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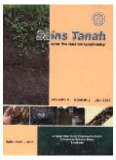

Rice-husk biochar effects on organic carbon, aggregate stability and nitrogen-fertility of coarse-textured Ultisols evaluated using *Celosia argentea* growth

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ABSTRACT

There are insufficient data supporting the enormous potential of biochar in highly weathered tropical soils. This glasshouse study assessed rice-husk biochar (RHB) effects on selected soil quality indices (soil organic carbon, aggregate stability and nitrogen fertility) of sandy-loam Ultisols which were evaluated using spinach (*Celosia argentea*) growth. Five RHB rates 0, 5, 10, 20, and 40 g per two-kg-soil (0, 7.5, 15, 30 and 60 t ha^{-1}, respectively) were studied under 0, 4, 8, and 12 weeks of incubation (WOI). Batched potting of treatments enabled sowing on one date. Treatment effects on soil quality were assessed at sowing and spinach growth six weeks later. Soil organic carbon generally increased with RHB rate, with the greatest increments (37%) in maximum rate relative to no-biochar control for 8 WOI. Aggregate stability also generally increased with RHB rate, the range being 7.21%-17.21% for 8 WOI, beyond which it decreased in 10 and 20 but not 40 g pot^{-1}. Total nitrogen was always highest in maximum rate, increasing with rate only for 8 WOI. Treatment affected plant height more clearly than leaf count. Optimum rates were 5 or 10 g pot–1 for 8 and 4 WOI, respectively (plant height) and 10 g pot^{-1} for 8 WOI (leaf count). Soil organic carbon influenced soil aggregate stability (R^2 = 0.505) which in turn was quadratically related to plant height (R^2 = 0.517), indicating stability threshold for spinach. Adding RHB at 40 g pot^{-1} (≈ 60 t ha^{-1}) to coarse-textured tropical soils is suggested to sustain its soil aggregating effect beyond the growth phase of short-cycle leafy vegetables which require a lower rate (10 g pot^{-1}) 8 weeks before sowing. The observed role of soil aggregate stability in spinach growth rather than the overall effects of RHB should guide further search for edapho-agronomic optimum rate of RHB.

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1. INTRODUCTION

Some agricultural and industrial wastes can be used as organic soil amendments of diverse forms to overcome the challenges of low fertility status of most soils of the tropics and improve agricultural production in the region. Owing to the coarse nature of their texture, the soils of tropical Africa are generally 'porous' (Obalum & Obi, 2014). This situation, coupled with the prevailing tropical climate, implies that the soil resources for agriculture in this region are highly leached of base-forming nutrients, rendering them acidic. The low soil fertility and the adverse impact on food production that is characteristic of tropical African agriculture is epitomized in southern Nigeria (Adubasim et al., 2017; Obalum et al., 2011; Uzoh et al., 2015). The use of organic amendments has been proposed to improve the overall quality of these low-fertility soils (Unagwu, 2019), which often reflects in soil organic carbon (SOC), aggregate stability and nitrogen (N)-fertility (Ogunezi et al., 2019; Umeugokwe et al., 2021). Because of the role of N in vegetative growth of plants, organic amendments have also been used to enhance the yields of particularly vegetable crops in these soils (Nwite et al., 2013; Nwite, Ogbodo, et al., 2012; Ogunezi et al., 2019).

Biochars are organic materials which are charred at temperatures between 300 and 700 °C with little or no oxygen concentrations (Nwajiaku et al., 2018). They have diverse properties depending on the method of pyrolysis and the feedstock used. Biochars improve specific surface area, soil aggregation, bulk density, total pore volume, available water content and permeability of especially sandy soils (Edeh et al., 2020; Ouyang et al., 2013; Pratiwi & Shinogi, 2016). It also improves soil chemical properties such as soil pH, SOC, total N, available phosphorus, cation exchange capacity and exchangeable bases (Abrishamkesh et al., 2015; Adekiya et al., 2019; Yunilasari et al., 2020), thereby making the soil suitable for sustainable crop production.

Biochar influences N transformation through its positive effects on the rates of ammonification and nitrification in soils (Liu et al., 2017; Zheng et al., 2013), and this often leads to increased retention and availability of N in the soil. Research has shown that biochar addition to soils can also increase crop yields (Varela Milla et al., 2013; Yamato et al., 2006). Reviews by Crane-Droesch et al. (2013), Igalavithana et al. (2016), and Chibuike-Ezepue et al. (2019) on the role of biochar in agriculture show that it improves the physical and chemical properties of soils as well as crop yields, and that these benefits are potentially more in highly weathered soils of the humid tropics than in richer soils of the world. In spite of all these pieces of evidence in favour of biochar in especially the humid tropical region, research on its role in soil and water conservation and management is still at the rudimentary stage in Nigeria. There exist several feedstocks for biochar. Plant sources such as wood, palm bunch, sugarcane bagasse, rice husk, etc. are good biochar feedstocks (Kizito et al., 2015; Nwajiaku et al., 2018; Varela Milla et al., 2013).

Feedstock selection has the largest influence on properties of biochars, with specific surface and cation exchangeability being greatest in wood-based and crop/grass residue-based biochars, respectively (Ippolito et al., 2020). These two biochars can thus be similar in sorption capacity. Specifically, rice-husk biochar (RHB) was reported to be comparable to wood-based biochar in absorbing ammonium N from piggery digestate slurry (Kizito et al., 2015). In Nigeria, rice husk (dust) waste is generated in large quantities daily (Nwite, Essien, et al., 2012), but is not as utilized, oftentimes to the detriment of the environment (Adubasim et al., 2018; Baiyeri et al., 2020). Rice husk is, as noted by Ezenne et al. (2019), not readily mineralisable. This attribute makes it a good candidate for conversion to biochar before use as soil amendment. Such conversion may be one way to harness rice husk to the benefit of agriculture and the environment. (Pratiwi et al., 2016) reported that RHB adsorbed ammonium and nitrate forms of N from a loamy soil thereby reducing their leaching and enhancing N-fertility of the soil. Generally, RHB effect in the soil becomes more evident as the application rate increases (Pratiwi & Shinogi, 2016).

Varela Milla et al. (2013) reported better growth of water spinach due to RHB in silt-loam Ultisols in southern Taiwan. The present study utilised RHB on sandy-loam Ultisols in southeastern Nigeria, with *Celosia argentea* (celosia or 'spinach') as test crop. Indications are that the yields of short-duration vegetable crops grown with organic amendment in these soils largely depend on SOC-induced increases in their aggregate stability and N fertility, among other indices of soil fertility (Ogunezi et al., 2019). Spinaches are important leafy vegetables in the tropics. They are associated with high nutritional values (Okorie et al., 2017; Olaniyi & Ojetayo, 2012), especially the young leaves usually harvested at 4–7 weeks of age. The objective of the study was to assess the effects of RHB on SOC, aggregate stability and total N in sandy-loam Ultisols, and to evaluate such effects based on the growth of spinach.

2. MATERIALS AND METHODS

2.1. Soil and its characteristics

The experiment was carried out at the glasshouse from Dec. 2016 to Mar. 2017. Topsoil (0-15 cm) was collected from the University of Nigeria Teaching & Research Farm located at Nsukka campus of the University in southeastern Nigeria. A small portion of the farm under fallow was identified and cleared, after which the topsoil was collected. The soil, deeply weathered brownish red coarse-textured Ultisols, is underlain by false-bedded sandstone. Some physicochemical properties of the soil before the study are shown (Table 1). The textural class is sandy loam, with lower content of silt than clay. As at pre-treatment sampling, key soil fertility indices were rated based on the range of values of each index after Chude et al. (2011); soil pH as strongly acidic (5.0-5.5), SOC as moderate (10-14 g kg^{-1}), total N as low (0.6-1.0 g kg^{-1}), available phosphorus as moderate (7-20 mg kg^{-1}), and exchangeable potassium was very low (0.12-2.0 mg kg^{-1}).

2.2 Biochar production, treatments and experimental design

The feedstock for the biochar was rice husk from the same source (Adani in southeastern Nigeria) as that used by Adubasim et al. (2018). The RHB was produced by pyrolysis (heating with limited oxygen) using an improvised set-up – a 5-L metallic box slightly punctured at the sides and placed on a closed-chamber furnace of burning wood supplying heat at a temperature in the range of 550-600°C.

Table 1. Physicochemical properties of the coarse-textured soil of the study

Soil properties	Values
Clay, < 0.002 mm (g kg^{-1})	160
Silt, 0.02-0.002 mm (g kg^{-1})	90
Fine sand, 0.20-0.02 mm (g kg^{-1})	240
Coarse sand, 0.20-2.00 (g kg^{-1})	510
Textural class	Sandy loam
pH (H_2O)	5.2
pH (KCl)	4.3
Soil organic carbon (g kg^{-1})	12.00
% Aggregate stability	9.24
Total nitrogen (g kg^{-1})	0.70
CN ratio	17.14
Available P (mg kg^{-1})	11.9
Exchangeable K (mg kg^{-1})	0.12
Exchangeable Ca (mg kg^{-1})	1.60
Exchangeable Mg (mg kg^{-1})	0.80
Exchangeable Na (mg kg^{-1})	0.15
Exchangeable H (mg kg^{-1})	1.80
Exchangeable Al (mg kg^{-1})	-
Effective-CEC (cmol kg^{-1})	4.47
% Base saturation	59.73
CEC (cmol kg^{-1})	9.20

Table 2. Some chemical properties of rice-husk biochar

Properties	Values
pH (H_2O)	7.8
pH (KCl)	6.9
Organic carbon (g kg^{-1})	179.60
Total nitrogen (g kg^{-1})	9.81
CN ratio	18.31
K (mg kg^{-1})	0.21
Ca (mg kg^{-1})	2.00
Mg (mg kg^{-1})	1.68
Na (mg kg^{-1})	0.33

The rice husk was placed inside the box and covered with a tight lid before heating was commenced. The box was continuously turned to ensure uniform burning of the rice husk until after about 30 min. when the smoke released from the punctured spots turned light green, an indication that the rice husk had completely charred. Some chemical properties of the RHB so produced are shown (Table 2).

The sampled topsoil was air-dried, sieved with 2-mm sieve and thoroughly mixed. The plastic pots used for the trials (width, 16 cm; depth, 17.5 cm) each received 2 kg of the sieved soil. The factor considered was RHB application rate, and there were five rates (treatments) viz 0, 5, 10, 20 and 40 g pot^{-1}, equivalent to 0, 7.5, 15, 30 and 60 t ha^{-1}, respectively (with soil bulk density assumed to be 1,500 kg m^{-3}). Treatment effects were tested separately for four soil-biochar incubation lengths including 0, 4, 8 and 12 weeks of incubation (WOI). For each incubation length, treatments were replicated three times in a completely randomized design (CRD), giving 15 potted soils per incubation length.

To achieve the four soil-biochar incubation lengths, application of RHB and soil potting was done in four batches of 15 potted soils (for a given incubation length) per batch, to synchronize the serial potting and sowing of spinach seeds, such that sowing was done on one date. Treatments were watered to about 60% water holding capacity. Before sowing, treatments were sampled and the soil samples processed for analyses for SOC, aggregate stability and total N.

2.3 Growing of spinach and agronomic sampling

Four spinach seeds were sown per potted soil. The potted soils were kept moist till seedling emergence three days after sowing. Thereafter, the seedlings were watered to augment the potted soils to field capacity every other day till the termination of the experiment. Weeding was done biweekly by hand picking. Data were collected on plant height and number of leaves per plant at six weeks after sowing. Plant height was taken using a flexible measuring tape from the base of the plant above the soil surface to the tip of the plant. The number of leaves was collected by counting.

2.4 Soil analyses

Soil samples were processed by air-drying to constant weight and sieving with 4.75 and 2-mm sieves before laboratory analyses. Aggregate stability of the soil was determined on the 4.75-2 mm aggregates using the wet sieving method (Kemper & Rosenau, 1986). In this method, 25 g of the aggregates was placed in the topmost of nested four sieves (2.00, 1.00, 0.50 and 0.25 mm). The set-up was first pre-soaked for 5 min. in a pool of water in the wet sieving machine. It was then oscillated 35 times in 1 min. in this pool of water. After wet-sieving, resistant aggregates on each sieve was transferred into beakers, oven-dried at 105°C for 24 h and weighed. Then, all the oven-dried water-stable aggregates (WSA) were merged and subjected to dispersion with 0.1N NaOH, after which the slurry was washed through 0.50 mm sieve to obtain the mass of sand > 0.50 mm. Aggregate stability of the soil was defined as percent WSA corrected for sand content of the aggregates, calculated thus:

$$\text{Aggregate stability} = \frac{\text{mass of WSA} - \text{mass of sand}>0.50\text{ mm}}{\text{initial mass of aggregates} - \text{mass of sand}>0.50\text{ mm}} \times 100\%$$

The SOC was determined by the Walkey-Black's wet dichromate oxidation method (Nelson & Sommers, 1996). Total N in the soil was determined using Kjeldahl digestion-distillation and titration method (Bremner & Mulvaney, 1983).

2.5 Statistical analysis

The data in three replicates were subjected to one-way analysis of variance (ANOVA) for experiments in CRD, using a linear model procedure with the help of the software GenStat Discovery Edition 4. This ANOVA was done separately for each of the four soil-biochar incubation lengths of this study which were 0, 4, 8 and 12 WOI. The least significant difference (LSD) test was used to separate means that were significant at $p \leq 0.5$. Also, pair-wise regressions were explored for the soil and crop data using Microsoft Excel.

3. RESULTS

3.1. Effects of biochar rate on soil organic carbon

The effects of the RHB amendment at varying rates on SOC concentrations in the sandy-loam soil for the four soil-biochar incubation lengths are presented in Figure 1. Generally, SOC increased with an increase in RHB rate; however, this trend tended to be truncated for the incubation length 12 WOI, but the highest values still in the 40 g pot^{-1}. Relative to non-amendment control, this RHB addition rate (40 g pot^{-1}) increased SOC concentration by 27.64, 37.07 and 35.77% for incubation lengths of 4, 8 and 12 WOI, respectively.

3.2. Effects of biochar rate on aggregate stability of the soil

The effects of the RHB amendment at varying rates on aggregate stability of the soil for the four soil-biochar incubation lengths are presented in Figure 2. The data presented show that, with the exception of incubation length of 0 WOI where the optimum rate was 20 g pot^{-1}, soil aggregate stability generally increased with an increase in RHB rate up till 40 g pot^{-1}; therefore, the aggregating effect of RHB in the soil increased with its application rate up till the highest rate. It seems too that 10 g pot^{-1} produced intermediate effects in the soil relative to lower and higher RHB rates, except for 12 WOI when soil aggregate stability did not increase linearly with application rate. The data further show that, at 12 WOI, the application of RHB at 10 and 20 g pot^{-1} reduced its soil aggregating effect, but that 40 g pot^{-1} still gave the highest values of aggregate stability.

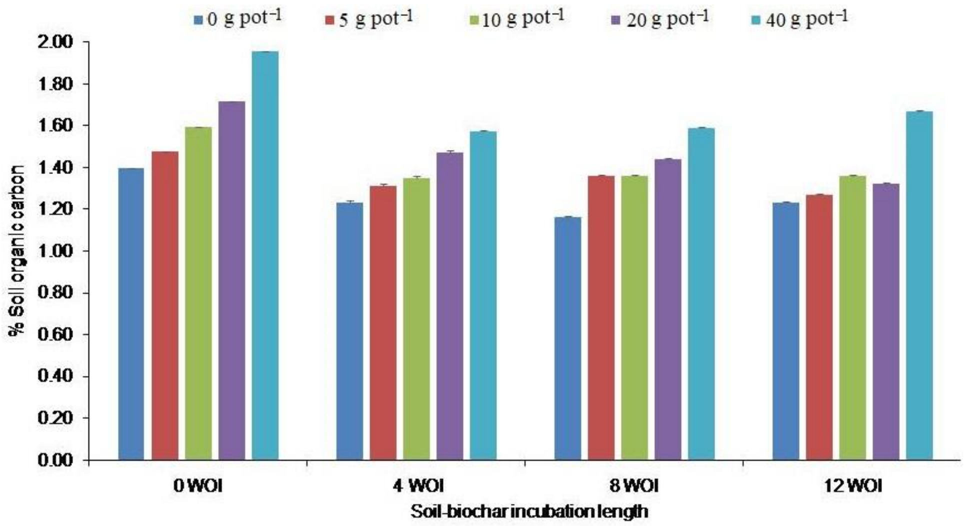

Figure 1. Effect of rice-husk biochar on soil organic carbon concentration in the sandy-loam Ultisols for the four soil-biochar incubation lengths. WOI – weeks of incubation; error bars represent the least significant difference at P ≤ 0.05 ($LSD_{0.05}$).

There was no relationship between RHB-induced variations in aggregate stability and SOC concentration in the soil (R^2 = 0.058; n = 20). The regression was repeated excluding the treatments for the soil-biochar incubation length of 0 WOI, when aggregate stability was yet to benefit from RHB-mediated increases in SOC. This time around, aggregate stability = 19.88SOC – 16.26 (R^2 = 0.505; n = 16). Thus, the RHB-mediated differences in SOC concentration in this sandy-loam tropical soil under investigation accounted for over 50% of the variations in its aggregate stability.

3.3. Effects of biochar rate on total nitrogen content of the soil

Treatment effects on soil total N content for the four incubation lengths are shown (Figure 3). The highest values were always due to the maximum rate of 40 g pot^{-1}. With the exception of 8 WOI, the rates 5, 10 and 20 g pot^{-1} showed no positive effect of application rate of the RHB. Since SOC generally increased with rate, this observation for N led to increases in CN ratio of the RHB-amended soils with rate (data not shown). The control had lower values than the rest for 0, 4 and 8 WOI. By contrast, the control was similar to 10 g pot^{-1} for 12 WOI. Notably, at 10 g pot^{-1}, RHB effect was suppressed for 8 and 12 WOI (Figure 3).

No relationship existed between SOC and total N in the soil (R^2 = 0.045; n = 20). The regression was repeated excluding the treatments for the soil-biochar incubation length of 0 WOI. This time around, the relationship improved, such that total N = 0.628SOC – 0.203 (R^2 = 0.383; n = 16).

3.4. Effects of biochar rate on growth of spinach

Treatment effects on plant height of spinach at six weeks of age are shown in Figure 4. The RHB rates giving the tallest plants were 20 g pot^{-1} for 0 WOI, 10 g pot^{-1} for 4 and 8 WOI, and 20 g pot^{-1} for 12 WOI. Close substitutes to these rates were either those above them (for 0 and 4 WOI) or those below them (for 8 and 12 WOI). For instance, 10 and 5 g pot^{-1} were similar for 8 WOI. Thus, in terms of spinach height, the optimum rates of RHB were 10 and 5 g pot^{-1} for soil-biochar incubation lengths of 4 and 8 WOI, respectively.

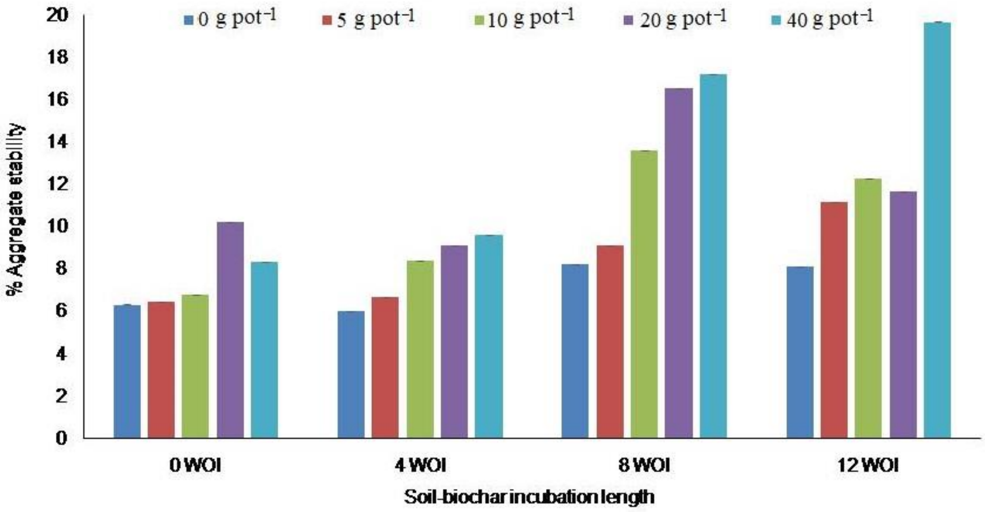

Figure 2. Effects of rice-husk biochar on aggregate stability of the sandy-loam Ultisols for the four soil-biochar incubation lengths. WOI – weeks of incubation; error bars represent least significant difference at P ≤ 0.05 ($LSD_{0.05}$).

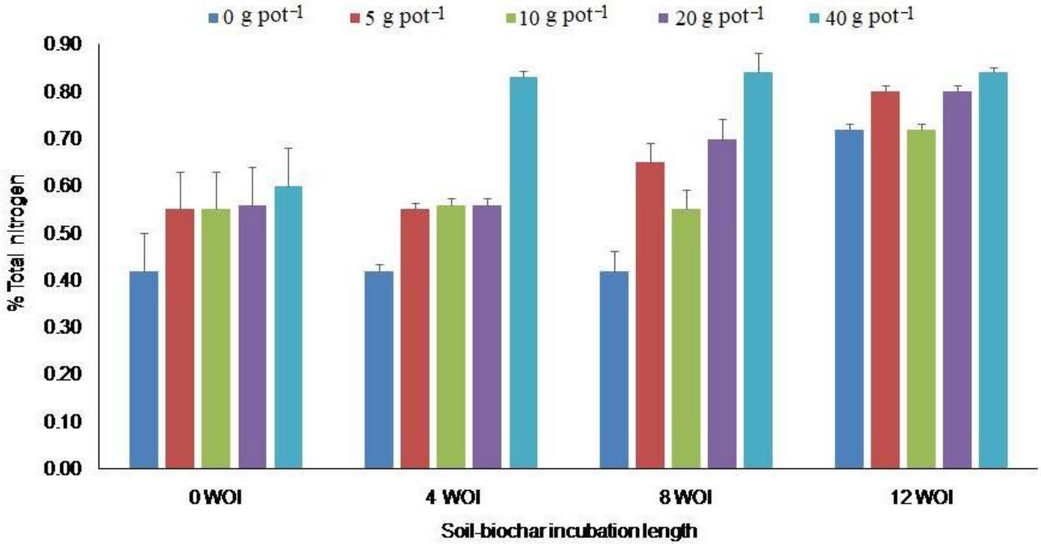

Figure 3. Effect of rice-husk biochar on total nitrogen content in the sandy-loam Ultisols for the four soil-biochar incubation lengths. WOI – weeks of incubation; error bars represent the least significant difference at P ≤ 0.05 ($LSD_{0.05}$).

The data in Figure 4 also show that the control gave the shortest plants across the four soil-biochar incubation lengths; however, it was similar to one or two other higher rates in all four incubation lengths except 8 WOI. The shorter plants in the control compared to the rest only for the 8 WOI is despite the fact that, averaged across RHB rates, this 8 WOI apparently gave the tallest plants among the four incubation lengths.

Treatment effects on the number of leaves per plant when the spinach was six weeks old are shown (Figure 5). The data show that, for two of the incubation lengths of 0 and 4 WOI, all three replicates of all five treatments had an equal number of leaves per plant. Variance only prevailed for 8 and 12 WOI where 10 and 20 g pot^{-1} showed number of leaves per plant different from the rest. However, for 8 WOI, replicates of treatments 10 and 20 g pot^{-1} still had equal values, making the variance to defy analysis. This was not the case for 12 WOI where the number of leaves was higher in 10 and 20 g pot^{-1} than the rest of the treatments. By examining the data for these two incubation lengths, we deduce statistically that for 8 WOI, as with 12 WOI, the number of leaves was equally higher in 10 and 20 g pot^{-1} than the rest.

3.5. The contrast in ecological and agronomic optimum rates

The RHB effects on soil quality indices of this study namely SOC, aggregate stability and total N which define ecological wellbeing showed that the best results were due to the maximum rate of 40 g pot^{-1} for 8 WOI. By contrast, the agronomic traits of plant height and leaf count had optimum rates between 5 to 10 g pot^{-1} for 4 to 8 WOI. Exploring the dependence of spinach growth on soil quality indices of this study, the only meaningful relationship obtained was between plant height and soil aggregate stability, and the best-fit curve was of the quadratic form (Figure 6).

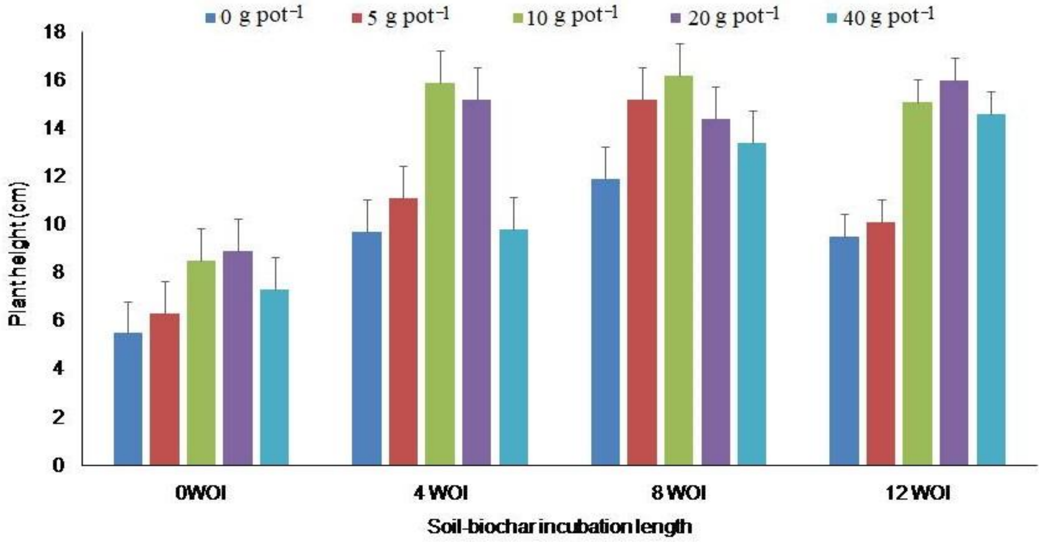

Figure 4. Effects of rice-husk biochar on plant height of spinach at six weeks after sowing for the four soil-biochar incubation lengths. WOI – weeks of incubation; error bars represent least significant difference at P ≤ 0.05 ($LSD_{0.05}$).

4. DISCUSSION

The need to use the biochar technology to improve the quality of coarse-textured Ultisols and vegetable production on them prompted this study on the potential of rice-husk biochar (RHB) as an amendment for the soils. Its effects on selected key indices of soil quality were assessed and such effects evaluated using *Celosia argentea* (celosia, also called spinach). The application of RHB at various rates to the low-fertility sandy-loam Ultisols of this study gave impressive results for the four soil-biochar incubation lengths concerning the selected soil quality indices and spinach growth. Van Zwieten et al. (2010) reported that biochar addition to soil increased its carbon content. In the present study, the results attained for 0 WOI could be viewed as reflecting the soil-biochar mixture, and not RHB's effect in the soil. Therefore, the RHB-mediated enhancement in SOC resides with the longer incubation lengths. The RHB would be expected to have its greatest effect on SOC concentration in the soil around 8 WOI. The SOC occupies a central position in defining soil quality (Obalum et al., 2017); so, RHB is crucial in enhancing the quality of the soil studied.

The increases in SOC with RHB rate were expected. Njoku et al. (2017) attributed high SOC levels due to RHB in Abakaliki area of southeastern Nigeria to high carbon to nitrogen (CN) ratio in RHB. However, Igwe et al. (2013) reported higher SOC due to pseudo-RHB (partially burnt rice husk) than to its feedstock in a lowland soil also at Abakaliki area, even with lower carbon content in the former than the latter. They opined that the ability of an amendment to enhance SOC might depend not on its carbon content, but on its engendering of an enabling environment for the process. Our soil and theirs not only belong to the same textural class (sandy loam), but also are of similar clay contents of 160 g kg^{-1}. It has been suggested that the enabling environment due to biochar to enhance SOC is by affecting the soil carbon environment and proliferation of soil microorganisms (Yan et al., 2019).

Biochar was reported to increase aggregate stability of clayey but not sandy temperate soils (Ghorbani et al., 2019; Soinne et al., 2014). The aggregate stabilizing effect of RHB in our study even increased with rate, highlighting its potential in highly weathered tropical soils. A similar effect of RHB in Guyana was linked to the porous structure of biochar (Persaud et al., 2018). Since SOC enhanced aggregate stability here, RHB stabilization in the soil could be a possible mechanism in the stability of RHB-amended soils. The observed reduction in effects of RHB where it was added at 10 and 20 g pot^{-1} for 12 WOI could be because its effects in sandy tropical soils are short-lived (Persaud et al., 2018), but the further increases in aggregate stability at 40 g RHB pot^{-1} having 2-kg soil (2% wt RHB) for the same 12 WOI suggest that this rate is needed to sustain the beneficial effects of RHB on aggregate stability of such soils for up to at least 12 weeks (three months) after application. At the application rate of 3% wt, Han et al. (2021) reported that biochar slightly reduced aggregate stability of a temperate soil within the first three months, only for improvements in aggregation of the soil to occur at the sixth month of incubation. This, related to our observation, is yet additional evidence of the potential of biochar in highly weathered tropical soils.

The rates 5, 10 and 20 g pot^{-1} had similar total N contents. Similar results were reported for Japanese sandy soil that received biochar up to 20 t ha^{-1} (Uzoma et al., 2011). Our data suggest that RHB rates > 20 g pot^{-1} (30 t ha^{-1}) could enhance the total N status of this low-SOC soil, possibly due to priming effect at those early incubation stages (Zimmerman et al., 2011). Also, our data point to 8 WOI as the best incubation length for realizing the effects of lower RHB rates on total N content of the soil. This is attributed to decreases nitrate-N leaching with an increase in RHB rate, more so as it was mixed (incorporated) with and not applied on the surface of this rather sandy soil (Oraegbunam et al., 2022).

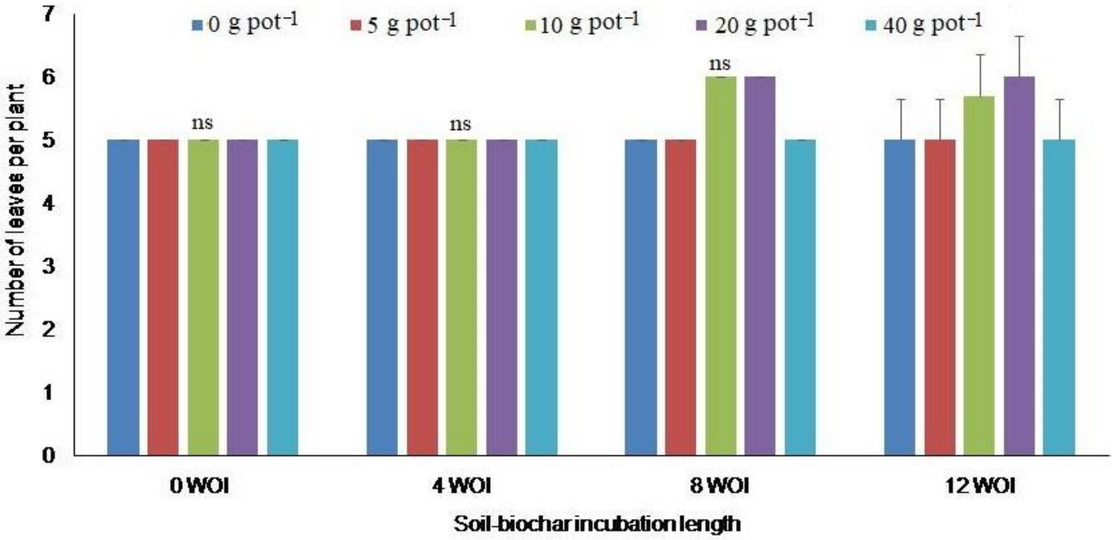

Figure 5. Effects of rice-husk biochar on number of leaves per plant of spinach at six weeks after sowing for the four soil-biochar incubation lengths. WOI – weeks of incubation; ns – non-significant; error bars represent least significant difference at $P \leq 0.05$ ($LSD_{0.05}$).

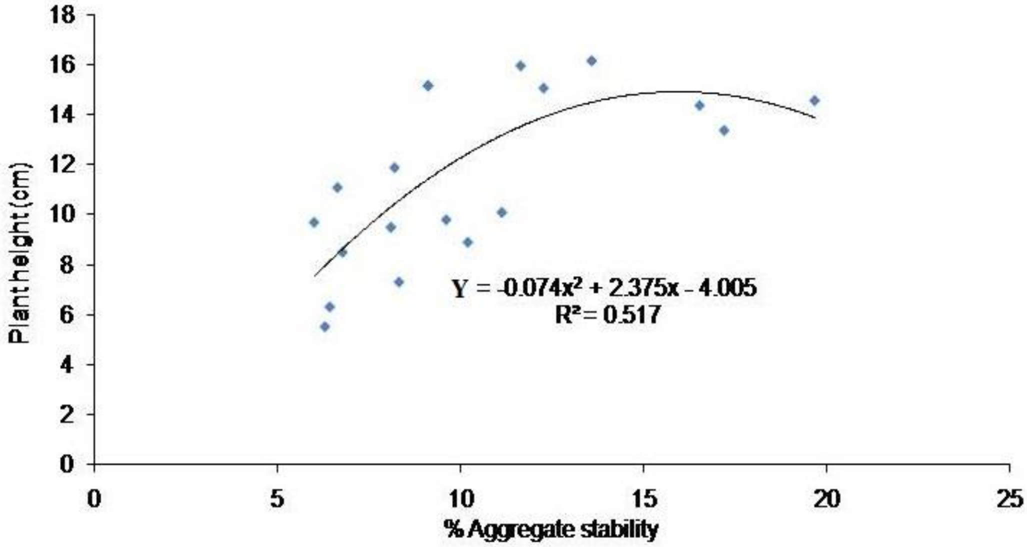

Figure 6. Relationship between plant height of spinach at six weeks after sowing and aggregate stability of the sandy-loam Ultisols as determined at sowing

The lower values in the control than the rest for 0, 4 and 8 WOI support Njoku et al. (2017) and Singh et al. (2018) that RHB increased total N. The control was similar to 10 g pot^{-1} for 12 WOI, suggesting that SOC mineralisation in unamended soils increases with incubation length.

Though the reason for the suppressed effect of 10 g pot^{-1} for 8 and 12 WOI is not clear, it should be recalled that both the soil studied and RHB had fairly high CN ratios of 17.14 and 18.31, respectively (Tables 1 and 2). The value for RHB is plausibly a reflection of its feedstock (rice husk) with a high CN ratio > 47 (Adubasim et al., 2018; Igwe et al., 2013). The CN ratio of RHB was much lower than that of its feedstock. This shows that the high temperatures that prevailed with the improvised pyrolysis used to produce RHB reduced N in the biochar (Chatterjee et al., 2020; Clough et al., 2013; Nwajiaku et al., 2018). It could be that the first 'actual RHB addition' rate (5 g pot^{-1}) and the associated RHB-induced increases in SOC did not, but the second (10 g pot^{-1}) did provoke a rather wide CN ratio in this soil already with an 'unfavourable' CN ratio, and that the ensuing CN ratio in the soil immobilized N.

The regression of SOC on total N in the soil became meaningful (R^2 = 0.383) only after excluding treatments for 0 WOI when there was virtually no SOC-N relationship, probably because of the initial adsorption of particularly nitrate-N in soils amended with biochars produced at high temperatures (Clough et al., 2013; Singh et al., 2018). This suggests that, with respect to N fertility of the soil, RHB may not be as fast mineralizing as inorganic N fertilizers. The regression done of SOC on total N for paddy fields without biochar amendment showed R^2 of 0.185 in a Nigerian tropical environment (Obalum et al., 2012), and 0.988 in a temperate environment (Cheng et al., 2016). The present observation thus shows that an intermediate proportion of total N flows from SOC in RHB-amended tropical soils.

One point implicit in the effects of RHB on spinach height is the underlying role of soil-biochar incubation length in determining the optimum application rate of RHB for spinach. The rates 10 g pot^{-1} (15 t ha^{-1}) and 5 g pot^{-1} (7.5 t ha^{-1}) could be deemed optimum for 4 and 8 WOI, respectively. For fast growth of spinach in these coarse-textured Ultisols, therefore, RHB should be applied at the rate of either 15 or 7.5 t ha^{-1} when seeds are sown four and eight weeks later, respectively. These results that higher rate with shorter incubation and lower rate with longer incubation produced similar effects were probably due to RHB-induced carbon mineralisation cum nutrient release with time.

The RHB effects on plant height show that the increases in the soil quality indices of this study are reflected in spinach growth (Chibuike-Ezepue et al., 2019). The control showed shorter plants than the higher-rate treatments only for 8 WOI which had the tallest plants among the incubation lengths. These observations further support the adoption of 8 WOI as the pre-sowing incubation length. Being a leafy vegetable, spinach should be valued less by plant height than leafiness, such that the optimum RHB rate should be decided giving leafiness due to importance. On this note, treatments 10 and 20 g pot^{-1} produced the highest number of leaves per plant. Because the results were similar for the duo, the lower rate of 10 g pot^{-1} (15 t ha^{-1}) would be adopted as optimum for leafiness in spinach. The growing of spinach and similar short-duration vegetables on sandy-loam Ultisols should, therefore, have RHB applied at 15 t ha^{-1} and the biochar-amended soil allowed for 8 WOI before sowing. This inference aligns with Adekiya et al. (2019) that, for short-duration vegetables, no initial yield benefits should be expected of biochar if added to sandy-loam tropical soils three weeks before planting.

Of the trio of SOC, total N and aggregate stability serving as the indices of soil quality in this study, aggregate stability was the only one whose variations reflected in spinach growth. For the soils under study, cucumber fruit yields and yield attributes were reported to vary with soil aggregate stability (Ogunezi et al., 2019). This earlier observation, supported by ours, shows that the widely held view that soil aggregate stability is not an important factor in arable crop production in the tropics may not hold true for vegetable crops in the coarse-textured Ultisols. In the present study, the relationship between spinach height and aggregate stability was of the quadratic form and hence showed a parabolic shape, suggesting that there is a threshold soil stability value beyond which spinach growth becomes impaired. Similar to this observation, Varela Milla et al. (2013) showed plotted data with a region indicating decreasing stem size of water spinach in RHB-amended soil with an increase in the ratio of water-holding capacity to silt serving as an index of soil aggregate stability in their study.

Spinach is known to be sensitive to N-fertility status of the soil (Olaniyi & Ojetayo, 2012), but this N is highly susceptible to loss through leaching in coarse-textured and well-structured soils. There probably existed an aggregate stability level in RHB-amended soils causing a reduction in the proportion of drainable pores (Edeh et al., 2020), leading to smaller loss of N to leaching in RHB-amended soils with aggregate stability value above this level. This aggregate stability level and associated high N-fertility status were attained in this study where RHB was applied at 60 t ha^{-1}, as supported by higher values of total N observed with this rate compared to the lower rates. However, spinach growth was influenced by soil aggregate stability but not total N, reasonably because these two physicochemical fertility indices of the soil were determined before sowing and not after growth of spinach when the purported reduction in the proportion of drainable pores and leaching of N occurred.

Notably, the maximum RHB rate of 40 g pot^{-1} for 8 WOI giving the highest values of soil quality indices of this study which define ecological wellbeing was different from the agronomically optimum rates found to be lower; between 5 to 10 g pot^{-1} for 4 to 8 WOI. The aforestated increases in CN ratio of RHB-amended soils which might have immobilized N and lowered its availability would partially explain this observation (Uzoma et al., 2011).

5. CONCLUSIONS

Rice-husk biochar (RHB) showed great prospects for the coarse-textured Ultisols especially for the 8 weeks of incubation (WOI) of soil-biochar mixture where the highest application rate of 40 g pot^{-1} (equivalent to 60 t RHB ha^{-1}) gave the greatest enhancement in soil quality indices represented here by soil organic carbon (SOC), aggregate stability and total N. For this 8 WOI, the RHB rate could relate linearly to SOC and total N contents of these soils. The SOC has a strong influence on aggregate stability of the re-structuring RHB-amended soils, and the increases in aggregate stability due to the 60 t ha^{-1} could be sustained for up to 12 WOI. Being that this highest rate of 60 t ha^{-1} produced the best effects, it was possible the optimum rate was not reached in this study.

The rate 15 t ha^{-1} for a soil-biochar incubation interval of 4 WOI and the rate of 7.5 t ha^{-1} for a longer incubation interval of 8 WOI could be substituted in the growing of spinach on coarse-textured Ultisols; however, the former is adopted for enhanced leafiness in spinach. From an agronomic viewpoint, soil aggregation is a major index of quality of these low-fertility soils when managed with RHB as a soil conditioner; the growth of short-duration leafy vegetables could benefit from RHB-induced aggregation of the soils, but might also be retarded beyond a certain threshold value of aggregate stability.

Further research is suggested to determine the exact optimum rate of RHB alongside the minimum time interval between addition and sowing in the production of spinach and similar leafy vegetables. Because of the outstanding role of soil aggregate stability in the current study, this suggested research may consider using as a criterion the rate leading to its value corresponding to maximum growth of spinach in a quadratic function rather than the 'most likely higher rate' giving the optimum values of the other soil quality indices and/or growth attributes of leafy vegetables.

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Declaration of Competing Interest

The authors declare no competing financial or personal interests that may appear and influence the work reported in this paper.

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