Characteristics of biochar from agricultural residues produced by traditional combustion and its potential as a soil amendment

Ali Rahmat[1], Sukamto[2], Santi Ari Respati[1], Fera Arum[1], Wiwiek Dwi Susanti[1], Yudia Azmi[3], Zurrahmi Wirda[4]

[1]Research Center for Limnology and Water Resources, National Research and Innovation Agency, Jakarta, Indonesia
[2]Department of Agricultural Product Technology, Faculty of Halal Industry, Universitas Nahdlatul Ulama Yogyakarta, Yogyakarta, Indonesia
[3]Department of Agrotechnology, Institut Teknologi Perkebunan Pelalawan Indonesia, Pangkalan Kerinci, Indonesia
[4]Department of Agroecotechnology, Faculty of Agriculture, Universitas Malikussaleh, Lhokseumawe, Indonesia

Article Info

Article history:

Received Feb 5, 2025
Revised Apr 23, 2026
Accepted May 22, 2026

Keywords:

Agriculture waste
Biochar
Pyrolisis
Soil improvement
Traditional burning

ABSTRACT

Biochar is a carbon-rich material produced through pyrolysis. However, pyrolysis methods that generate high-quality biochar typically require expensive equipment and technical expertise. This study examines the characteristics of biochar produced from rice husk, cassava wood, and corn cobs using a traditional burning method as an alternative to pyrolysis. The research results showed that the carbon content of biochar produced using traditional methods was comparable to, or even higher than, biochar produced using more advanced pyrolysis methods. Corncob biochar had the highest carbon content among all samples. X-ray fluorescence (XRF) analysis revealed that rice husk biochar had the highest silica content, while cassava wood biochar showed higher percentages of calcium (Ca) and magnesium (Mg) than the other biochars. X-ray diffraction (XRD) characterization results indicated a higher degree of graphitic crystallinity in the corncob biochar, while Fourier transform infrared spectroscopy (FTIR) spectra confirmed the presence of hydroxyl groups, aromatic C=C, and cellulose residues in all samples. thermogravimetric–differential thermal analysis (TG-DTA) and differential scanning calorimetry (DSC) analyses provided insights into thermal behavior and carbonization levels, with corncob biochar having the highest carbon content and thermal resistance. The application of biochar to acidic soils has been shown to significantly increase soil pH and organic carbon content. The simple combustion method used in this study is capable of producing biochar with diverse physicochemical properties, thus offering a sustainable approach to soil improvement, increased nutrient retention, and carbon sequestration, while providing added value to agricultural waste and waste valorization strategy.

Corresponding Author:

Santi Ari Respati
Research Center for Limnology and Water Resources, National Research and Innovation Agency
Jakarta, Indonesia
Email: sant013@brin.go.id

1. INTRODUCTION

Indonesia is an agricultural country where one of the pillars of the national economy is the agricultural sector. The vast agricultural areas with a wide variety of crops, especially food crops, produce post-harvest waste. If unmanaged, this waste can cause environmental problems or serve as a host for pests and diseases [1]. In sustainable agriculture, agricultural waste should not be a burden but rather a valuable resource [2]. As the global population continues to rise, impact on increasing the demand for food, putting immense pressure on soil health and natural resources [3]. Amidst this challenge lies an opportunity to repurpose agricultural residues such as cassava wood, rice husks, and corn cobs into biochar as a soil amendment that holds significant promise for improving soil condition [4].

Soil amendment with biochar is recognized as a significant method for enhancing soil ecological functions and serves as a crucial strategy for addressing climate change by sequestering CO_2 in the earth [4], [5]. Biochar is associated with its capacity to mitigate climate change via carbon sequestration in the soil. Biochar exhibits properties such as resistance to microbial degradation and chemical transformation [6]. The characteristics of biochar, including its porous structure, high cation exchange capacity, and capacity for nutrient retention, markedly enhance soil fertility, water retention, and microbial activity [7]. The quality of biochar is contingent upon the material utilized and the production methods employed.

Biochar is typically produced through pyrolysis, the thermal decomposition of organic material in limited oxygen. This method is well-established and widely studied for its ability to yield high-quality biochar with consistent properties [8]. However, pyrolysis often requires costly equipment and technical expertise [9], limiting its accessibility, especially among smallholder farmers in rural areas. In contrast, simple combustion, a traditional open burning technique, offers a more accessible and low-cost alternative for producing biochar on a community scale [10]. While this approach lacks the precise control of modern pyrolysis, it aligns well with the principles of local resource utilization and circular economy, making it particularly relevant in low-resource agricultural settings.

Historically, the concept of enhancing soil using charcoal-based amendments is not new. Indigenous Amazonian communities have practiced the creation of *terra preta*, or "dark earth," for centuries. These highly fertile soils were enriched with organic waste and charcoal, demonstrating long-term improvements in crop productivity and soil stability. The *terra preta* model has since inspired contemporary efforts to use biochar as a regenerative farming input that both revitalizes degraded soils and contributes to climate change mitigation [11].

Based on this traditional knowledge, this study explores the fabrication of terra preta-inspired biochar using local agricultural residues through a simple combustion method. This research focuses on materials commonly found as waste in tropical agriculture, particularly in Indonesia, such as rice husks, cassava wood, and corn cobs, which are generally abundant. By examining the structural, chemical, and thermal properties of the resulting biochar, additional tests on infertile soils were conducted to assess its potential as a sustainable soil amendment and support its application in resource-constrained communities.

2. METHOD

This study comprises three main stages: i) sample preparation and biochar production; ii) characterization and analysis; and iii) soil amendment trials. Agricultural waste feedstocks are rice husk, cassava wood, and corn cob, were converted into biochar using a traditional combustion technique. The resulting biochar was then dried, ground, and sieved prior to further analysis. Characterization involved assessing the chemical composition, thermal stability, and structural properties of the biochar using various analytical techniques. Ultimate analyses were conducted to ensure a comprehensive evaluation of the material's properties.

2.1. Feedstock preparation and biochar production

Biomass feedstocks such as rice husk, cassava wood, and corn cob were collected from local farmers in the Natar Sub-district, South Lampung District, Lampung Province, Indonesia. These materials, primarily derived from agricultural waste, were air-dried prior to use. The cassava wood was roughly cut into pieces of 3–10 cm, while the small-sized corn cobs required no pre-treatment.

The biochar production was conducted using a traditional open burning method commonly practiced by local farmers, as shown in Figure 1. The feedstocks were ignited using a small amount of fuel and paper explained in Figure 1(a). As combustion began, additional biomass was added on top to smother the flames and reduce oxygen availability, an essential condition for achieving carbonization through incomplete combustion. This process continued for several hours, depending on the amount and density of the material. The burning was considered complete when the smoke changed from dense white to light blue or translucent. The fire was then extinguished with water to stop further combustion, as explained in Figure 1(b). The resulting biochar was cooled to room temperature and sun-dried until fully dry, as shown in Figure 2.

Once the biochar products, cassava wood in Figure 2(a), rice husk in Figure 2(b), and corn cob in Figure 2(c), underwent drying and packaging, they were transported to the Research Center for Limnology and Water Resources, part of the National Research and Innovation Agency (NRIA), in Cibinong Subdistrict, Bogor District, West Java, Indonesia. The samples were then oven-dried at 105 °C for 24 hours, cooled, crushed, and sieved using a 60-mesh sieve. Only the fraction passing through the sieve was used for further analysis.

(a) (b)

Figure 1. Traditional biochar production in (a) feedstock burning and (b) final biochar product

(a) (b) (c)

Figure 2. The appearance of the biochars made by (a) cassava wood, (b) rice husk, and (c) corn cob

2.2. Characterization of biochar

The functional groups present in the biochar materials were identified using Fourier transform infrared (FTIR) spectroscopy (FTIR-UATR, PerkinElmer spectrum two). Thermal stability and biomass content were evaluated through thermogravimetric-differential thermal analysis (TG-DTA). The chemical and oxide compositions were determined using X-ray fluorescence (XRF) spectroscopy (Omnian ED-XRF, PANalytical Epsilon 3 XLE). Ultimate analysis was performed using a Leco CHN 628 analyzer, with ASTM D5373 for carbon (C), hydrogen (H), and nitrogen (N), and ASTM D4239 for sulfur (S).

2.3. Soil amendments trials

The soil used in this study was ultisol, which is known for its acidic properties. Soil samples were collected from the area surrounding the Research Center for Limnology and Water Resources. After collection, the soil was air-dried for 4–7 days, then crushed and sieved using a 2 mm mesh. A 1 kg portion of the sieved soil was weighed for each experimental unit. The experiment consisted of four treatments: no biochar (B0), rice husk biochar (B1), cassava wood biochar (B2), and corn cob biochar (B3), each applied at rate of 50 tons per hectare. Each treatment was replicated three times, resulting in total of 12 experimental pots. All treated soils were then incubated for 85 days. Two main soil parameters were measured: soil pH and soil organic carbon content. Soil pH was measured using a Horiba LAQUAtwin pH-11, while soil organic carbon was analyzed using the Walkley and Black method.

2.4. Data analysis

This study obtained two types of data: biochar characteristics and soil amendment test results. The biochar characteristics were analyzed descriptively by comparing each biochar type based on the measured parameters. Meanwhile, data from the soil amendment test were analyzed using analysis of variance (ANOVA) at a 5% significance level. If the ANOVA results showed significant differences between treatments, the analysis was continued with the least significant difference (LSD) test as a further test.

3. RESULTS AND DISCUSSION
3.1. Characteristics of biochar

The ultimate analysis data (C, H, N, S) in Table 1 and the elemental content from the XRF analysis in Figure 3 illustrate the chemical composition of biochar produced via the simple combustion method. Table 1 indicates that the carbon content of the biochar varies between 38.73% and 80%. Corn cob biochar exhibited the highest total carbon content at 80%, followed by cassava wood biochar at 64.09%. In contrast, rice husk biochar demonstrated the lowest carbon content at 38.73%.

Table 1. Ultimate content of rice husk, cassava wood, and corn cob biochar

Parameter	Ultimate						
	Unit	Rice husk	Rice husk [x]	Cassava wood	Cassava wood [y]	Corn cob	Corn cob [z]
Carbon	%	38.73	35.67	64.09	58.46	80.00	71.49
Hydrogen	%	2.14	2.17	2.68	2.25	2.14	3.06
Nitrogen	%	0.18	0.73	1.54	1.28	0.47	0.85
Sulphur	%	0.09	-	0.15	-	0.05	0.03
Oxygen	%	12.00		11.96	-	8.29	10.26

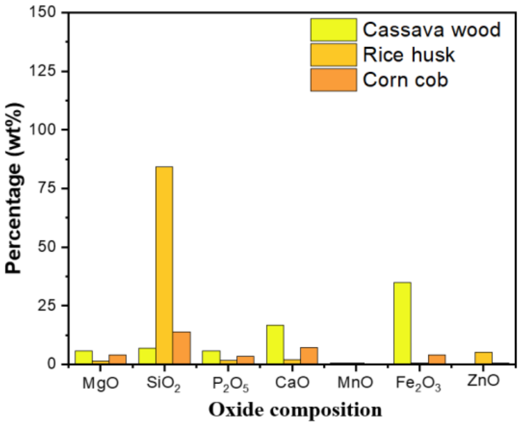


Figure 3. Oxide content on the three different biochars

The hydrogen content across the three types of biochars exhibited a comparable range of 2.14–2.68%. Cassava wood biochar exhibited the highest nitrogen content at 1.5%, whereas the other two biochars recorded levels below 0.5%. The highest sulfur content was identified in cassava wood biochar at 0.15%, whereas the other two types exhibited levels below 0.1%.

Cassava wood biochar exhibits higher nitrogen and sulfur contents compared to other biochars; however, these values remain relatively low. This aligns with the properties of biochar, which does not possess high nitrogen or sulfur content as a fertilizer. In assessing biochar quality, the primary parameter of concern is carbon content, as biochar is recognized as a carbon-rich material. The carbon content of the biochar in this study was significantly affected by the type of raw material utilized.

Table 1 presents the data from this study alongside comparative data from previous studies that utilized furnaces or more advanced equipment for biochar production. A prior study utilized a furnace for the production of rice husk biochar, maintaining a pyrolysis temperature of 450 °C for a duration of 4 hours [12]. In comparison to the findings of this study, the carbon content of biochar generated through traditional methods was found to be 3% higher than that of biochar produced using the advanced method. Previous research indicated that pyrolysis of cassava wood biochar in a furnace at temperatures ranging from 450 to 500 °C resulted in a carbon content of 58.46% [13]. This value is roughly 6% lower than the carbon content of cassava wood biochar generated through the simple combustion method employed in this study. A comparable trend was observed for corn cob biochar; biochar generated in a pyrolysis reactor chamber at 500 °C for 1 hour exhibited a carbon content of 71.49% [14], which is 8.5% lower than that of simple combustion-produced corn cob biochar.

The findings suggest that a straightforward, simple combustion method can yield biochar with a carbon content comparable to, or exceeding, that of biochar generated through more sophisticated pyrolysis techniques. This suggests that simple combustion/traditional combustion methods may be more widely adopted by small-scale farmers, primarily because of their simplicity and the absence of specialized equipment needed. The XRF analysis revealed the elemental and oxide composition of the biochars, which directly influence their potential application as soil amendments. As shown in Figure 3, the rice husk biochar exhibited an exceptionally high silica (SiO_2) percentage of 84.24%, consistent with the inherently high silica concentration typically found in rice husks (15–20%) [15]. Elevated silica levels in soil are beneficial, as they enhance plant tolerance to abiotic stress, improve photosynthetic efficiency, and increase overall crop productivity [16].

The cassava wood biochar contained the highest phosphorus percentage (5.90% P_2O_5), followed by corn cob (3.46%) and rice husk (1.72%). Phosphorus is a critical macronutrient for plant development, and biochar enriched with P_2O_5 may enhance phosphorus availability and retention in soil systems [17]. Moreover, the cassava wood biochar also showed the highest calcium oxide (CaO) percentage at 16.85%, in comparison to corn cob (7.20%) and rice husk (2.05%). The presence of CaO contributes to soil pH regulation, which in turn facilitates improved nutrient availability and supports microbial activity in acidic soils [18].

Additionally, the cassava wood biochar exhibited a considerably higher iron oxide (Fe_2O_3) percentage (35.02%) compared to corn cob (4.22%) and rice husk (0.69%). Iron oxides in biochar play a significant role in promoting the immobilization of heavy metals, thus contributing to potential applications in soil remediation. The biochars also contained varying levels of other metal oxides, including magnesium oxide (MgO), manganese oxide (MnO), and zinc oxide (ZnO), which may contribute to nutrient supply, catalytic activity, and other beneficial soil interactions [19].

The thermal behavior and degradation profile of biochars derived from rice husk, cassava wood, and corn cob were examined using thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC), as shown in Figure 4. These analyses provided valuable insights into the thermal stability and degradation patterns during biochar formation. The TGA curve in Figure 4(a) showed a significant mass loss below 200 °C for all biochar samples, indicating moisture evaporation [20]. This was supported by DSC in Figure 4(b), which showed an endothermic peak near 70 °C, corresponding to water loss [21].

DSC results also revealed an exothermic event around 98 °C, likely related to the oxidation of residual organic compounds and the formation of carbon. Notably, the rice husk biochar showed a lower negative heat flow than the cassava wood and corn cob biochars. This is likely due to its high silica content (15–20%), which acts as a thermal insulator and reduces overall heat flow during analysis [22].

The TGA results further indicated differences in carbon content among the samples: cassava wood (75.2 wt%), rice husk (78.25 wt%), and corn cob (83.21 wt%). These differences align with the feedstocks' natural compositions. Corn cob has the highest cellulose and hemicellulose content (70–80%), followed by rice husk (54–70%), and cassava wood (40–62%). Higher carbohydrate content leads to greater carbon formation during pyrolysis, which explains the higher carbon yield in corn cob and rice husk biochars compared to cassava wood.

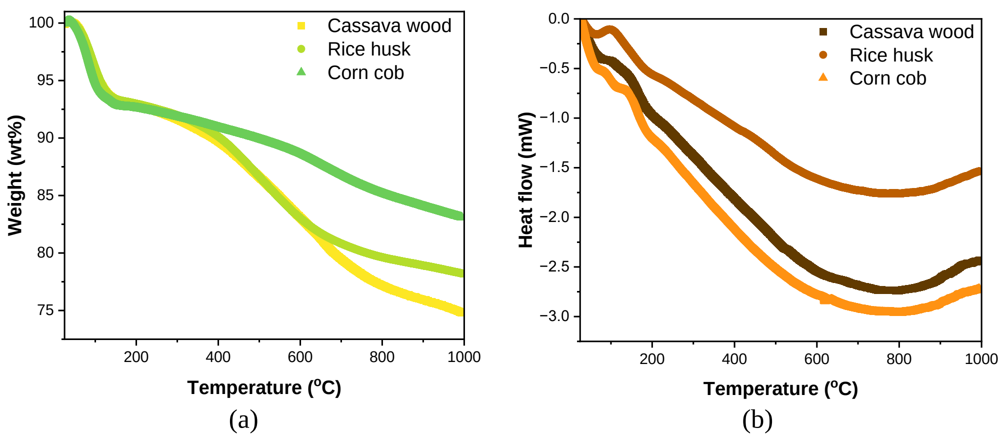
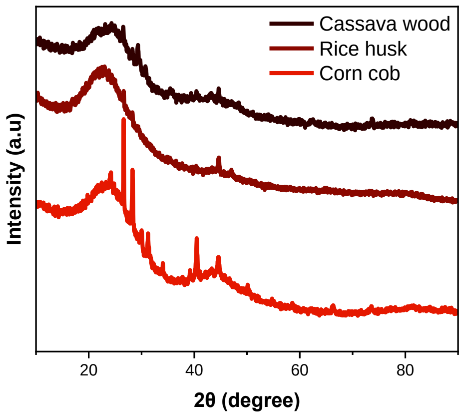


Figure 4. Thermal analysis of three biochar samples in (a) TGA and (b) DSC profiles

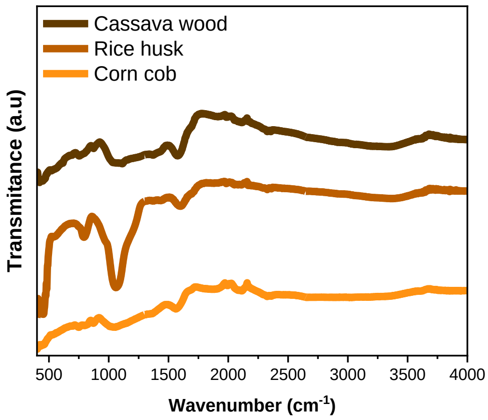
Figure 5 shows the structural characterization of three biochar samples. The X-ray diffraction (XRD) analysis of biochars derived from rice husk, cassava wood, and corn cob revealed distinct crystalline features associated with their original chemical compositions, as shown in Figure 5(a). All samples exhibited a broad peak around 2θ=22.96°, which corresponds to the (002) plane of graphitic carbon and indicates the presence of disordered or amorphous carbon formed from the thermal degradation of lignocellulosic components such as cellulose, hemicellulose, and lignin [23]. Among the samples, corn cob biochar exhibited a relatively higher degree of structural ordering, as evidenced by more pronounced diffraction peaks at 2θ=26.72°, 28.2°, 40.6°, and 44.76°. Following the assignment in [24], these peaks can be attributed to the 002, 100, and 101 planes of turbostratic carbon structures and/or crystalline mineral phases, suggesting the development of more ordered carbon domains during pyrolysis.

The enhanced structural ordering of corn cob biochar can be attributed to its greater cellulose and hemicellulose content (70–80%) compared to rice husk (54–70%) and cassava wood (40–62%). These carbohydrate polymers decompose during pyrolysis and promote the development of graphitic structures. Consequently, all biochar samples exhibited diffraction features in the range of 2θ=43–45°, which are commonly associated with turbostratic carbon structures corresponding to the 100/101 planes. The broad peaks observed in cassava wood and rice husk biochars indicate highly disordered aromatic carbon domains, whereas the more pronounced peak in corn cob biochar suggests a relatively greater structural alignment after carbonization [25]. Overall, the XRD results demonstrate that feedstock composition strongly influences the structural characteristics of biochar. The higher structural ordering observed in corn cob biochar may be beneficial for applications such as energy storage, catalysis, and adsorption, where improved carbon organization can enhance material performance [26].

The FTIR spectra of the three biochars, shown in Figure 5(b), display a broad band around 3,500 cm^{-1}, which corresponds to O–H stretching vibrations. A peak at 1,587 cm^{-1} is attributed to C=C stretching in aromatic structures. The peak at 1,062 cm^{-1} is characteristic of C–O–C vibrations from the active ethers or esther in cellulose and hemicellulose, indicating that some polysaccharide structures were not completely decomposed during pyrolysis [27]. In the rice husk biochar, this band appears more intense due to overlapping Si–O–Si stretching and bending vibrations, which originate from the silica content.



(a)



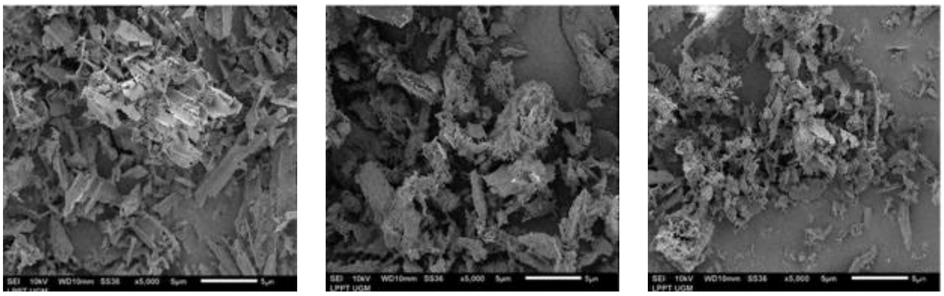
(b)

Figure 5. Structural characterization of three biochar samples in (a) XRD patterns and (b) FTIR spectra

The scanning electron microscopy (SEM) images in Figure 6 illustrate the surface morphology of cassava wood, rice husk, and corn cob biochars. The cassava wood biochar in Figure 6(a) exhibits a rough and porous surface with numerous cavities and crevices. This irregular and randomly shaped porosity results from the release of volatile matter during pyrolysis [28]. The particle sizes range from small, irregular fragments to larger, compact aggregates, indicating a broad distribution of pore sizes and surface areas. Small particles scattered on the surface may represent remnants of cellulosic fibers embedded within a carbonized lignin matrix, which contributes to the black appearance of the biochar.

The rice husk biochar in Figure 6(b) exhibits a smoother and more uniform surface compared to cassava wood biochar. This can be attributed to the high silica content in rice husk, which hinders the pore development of biochar [29]. The particles are generally smaller and more consistent in size, and large aggregates are less prevalent. Small, spherical features on the surface may represent silica or other mineral components derived from the original biomass.

The corn cob biochar in Figure 6(c) has a surface morphology that lies between the smooth structure of rice husk and the porous surface of cassava wood biochar. It contains both small pores and larger, asymmetrical particles. The particle size distribution ranges from compact aggregates to fine, irregular fragments, suggesting a heterogeneous surface structure. Scattered small particles could be residual fibers, while the larger ones may originate from carbonized starch or other organic matter present in the corn cob.



(a) (b) (c)

Figure 6. SEM images of biochar from (a) cassava wood, (b) rice husk, and (c) corn cob

3.2. Effect of biochar application on soil pH, soil organic carbon, and its potential as a soil amendment

Soil pH and soil organic carbon are critical parameters indicative of soil fertility levels. Figure 7 indicates that the soil pH in the control treatment was measured at 6.5, which classifies the soil as acidic [24]. The soil amended with biochar exhibited a notable increase in pH. The data indicate a pH increase of 0.40–0.57 units, equating to approximately 6–8.7%, as a result of biochar application. The increase signifies a favorable condition, as the availability of essential nutrients for plants is typically enhanced in soil with a pH near neutral (pH±7).

The rise in soil pH following biochar application is linked to the elemental composition of the biochar. The XRF analysis results presented in Figure 3 indicate that biochar contains several significant elements, including calcium (Ca) and magnesium (Mg). Basic cations, including Ca^{2+} and Mg^{2+}, contribute to the liming process by neutralizing acid ions present in the soil. Biochar typically contains salt-based ions, including K^+, Ca^{2+}, and Mg^{2+}, which can be released and exchanged with acid cations such as Al^{3+} and H^+ upon application to the soil. The change in the exchange process decreases the H^+ concentration, resulting in an increased pH [30]. Furthermore, when correlating elemental content with changes in soil pH, treatment B3 (soil treated with cassava wood biochar) showed the highest pH value compared to the other treatments. This finding is consistent with the elemental analysis results, which showed that cassava wood biochar had the highest calcium and magnesium content among all biochar types tested. These two basic cations play a crucial role in increasing soil pH through the neutralization of acid ions.

According to Figure 8, the treatment with cassava wood biochar exhibited the maximum soil organic carbon content at 1.85%, whereas the control treatment recorded the lowest at 1.36%. The application of biochar led to an enhancement in soil organic carbon ranging from 18.38% to 36.03%. The rise was attributed to the incorporation of carbon-rich biochar into the soil, thereby enhancing the overall soil organic carbon content. This discovery corresponds with prior research. Ernest *et al.* [31] documented a substantial rise in soil organic carbon concentration following the application of biochar. Moreover, Gong *et al.* [32] asserted that the incorporation of biochar consistently elevated soil organic carbon levels owing to the substantial organic matter component included in the biochar.

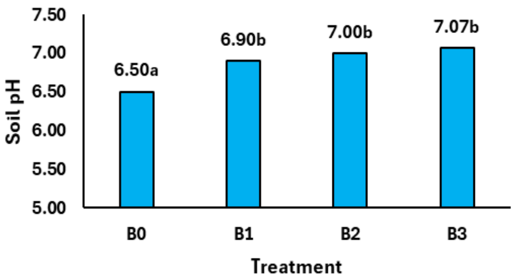


Figure 7. Effect of biochar amendment on soil pH over 85-day incubation

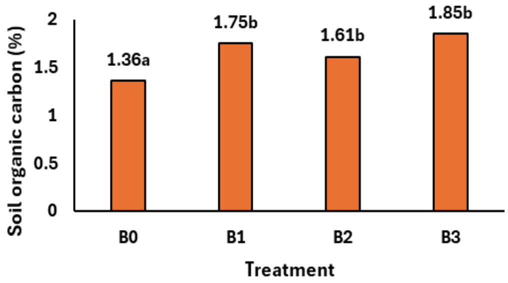


Figure 8. Effect of biochar amendment on soil organic content over 85-day incubation

The data indicate that biochar derived from rice husks, cassava stalks, and corn cobs, produced through traditional methods, shows potential as a soil amendment. The chemical characteristics of biochar reveal its potential, as all three types contain basic cations, including calcium and magnesium, along with macronutrients such as nitrogen, phosphorus, and sulfur. The addition of biochar to soil enhances the availability of nutrients for plants. Additionally, elevated soil pH and the presence of basic cations in biochar contribute to the mitigation of aluminum toxicity, particularly in acidic soils like ultisols. This elucidates the significance of biochar application in enhancing nutrient retention and overall soil quality.

Biochar, a carbon-rich material derived from biomass pyrolysis, has attracted increasing interest as a soil amendment due to its potential to enhance soil properties. According to Table 1, biochar contains high levels of carbon and has been shown to increase soil organic carbon content. Soil organic carbon can influence the physical, chemical, and biological properties of soil. Biochar amendments can improve soil physical properties by increasing water-holding capacity, reducing bulk density, and enhancing porosity. These benefits are particularly important in sandy or nutrient-poor soils, where biochar can support better root growth and plant development [33].

Biochar is characterized not only by its high carbon content but also by its well-developed porous structure, as illustrated on the biochar surface in Figure 6. The porous structure enhances the volume of internal pore space for water retention, while biochar in the soil promotes soil aggregate formation. This process leads to the formation of larger macropores, which enhances water infiltration and retention. This condition results in reduced soil bulk density and enhances available water capacity. The characteristics elucidate the positive impact of biochar on soil pore space and water-holding capacity. This finding aligns with the research conducted by Kabir *et al.* [34], which indicated that biochar application significantly enhanced soil physical properties by increasing porosity and water retention.

The carbon content and pore size of biochar influence soil physical properties and significantly affect soil biological properties, especially microbial activity. Biochar serves as a stable microhabitat for soil microorganisms, with its porous structure offering a protective environment that facilitates microbial colonization and activity. Biochar serves as a carbon source that provides energy and nutrients for microbes, while enhancing soil environmental conditions through improvements in pH, water-holding capacity, and aeration. The interplay of these factors enhances soil microbial biomass, diversity, and activity. The results align with previous studies [2], [35].

This study's findings indicate that biochar derived from agricultural waste, created through a simple production technique, has the potential to greatly enhance soil quality. This method holds significant importance for sustainable agricultural systems in tropical areas, particularly within ASEAN nations, as it can be readily implemented by small-scale farmers without requiring expensive infrastructure or technology. Moreover, this study demonstrates that the conversion of rice husks, cassava wood, and corn cobs into biochar serves as an effective method for the valorization of organic waste. The use of this abundant agricultural waste can mitigate environmental pressures from organic residue accumulation while generating a soil amendment of significant agronomic value. The produced biochar serves as an ameliorant, enhancing soil fertility and thereby promoting sustainable land management practices. This approach provides a dual solution by addressing agricultural waste issues and enhancing soil quality sustainably.

The findings suggest that the quality of biochar generated through this simple technique is comparable to that produced by more advanced technologies, showing no significant differences. Consequently, basic biochar can act as a valuable approach for enhancing soil fertility and overall health. The use of biochar by smallholder farmers can enhance the resilience of food production systems through the improvement of the soil's physical, chemical, and biological properties. This approach additionally contributes to the sustainable preservation of soil resources over the long term. These findings indicate that utilizing biochar created through simple techniques is a viable and sustainable strategy for preserving soil quality, thereby supporting agricultural sustainability for future generations.

4. CONCLUSION

According to the study's findings, biochar made from traditional biomass combustion techniques, especially from rice husks, cassava wood, and corn cobs, has properties that are similar to those of biochar made with advanced pyrolysis techniques. Following thorough evaluation with FTIR, TG-DTA, XRD, and XRF, it was determined that the biochar contained essential nutrients and had physicochemical characteristics that aid in the enhancement of soil quality. Following application, soil pH and soil organic carbon (SOC) content significantly increased, indicating the efficacy of biochar as a soil ameliorant. These results demonstrate that a traditional/simple technique for producing biochar can yield a product fit for application as a soil amendment, providing a low-energy, more accessible, and economical substitute to promote sustainable farming methods.

FUNDING INFORMATION

The authors declare that no specific funding was received from public, private, or non-profit organizations for the conduct of this research.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Ali Rahmat	✓	✓		✓	✓	✓			✓			✓	✓	
Sukamto					✓			✓	✓	✓	✓			
Santi Ari Respati		✓				✓	✓		✓				✓	
Fera Arum		✓	✓	✓		✓	✓			✓			✓	
Wiwiek Dwi Susanti		✓				✓	✓			✓				
Yudia Azmi					✓			✓	✓	✓				
Zurrahmi Wirda					✓			✓	✓	✓				

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors have no competing interests to declare regarding the publication of this article.

REFERENCES

[1] Q. Xu *et al.*, "A comprehensive review on agricultural waste utilization through sustainable conversion techniques, with a focus on the additives effect on the fate of phosphorus and toxic elements during composting process," *Science of The Total Environment*, vol. 942, 2024, doi: 10.1016/j.scitotenv.2024.173567.

[2] S. Khawkomol *et al.*, "Potential of biochar derived from agricultural residues for sustainable management," *Sustainability*, vol. 13, no. 15, 2021, doi: 10.3390/su13158147.

[3] M. M. Maja and S. F. Ayano, "The impact of population growth on natural resources and farmers' capacity to adapt to climate change in low-income countries," *Earth Systems and Environment*, vol. 5, no. 2, pp. 271–283, 2021, doi: 10.1007/s41748-021-00209-6.

[4] J. Nepal, W. Ahmad, F. Munsif, A. Khan, and Z. Zou, "Advances and prospects of biochar in improving soil fertility, biochemical quality, and environmental applications," *Frontiers in Environmental Science*, vol. 11, 2023, doi: 10.3389/fenvs.2023.1114752.

[5] D. Woolf, J. E. Amonette, F. A. S.-Perrott, J. Lehmann, and S. Joseph, "Sustainable biochar to mitigate global climate change," *Nature Communications*, vol. 1, no. 5, 2010, doi: 10.1038/ncomms1053.

[6] V. Mulabagal *et al.*, "Biochar from biomass: a comprehensive approach to CO2 sequestration and utilization, soil amendment, power generation, PFAS removal, healthcare, and sustainable food solutions," in *Handbook of Climate Change Mitigation and Adaptation*, New York: Springer New York, 2024, pp. 1–72, doi: 10.1007/978-1-4614-6431-0_80-3.

[7] S. Shyam, S. Ahmed, S. J. Joshi, and H. Sarma, "Biochar as a soil amendment: implications for soil health, carbon sequestration, and climate resilience," *Discover Soil*, vol. 2, no. 1, 2025, doi: 10.1007/s44378-025-00041-8.

[8] V. K. Kumar and N. L. Panwar, "Pyrolysis technologies for biochar production in waste management: a review," *Clean Energy*, vol. 8, no. 4, pp. 61–78, 2024, doi: 10.1093/ce/zkae036.

[9] H. Afash, B. Ozarisoy, H. Altan, and C. Budayan, "Recycling of tire waste using pyrolysis: an environmental perspective," *Sustainability*, vol. 15, no. 19, 2023, doi: 10.3390/su151914178.

[10] M. Ainatzoglou, E. Tsiaras, V. G. Papadakis, S. Tampekis, and F. A. Coutelieris, "Biochar production from olive tree prunings by using open flame pyrolysis," *International Journal of Energy Sector Management*, vol. 19, no. 5, pp. 1131-1144, 2025, doi: 10.1108/IJESM-10-2024-0057.

[11] D. Neina and B. Glaser, "Terra preta production from Ghanaian and Zambian soils using domestic wastes," *Scientific Reports*, vol. 14, no. 1, 2024, doi: 10.1038/s41598-024-75521-y.

[12] Hidayat *et al.*, "Analysis of rice husk biochar characteristics under different pyrolysis temperature," *IOP Conference Series: Earth and Environmental Science*, vol. 1201, no. 1, 2023, doi: 10.1088/1755-1315/1201/1/012095.

[13] S. Wijitkosum and T. Sriburi, "Applying cassava stems biochar produced from agronomical waste to enhance the yield and productivity of maize in unfertile soil," *Fermentation*, vol. 7, no. 4, 2021, doi: 10.3390/fermentation7040277.

[14] P. Rattanaphaiboon, N. Homdoung, and N. Tippayawong, "Production and characterization of corncob biochar for agricultural use," *AIP Conference Proceedings*, vol. 2681, 2022, doi: 10.1063/5.0117160.

[15] L. F. Morales, K. Herrera, J. E. López, and J. F. Saldarriaga, "Use of biochar from rice husk pyrolysis: assessment of reactivity in lime pastes," *Heliyon*, vol. 7, no. 11, 2021, doi: 10.1016/j.heliyon.2021.e08423.

[16] H. Wakudkar and S. Jain, "A holistic overview on corn cob biochar: a mini-review," *Waste Management & Research*, vol. 40, no. 8, pp. 1143–1155, 2022, doi: 10.1177/0734242X211069741.

[17] S. C. G. Matoso, P. G. S. Wadt, V. S. de S. Júnior, and X. L. O. Pérez, "Soil mineralogy-controlled phosphorus availability in soils mixed with phosphate fertiliser and biochar," *Environmental Technology*, vol. 44, no. 25, pp. 3820–3833, 2023, doi: 10.1080/09593330.2022.2074318.

[18] J. P. Otoni, S. C. G. Matoso, X. L. O. Pérez, and V. B. da Silva, “Potential for agronomic and environmental use of biochars derived from different organic waste,” *Journal of Cleaner Production*, vol. 449, 2024, doi: 10.1016/j.jclepro.2024.141826.
[19] A. J. G. de Faria *et al.*, “Elemental analysis of biochar-based fertilizers via portable X-ray fluorescence spectrometry,” *Environmental Technology & Innovation*, vol. 23, 2021, doi: 10.1016/j.eti.2021.101788.
[20] X. He, X. Chen, X. Wang, and L. Jiang, “Optimization of activated carbon production from corn cob using response surface methodology,” *Frontiers in Environmental Science*, vol. 11, 2023, doi: 10.3389/fenvs.2023.1105408.
[21] K. Rueangsan *et al.*, “Bio-oil and char obtained from cassava rhizomes with soil conditioners by fast pyrolysis,” *Heliyon*, vol. 7, no. 11, 2021, doi: 10.1016/j.heliyon.2021.e08291.
[22] A. A. H. Saeed *et al.*, “Moisture content impact on properties of briquette produced from rice husk waste,” *Sustainability*, vol. 13, no. 6, 2021, doi: 10.3390/su13063069.
[23] Y. Nakayasu, Y. Goto, Y. Katsuyama, T. Itoh, and M. Watanabe, “Highly crystalline graphite-like carbon from wood via low-temperature catalytic graphitization,” *Carbon Trends*, vol. 8, 2022, doi: 10.1016/j.cartre.2022.100190.
[24] X. Teng *et al.*, “Effects of biochar on soil properties as well as available and TCLP-extractable Cu contents: a global meta-analysis,” *Scientific Reports*, vol. 15, no. 1, 2025, doi: 10.1038/s41598-025-18170-z.
[25] Z. Wang, C. Liu, J. Ouyang, B. Xue, J. Xu, J. Zhai, and R. Xiao, “Porous carbon materials derived from rice husk pyrolysis with NaCl/Na_2CO_3 binary molten salt for CO_2 capture,” *Industrial Crops and Products*, vol. 227, 2025, doi: 10.1016/j.indcrop.2025.120808.
[26] M. S. Yeasmin and M. I. H. Mondal, “Synthesis of highly substituted carboxymethyl cellulose depending on cellulose particle size,” *International Journal of Biological Macromolecules*, vol. 80, pp. 725–731, 2015, doi: 10.1016/j.ijbiomac.2015.07.040.
[27] A. Hariharan, V. Harini, S. Sandhya, and S. Rangabhashiyam, “Waste Musa acuminata residue as a potential biosorbent for the removal of hexavalent chromium from synthetic wastewater,” *Biomass Convers. Biorefinery*, vol. 13, no. 2, pp. 1297–1310, 2023, doi: 10.1007/s13399-020-01173-3.
[28] H. Deng, Y. F. Li, S. Q. Tao, A. Y. Li, Q. Y. Li, and L. N. Hu, “Efficient adsorption capability of banana and cassava biochar for malachite green: removal process and mechanism exploration,” *Environmental Engineering Research*, vol. 27, no. 3, 2022, doi: 10.4491/eer.2020.575.
[29] V. Tsolis and P. Barouchas, “Biochar as soil amendment: the effect of biochar on soil properties using VIS-NIR diffuse reflectance spectroscopy, biochar aging and soil microbiology—a review,” *Land*, vol. 12, no. 8, 2023, doi: 10.3390/land12081580.
[30] S. Garbuz, A. Mackay, M. C.-Arbestain, B. DeVantier, and M. Minor, “Biochar amendment improves soil physico-chemical properties and alters root biomass and the soil food web in grazed pastures,” *Agriculture, Ecosystems & Environment*, vol. 319, 2021, doi: 10.1016/j.agee.2021.107517.
[31] B. Ernest, P. Z. Yanda, A. Hansson, and M. Fridahl, “Long-term effects of adding biochar to soils on organic matter content, persistent carbon storage, and moisture content in Karagwe, Tanzania,” *Scientific Reports*, vol. 14, no. 1, 2024, doi: 10.1038/s41598-024-83372-w.
[32] H. Gong, Y. Li, and S. Li, “Effects of the interaction between biochar and nutrients on soil organic carbon sequestration in soda saline-alkali grassland: a review,” *Global Ecology and Conservation*, vol. 26, 2021, doi: 10.1016/j.gecco.2020.e01449.
[33] S. Mia, N. Uddin, S. A. A. M. Hossain, R. Amin, F. Z. Mete, and T. Hiemstra, “Production of biochar for soil application: a comparative study of three kiln models,” *Pedosphere*, vol. 25, no. 5, pp. 696–702, 2015, doi: 10.1016/S1002-0160(15)30050-3.
[34] E. Kabir, K. H. Kim, and E. E. Kwon, “Biochar as a tool for the improvement of soil and environment,” *Frontiers in Environmental Science*, vol. 11, 2023, doi: 10.3389/fenvs.2023.1324533.
[35] M. Wang, X. Yu, X. Weng, X. Zeng, M. Li, and X. Sui, “Meta-analysis of the effects of biochar application on the diversity of soil bacteria and fungi,” *Microorganisms*, vol. 11, no. 3, 2023, doi: 10.3390/microorganisms11030641.

BIOGRAPHIES OF AUTHORS

Ali Rahmat is a researcher specializing in soil science, hydrology, and environmental materials. He obtained his doctoral degree from Gifu University, Japan, with a strong academic background in soil science, soil–water interactions, and sustainable land management. His research interests focus on the development and application of biomass-derived materials, particularly biochar and activated carbon, for soil amendment, environmental remediation, and sustainable waste management. He has authored numerous scientific publications related to biochar characterization, pyrolysis of agricultural residues, soil improvement, composting technology, and climate change adaptation. His research also covers sustainable agricultural systems and environmental conservation strategies. Through his multidisciplinary expertise, he contributes to the advancement of sustainable technologies for agricultural and environmental applications. He can be contacted at email: alir001@brin.go.id.

Sukamto holds a Ph.D. in Soft Matter Science from Hokkaido University, Japan. His research interests include inorganic chemistry, materials science, polymers, composite materials, and the development of functional materials for environmental applications. His research focuses on the synthesis, modification, and characterization of advanced materials, including biochar, silica-based composites, biopolymer materials, and adsorbents for sustainable environmental technologies. He has authored several scientific publications related to agricultural waste conversion, biochar production through pyrolysis, material characterization, and adsorption systems for pollutant removal. His expertise in material chemistry and functional material development supports the advancement of sustainable solutions for environmental management and resource utilization. He can be contacted at email: sukamto@unu-jogja.ac.id.

Santi Ari Respati holds a bachelor's degree in Chemical Engineering. She is a researcher with expertise in chemical analysis, material processing, and environmental material characterization. Her research interests include the development and evaluation of functional materials, mineral processing, and biomass-derived materials for sustainable applications. She has been involved in several studies related to biochar production from agricultural residues, pyrolysis processes, and characterization of material properties for environmental management. Her background in chemical engineering supports the analysis and development of sustainable materials, particularly in the conversion of waste resources into value-added products. She can be contacted at email: sant013@brin.go.id.

Fera Arum holds a Master of Engineering degree in Mining Engineering with a specialization in Hydrogeology. Her research interests include hydrogeology, environmental management, material characterization, and sustainable utilization of natural resources. She has been involved in research related to the physical characterization of geological materials, environmental assessment, and the development of biomass-derived materials, including biochar produced from agricultural waste through pyrolysis processes. Her multidisciplinary background supports studies on sustainable resource management, waste valorization, and the application of environmentally friendly materials. She can be contacted at email: fera001@brin.go.id.

Wiwiek Dwi Susanti holds a Master of Engineering degree in Civil Engineering with a specialization in Water Resources Engineering. She has over 20 years of professional and research experience in hydrology, water resources management, environmental assessment, and disaster risk management. Her research focuses on hydrological analysis, flood resilience, watershed management, and sustainable environmental approaches. She has contributed to studies related to environmental management and the development of biomass-derived materials, including biochar production from agricultural waste for sustainable resource utilization. Her multidisciplinary expertise supports the integration of water resources engineering, environmental sustainability, and innovative material applications for addressing environmental challenges. She can be contacted at email: wiwi008@brin.go.id.

Yudia Azmi is a permanent lecturer in the Department of Agrotechnology at the Institute of Plantation Technology, Pelalawan, Indonesia. Her research interests include agronomy, plant biotechnology, tissue culture, sustainable agriculture, and the utilization of agricultural and plantation waste. She has authored several scientific publications related to plant cultivation, oil palm waste management, biofertilizer development, and the conversion of biomass residues into value-added products, including biochar and activated carbon. Her research also focuses on the application of sustainable technologies to improve agricultural productivity and support environmentally friendly farming systems. Her expertise in plant science and agricultural waste utilization contributes to the development of biochar-based approaches for soil improvement and sustainable resource management. She can be contacted at email: yudiaazmi@gmail.com.

Zurrahmi Wirda is a permanent lecturer in the Department of Agroecotechnology, Faculty of Agriculture, Malikussaleh University, Indonesia. Her research interests include agroecotechnology, crop science, organic farming, plant cultivation, and sustainable agricultural systems. She has authored several scientific publications related to soil fertility improvement, organic fertilizer application, eco-friendly agricultural technologies, pest management, and the utilization of biological resources to enhance crop productivity. Her research also focuses on the application of sustainable approaches, including biofertilizers, organic amendments, and biomass-derived materials, to improve soil quality and agricultural sustainability. Her expertise in agroecology and sustainable farming contributes to the development of environmentally friendly strategies for agricultural waste utilization and soil management. She can be contacted at email: zurrahmi.wirda@unimal.ac.id.