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Enhancing soil chemical properties of tropical acrisols using biochar and biochar-compost amendments

Theeba Manickam

Soil Science, Water and Fertiliser Research Centre, MARDI Headquarters, 43400, Serdang, Selangor, Malaysia

Abstract

Tropical soils, such as Malaysia's haplic Acrisols, are often challenged by acidity, low nutrient availability and low productivity. This study investigated the potential of co-composting rice husk biochar (RHBC), a byproduct from local rice mills, with poultry manure to improve these soil conditions. Four soil amendments were evaluated: (1) RHBC alone, (2) composted poultry manure (Co), (3) co-composted poultry manure with RHBC at 5% (Co-BC5) and (4) co-composted poultry manure with RHBC at 10% (Co-BC10), with an untreated control. A 30-day soil incubation experiment demonstrated significant improvements in soil properties, especially with Co-BC10. Soil pH increased by up to 0.8 units, approaching the optimal range for nutrient availability. Total carbon content rose by 26%, with Co-BC10 contributing the most due to the stabilisation of organic carbon. Nutrient availability also improved, with total nitrogen rising by up to 13%, available phosphorus by 26%, and exchangeable potassium by 18%. Among the treatments, Co-BC10 consistently outperformed the others in enhancing soil properties. These results emphasise the potential of Co-BC10 as an effective amendment for tropical soils, offering promising implications for sustainable agriculture. Further research into long-term field applications and higher dosage rates could help optimise its benefits for broader agricultural use.

Keywords: *biochar, compost, poultry manure, haplic Acrisols and cation exchange capacity*

Introduction

Tropical soils are often characterised by nutrient deficiencies due to the rapid mineralisation of soil organic matter (Jenkinson et al. 1991). The incorporation of biochar with organic materials into such soils has gained considerable attention in recent years for its potential to improve sustainable crop productivity and soil fertility (Naeem et al. 2018). Studies have demonstrated that co-composted biochar can significantly enhance soil nutrient content. For instance, Agegnehu et al. (2016) reported improvements in soil organic carbon (SOC), total nitrogen (N), available phosphorus (P), exchangeable calcium (Ca), and cation exchange capacity (CEC) in tropical Ferrallisols amended with co-composted biochar. Similarly, Qayyum et al. (2017) observed that adding 2% garden peat biochar co-composted with farm manure to acidic soils increased soil electrical conductivity (EC), organic matter (OM), nitrogen (N), and potassium (K). Enhanced crop growth in soils treated with co-composted biochar has been attributed to improved nutrient availability and uptake compared to the application of biochar alone (Agegnehu et al. 2016; Schulz et al. 2014). Despite these advancements, there is limited research on using composted rice husk biochar derived from local rice mills in Malaysia to improve weathered soils. Malaysia is among the major rice-producing nations, with a total paddy production of 1.8 million mt in 2020 (Dorairaj and Govender 2023), generating approximately 360,000 tons of rice husk (20% of weight). Rice husks are widely used as a fuel source through gasification in cyclonic furnaces, primarily to generate heat for rice drying. This process produces rice husk biochar (RHBC) as a byproduct, with a recovery rate of approximately 30%, leading to an estimated annual production of 108,000 metric tons of RHBC (Shafie 2015; Pode 2016). Co-composting RHBC with poultry manure or direct application to soil as amendments could unlock its potential for sustainable waste management and improved soil productivity.

Haplic Acrisols, locally known as the Bungor soil series, represent a highly weathered soil type extensively used for agricultural purposes in Malaysia. These soils are

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Author's full names: Theeba Manickam
Corresponding author: theeba@mardi.gov.my

predominantly found in tropical and subtropical regions and are classified under the FAO World Reference Base for Soil Resources (FAO 2015). They are typically characterised by low base saturation, strong acidity (pH <5.5), and a high susceptibility to erosion, making them inherently challenging for sustainable agricultural production. The low cation exchange capacity (CEC) and poor nutrient-holding ability further exacerbate the difficulty in maintaining soil fertility, thereby limiting plant nutrient availability and overall productivity. Despite these limitations, Acrisols are well-suited for certain acid-tolerant and undemanding crops, such as pineapple (*Ananas comosus*), cashew (*Anacardium occidentale*), oil palm (*Elaeis guineensis*) and rubber (*Hevea brasiliensis*), which have been traditionally cultivated on these soils with moderate success (Department of Agriculture Malaysia, 2018). However, their productivity remains constrained without appropriate soil management strategies. The cultivation of short-term vegetable crops and a wider variety of annual fruit crops on Bungor soil requires targeted interventions, including soil amendment practices such as liming, organic matter incorporation, and the application of appropriate fertilisers to improve nutrient availability and soil structure.

To address these challenges, this study investigates the effects of co-composting RHBC with poultry manure on haplic Acrisols. While both compost and biochar are known for their soil-enhancing properties, their co-application provides synergistic benefits that address both short-term and long-term soil fertility challenges more effectively than using either amendment alone. Compost supplies readily available nutrients, promotes microbial activity, and enhances soil structure, while biochar stabilises organic matter, improves nutrient retention, mitigates soil acidity, and increases water-holding capacity. The combination of these amendments creates a more balanced soil environment, reducing nutrient leaching and enhancing overall soil health, which is crucial for sustaining crop productivity in highly weathered soils. Previous studies have highlighted the advantages of incorporating biochar into composting processes. Steiner et al. (2010) reported that co-composting 20% pine chip biochar with poultry manure significantly reduced ammonia (NH_3) and hydrogen sulphide (H_2S) emissions while increasing nitrogen retention in the compost, thereby improving its fertilisation potential. Similarly, Jindo et al. (2012) found that adding 2% oak tree biochar to poultry manure and crop biomass waste positively influenced the chemical and biochemical properties of the resulting compost. Biochar functioned as a bulking agent that facilitated aeration, adsorbed greenhouse gases, controlled odour, enhanced microbial population retention, and improved nutrient and water retention for better plant uptake. Antonangelo et al. (2021) further highlighted the importance of biochar's large specific surface area, high porosity, and polyfunctional groups, which facilitate the composting process and enhance the quality of the final compost product.

Understanding these variations is crucial for identifying the most effective soil amendment strategies to enhance Bungor soil productivity for short-term vegetable and annual fruit crop cultivation. Therefore, this study adopts a full-scale composting approach to evaluate the effects of co-composted RHBC compared to the direct application of RHBC and composted poultry manure in a short-term soil incubation experiment. It is hypothesised that co-composting RHBC with poultry manure will enhance soil fertility and productivity in haplic Acrisols more effectively than applying RHBC or composted manure alone by improving nutrient retention and increasing essential macronutrient levels, including carbon, nitrogen, phosphorus, and potassium. These enhancements are expected to promote more efficient nutrient utilisation, reduce leaching, and provide a more sustainable soil amendment strategy, particularly for cultivating short-term vegetable and annual fruit crops on highly weathered acrisols.

Materials and method

Preparation of biochar and co-composted biochar

A two-kilogram sample of RHBC was collected from five separate piles at the BERNAS Rice Mill in Kuala Kedah and air-dried before analysis and composting. The RHBC was a byproduct of a gasification system utilising a cyclonic furnace at the mill. Compost was prepared by mixing air-dried RHBC with raw poultry manure sourced from a broiler farm in Selangor. Three types of compost were produced: Co-BC10, which contained 10% RHBC and 90% poultry manure; Co-BC5, which contained 5% RHBC and 95% poultry manure; and Co, which consisted entirely of poultry manure. The initial C/N ratio of the composting mixture was approximately 25, based on the C/N characteristics of the raw materials. Manual mixing of RHBC and poultry manure was carried out using a spade to ensure uniform distribution.

Each compost pile was initially set at a weight of 300 kg and positioned on top of covered pallets measuring 1.5 m^2. This setup was designed to control surface volume and prevent contamination from nearby compost leachates. Water was added during the mixing process to regulate the initial composting moisture content, maintaining it at approximately 50 – 60%, which is considered optimal for microbial decomposition (Bernal et al. 2009). During the thermophilic composting phase, when temperatures exceeded 60°C, daily mixing was conducted to promote aeration and uniform decomposition. Water was also added during each mixing event to maintain adequate moisture levels. The composting process was considered complete when the pile's temperature returned to ambient levels and remained stable for one week. Additional indicators of compost maturity, such as the presence of an earthy odor and changes in colour, were assessed following the composting guidelines outlined by Aini et al. (2008)

While the chemical properties of the matured RHBC-manure compost and fresh RHBC, as detailed in *Table 1*, and Scanning Electron Micrograh (SEM) images of RHBC compost shown in *Figures 1* and *2*, were not directly discussed as part of the study's results, they are provided for reference to support the discussion of their effects on soil properties.

Table 1. Chemical properties of co-composted RHBC with chicken manure, composted chicken manure and fresh RHBC (dry weight)

Properties/type of compost	Co	Co-BC5	Co-BC10	RHBC*
Total nitrogen %	1.71 ± 0.02^{b}	1.76 ± 0.02^{ab}	1.81 ± 0.02^{a}	0.6 ± 0.02
Total phosphorus %	1.46 ± 0.03^{a}	1.45 ± 0.02^{a}	1.48 ± 0.04^{a}	0.12 ± 0.01
Total K %	1.80 ± 0.03^{b}	2.12 ± 0.21^{b}	2.19 ± 0.20^{a}	1.2 ± 0.12
Total Ca %	1.44 ± 0.05^{b}	1.69 ± 0.07^{b}	1.78 ± 0.08^{a}	1.1 ± 0.06
Total Mg %	0.91 ± 0.23^{a}	0.97 ± 0.26^{a}	1.0 ± 0.18^{a}	0.25 ± 0.01
pH_{water}	7.0 ± 0.15^{b}	7.45 ± 0.12^{a}	8.4 ± 0.29^{a}	9.1 ± 1.1
Total carbon %	22.5 ± 1.29^{c}	24.2 ± 0.9^{b}	26.2 ± 1.5^{a}	28.5 ± 0.5
Organic matter %	33.2 ± 2.5^{b}	35.8 ± 1.63^{ab}	39.2 ± 0.95^{a}	NA

NA= not available
All values (mean standard error) are the average of three replications of samples: RHBC = Sole RHBC, Co- Poultry manure compost without RHBC, Co-BC5= Poultry manure co-composted with 5% RHBC and Co-BC10 = Poultry manure co-composted with 10% RHBC. Statistical significance at a 95 % confidence interval (p <0.05) based on the Duncan Multiple Range Test (DMRT) is shown by the different letters.
*RHBC properties were not compared with compost statistically

Soil incubation experiment

A 30-day incubation experiment was conducted using haplic Acrisols soil sourced from an undisturbed forest in Serdang, Malaysia. Soil samples were collected from a depth of 0 – 20 cm, air-dried and sieved before use. A total of 100 g of dry soil was placed in 200 mL glass beakers, which were pre-incubated at 70% water-holding capacity for five days to stabilise microbial activity before amendment application. Four soil amendment treatments were applied at a rate of 10 g/kg of soil to assess their effects on soil properties. The treatments were as follows: T1, rice husk biochar (RHBC) alone; T2, composted poultry manure alone; T3, co-composted RHBC (5%) and poultry manure (Co-BC5); and T4, co-composted RHBC (10%) and poultry manure (Co-BC10). The soil amendments were air-dried, sieved and homogenously mixed with the soil before being placed in glass beakers. Additionally, a control treatment without any amendments was included to serve as a baseline for comparison. Each treatment was replicated three times and the beakers were covered with plastic film to allow gas exchange while minimising moisture loss. Throughout the incubation period, beakers were weighed every three days, and water was added as needed to maintain moisture levels. On day 30, soil subsamples were analysed for pH using a 1:2.5 w/v water suspension, total carbon and nitrogen using a Dumas CHNOS analyser, cation exchange capacity (CEC), exchangeable potassium (Exch K) determined using the double leaching method with ammonium acetate (Chapman 1965). In this study, the Bray & Kurtz (1945) method was employed to determine available phosphorus (Avl P). This technique is particularly effective for low-pH soils such as haplic Acrisols, where phosphorus tends to bind with aluminium and iron oxides, reducing its availability to plants. The method utilises a weakly acidic solution of ammonium fluoride (NH_4F) and hydrochloric acid (HCl) to extract phosphorus from soil particles, facilitating its analysis

Statistical analysis

The collected data were statistically analysed using a one-way analysis of variance (ANOVA) in SAS software version 9.4 to determine the effects of different treatments on soil properties. A significance level of 95% confidence ($P \leq 0.05$) was applied to assess whether the observed differences among treatments were statistically significant. To further differentiate and compare the means of individual treatments, the Duncan Multiple Range Test (DMRT) was employed.

Results and discussion

Effect of co-composted RHBC-poultry manure and RHBC on soil chemical properties of haplic Acrisols

Soil pH

All the amended soils exhibited an increase in soil pH compared to the control (*Table 6*) after the 30-day laboratory incubation period. The addition of co-composted poultry manure with RHBC at both rates, sole RHBC, and sole poultry manure compost at the rate of 10g/kg soil or approximately 20 t/ha, led to an increase in soil pH ranging from 0.4 to 0.8 resulting the soil pH of 5.25 to 5.6 from initial 4.8. Specifically, sole application of fresh RHBC and Co-Composted Poultry manure with RHBC at 10% (Co-BC10) application to soil, significantly elevated soil pH (5.6 and 5.5 respectively) compared to other amendments (Co and Co-BC5). According to Islam et al. 1980, the wide majority of mineral nutrients are readily available to plants when soil pH is near to neutral between 5.5 and 7.5, and this is in special important for acidic nature of Acrisols. Although the pH value in RHBC-treated soil exhibited a slightly higher trend compared to Co-BC10 by 0.07 unit, the difference was not statistically significant. The significant increase in pH observed in RHBC-treated soil is likely attributed to its inherently high alkalinity (pH 8.9) relative to the final pH in co-composted RHBC with poultry manure in Co-BC10 (pH 8.2) and Co-BC5 (pH 7.5). The process of co-composting biochar with manure or other organic substrates can moderate its overall pH effect, as the production of organic acids during composting partially neutralises the alkalinity of fresh biochar. This pH-balancing effect is consistent with findings by Bass et al. (2016), who reported that compost (pH 7.5) had a counteracting influence on the higher pH of biochar (pH 8.1).

In a study by Tasneem et al. (2017), biochar from acacia trees (pH 7.2) applied at 20 t/ha showed a considerable increase in soil pH immediately after application at day 0, maintaining the effect during the 50-day incubation period with a maximum increase of 8%. Another study by Kwame et al. (2021) reported that the application of biochar from wood and rice husk increased soil pH by 0.29 to 2.29 units after 30 days of incubation. The effects were more pronounced when biochar was applied at 20 t/ha with compost and co-composted biochar with poultry manure and rice straw, owing to the higher pH value of these combined materials compared to fresh biochar. This is slightly contrary to the findings of the current study. During the composting process of RHBC with manure, the initial pH of the mixture was lower than that of fresh RHBC, with values recorded at 7.0 for Co-BC5 and 7.2 for Co-BC10, whereas fresh RHBC exhibited a pH of 8.9. This initial reduction in pH can be attributed to the dilution effect caused by the lower pH of the manure substrate (6.6), which likely influenced the overall pH of the composting mixture. As the composting process progressed over 60 days, microbial activity and organic matter decomposition led to gradual pH increases due to the breakdown of organic acids and the release of mineral components. However, despite this increase, the final pH of the composted RHBC-manure remained lower than that of fresh RHBC.

The amendment of 10% RHBC in poultry manure in Co-BC10 had a greater effect on soil pH compared to Co-BC5, indicating that the 5% dosage is inadequate to provide a immediate and significant liming capacity in this study. This aligns with a study by Bass et al. (2016), which discussed that soil pH under COMBI (biochar compost) with low dosage did not significantly increase from control. Kwame et al. (2021) also reported that co-composted biochar at 25% with poultry manure and rice straw exhibited the highest pH of 8.5 compared to other biochar compost and fresh biochar in the study, subsequently increased the pH by 2.29 unit after 30 days of incubation. Increasing soil pH is crucial for improving nutrient bioavailability in acidic soils, as most essential nutrients are optimally soluble and accessible to plants within a pH range of 5.5 to 7.5 (Islam et al. 1980). In highly weathered or acidic soils, low pH conditions often lead to nutrient immobilisation, particularly phosphorus, which tends to bind with aluminum and iron oxides, rendering it unavailable to plants. By increasing soil pH, these chemical interactions are reduced, enhancing the release of essential nutrients into the soil solution for plant uptake. Furthermore, maintaining a balanced pH creates a more favourable environment for soil microbial communities, which play a fundamental role in organic matter decomposition and nutrient mineralisation (Rousk et al. 2010). Soil microbes, including bacteria and fungi, are highly sensitive to pH fluctuations, and their diversity and activity are generally suppressed in highly acidic conditions. A shift toward neutral pH not only promotes microbial proliferation but also enhances enzymatic activity involved in organic matter degradation, nitrogen cycling, and phosphorus solubilisation. These microbial-mediated processes contribute significantly to improving soil fertility and sustaining long-term nutrient availability (Aciego Pietri & Brookes 2008).

Additionally, improved soil pH conditions support key biogeochemical processes essential for maintaining soil health and productivity. Enhanced nitrogen transformations, including nitrification and mineralisation, ensure a steady supply of plant-available nitrogen, while increased phosphorus solubilisation prevents nutrient lock-up, making phosphorus more accessible to crops (Zhao et al. 2018). These changes collectively contribute to higher nutrient use efficiency, promoting better plant growth and higher crop yields in previously nutrient-deficient acidic soils.

Total carbon

Total carbon (TC) in all the amended soils were greater than the control with the increase in range (15 – 26%). The TC in soil applied with Co-BC10 and RHBC exhibits similar value and demonstrated the highest increase about 26%, followed by Co-BC5 (by 15%) and Co (by 13%) from initial soil TC value. TC in RHBC and Co-BC10 amended soil is significantly higher compared to Co, indicating decomposition of TC is more stable expected from the addition of recalcitrant carbon from RHBC via both method of applications. This is in accordance to study by Yuan et al. (2017) who stated co-composted biochar effects were more significant than application of compost alone due to greater and more stable organic C, which is resistant biological degradation and consequently enhance soil carbon sequestration.

Kwame et al. (2021) reported TOC increase by 81.5 to 117.3% after 30 days of soil application with the combined application of biochar and compost applied at 40t/ha. While in the current study the increase is lower reflected by the amount of TC incorporated into soil from lower TC content in RHBC and composted RHBC manure as compared to biochar and compost in the reported study which exhibits higher carbon content > 40%. Soil carbon is closely associated with soil organic matter (SOM), a crucial component for improving soil quality by enhancing nutrient availability, water retention capacity, and microbial activity, all of which contribute to increased plant productivity (Agegnehu et al. 2015). The significant increase in total soil carbon (TC) observed in RHBC manure-compost-amended soil indicates an accumulation of SOM, creating a more favourable environment for microbial proliferation and enzymatic activity. Soil microorganisms play a key role in decomposing organic matter, facilitating nutrient mineralisation, and improving soil aggregation, which are essential processes for maintaining soil fertility (Chen et al. 2018; Richardson & Simpson 2011).

Furthermore, biochar-based compost amendments such as RHBC contribute to long-term carbon stabilisation by reducing microbial carbon losses while improving soil aeration and water retention (Lehmann et al. 2011). The increase in SOM not only supports beneficial microbial communities but also minimises nutrient leaching, ensuring essential elements remain available within the root zone for plant uptake (Frimpong et al. 2021). These findings highlight the role of RHBC manure-compost amendments in enhancing soil carbon sequestration, sustaining soil fertility, and ultimately improving crop productivity.

Soil nitrogen, available P and exchangeable K

The application of various soil amendments, including rice husk biochar (RHBC), poultry manure compost (Co), and co-composted RHBC with poultry manure (Co-BC), resulted in a noticeable improvement in soil nutrient content. The increase in TN, Avl P, and Exch K ranged from 3.8% to 13%, 5% to 26%, and 11% to 18%, respectively, compared to the initial nutrient status of the soil. Among the treatments, the co-composted manure with the highest RHBC dosage (Co-BC10) showed the most pronounced nutrient enhancement. Specifically, Avl P and Exch K increased by 9% and 5%, respectively, in the Co-BC10 treatment compared to the manure compost alone. However, TN did not show a significant increase in Co-BC10 relative to the manure compost.

The Co-BC5 treatment, with a 5% RHBC dosage, did not result in significant differences in nutrient status when compared to the Co treatment, indicating that the lower RHBC application did not substantially alter the nutrient dynamics in the soil. While TN increases in Co-BC5 were not significant compared to Co, there was a trend toward higher nitrogen values by 3.5% for Co-BC5 and 5.4% for Co-BC10. This suggests that, although the nitrogen increase was not immediately significant, a higher application rate of co-composted RHBC manure might eventually lead to a greater increase in TN, possibly due to better nitrogen mineralisation facilitated by the higher nitrogen content inherent in the RHBC-manure compost mix. Supporting this observation, a study by Albert and Kwame (2018) showed that biochar compost applied at a 2% rate (approximately 40 t/ha) resulted in a significant increase in soil mineral nitrogen after a 14-day incubation period, compared to the use of biochar or compost alone. This effect was attributed to the enhanced mineralisation of nitrogen in biochar compost due to its higher inherent nitrogen content, which contrasts with biochar's lower nitrogen mineralisation capacity due to its high C:N ratio. These findings align with the current study's results, suggesting that the increased nitrogen availability in the Co-BC treatments was largely driven by the improved mineralisation facilitated by the co-composted materials. Despite a 5% increase in Avl P from the initial soil status, soil amended with fresh RHBC showed significantly lower values compared to co-composted manure RHBC (Co-BC10, Co-BC5), and composted poultry manure in Co. The inherently low nutrient content of RHBC (as shown in *Table 2*) may have played a minimal role in enriching soil phosphorus and nitrogen.

Table 2. Effects of amendments on soil chemical properties

Treatment	pH	N (%)	Avail P (mg/kg)	Exch K (mg/kg)	C (%)	C/N	CEC Cmol (+)/kg
Control	4.68 ± 0.07^{c}	0.060 ± 0.002^{b}	28.5 ± 1.32^{c}	55.2 ± 0.76^{c}	0.76 ± 0.060^{c}	12.6 ± 0.7^{b}	5.6 ± 0.1^{c}
RHBC	5.60 ± 0.1^{a}	0.062 ± 0.003^{ab}	29.0 ± 1.00^{c}	63.3 ± 2.51^{b}	1.04 ± 0.062^{a}	16.8 ± 1.71^{b}	6.26 ± 0.15^{ab}
Co	5.25 ± 0.05^{b}	0.064 ± 0.003^{ab}	32.8 ± 0.76^{b}	62.6 ± 0.57^{b}	0.94 ± 0.04^{b}	14.5 ± 0.05^{ab}	6.10 ± 0.1^{b}
Co-BC5	5.29 ± 0.01^{b}	0.067 ± 0.001^{a}	33.8 ± 0.77^{b}	62.3 ± 1.52^{b}	0.95 ± 0.067^{ab}	14.2 ± 1.04^{a}	6.16 ± 0.15^{ab}
Co-BC10	5.51 ± 0.07^{a}	0.068 ± 0.001^{a}	36.0 ± 1.00^{a}	66.1 ± 1.75^{a}	1.04 ± 0.068^{a}	14.9 ± 1.57^{a}	6.33 ± 0.15^{a}

All values (mean standard error) are the average of three replications of the incubation experiment with treatments: C = control (no amendment), RHBC = Sole RHBC, Co- Poultry manure compost without RHBC, Co-BC5= Poultry manure co-composted with 5% RHBC and Co-BC10 = Poultry manure co-composted with 10% RHBC. Statistical significance at a 95% confidence interval (p <0.05) based on the Duncan Multiple Range Test (DMRT) is shown by the different letters

The highest levels of TN, Avl P and Exch K observed in the Co-BC10 treatment indicate a synergistic interaction between rice husk biochar (RHBC) and poultry manure at a 10% dosage, enhancing nutrient availability for plant uptake compared to other treatments. The increase in soil pH in this treatment likely facilitated greater nutrient retention and release throughout the incubation period. This observation aligns with findings by Sasmita et al. (2017) and Agegnehu et al. (2015), who reported that biochar and biochar compost amendments improve phosphorus availability by mitigating soil acidity, thereby reducing phosphate fixation by aluminum and iron oxides. Although the increase in nutrient content in Co-BC10 was not statistically significant, the stabilisation of soil pH in this treatment may have contributed to maintaining nutrient availability over time (Agegnehu et al. 2015). While microbial diversity was not directly analysed in this study, the observed rise in soil pH in biochar compost-amended treatments, particularly Co-BC10, is expected to influence microbial-mediated nutrient cycling. Soil pH is a major determinant of microbial diversity, enzymatic activity, and biogeochemical processes, as it modulates the composition and functional capabilities of microbial communities (Rousk et al. 2010).

The elevation of soil pH from 4.8 to 5.6 in Co-BC10 falls within the optimal range for bacterial and actinomycete proliferation, microbial groups that play key roles in nutrient mineralisation and organic matter decomposition (Aciego Pietri and Brookes 2008). A shift toward more neutral pH conditions can enhance the activity of beneficial microorganisms, particularly phosphate-solubilising bacteria (PSB) and nitrifying bacteria, which are essential for phosphorus solubilisation and nitrogen transformations, respectively (Zhao et al. 2018). Additionally, biochar's porous structure can serve as a microbial habitat, further promoting microbial colonisation and enzymatic activity (Lehmann et al. 2011). Thus, the pH increase observed in Co-BC10 likely contributed to more efficient microbial-driven nutrient cycling, reinforcing its potential for long-term soil fertility improvement.

SEM images (*Figures 1* and *2*) revealed the intricate porosity of RHBC, with numerous meso- and macropores that physically trap manure particles, supporting the notion of nutrient retention within the biochar structure. The elemental analysis of RHBC compost in Co-BC10 showed the presence of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), silicon (Si), and oxygen (O), confirming that the composted RHBC retains essential nutrients. This observation supports previous research by Nguyen et al. (2004) and Yu et al. (2006), who demonstrated that biochar's porous structure plays a crucial role in retaining nutrients, thus enhancing nutrient availability in the soil. The extent of nutrient retention is largely determined by the particle size of the substrates, as smaller particles are more likely to penetrate the pores and be retained, further increasing nutrient availability for plant uptake.

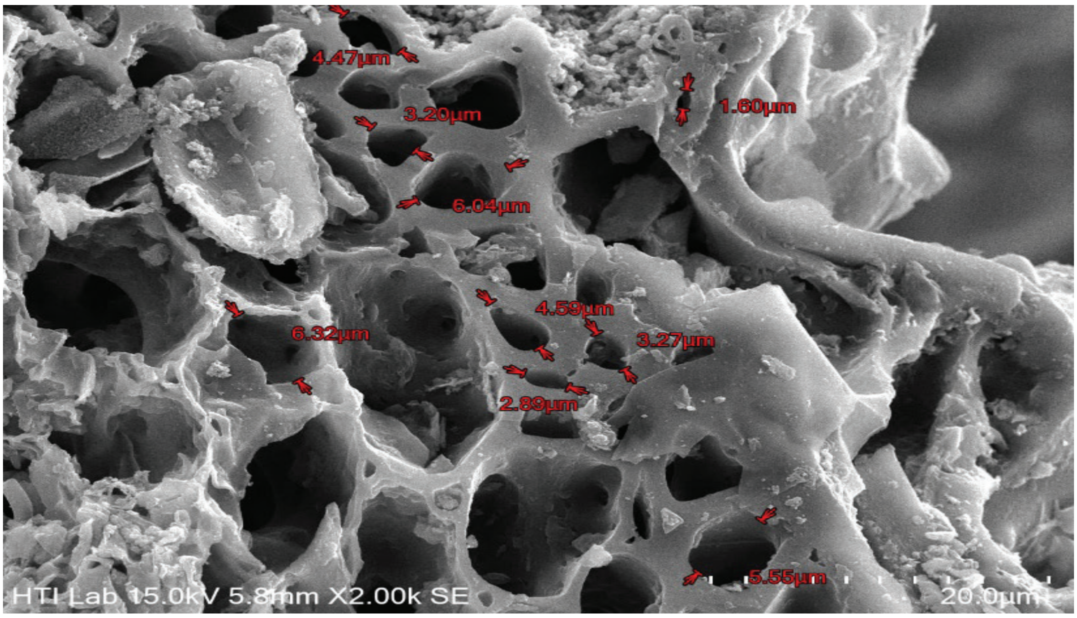

Figure 1. SEM image of the transversal section of RHBC revealing its skeletal structure with pore diameter sizes in µm at a 2000x magnification.

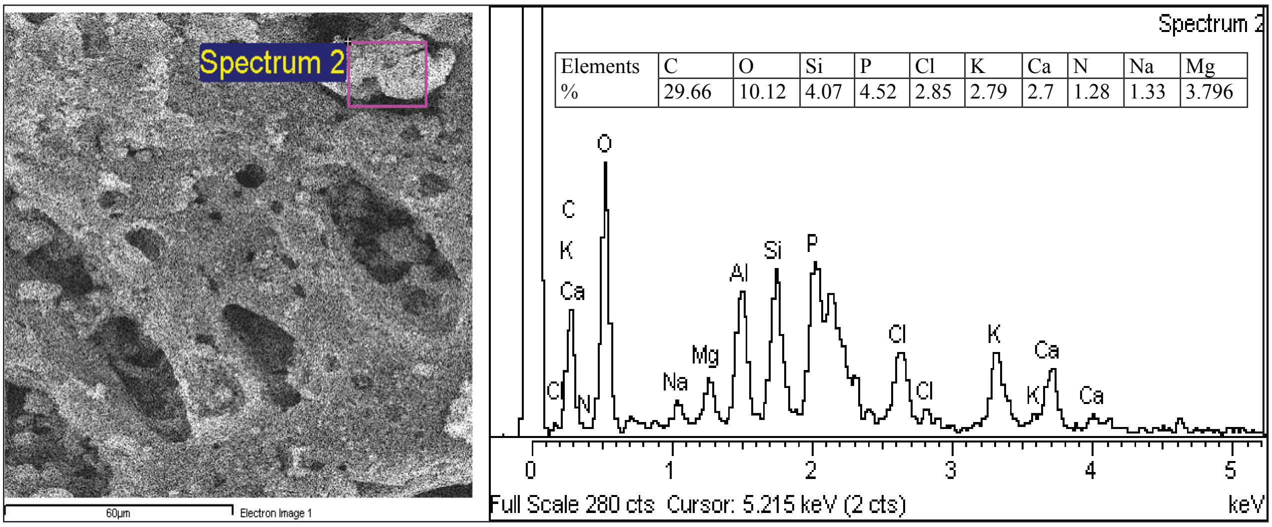

Figure 2. SEM along with EDS analysis of substrate trapped in pore of RHBC in Co-BC10 sample, captured at a magnification of 1500x labeled as Spectrum 2

Soil C:N ratio

Soil treated with fresh RHBC exhibited significantly lower nitrogen content compared to Co-BC10 and showed no significant difference with other treatments. This indicates that a single application of RHBC is insufficient to provide immediate enhancement of the soil nutrient status, aligning with the report by Lehmann and Joseph (2017), which suggests that pure biochar does not directly enrich soil nutrients due to the expected elevated C:N ratio, thereby reducing nitrogen mineralisation. The explanation is supported in this study, where the C:N ratio of RHBC is much higher (47) than in Co-composted RHBC-manure (13-14). Gerald (2019) explained that a C:N ratio of organic substrate between 10 and 15 is optimal for rapid mineralisation of organic matter and release of nutrients for plant uptake. Examining the C: N levels in RHBC and compost substrates, the C:N ratio in soil amended with Co-BC 10 and Co-BC5 showed significantly lower C:N ratios compared to sole RHBC-amended soil. Although not significant compared to soil with sole manure compost application in Co, the increase in C:N ratio was the highest in the sole RHBC-amended plot, rising by 30% from the initial soil C:N level, followed by Co-BC10 (19%), Co-BC5 and Co (about 8%). This implies that the use of 20t/ha for all amendments contributed to achieving a soil C:N ratio between 14 – 16, a balance recommended for organic matter decomposition, nutrient release and plant uptake (Gerald 2019). Nevertheless, Howell (2005) suggests a soil C:N ratio of 24 as optimal for microbes to obtain ample carbon and nitrogen for proliferation, which was not achieved in 30 days of incubation period in the current study.

Soil CEC

The rise in exchangeable potassium is linked to an increase in CEC in soil treated with co-composted RHBC manure (by 12%) and sole RHBC application (10%) from the initial soil CEC value. The immediate enhancement of soil CEC within 30 days of soil incubation in these treatments could be attributed to higher exchangeable bases found in the ash fraction and functional groups, such as carboxylic groups, present in RHBC. This observation aligns with the findings of Nigussie et al. (2012) who reported that the ash in biochar aids in the immediate release of mineral nutrients like calcium and potassium for crop use by improving soil exchangeable bases and CEC. The similar study also showed that the highest increase in exchangeable potassium occurred in biochar compost applied at 40t/ha under haplic ferrallisol soil, exhibiting the highest increase in soil effective cation exchange capacity (ECEC) at 8.56 cmol(+)/kg, consistent with the current study. However, the increase in CEC and exchangeable potassium in the haplic Acrisols of the current study was not as high as study by Albert and Kwame (2018) likely due to the lower dosage of biochar used and its lower concentration in the co-composting with poultry manure.

Conclusion

The application of co-composted RHBC-manure at a 10% dosage (Co-BC10) significantly enhanced soil TN and Avl P in weathered haplic Acrisols within 30 days, outperforming sole RHBC, RHBC-manure compost at 5% (Co-BC5), and sole poultry manure compost. Although sole RHBC exhibited comparable effects on soil pH, Exch K and CEC to Co-BC10, it demonstrated greater effectiveness than sole poultry manure compost. These findings suggest that co-composted RHBC at 10% optimally improves soil chemical properties, offering the most substantial enhancement in soil fertility compared to other treatments during the short-term soil incubation period. However, the results from this controlled laboratory incubation study only provide insights into short-term nutrient dynamics and do not fully capture the long-term stability and sustainability of RHBC compost as a soil amendment. Over time, factors such as microbial decomposition, nutrient leaching and changes in organic matter stability may influence the persistence of these improvements under field conditions. Therefore, long-term field trials are necessary to evaluate the residual effects of RHBC-manure compost on nutrient retention, organic carbon stabilisation, and overall soil health. Additionally, research should focus on determining optimal application rates and amendment frequencies to sustain long-term soil fertility and crop productivity in highly weathered Acrisols.

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