice husk serving as biochar feedstock was obtained from a rice-milling industry for mixed rice varieties at Adani in southeastern Nigeria, which served as the source of rice husk used in Adubasim et al. (2018). The RHB was produced by pyrolysis (heating with limited oxygen) using a simple home-built pyrolyser (a 10-Litre metallic cylinder slightly punctured at the sides and placed on a closed-chamber furnace of burning wood supplying heat at 500-550 °C). The rice husk was placed inside the cylinder and covered tightly with a lid before heating was commenced. The box was continuously turned to ensure uniform burning of the rice husk. The process lasted until about 30 min., when the smoke released from the punctured spots turned light green, indicating that the rice husk had charred entirely.

Treatments, Experimental Design, and Soil-Biochar Incubation

Biochar was thoroughly mixed with the soil at five rates namely 0, 5, 10, 20 and 40 g per 2 kg potted soil, corresponding to field application rate of 0, 7.5, 15, 30 and 60 Mg ha^{-1}, respectively to 20-cm soil depth (assuming the bulk density of the soil to be 1,500 kg m^{-3}). Treatments of RHB application rate were incubated in plastic pots (0.18 m deep with an internal diameter of 0.16 m). Treatment effects were tested separately for five soil-biochar incubation intervals, which were 0, 2, 4, 8, and 12 weeks of incubation (WOI). The potting and application of RHB were made in five batches to enable concurrent sampling for these five intervals. The five treatments were replicated three times for each incubation interval in a completely randomized design, such that there were 15 potted soils per incubation interval and 75 potted soils in all.

The potted RHB-amended soils were watered using deionized water to approximately. 60% water holding capacity, and the initial weight of each potted soil in this state was recorded. They were weighed every seven days, after which deionized water was added to compensate for weight loss and restore the soil to its initial water content state. The average room temperature was ~25-28 ^{o}C during the entire incubation period.

Soil Sampling and Analyses

The effects of RHB on the chemical fertility of the incubated potted soils were assessed. At the batching-enabled synchronized end of the five incubation intervals, the RHB-amended potted soils were sampled and processed for physicochemical analyses. The soil samples were air-dried at room temperature to constant weight, crushed, and passed through a 2-mm sieve before analyses.

Soil pH was determined in suspensions of deionized water and 0.1N KCl in a 1.0:2.5 soil-liquid mass ratio and measured potentiometrically (McLean, 1982). Total N content of the soil was determined using the Kjeldahl digestion-distillation and titration method as described by Bremner and Mulvaney (1983). Available P in the soil was determined on the extract of Bray-2 acid solution by the colorimetric procedure outlined by Olsen and Sommers (1982). Apparent CEC of the soil was determined using the ammonium acetate (NH_4OAc) displacement-saturation method involving 1N NH_4 OAc buffered at pH 7 to leach the soil before the required titration (Rhoades, 1982).

Further, the soil contents of the exchangeable bases (K^+, Ca^{2+}, Mg^{2+}, and Na^+) were determined on the NH_4OAc leachate. A flame photometer was used to determine K^+ and Na^+, while the complexometric titration utilising 0.01N EDTA (ethylene diamine tetra-acetic acid) was used to determine Ca^{2+} and Mg^{2+}. Soil content of the exchangeable acidity (H^+ and Al^{3+}) was determined by saturating samples with 1N KCl and titrating with NaOH as described by Mclean (1982).

Statistical Analyses

Data for each incubation interval were subjected to a one-way analysis of variance using a linear model approach appropriate for a CRD experiment, with the help of the software GenStat Discovery Edition 4. The least significant difference test was employed to differentiate means, showing significant

Table 1: The soil's initial physical and physicochemical properties (n = 3, mean $\pm$ std. dev.)

Soil properties	Values
Clay (g kg^{-1})	163
Silt (g kg^{-1})	87
Fine sand (g kg^{-1})	233
Coarse sand (g kg^{-1})	517
Textural class	Sandy loam
Mean-weight diameter of soil aggregates (mm)	18.64 $\pm$ 0.40
% Aggregate stability	9.23 $\pm$ 0.73
Soil pH-H_2O	4.83 $\pm$ 0.35
Soil pH-KCl	4.33 $\pm$ 0.29
Soil organic carbon (g kg^{-1})	11.99 $\pm$ 2.90
Total nitrogen (g kg^{-1})	0.45 $\pm$ 0.06
Available phosphorus (mg kg^{-1})	9.30 $\pm$ 0.32
Exchangeable potassium, K^+ (cmol kg^{-1})	0.05 $\pm$ 0.01
Exchangeable calcium, Ca^{2+} (cmol kg^{-1})	1.00 $\pm$ 0.40
Exchangeable magnesium, Mg^{2+} (cmol kg^{-1})	0.80 $\pm$ 0.05
Exchangeable sodium, Na^+ (cmol kg^{-1})	0.05 $\pm$ 0.01
Exchangeable aluminium, Al^{3+} (cmol kg^{-1})	0.41 $\pm$ 0.05
Exchangeable hydrogen, H^+ (cmol kg^{-1})	0.85 $\pm$ 0.08
Apparent cation exchange capacity, CEC (cmol kg^{-1})	6.55 $\pm$ 0.55

Table 2. Some physicochemical properties of the rice-husk biochar used in this study (n = 3, mean ± std. dev.).

Parameter	Value	Parameter	Value
pH-H_2O	8.57 ± 0.25	Potassium, K (g kg^{-1})	2.10 ± 0.10
pH-KCl	7.63 ± 0.38	Calcium, Ca (g kg^{-1})	20.30 ± 2.50
Organic C (g kg^{-1})	199.80 ± 1.70	Magnesium, Mg (g kg^{-1})	16.80 ± 0.30
Nitrogen, N (g kg^{-1})	9.80 ± 0.40	Sodium, Na (g kg^{-1})	3.30 ± 0.30

differences at the 5% probability level ($p \leq 0.05$), denoted $LSD_{0.05}$. Also, we subjected the soil data to multivariate correlations. To do this, the soil organic carbon (SOC) content in this study, which was consistently highest with 60 Mg ha^{-1} as already reported elsewhere (Ebido et al., 2021), and the soil fertility indices reported here were involved.

RESULTS

Soil Physicochemical Properties before Biochar Treatment

Table 1 shows the texture and some physicochemical properties of the soil of this study prior to biochar application. The soil pH was relatively low; hence, the soil was acidic in reaction. Also, SOC, total N, available P, exchangeable bases (K^+, Ca^{2+}, Mg^{2+}, and Na^+), apparent CEC, and percent base saturation were generally low.

Table 2 shows some physicochemical properties of the RHB used as soil amendment in this study. The RHB had an alkaline pH of 8.57 and a high organic carbon content. Its constituents were such that N and the base-forming essential and beneficial nutrient elements (K, Ca, Mg, and Na) all indicated very high values compared to the soil.

Effects of RHB on Soil Physicochemical Properties at Different Intervals

Figure 1 shows the effects of RHB on the soil pH of the sandy-loam Ultisols at the different soil-biochar incubation intervals of the study. The addition of RHB to the soil at various rates affected soil pH. All the RHB-amended potted soils always showed higher values compared to the unamended control (0 Mg ha^{-1}); the only exceptions were for soil pH-H_2O measured at 0 WOI (when the control and the application rate 7.5 Mg ha^{-1} were similar) and soil pH-KCl at 12 WOI (when 15 Mg ha^{-1} was higher than the control). Apart from 2 WOI, when 15 and 30 Mg ha^{-1} showed lower soil pH than 60 Mg ha^{-1}, increasing the application rate beyond 15 Mg ha^{-1} did not cause further increases in soil pH, such that this RHB rate could generally be adjudged the optimum across the incubation intervals. The effects of RHB on soil pH were most pronounced between

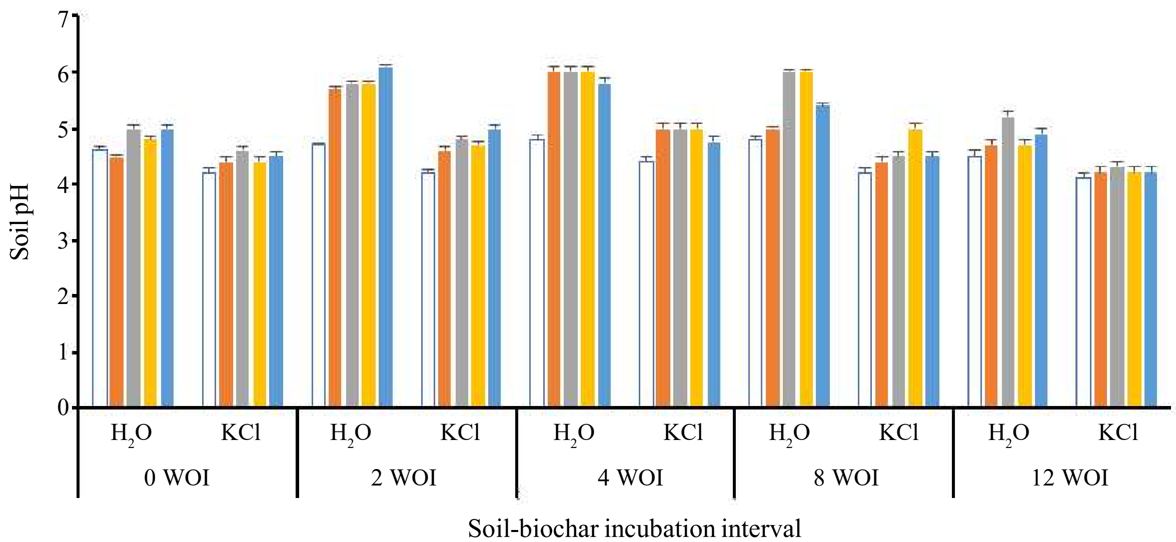

Figure 1. Effects of rice-husk biochar on soil pH under the different soil-biochar incubation intervals. Error bars represent LSD at a 5% probability level ($LSD_{0.05}$). ▫ : 0 Mg ha^{-1}, ▪ : 7.5 Mg ha^{-1}, ▪ : 15 Mg ha^{-1}, ▪ : 30 Mg ha^{-1}, ▪ : 60 Mg ha^{-1}.

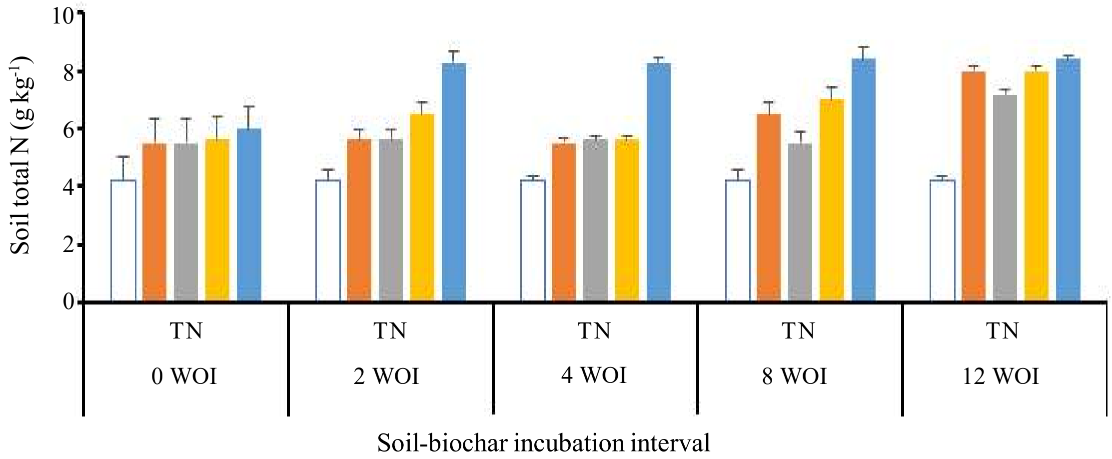

Figure 2. Effects of rice-husk biochar on soil total N under the different soil-biochar incubation intervals. Error bars represent LSD at a 5% probability level ($LSD_{0.05}$). ▭ : 0 Mg ha^{-1}, ■ : 7.5 Mg ha^{-1}, ■ : 15 Mg ha^{-1}, ■ : 30 Mg ha^{-1}, ■ : 60 Mg ha^{-1}.

2 and 8 WOI, and appeared to reduce at 12 WOI. For instance, relative to the control, soil pH-H_2O increased due to the Optimal 15 Mg ha^{-1} by 25.00% at 8 WOI but by 15.56% at 12 WOI (Figure 1). The lowest actual application rate of 7.5 Mg ha^{-1} recorded the lowest increases in soil pH-H_2O over the control by 0.2 units (4.17% increase) at 8 WOI. In contrast the highest application rate of 60 Mg ha^{-1} recorded the highest increases in soil pH-H_2O over the control by 1.4 units (29.79% increase) at 2 WOI.

The effects of the RHB application at varying rates on total N content of the soils for the five soil-biochar incubation periods are shown (Figure 2). Soil total N differed among the varying rates of RHB. The control consistently showed lower values compared to the amended soils. All amended soils indicated similar values and were higher than the control at the first sampling (0 WOI), but 60 Mg ha^{-1} was higher than the rest of the treatments for all the other incubation durations. This highest RHB rate increased soil total N by 42.86%, 97.62%, 97.62%, 100%, and 100% relative to the control for the 0 (day 1), 2, 4, 8, and 12 WOI, respectively. Notably, 15 Mg ha^{-1} consistently caused the lowest increases, similar to 7.5 Mg ha^{-1} during 0-4 WOI.

The effects of the RHB on available P content of the soil for the five soil-biochar incubation periods are presented in Figure 3. Treatment of RHB rates

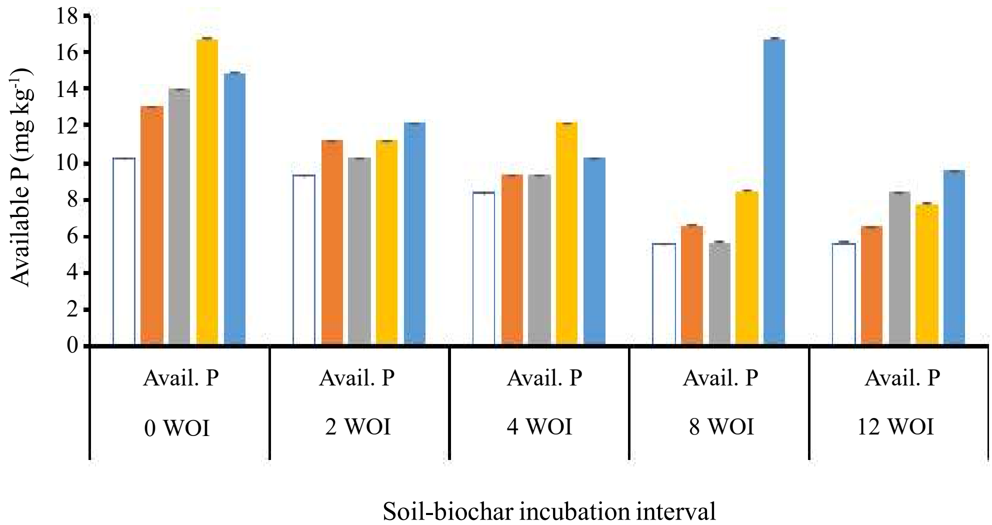

Figure 3. Effects of rice-husk biochar on available P content of the soil under the different soil-biochar incubation intervals. Error bars represent LSD at a 5% probability level ($LSD_{0.05}$). ▭ : 0 Mg ha^{-1}, ■ : 7.5 Mg ha^{-1}, ■ : 15 Mg ha^{-1}, ■ : 30 Mg ha^{-1}, ■ : 60 Mg ha^{-1}.

affected the available P content of the soil. Though 30 Mg ha^{-1} was the best at 0 and 4 WOI, 60 Mg ha^{-1} was generally the best. Relative to the control, this highest rate increased available P by 29.90%, 22.29%, 202.16%, and 70.54% at 2, 4, 8, and 12 WOI, respectively. The soil available P generally decreased with time since soil-biochar incubation until 8 WOI, when the highest relative increases occurred due to the highest rate. Notably, these relative increases in soil available P were about three times more at 8 WOI than 12 WOI (202.16% vs 70.54%).

RHB's effects on the soil's capacity to exchange base-forming cations across the incubation periods are shown (Figure 4a and b). The exchangeable bases did not always increase with rates of RHB; the unamended control was sometimes similar to 7.5 and/or 15 Mg ha^{-1}. However, the highest values were always found in 30 and/or 60 Mg ha^{-1}, with these effects being most pronounced at 12 WOI for K^+ and Na^+ (Figure 4a) and 0 WOI for Ca^{2+} and Mg^{2+} (Figure 4b). These two rates 30 and 60 Mg ha^{-1} generally enhanced the soil content of K^+ more than Na^+, on one hand,

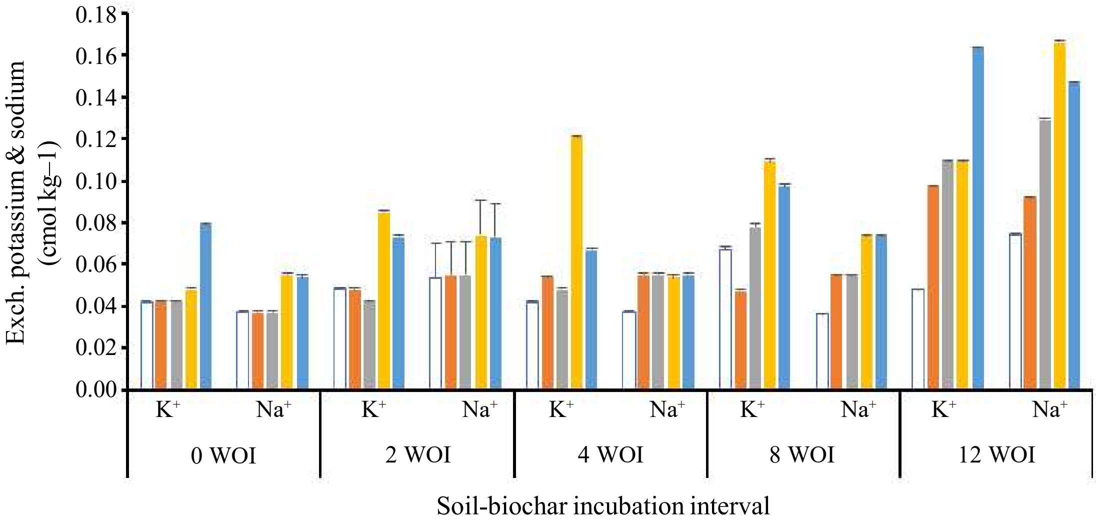

Figure 4A. Effects of rice-husk biochar on soil K^+ and Na^+ contents under the different soil-biochar incubation intervals. Error bars represent LSD at a 5% probability level ($LSD_{0.05}$). : 0 Mg ha^{-1}, : 7.5 Mg ha^{-1}, : 15 Mg ha^{-1}, : 30 Mg ha^{-1}, : 60 Mg ha^{-1}.

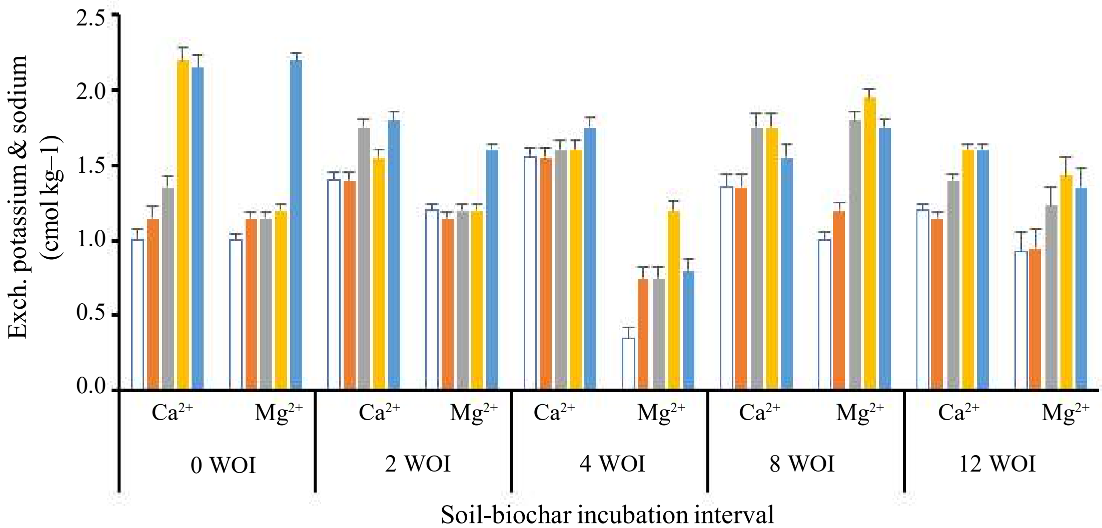

Figure 4b: Effects of rice-husk biochar on soil Ca^{2+} and Mg^{2+} contents under the different soil-biochar incubation intervals. Error bars represent LSD at a 5% probability level ($LSD_{0.05}$). : 0 Mg ha^{-1}, : 7.5 Mg ha^{-1}, : 15 Mg ha^{-1}, : 30 Mg ha^{-1}, : 60 Mg ha^{-1}.

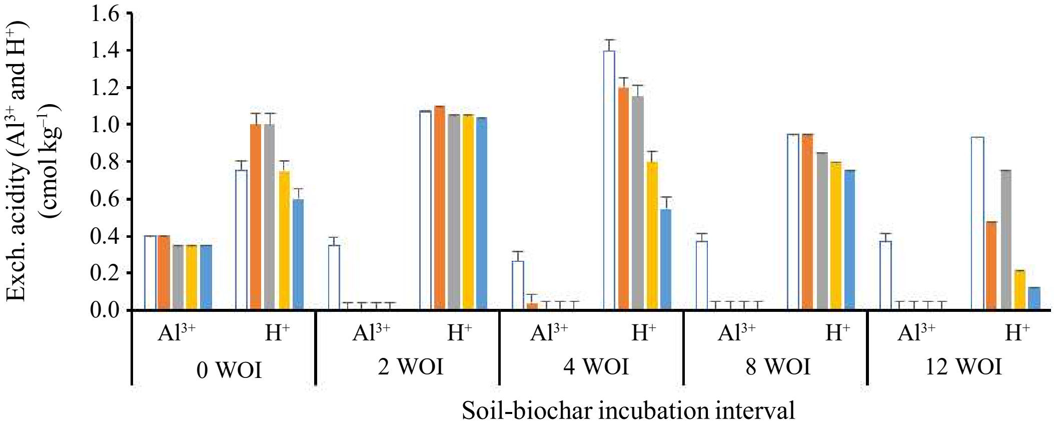

Figure 5: Effects of rice-husk biochar on exchangeable acidity of the soil under the different soil-biochar incubation intervals. Error bars represent LSD at a 5% probability level ($LSD_{0.05}$). ▫ : 0 Mg ha^{-1}, ▪ : 7.5 Mg ha^{-1}, ▪ : 15 Mg ha^{-1}, ▪ : 30 Mg ha^{-1}, ▪ : 60 Mg ha^{-1}.

and of Mg^{2+} more than Ca^{2+}, on the other. The cases of 60 Mg ha^{-1} not causing higher values than 15 Mg ha^{-1} did not occur for K^+ (Figure 4a), but occurred for Ca^{2+} and Mg^{2+} (Figure 4b). Notably, Mg^{2+} generally decreased from 0 WOI to 4 WOI and thereafter increased again at 8 WOI, with the application rate of 30 Mg ha^{-1} being the only exception.

The treatment of RHB also affected the exchangeable acidity (Al^{3+} and H^+) of the soil across the incubation periods (Figure 5). The Al^{3+} concentration was lowered beyond 7.5 Mg ha^{-1} RHB at 0 WOI and mainly occurred in traces in RHB-amended soils for the other incubation durations. The H^+ showed an overall trend suggesting decreases with increasing rate of RHB up to 60 Mg ha^{-1}. The effects of RHB on Al^{3+} and H^+ were pronounced starting from 2 and 4 WOI, respectively.

Treatment effects on the apparent CEC of the soil at the five soil-biochar incubation periods are presented in Figure 6. The apparent CEC generally increased as the RHB application rate increased, with the highest values due to 60 Mg ha^{-1}. This highest application rate increased apparent CEC by 125.98%, 20.60%, 22.33%, 24.12%, and 48.24% relative to the control, respectively, at 0, 2, 4, 8, and 12 WOI. The observed exception at 8 WOI, when 30 Mg ha^{-1} was significantly higher than 60 Mg ha^{-1} by 11.16%, is worth mentioning.

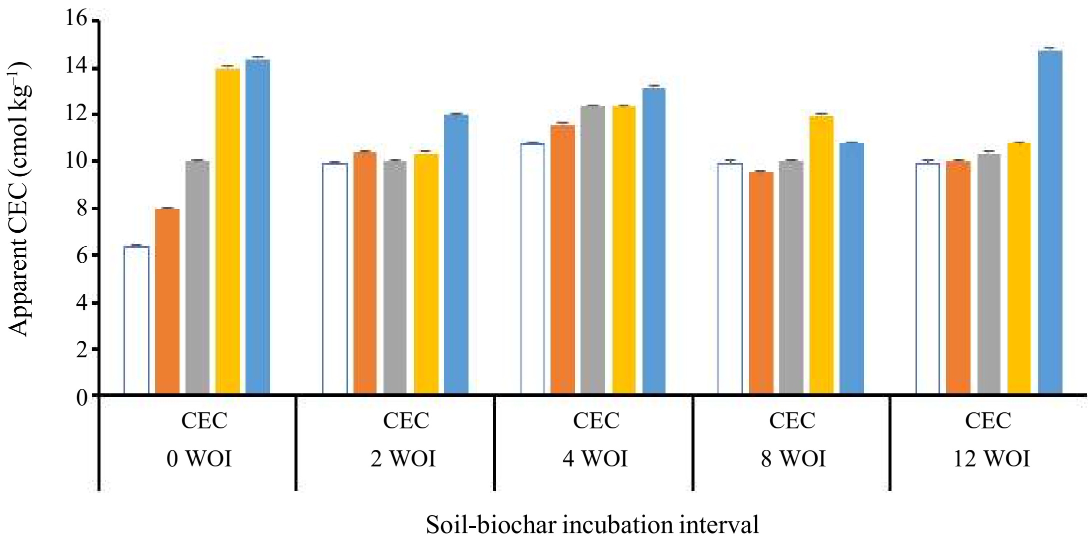

Figure 6. Effects of rice-husk biochar on the soil's apparent cation exchange capacity (CEC) under the different soil-biochar incubation intervals. Error bars represent LSD at a 5% probability level ($LSD_{0.05}$). ▫ : 0 Mg ha^{-1}, ▪ : 7.5 Mg ha^{-1}, ▪ : 15 Mg ha^{-1}, ▪ : 30 Mg ha^{-1}, ▪ : 60 Mg ha^{-1}.

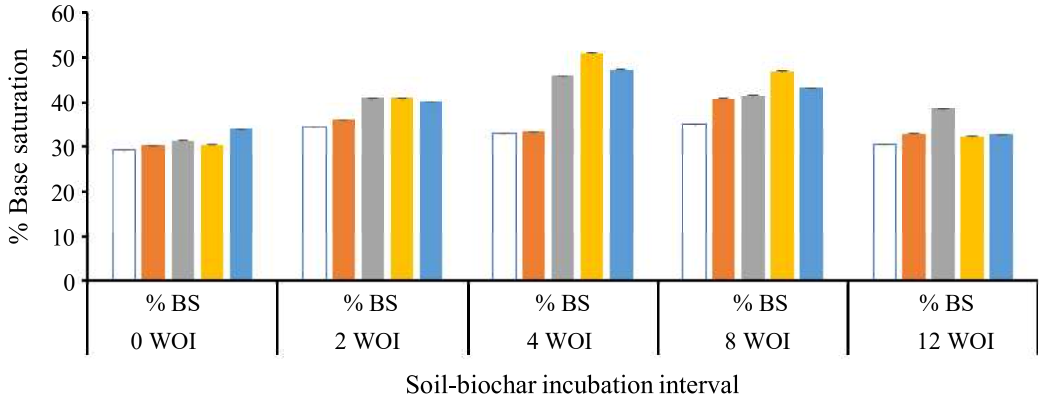

Figure 7. Effects of rice-husk biochar on percent base saturation of the soil under the different soil-biochar incubation intervals. Error bars represent LSD at a 5% probability level ($LSD_{0.05}$). : 0 Mg ha^{-1}, : 7.5 Mg ha^{-1}, : 15 Mg ha^{-1}, : 30 Mg ha^{-1}, : 60 Mg ha^{-1}.

Treatment effects on percent base saturation of the soil at the five soil-biochar incubation periods are presented in Figure 7. The data show that the effects of RHB depend on the duration of the soil-biochar incubation, with the optimum rate generally lying between 15 and 30 Mg ha^{-1}. Relative to the control, 15 Mg ha^{-1} increased base saturation by 18.21% and 25.51% at 0 and 12 WOI, respectively, while 30 Mg ha^{-1} increased base saturation by 82.03% and 34.03% at 4 and 8 WOI, respectively, when mineralisation appeared to have peaked.

The results of the multivariate correlations are shown (Table 3). First, total N that showed to require up to the highest rate of RHB being 60 Mg ha^{-1} was found to have the highest number of predictors, including soil Al^{3+}, H^+, SOC, and pH, which showed best results with 7.5, 60, 60, and 15 Mg ha^{-1}, respectively. Also, R^2 values were highest with this multi-correlation between total N and other soil fertility indices. The next was the apparent CEC that also showed a requirement of 60 Mg ha^{-1}, but correlating with K^+, Ca^{2+}, and total exchangeable bases (being) the sum of the four base-forming cations namely K^+, Ca^{2+}, Mg^{2+}, and Na^+, that showed best results with 30-60 Mg ha^{-1}.

DISCUSSION

The sandy-loam Ultisols of this study, being 'porous'/well-drained and hence highly leached of base-forming cations, were acid and nutrient-poor. It is a common observation in highly leached 'tropical' Ultisols. The generally low initial values of SOC, exchangeable bases, apparent CEC, and percent base saturation represent the typical values for the fallow and/or cultivated soils of the area (Obalum et al., 2011; Onah et al., 2021; Ifeanyi-Onyishi et al., 2024).

Applying RHB led to increases in soil pH and overall fertility status. The liming effect of RHB in this acid soil could be linked to its high pH (8.57) and dominance by alkaline carbonates and alkali earth metals (Li et al., 2016; Dai et al., 2017). Several soil-biochar incubation studies have reported similar increases in soil pH (Van Zwieten et al., 2010; Rogovska et al., 2014; Manolikaki & Diamadopoulos,

Table 3. Results of the multivariate correlations among the soil fertility indices (n = 25).

Soil fertility index and its multi-correlation with others‡	R^2	Adj. R^2	SEE
Total N = $0.883 - 0.760Al^{3+} - 0.111H^+ + 0.321SOC - 0.103pH\text{-}H_2O$	0.853	0.823	0.061
Available P = $-6.987 + 11.690SOC$	0.544	0.524	2.227
Apparent CEC = $2.050 + 7.404Ca^{2+} + 29.487K^+ - 1.601TEB$	0.815	0.788	0.873
Percent base saturation = $31.799 - 26.836Al^{3+}$	0.535	0.514	4.479

‡For the four multivariate correlations shown, all the predictors (constant and independent variables) contributed significantly ($p \leq 0.05$) to the correlations; the only exception was found in the case of total N, where H^+ contributed marginally significantly ($p \leq 0.10$) to the correlation. R^2 - coefficient of determination, Adj. R^2 - adjusted R^2, SEE - standard error of the estimate; SOC - soil organic carbon, CEC - cation exchange capacity, TEB - total exchangeable bases

2017; Ghorbani & Amirahmadi, 2018; Ndzeshala et al., 2023). The treatment effect on soil pH being more negligible at 12 WOI than 4-8 WOI appears to suggest that the liming effect of RHB and other biochars in soils is transient (Hass et al., 2012; Shetty & Prakash, 2020), contrary to that of cattle-dung biochar in the soil studied (Ndzeshala et al., 2023). The most significant increases in soil pH due to 15 Mg ha^{-1} occurring at 8 WOI points to this incubation stage as marking the peak of RHB effects in the soil. This is considering the dependence of especially its P-fertility/productivity on soil pH (Ugwu et al., 2024).

The soil total N data show RHB's effectiveness in N-fertility management of tropical soils (Njoku et al., 2017; Mavi et al., 2018). The increases in soil total N with increasing RHB rate were such that the effect of 60 Mg ha^{-1} was generally higher than those of the lower rates at the different incubation intervals. It was possibly due to the priming effect in this low-SOC soil (see Table 1) at those early incubation stages (Zimmerman et al., 2011), and points to the importance of a high application rate of RHB (Pratiwi & Shinogi, 2016). Compared to the 0 and 12 WOI, the incubation intervals 2-8 WOI were when the effect of 60 Mg ha^{-1} on soil total N content was outstanding. This observation is attributed to decreases in nitrate-N leaching due to the mixing of the rather sandy soil with RHB at this high rate. It shows that any transient effect of biochar in the soil may not be experienced before 8 WOI (Oraegbunam et al., 2022).

The increases in available P due to the RHB were most pronounced at 8 WOI. In our opinion, this observation was a reflection of the priming effect following RHB application, the associated increases in SOC (Ebido et al., 2021) of which, coupled with the unusually wet condition of the incubated soils, caused the pre-analysis conventional air-drying of the soil samples to give higher available P values (Obalum & Chibuike, 2017). The present results are similar to those of Kartika et al. (2021), who found that continuous watering of biochar-treated soil doubled available P, and again indicate RHB effects in the soil peaking at 8 WOI. Chukwuma et al. (2024) reported similar patterns of P release from two sandy-loam soils from southeastern Nigeria (including the one under investigation) following amendment with three animal manures, showing also increases at 8 WOI but with a peak at 16 WOI. The present observation was plausibly due to the oxidic mineralogy of the highly weathered soil investigated and the relatively less dependence of its P sorption/desorption and precipitation on organic amendments (Chukwuma et al., 2024). Compared to Chukwuma et al. (2024), the peak of P release was attained earlier at 8 WOI because manures mineralise relatively slower than biochar.

The apparent decreases in soil content of available P at 8 and 12 WOI may not be associated with any effect of soil pH, showing no corresponding reduction in values. Again, these decreases may not be due to the SOC effect, as there were no corresponding decreases in SOC content with increasing incubation duration (Ebido et al., 2021).

Treatment increased exchangeable bases but decreased exchangeable acidity in this study, an observation that is consistent with other studies (Qian et al., 2013; Shetty & Prakash, 2020). Lehmann et al. (2003) and Chan et al. (2008) also reported similar results, including treatment effects on K^+ and Na^+ being most pronounced at 12 WOI, marking the end of the incubation. However, treatment effects on Ca^{2+} and Mg^{2+} were most pronounced at the beginning of the incubation, which contradicts Silber et al. (2010), who also found that Ca^{2+} released from maize straw biochar increased with decreasing soil pH. The Mg^{2+} but not Ca^{2+} showed a sinusoidal trend, with lowest values at 4 WOI. It was probably because, in the present study, Mg^{2+} was less dependent on soil pH and hence had a weaker competitive ability than Ca^{2+} to occupy the exchange site of the soil under investigation, understandably because of the widely known smaller geo-pedological supply of the former compared to the latter in soils.

To buttress this observed relative dependence of Ca^{2+} and Mg^{2+} on soil pH and their relative contributions to cation exchange, we show the coefficients of their correlations (r) with soil pH to be 0.43 and 0.19, respectively, and with apparent CEC to be 0.80 and 0.25, respectively. The sinusoidal trend observed for Mg^{2+} was not evident for 30 Mg ha^{-1}, a pointer to this rate being the optimum for the management-responsive plant-nutrient exchangeable bases. The observation that the rate of 30 Mg ha^{-1} could enhance the exchangeable bases agrees with Shetty and Prakash (2020).

The decreases in exchangeable acidity of the soil would contribute to explaining the observed liming effect of RHB. Yamato et al. (2006) reported reductions in exchangeable acidity of acid soils amended with biochar derived from Acacia bark. With their porosity and large surface area, biochars can increase the capacity of soils to adsorb acidic cations (Liang et al., 2006; Dang et al., 2018) and/ or to co-precipitate Al^{3+} with silicate clay particles, a situation which fixes this acid-forming cation in soils (Zhao et al., 2015; Qian et al., 2016). The occurrence of Al^{3+} in traces in RHB-amended soils during 2-12 WOI shows that RHB can decrease Al toxicity in soils, as suggested by several reports (Qian et al., 2013, 2016; Xiao et al., 2018).

The increases in apparent CEC may be a product of high Ca and Mg contents and hence high pH of the RHB, alongside its high porosity and specific surface area and associated increases in exchange sites (Masuli et al., 2010; Jien & Wang, 2013). Over time, biochar incorporated into the soil oxidizes and creates negatively charged surfaces, further increasing soil CEC (Mehmood et al., 2018). The rather sandy texture of the soil under study might have contributed to the appreciable effect of RHB on its CEC (Ghorbani et al., 2019). The higher apparent CEC with 30 than 60 Mg ha^{-1} only at 8 WOI could be because it was only at this incubation stage that 30 Mg ha^{-1} showed higher values than 60 Mg ha^{-1} in terms of Ca^{2+} (see Figure 4b) whose contribution to the said apparent CEC of the soil was pretty significant ($r = 0.80$).

Base saturation was perhaps the only index of soil fertility in this study for which RHB applied at 15 or 30 Mg ha^{-1} would be adequate. Similar to our data, Jubaedah and Nurida (2021) reported that RHB improved base saturation by 18%. The present results could be linked to increases in soil pH and exchangeable bases (Jien & Wang, 2013).

This study agrees with Alburquerque et al. (2014) that adding biochar derived from rice straw and husks to the soil can enhance its pH and fertility status. The lowest application rate in this study of 7.5 Mg ha^{-1} always presented an improvement over the control for such critical indicators of soil fertility in the tropics including soil pH (except at 0 WOI) and total N and available P. This was also the case in some of the incubation intervals for the rest of the soil fertility indices. These observations highlight the low-fertility status of these coarse-textured Ultisols and show the high prospects of RHB in their soil fertility management.

Overall, our data suggest that 15, 30-60, and 15-30 Mg ha^{-1} were the optimal RHB rates for improving soil pH, the exchangeable bases, and base saturation, respectively, whereas it was 7.5 Mg ha^{-1} for reducing soil Al^{3+}. The biochar's effect on soil pH reflects phenomena related to the exchange of base/acid-forming cations and decreases in Al^{3+}. One such phenomenon may be SOC mineralisation as defined by the prevailing soil hydrothermal regime (Obalum et al., 2024). The data of the present study also show that soil pH did not increase with the observed increases in the exchangeable bases due to RHB rates above 15 Mg ha^{-1}, suggesting the existence of limits above which biochar-induced increases in base saturation do not contribute to the alleviation of the acidity problem of coarse-textured tropical soils. The highest rate of 60 Mg ha^{-1} generally produced the most significant desired effects on most soil fertility indices, including total N, available P, apparent CEC, and H^+ (NP-CEC/H^+).

Notably, the optimal rate of 60 Mg ha^{-1} for NP-CEC/H^+ also gave the highest increases in soil aggregate stability in this study, which was reported elsewhere (Ebido et al., 2021), suggesting that these two soil parameters are related. Ebido et al. (2021) demonstrated that soil aggregate stability was the key determinant of Celosia argentea growth, while also showing the former's threshold (attainable with < 60 Mg ha^{-1} at 8 and 12 WOI) beyond which C. argentea growth might be impaired. With the implied association between aggregate stability and NP-CEC/H^+, and the threshold values of the former in terms of C. argentea growth, we reason that a similar threshold may prevail for NP-CEC/H^+. So, improvements in NP-CEC/H^+ due to 60 Mg ha^{-1} might engender a situation of 'superfluous' nutrients in the soil, such that RHB effects on soil fertility of coarse-textured Ultisols should be optimum at a rate of x Mg ha^{-1}, whereby $30 < x < 60$.

In proposing the above range of RHB application rate (30-60 Mg ha^{-1}), we considered not only the possibility of attaining threshold values for the parameters in the NP-CEC/H^+ group before 60 Mg ha^{-1}, but also soil pH which showed to require a lower optimal rate of 15 Mg ha^{-1}, as well as apparent CEC which indicated higher values in 30 than 60 Mg ha^{-1} at 8 WOI when RHB effects seemingly peaked. Soil pH plays a critical role in plant nutrient status and crop productivity (Ogunezi et al., 2019; Onah et al., 2021, 2023), just as CEC occupies a central place in indexing soil fertility and crop productivity (Obalum et al., 2013; Nwite et al., 2017). The proposition of 30-60 Mg ha^{-1} as the range of optimum application rate of RHB could be said also to have an agronomic backing, in that the suggested rate for growing C. argentea of 15 Mg ha^{-1} produced similar effect as 30 Mg ha^{-1} for almost all the incubation durations (Ebido et al., 2021).

The results of the multivariate correlations support the adoption of 30-60 Mg ha^{-1} as the optimal range of RHB rate that will take care of all the soil fertility indices considered of the coarse-textured Ultisols investigated. The four predictors of total N are components of apparent CEC, viz. Al^{3+} and H^+ and/or their major influencers viz. SOC and pH (Obalum et al., 2013). Also, a bioavailability association exists between total N and Ca^{2+} in coarse-textured tropical soils under organic soil fertility management (Ebido et al., 2024). Juxtaposing these two considerations, adopting 30-

60 Mg ha^{-1} as the range of application rate resulting in the optimum values of the exchangeable bases that define apparent CEC would be rational.

By examining soil pH data during 2-8 WOI and at 12 WOI, the effects of RHB appear transient. First, ammonia is produced during the decomposition of agro-residues, increasing their alkalinity and hugely contributing to their N content (Nahm, 2003), such that incubation of soil and these residues including biochar often leads to soil N concentration that relates inversely to soil pH (Yuan et al., 2011; Oraegbunam et al., 2023). Supporting further this phenomenon of an inverse relationship of soil pH with total N in biochar-amended tropical soils is the recent report that rice-husk biochar alone enhanced soil pH over its co-application with N-fertilizer in Cote d'Ivoire (Iboko et al., 2025). It is, therefore, unsurprising that 15 Mg ha^{-1} was the optimal rate for soil pH and resulted in the lowest RHB-induced increases in total N whose own optimal rate was 60 Mg ha^{-1}. For the RHB of our study, its high N content could have facilitated soil nitrification, thereby influencing soil pH at 12 WOI - the end of the incubation period (Shetty & Prakash, 2020). Also, the seemingly transient effects of RHB translating into its fast mineralisation suggest that the pyrolysis temperature for its feedstock of 500-550 °C was relatively low (McBeath & Smernik, 2009), and/or that the RHB was rich in ash and aliphatic chemicals (Harris et al., 2013).

Overall, the observed treatment effects on soil pH during 2-8 WOI and the tendency for these effects to be reduced thereafter suggest that the effects of RHB in the coarse-textured Ultisols under investigation peak around the eighth week after its application to the soil. The pattern of treatment effects on soil pH as well as , total N, available P, and CEC supports this inference on the time of peaking of RHB effects in these soils.

CONCLUSIONS

Applying RHB is an effective organic-based soil fertility management option for highly weathered/leached coarse-textured Ultisols. The RHB could lead, generally, to increases in soil pH, total N, available P, exchangeable bases, CEC, and base saturation, but decreases in exchangeable acidity (Al^{3+} and H^{+}) over 12 weeks of monitoring for changes in fertility status of the soils. The optimum application rate would depend on the physicochemical fertility index of interest and/or the time since addition of the RHB amendment when the desired changes are expected to occur within these three months. About 15 Mg ha^{-1} of RHB would be required to optimally increase the soil pH of these Ultisols, even when half of this rate would be adequate for reducing their Al^{3+}. The RHB may need to be added at $\geq$ 60 Mg ha^{-1} for the desired effects on total N, available P, CEC, and H^{+}, but at 30-60 and 15-30 Mg ha^{-1} for such effects on exchangeable bases and base saturation, respectively.

The data attained in this study, put together, form an all-encompassing RHB application rate in the range of 30-60 Mg ha^{-1}. Indications are that the positive effects of RHB on the overall fertility status of the soils may reach the peak around the eighth week, and thereafter become reduced. The proposed range of RHB application rate (30-60 Mg ha^{-1}) to coarse-textured Ultisols would subsist pending when it would be established that those soil fertility indices shown to require at least ($\geq$) 60 Mg ha^{-1} would be improved further at rates over this, and that the alterations in soil pH due to such higher rates would not lead to nutrients imbalance.

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