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Optimization of Biochar Quality from Palm and Cacao Waste through Variation of Pyrolysis Temperature and Duration as a Soil Amendment Material

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Abstract: Palm and cacao waste are high-quality raw materials for producing quality biochar that enhances soil fertility, provided that the biochar production process takes into account various aspects of pyrolysis. The pyrolysis conditions, such as temperature and duration, significantly impact the quality of the biochar produced as a soil amendment. The type of raw material, pyrolysis temperature, duration, and other conditions affect the ash content, pH, functional groups of the biochar, the morphological structure of the surface, and other chemical characteristics of the biochar. The objective of this research is to find the best formulation of biochar made from Palm Kernel Shells (PKS), Palm Oil Empty Bunches (POEB), Cacoa Pod Husks (CPH) and a mixture of PKS: POEB: CPH based on the physicochemical properties of the biochar produced at pyrolysis temperatures of 350, 450 and 550°C with durations of 2 and 4 h. The research used a pyrolysis reactor designed to produce biochar at controlled temperatures, digitally recorded throughout the pyrolysis process. FTIR and SEM analyses were performed to examine changes in functional groups and the morphological structure of the biochar surface. Additionally, the chemical characteristics of the biochar were analyzed, including ash content, pH, organic carbon, total nitrogen, total phosphorus, total potassium, total calcium, total magnesium, Cation Exchange Capacity (CEC), and moisture content. The results provide insights into the quality of biochar produced from different raw materials, temperatures, and durations of pyrolysis. The research shows that shifts in aliphatic and aromatic CH groups occur with increased temperature and duration of pyrolysis across various types of agricultural waste biochar. The surface morphological structure and several physicochemical characteristics of the biochar, such as moisture content, ash content, organic carbon, total nitrogen, total phosphorus, total potassium, total calcium, total magnesium, and CEC, vary due to different temperatures and durations of pyrolysis for each type of palm and cacao raw material.

Keywords: Palm and Cacao Biochar, Pyrolysis Temperature and Duration, Characterization

Introduction

Understanding the complexity of managing agro-industrial waste, particularly from palm oil and cacao, is imperative in pursuing environmental and agricultural sustainability. Biochar, a product produced through pyrolysis, has garnered attention as an effective method for managing these wastes. Aligned with this notion, our study focuses on optimizing pyrolysis temperature and duration to produce high-quality biochar (Sato *et al*., 2019).

Awareness of the importance of sustainable waste management has driven the need to explore effective and environmentally friendly technologies. Zakaria *et al*. (2023) highlight biochar production as a potential method to mitigate the environmental impact of palm and cacao waste. This forms the foundation for our research, aiming to optimize pyrolysis parameters.

The study by Munongo *et al*. (2017) provides significant insights into the characteristics of biochar produced from cacao waste. These findings serve as a valuable starting point to evaluate the potential of similar palm waste as a biochar source. Therefore, our research adopts an evidence-based approach to develop optimal strategies.

In the Sub-Saharan African context, as studied by Zanli *et al.* (2022), unique environmental challenges emerge where biochar can offer adaptive solutions. Our research is inspired by a similar need to support agricultural sustainability in other regions by using agro-industrial waste.

Proper setting of pyrolysis parameters is essential to maximize the benefits of biochar, as demonstrated by Vieira *et al.* (2020) in their study using rice husks. This will be further investigated in our study, focusing on palm and cacao waste.

Contrarily, Anyaoha *et al.* (2018) point out that while palm fruit waste offers potential as a soil amendment, clear limitations must be considered. Our study responds by exploring in depth how pyrolysis affects the quality of biochar from this waste.

Amoah-Antwi *et al.* (2020) suggest that soil quality restoration can be enhanced through the use of biochar and brown coal waste. In this context, our research will explore how biochar from palm and cacao waste can contribute to these efforts.

Nsubuga *et al.* (2023) emphasize the importance of optimizing adsorbent dosage and contact time for the effectiveness of biochar. Our study will adopt a similar approach to ensure the produced biochar meets the expected standards. Furthermore, Rashidi and Yusup (2020) emphasize the need for standardization in the biochar production process. This study will contribute to the existing literature by proposing standard protocols for producing biochar from palm and cacao waste.

Next, Vaštyl *et al.* (2022) provide insights into the influence of pyrolysis temperature on the quality of the product derived from cacao waste pyrolysis. This knowledge will be integrated into our experiments to determine the ideal temperature settings.

Subsequently, Ighalo *et al.* (2023) offer an overview of biochar production from coconut waste. Our study will extend this understanding by focusing on palm and cacao waste, using similar yet tailored methods.

This research acknowledges that pyrolysis temperature has a significant impact on the physicochemical and structural properties of biochar, as illustrated by Sato *et al.* (2019). We aim to determine the optimal temperature range that produces high-quality biochar from agro-industrial waste. Zakaria *et al.* (2023) have shown that pyrolysis duration is another key variable in effective biochar production. This study aims to thoroughly investigate how duration affects biochar characteristics.

The novelty of this research lies in the detailed exploration of pyrolysis conditions tailored specifically for palm and cacao waste. We aim to offer effective and innovative technical solutions for soil improvement using biochar. By integrating findings from existing literature, this research strives to make a substantial contribution to the management of agro-industrial waste. We hope to enrich the knowledge corpus with empirical data that can be applied to sustainable agricultural practices.

This study not only explores the optimization of pyrolysis conditions but also evaluates the potential of biochar as a sustainable soil improver. We hope to find a balance between production efficiency and agronomic benefits. This research approaches this sustainability challenge based on scientific evidence, aiming to provide reliable recommendations for practitioners and policymakers. This effort could potentially have significant environmental and economic impacts.

With rigorous methodology and detailed analysis, this study is expected to provide new understanding and improved methods in biochar production. We are committed to pursuing scientific excellence and practical relevance. This research is designed to fill gaps in the literature on the use of palm and cacao waste. We anticipate that our findings will pave new pathways for further research. In this study, we will also explore the broader applications of biochar, including soil remediation and waste management. Innovation and practical application are at the core of our research efforts.

This research will provide evidence supporting biochar from palm and cacao waste as a sustainable alternative. We aim to develop biochar that is not only sustainable but also economically viable. This study offers an innovative solution for enhancing the quality of biochar from agro-industrial waste. We hope to make a significant contribution to the fields of agroecology and environmental sustainability.

Materials and Methods

Palm and Cacao Waste

The raw materials, consisting of palm kernel shells and empty palm bunches, were obtained from a palm oil processing plant located in the Aceh Tamiang district. Cacao fruit peel waste was sourced from a community plantation in the Idi subdistrict, East Aceh district. These materials palm kernel shells, palm oil empty bunches, and Cacoa pod husks were dried for approximately 10 days to reduce their moisture content to below 14%. Prior to the biochar production process, an analysis of the raw materials' characteristics was conducted, including cellulose, hemicellulose, lignin, Phosphorus (P), Potassium (K), Calcium (Ca), Magnesium (Mg), organic carbon, pH, moisture content, ash content, Nitrogen (N) and C/N Ratio.

Research Tools and Materials

The tools and materials used in the research include a set of biochar pyrolysis reactor tools with temperatures recorded throughout the manufacturing process, memert brand ovens, nitrogen distillation devices, flame photometer, Shimadzu brand AAS, Spectro photo meter, pH meter electrode, and a number of other chemical equipment for laboratory analysis. The materials used in the study, namely palm oil waste and cacao fruit peels as raw materials for biochar and a number of chemicals for laboratory analysis.

Biochar Production Technique

For biochar production, 3 kg of each raw material was prepared in pyrolysis pottery boxes made of steel plate, measuring 50×30×20 cm. Subsequently, these boxes were placed in a pyrolysis apparatus and connected to electricity. The machine was turned on and the temperature was set at 350, 450, and 550°C with durations of 2 and 4 h for each type of raw material. Once the pyrolysis time was reached, the pottery was removed from the pyrolysis reactor and the resulting embers were quenched with tap water until all pores were saturated. After 60 min, the biochar was drained into a bucket and left for 24 h, then weighed and sieved through a 2 mm mesh. Biochar produced at each pyrolysis temperature of 350, 450, and 550°C, for durations of 2 and 4 h, using raw materials of Palm Karnel Shells (PKS), Palm Oil Empty Bunches (POEB), Cacao Pod Husk (CPH) and a mixture of PKS: POEB: CPH, produced in 24 types of biochar, replicated three times to yield 72 biochar combinations.

Physical and Chemical Characteristics Analysis of Biochar

The chemical analysis of biochar included ash content, Carbon (C), total Nitrogen (N), pH, as well as Phosphorus (P), Potassium (K), Calcium (Ca), Magnesium (Mg), and the Cation Exchange Capacity (CEC) of biochar. Additionally, changes in functional groups were analyzed using FTIR, and the surface morphology of biochar was examined through SEM analysis. The results from these analyses provided insights into the quality of biochar produced from different raw materials, pyrolysis temperatures, and durations.

Research Design and Data Analysis

The study employed a Completely Randomized Design (CRD) with three factors and three replications. The first factor was pyrolysis temperature, with three levels; the second factor was pyrolysis duration, with two levels; and the third factor was biochar type, with four levels. Data analysis was performed using one-way Analysis of Variance (ANOVA) with a confidence level of 5%. Significant effects were further tested using Duncan's Multiple Range Test (DMRT) at an α level of 0.05. Descriptive analyses were also conducted for the observation of functional groups and the surface morphology of biochar.

Results

Characteristics of Plantation Waste Biomass

The raw materials used in this study include palm oil and cacao waste sourced from Aceh Tamiang and East Aceh, areas adjacent to Langsa City in the province of Aceh. The physicochemical characteristics of this plantation waste biomass are presented in Table 1.

Table 1 describes the chemical and physical characteristics of the biochar feedstock such as Cellulose, Hemicellulose, Lignin, Phosphorus (P), Potassium (K), Calcium (Ca), Magnesium (Mg), Organic Carbon, pH, moisture content, ash content, Nitrogen (N) and C/N Ratio, among other relevant parameters measured in this study. This table will provide essential data for understanding the suitability of the waste for biochar production and its potential impact on soil amendment efficac (Table 1).

Physicochemical Characteristics of Biochar Due to Differences in Pyrolysis Temperature, Duration, and Raw Material

pH of Biochar

The treatment of temperature, pyrolysis duration, and type of raw material significantly affect the pH values of palm and cacao biochar. Table 2 demonstrates that the pH levels of biochar for each raw material, pyrolysis temperature, and duration differ significantly as per the Duncan test at α level 0.05. Pyrolysis at various raw materials and times shows a trend of increasing biochar pH.

Organic Carbon Content, Total Nitrogen and C/N Ratio

The Duncan test at α level 0.05 shows both significant and non-significant differences in the increase of organic carbon content, total nitrogen, and C/N ratio of biochar from one-way tests among pyrolysis temperature, duration, and biochar biomass raw materials. The organic carbon content (Table 2) shows a trend of increase with increasing pyrolysis temperature and duration.

The highest total nitrogen content was found in the TKKS biochar treatment at a pyrolysis temperature of 450°C with a duration of 4 h, while the lowest total nitrogen was found in the Palm Karnel Shells (PKS) biochar treatment at a pyrolysis temperature of 350°C with a duration of 2 h. The highest C/N ratio was observed in the Palm Karnel Shells (PKS) treatment at a pyrolysis temperature of 350°C and duration of 2 h and the lowest C/N ratio was found in the mixed biochar treatment of PKS: POEB: CPH at a pyrolysis temperature of 550°C for 4 h.

Table 1: Chemical characteristics of palm oil and Cacoa waste as Biochar raw materials

			Plantation waste			
No.	Observation parameters	Unit	Palm Karnel Shells (PKS)	Palm Oil Empty Bunches (POEB)	Husk (CPH) Cacoa Pod	Mix PKS: POEB: CPH
1	Cellulose	%	47.28	52.40	27.28	48.70
2	Hemicellulose	%	32.40	25.82	24.72	30.18
3	Lignin	%	25.62	23.38	47.27	27.38
4	C-organic	%	65.96	55.41	42.72	52.74
5	N-total	%	0.56	0.92	1.02	0.75
6	C/N ratio	-	117.79	60.23	41.88	70.32
7	P-Total	%	0.40	0.72	0.64	0.55
8	K-total	%	5.30	4.30	2.82	1.96
9	Ca-Total	%	3.40	2.42	1.38	1.06
10	Mg-Total	%	1.98	1.04	0.52	0.48
11	Water content	%	9.74	12.20	10.27	11.85
12	Ash content	%	4.96	6.42	7.83	8.18
13	pH	-	5.54	5.62	5.48	5.70

Table 2: Physicochemical characteristics of palm oil and cacao waste biochar due to temperature treatment and pyrolysis duration

	Observation parameters										
Treatment combination	pH	C-organic (%)	N-total (%)	C/N ratio	P-total (%)	K-total (%)	Ca-total (%)	Mg-total (%)	CEC Cmo kg-1	Ash content (%)	Water content (%)
$T_1D_1B_1$	6.39a	31.72a	0.31a	101.72g	0.09ab	0.04a	0.57cdef	0.08ab	7.77a	2.86a	2.71a
$T_1D_1B_2$	7.02ab	36.53cde	0.60BC	61.01de	0.05a	0.91efgh	0.55bcde	0.09abc	9.42a	6.67def	5.90cd
$T_1D_1B_3$	7.54bc	36.13cd	0.66c	55.71cds	0.09ab	0.78eph	0.42abc	0.11abc	10.77ab	2.80a	6.74def
$T_1D_1B_4$	6.80a	34.56bc	0.81de	42.86ab	0.12ab	0.56d	0.33a	0.07ab	9.92a	3.47a	3.70ab
$T_1D_2B_1$	7.51bc	33.44ab	0.33a	102.28g	0.10ab	0.09a	0.57cdef	0.11abc	7.13a	3.22a	3.70ab
$T_1D_2B_2$	8.09cde	37.78de	0.69cd	54.83cds	0.19BC	0.99gh	0.58defg	0.15bcd	11.00ab	6.95eph	7.04efg
$T_1D_2B_3$	8.09cde	36.80cd	0.69cd	54.10bcd	0.30cde	0.96fgh	0.52bcd	0.18cde	10.40a	3.07a	6.11de
$T_1D_2B_4$	7.47bc	38.52def	0.82def	47.24abc	0.26cd	0.74e	0.40ab	0.05	9.63a	3.48a	6.78def
$T_2D_1B_1$	7.65bcd	35.71bcd	0.50b	72.37f	0.13ab	0.19ab	0.60defg	0.18cde	8.53a	5.03b	4.79BC
$T_2D_1B_2$	9.09ghi	60.30h	0.98fg	61.50de	0.40defg	2.04m	1.13h	0.67h	34.90h	7.80fg	11.64k
$T_2D_1B_3$	9.44hi	43.39h	0.89efg	48.71abc	0.65h	1.86l	0.83hi	0.49i	35.13h	6.97eph	9.30ij
$T_2D_1B_4$	8.85fgh	46.24i	1.01gh	45.90abc	0.61ij	1.04h	0.74gh	0.28fg	27.92fg	6.83def	9.33ij
$T_2D_2B_1$	8.05cde	38.53def	0.56bc	68.42eph	0.31cdef	0.35BC	0.57cdef	0.15bcd	8.39a	6.59cdef	5.47cds
$T_2D_2B_2$	9.58ij	63.38k	1.16h	54.89cds	0.86k	2.31n	1.59k	0.91k	36.31h	10.42i	14.22l
$T_2D_2B_3$	9.12ghi	40.69fg	0.84def	48.92abc	0.40defgh	1.43h	0.69efgh	0.32gh	30.51g	6.61def	8.11ghij
$T_2D_2B_4$	8.44efg	40.62fg	0.89efg	46.19abc	0.54hij	1.02gh	0.66defg	0.26efg	23.11de	6.35cde	8.42hij
$T_3D_1B_1$	8.89fghi	48.07i	1.03gh	46.95abc	0.45fgh	0.51cd	0.92i	0.54i	8.33a	7.64f	8.65hij
$T_3D_1B_2$	9.48hi	62.28jk	1.03gh	60.95de	0.33cdef	1.27ij	0.72fgh	0.40h	26.43of	9.75hi	9.38h
$T_3D_1B_3$	9.21hi	38.97eph	0.81de	48.58abc	0.30cde	1.21i	0.66defg	0.25efg	22.08d	6.00bcde	8.34ghij
$T_3D_1B_4$	8.07cde	41.79gh	0.91efg	46.23abc	0.47ghi	0.90efgh	0.53bcde	0.22def	15.43c	6.12bcde	7.97fghi
$T_3D_2B_1$	9.29hi	48.64i	1.02gh	48.59abc	0.41efgh	0.50cd	0.74gh	0.36h	8.31a	7.80fg	8.66hij
$T_3D_2B_2$	9.41hi	60.40h	0.98fg	62.02de	0.47ghi	1.62k	0.82hi	0.55i	23.84de	8.89gh	11.41k
$T_3D_2B_3$	10.15h	37.08cde	0.83def	44.92abc	0.34defg	1.20i	0.55bcde	0.20def	20.19d	5.62bcd	8.35ghij
$T_3D_2B_4$	8.34def	37.64de	0.90efg	41.90a	0.38defg	0.84efg	0.53bcde	0.18cde	14.48BC	5.41bc	7.66fgh

Information:

- T_1 = Pyrolysis Temperature 350°C, T_2 = Pyrolysis Temperature 450°C, T_3 = Pyrolysis Temperature 550°C, D_1 = 2 h, D_2 = 4 h, B_1 = PKS, B_2 = POEB, B_3 = CPH, B_4 = PKS: POEB: CPH
- Numbers followed by the same letter in the same column and parameters are not significantly different according to the DMRT test at the α level of 0.05

Content of P, Ca, and Total Mg

The levels of P, Ca, and Mg in biochar from each type of palm oil and cacao waste at various pyrolysis temperatures and durations show significant and non-significant differences according to the Duncan test at α level 0.05 (Table 2). Total P levels in biochar range from 0.05-0.86%, total K from 0.04-2.31%, total Ca from 0.33-1.59%, and total Mg from 0.08-0.91%. The best values were found in the Palm Oil Empty Bunches (POEB) biochar treatment at a pyrolysis temperature of 450°C with a duration of 4 h ($T_2D_2B_2$). Total P levels in biochar produced from palm and cacao waste are generally low, but biochar Palm Oil Empty Bunches (POEB) at a pyrolysis temperature of 450°C for 4 h has better total P levels compared to biochar from other raw materials at different temperatures and durations.

Cation Exchange Capacity (CEC) of Biochar

The highest CEC in biochar was observed in the Palm Oil Empty Bunches (POEB) treatment at a pyrolysis temperature of 450°C and a duration of 4 h ($T_2D_2B_2$), while the lowest CEC was found in the Palm Karnel Shells (PKS) treatment at a pyrolysis temperature of 350 °C and a duration of 4 h ($T_1D_2B_1$). The results from the Duncan test at an α level of 0.05 indicated significant and non-significant differences in the CEC of each biochar type from plantation waste biomass across different temperatures and durations of pyrolysis. The research findings (Table 2) also show that each type of biochar from plantation waste achieves its best CEC at varying temperatures and durations of pyrolysis. There was a trend of decreasing CEC in each type of biochar as the temperature and duration of pyrolysis increased. For Palm

Karnell Shells (PKS) biochar, the highest CEC was observed at a temperature of 550°C and a duration of 2 h, while the lowest was at 350°C for 4 h, indicating a trend of decreasing CEC with longer pyrolysis durations. For Palm Oil Empty Bunches (POEB) biochar, the highest CEC was at a pyrolysis temperature of 450°C and a duration of 4 h, whereas the lowest was at 350°C for 2 h, with a decrease in CEC noted at 550°C for both 2 and 4-h durations. Biochar from Cacao Pod Husks (CPH) biomass and the PKS: POEB: CPH mixture showed the highest CEC at a pyrolysis temperature of 450°C and a duration of 2 h, with a decrease in CEC with increasing temperature (550°C) and longer pyrolysis duration (from 2-4 h). This decrease is likely related to the reduction in the active surface area and the decomposition of phenolic acid and carboxyl functional groups, impacting the decrease in CEC of biochar.

Ash Content of Biochar

The highest ash content was found in the Palm Oil Empty Bunches (POEB) biochar treatment at a pyrolysis temperature of 450°C and a duration of 4 h (10.42%), while the lowest ash content was observed in the Cacao Pod Husks (CPH) biochar treatment at a pyrolysis temperature of 350°C and a duration of 2 h (2.86%). The results of the Duncan test at an α level of 0.05 showed significant and non-significant differences in the ash content of each type of biochar from plantation waste at different temperatures and durations of pyrolysis. The ash content of each type of biochar at various temperatures and durations also reaches its respective highest values. For Kernel Shells (PKS) biochar, the highest ash content was at a pyrolysis temperature of 550°C and a duration of 4 h (7.80%), while the lowest was at 350°C for 2 h (2.86%). Palm Oil Empty Bunches (POEB) biochar showed the highest ash content at a pyrolysis temperature of 450°C and a duration of 2 h (10.42%) and the lowest at 350°C for 2 h (6.67%). For Cacao Pod Husks (CPH) biochar, the highest ash content was at a pyrolysis temperature of 450°C and a duration of 2 h (6.61%) and the lowest at 350°C for 2 h (2.80%). Similarly, the mixed biochar PKS: POEB: CPH showed the highest ash content at a pyrolysis temperature of 450°C and a duration of 2 h (6.83%), while the lowest was at 350°C for 2 h (3.47%). The ash content from the study increased with increasing pyrolysis temperature and duration, but there was a decrease again in some types of materials at a temperature of 550°C for both 2 and 4-h durations for Palm Oil Empty Bunches (POEB), Cacoa Pod Husks (CPH) and mixed PKS: POEB: CPH biochar. This indicates that some components of the raw biochar materials are readily combustible; additionally, the increase in ash content is suspected to be related to the volatilization of molecules that also enrich the inorganic elements of the produced biochar. Higher pyrolysis temperatures produce biochar with characteristics such as higher pH, specific surface area, ash content, and pore volume compared to low-temperature pyrolysis. Research by Li *et al*. (2023) reported that biochar from wood biomass has a lower ash content than that from elephant grass and corn cob biomass, where at lower pyrolysis temperatures, the ash content is lower than at higher temperatures. Further, research by Puspita *et al*. (2021) reported that pyrolysis temperature and raw materials in the production process of biochar influence characteristics such as biochar yield, moisture content, water-holding capacity, electrical conductivity, volatile substances, ash content, and bound carbon.

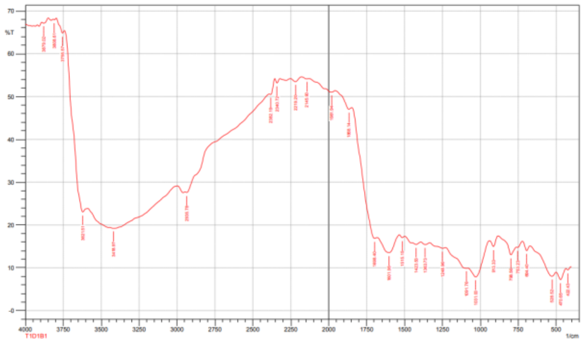
Moisture Content of Biochar

Table 2 indicates that the highest moisture content in biochar was found in the Palm Oil Empty Bunches (POEB) treatment at a pyrolysis temperature of 450°C and a duration of 2 h (14.22%), while the lowest moisture content was observed in the Palm Kernel Shells (PKS) biochar treatment at a pyrolysis temperature of 350°C and a duration of 2 h (2.71%). Table 2 also shows that the moisture content of biochar from each type of plantation waste biomass varies, which is attributed to the differences in the compounds contained in the biomass waste such as lignin and cellulose content, affecting the formation of different types of carbon, ultimately influencing the water-holding capacity of the biochar.

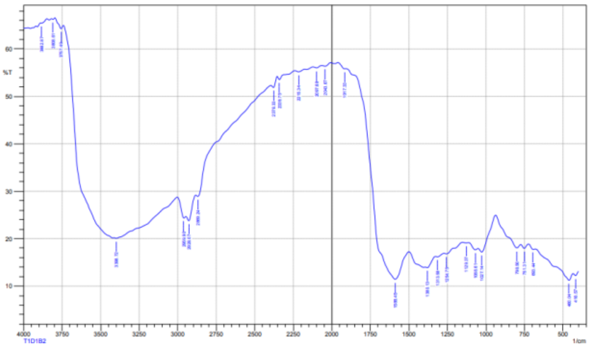
According to Li *et al*. (2020), biochar is a heterogeneous compound rich in carbon and aromatic minerals. The formation of high carbon also occurs at different pyrolysis temperatures and durations for each type of biochar, which is also suspected to be one of the factors in the variation in moisture content at different pyrolysis temperatures, durations, and biochar raw materials. The level of moisture content in biochar serves as an indicator of biochar's ability to hold water. One of the properties of biochar is its high capacity to retain and hold water. It is believed that biochar is one of the soil amendment materials that can improve the soil's water retention capacity due to the water-holding characteristics of biochar. This is consistent with the findings of Razzaghi *et al*. (2020), who reported a significant increase in soil moisture content by 45% in coarse-textured soils compared to an increase of 14-21% in fine-textured soils from the addition of biochar. Furthermore, according to Amalina *et al*. (2022), the properties of biochar are highly determined by the conditions during production and the type of biomass used.

FTIR Spectrum Characteristics of Palm Oil and Cacao Waste Biochar

The main absorbance peaks of the biochar derived from various temperatures and durations of pyrolysis from plantation waste are displayed in Fig. 1. The FTIR analysis results show that the main biochar absorbance occurs within the wavenumber range of 409.89 cm^{-1} to 3946.53 cm^{-1}. Biochar produced from different raw materials of plantation waste at various pyrolysis temperatures and durations exhibits principal functional groups such as OH, NH, aliphatic CH, aromatic carbonyl/carboxyl (C = O), Carboxylate (CO), esters, phenol, COC, C -OH, aromatic CH and OH bending. The FTIR results also indicate a decrease in aliphatic CH stretching and an increase in aromatic CH stretching as the pyrolysis temperature increases, across different durations. Biochar containing surface O, H, and OH groups can, when hydrolyzed or oxidized, develop negative and positive charges, enhancing its capacity for cation or anion exchange. According to Pratama *et al*. (2018), the production process of biochar, involving heating in the absence of oxygen, leads to the decomposition of functional groups from the carbon surface. Further research by Setiawan and Siregar (2023) states that pyrolysis of biochar from Palm Oil Empty Bunches (POEB) raw material at 400°C produces higher amounts of compounds with aliphatic and acyclic hydrocarbon groups, as well as methane.



(a)



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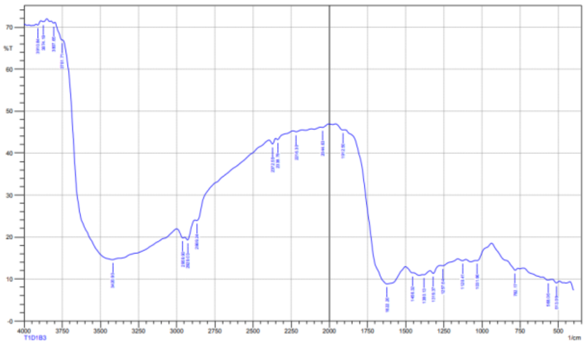

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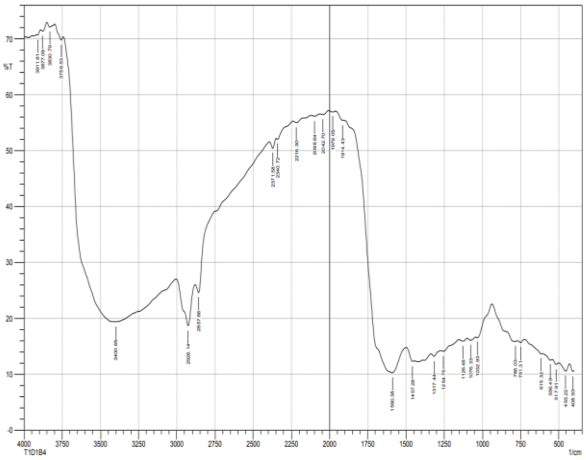

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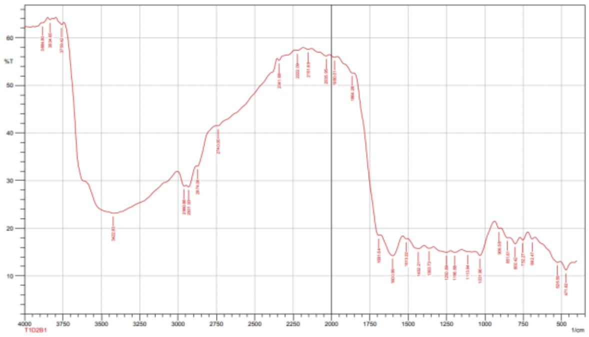

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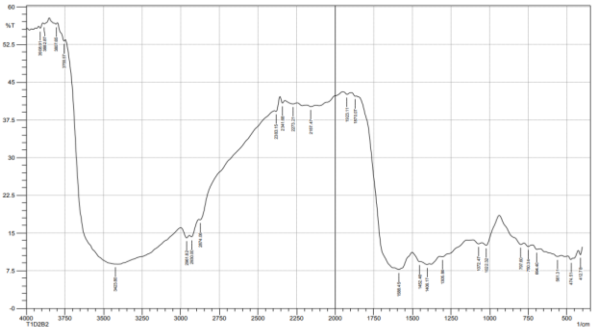

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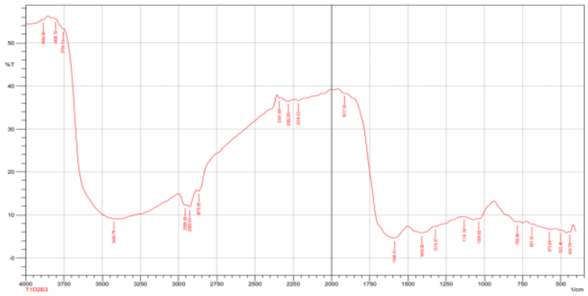
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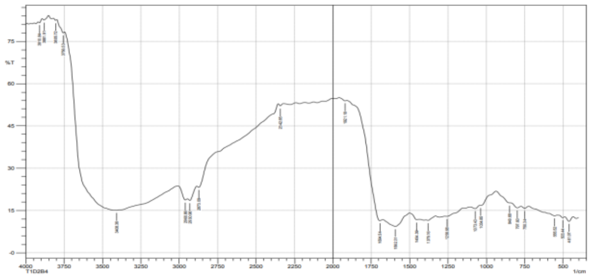
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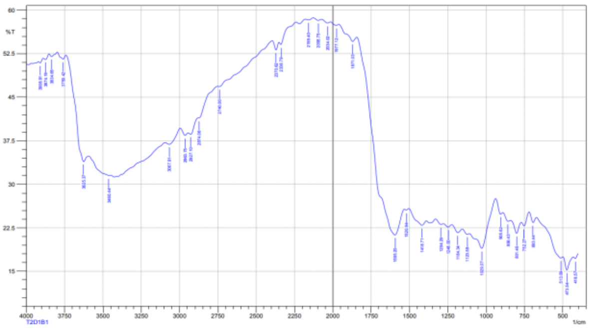
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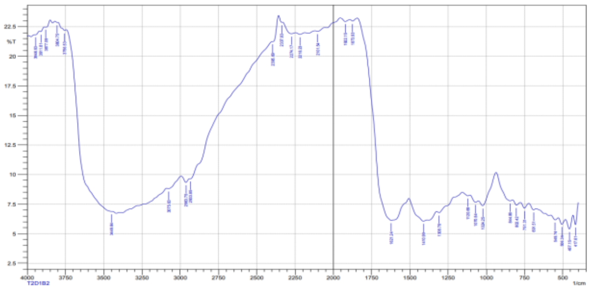
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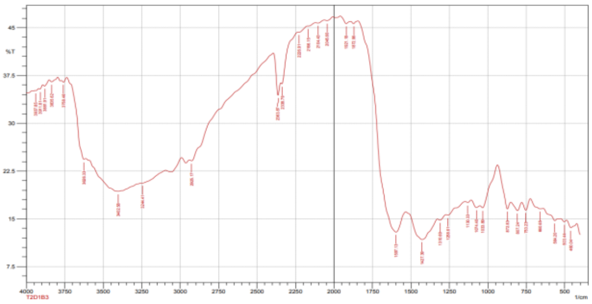
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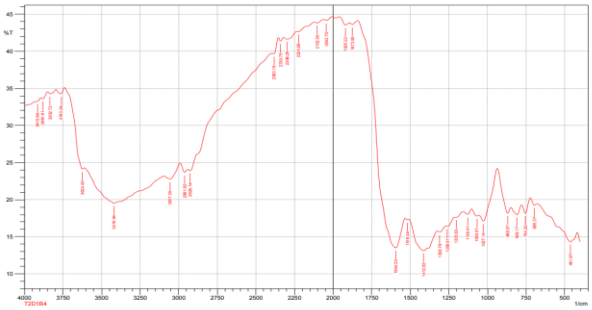
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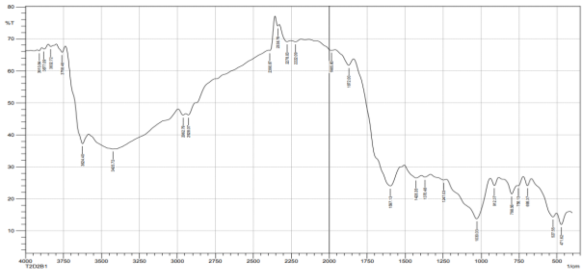
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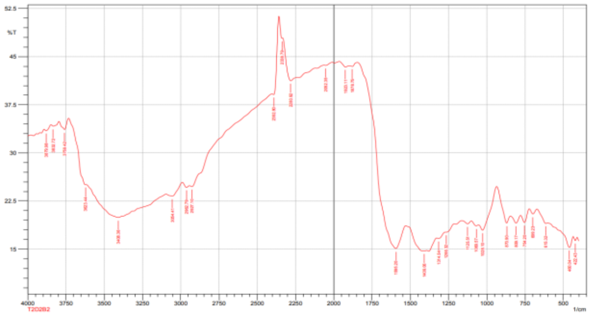
(m)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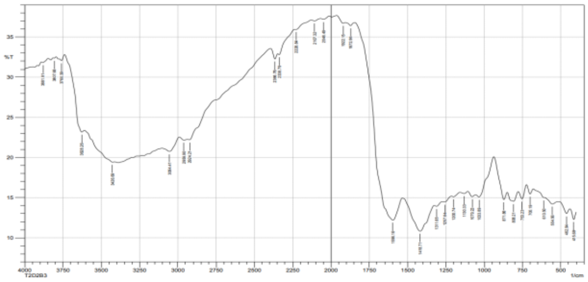
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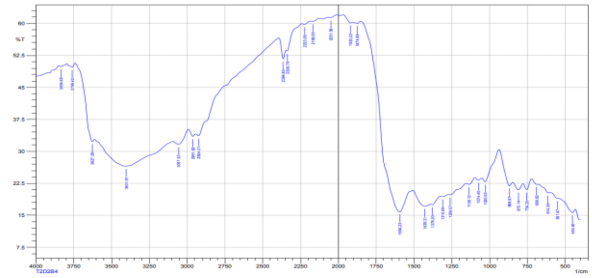
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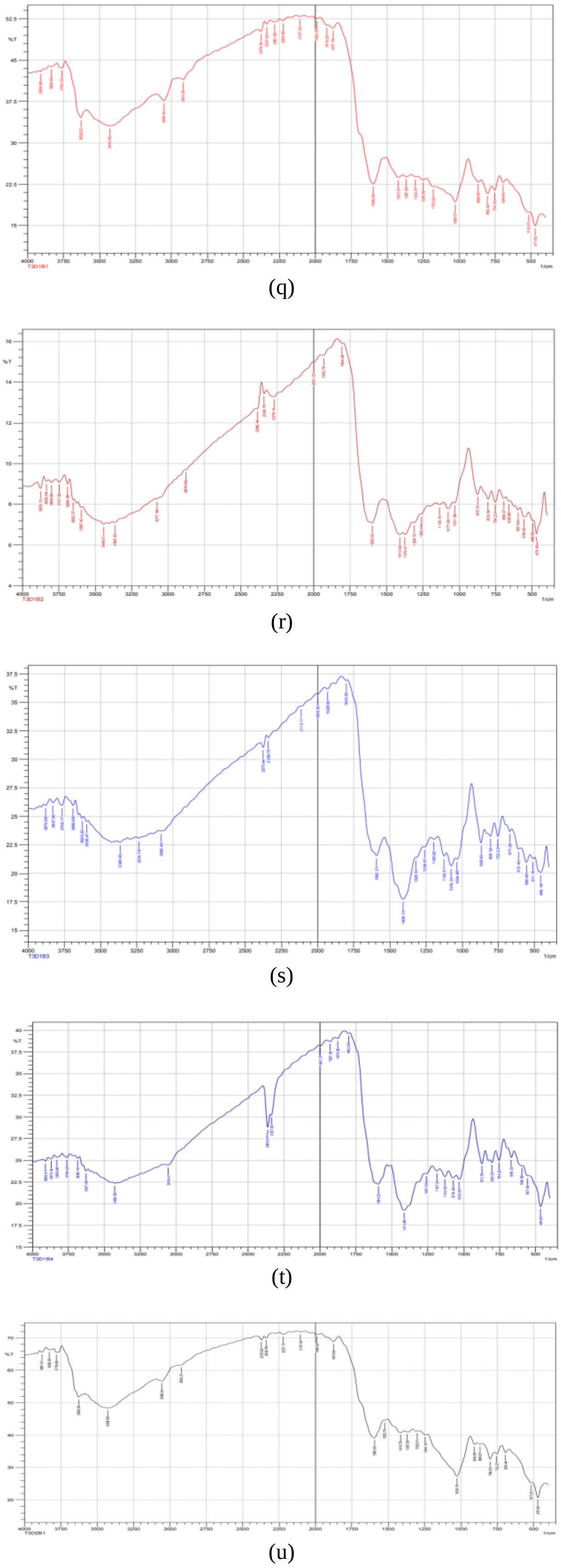

(q)

(r)

(s)

(t)

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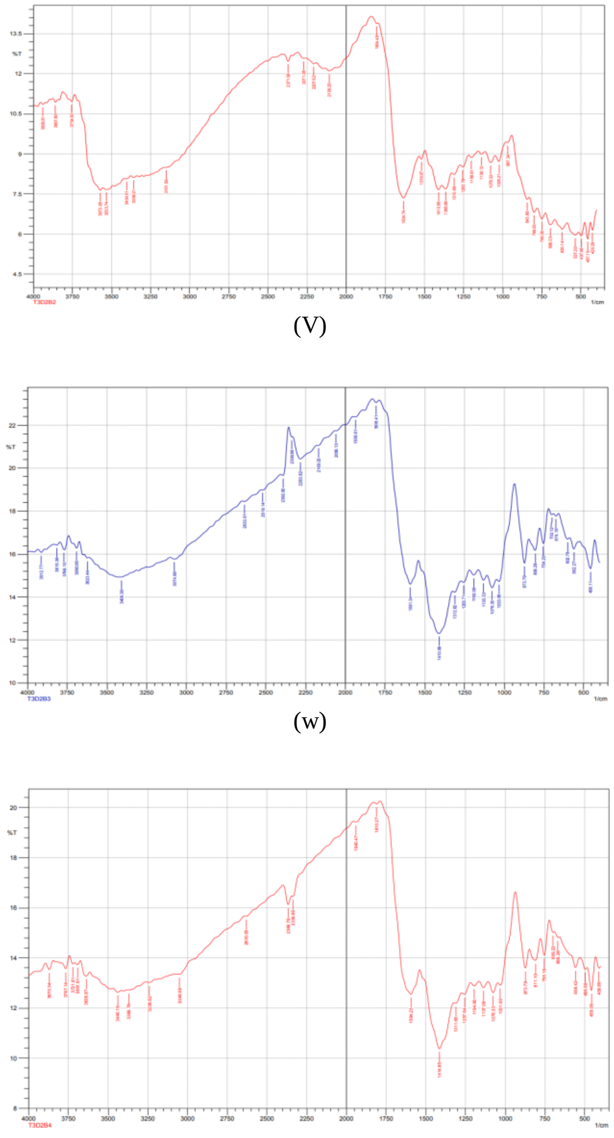


(V)

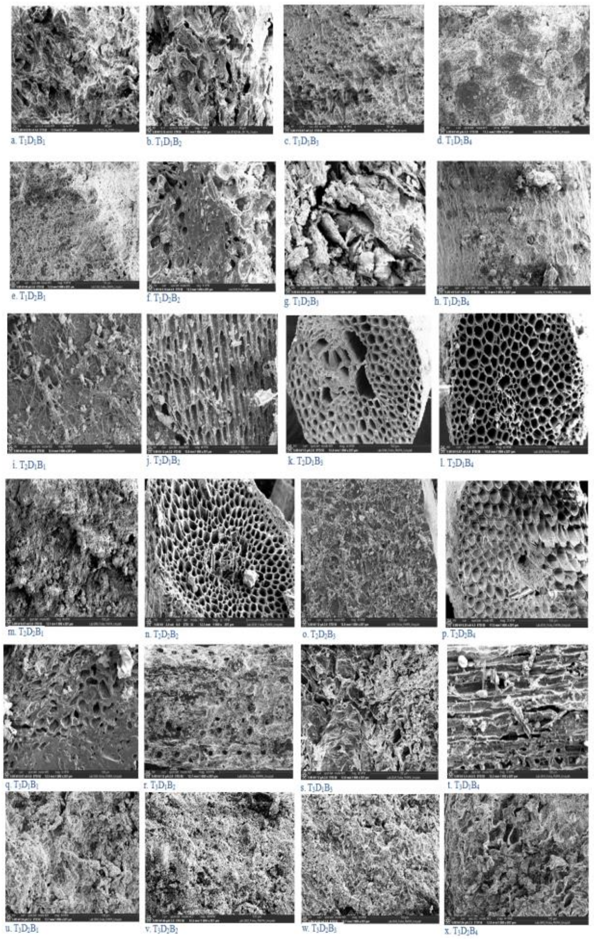
(w)

(x)

Fig. 1: FTIR spectrum of palm biochar and cacao at various temperatures and different pyrolysis durations

Scanning Electron Microscopy (SEM) Characteristics

The results of the SEM analysis for palm and cacao waste biochar at various temperatures and durations of pyrolysis are presented in Fig. 2. This figure shows that the biochar produced has a well-defined porous structure at certain temperature levels for each type of biochar raw materials. The formation of this effective porous structure in each type of biochar varies with the temperature and duration of pyrolysis. This variation is largely due to the devolatilization processes occurring during pyrolysis, which affects the surface and internal porosity of each raw material.



a. $T_1D_1B_1$ b. $T_1D_1B_2$ c. $T_1D_1B_3$ d. $T_1D_1B_4$

e. $T_1D_2B_1$ f. $T_1D_2B_2$ g. $T_1D_2B_3$ h. $T_1D_2B_4$

i. $T_2D_1B_1$ j. $T_2D_1B_2$ k. $T_2D_1B_3$ l. $T_2D_1B_4$

m. $T_2D_2B_1$ n. $T_2D_2B_2$ o. $T_2D_2B_3$ p. $T_2D_2B_4$

q. $T_3D_1B_1$ r. $T_3D_1B_2$ s. $T_3D_1B_3$ t. $T_3D_1B_4$

u. $T_3D_2B_1$ v. $T_3D_2B_2$ w. $T_3D_2B_3$ x. $T_3D_2B_4$

Fig. 2: Surface morphology of biochar at different pyrolysis Temperatures (T), Durations (D) and Types of biochar raw materials (B)

According to Hamissou *et al*. (2023), biochar exhibits a rough and porous surface that can be distinctly identified using SEM micrographs. The porous nature of biochar is critical for its application in soil amendment as it enhances the material's ability to retain water and nutrients, thereby supporting better soil structure and fertility. The SEM images illustrate how pyrolysis conditions influence the physical texture and structural integrity of the biochar, impacting its functional properties such as surface area, pore size distribution, and overall porosity.

These characteristics are essential for understanding how biochar interacts with soil and plant systems, including its role in improving soil aeration, water retention, and nutrient availability. The variability in pore structure as seen in the SEM images under different conditions suggests that optimizing pyrolysis parameters is crucial for tailoring biochar properties to specific agricultural or environmental needs.

The chemical changes in biochar occur as water and organic gases are lost during pyrolysis. Biochar with micro-porosity has the capability to store water, thereby enhancing its water-holding capacity when used as a soil amendment. This aligns with the findings of Bruun *et al*. (2014), who reported that the application of biochar as a soil amendment in sandy soil layers increased the root density of barley plants in critical soil profile layers and improved the available water capacity for plants. Further supporting this, Gąsior and Tic (2017) stated that the application of biochar as a soil amendment is facilitated by biochar's highly porous structure, providing a medium for microbial growth that can enhance soil fertility and the soil's water retention capability due to the porosity and specific surface area of biochar.

Discussion

The results of previous studies show that biochar raw materials to temperature and pyrolysis time determine the characteristics of biochar quality. This is shown from the results of research by Wang *et al*. (2020a) which reported that biochar produced from pig manure waste by slow pyrolysis at different temperatures (350-750°C) with different pyrolysis times increased the physico-chemical properties of biochar such as ash content, pH, mineral nutrients and a number of heavy metals as the temperature and pyrolysis time increased.

The lowest pH value was observed in the Palm Kernel Shells (PKS) treatment at a pyrolysis temperature of 350°C for a duration of 2 h, with a pH of 6.39, while the highest pH was found in the Cacoa Pod Husks (CPH) biochar treatment at a pyrolysis temperature of 550°C for a duration of 4 h, with a pH of 10.15. This is due to the thermal degradation caused by high pyrolysis, which increases the ash content of each biochar, thereby affecting the rise in biochar pH. Furthermore, the carbonate salts from alkaline minerals produced during pyrolysis also contribute to the increase in biochar pH. According to Ronsse *et al*. (2013), there is a positive correlation between increasing pyrolysis temperature and the pH of biochar solutions, higher calorific value, and larger surface area of biochar.

According to Hery Astuti *et al*. (2018), the organic carbon content of biochar increases at temperatures from 350-400°C and decreases as pyrolysis temperature increases to 450-550°C. At temperatures between 450-550°C, carbon elements evaporate along with the evaporation of other organic elements such as N, S, O, and H. Moreover, increasing the pyrolysis temperature leads to the release of volatile compounds from biochar, impacting the increase in fixed carbon, total carbon, and stable carbon in biochar and enhancing the calorific value of biochar (Crombie and Mašek, 2015). According to Sukmawati (2020), one of the criteria for biochar used as a soil amendment is its C/N ratio.

According to Domingues *et al*. (2017), biochar with high ash content is a source of P and K for plants and shows a high Cation Exchange Capacity (CEC), making it a high potential for retaining nutrients in the soil. Additionally, changes in functional groups are suspected to contribute to the increased total P, K, Ca, and Mg in biochar. This aligns with the views of Zama *et al*. (2017), who state that significant changes occur in the chemical or physical structure of organic functional groups in biochar when pyrolysis temperature increases from 350-650°C, resulting in changes in the concentration of inorganic mineral components such as CO_3^{2-}, PO_4^{3-} and SO_4^{2-} and cations like Al^{3+}, Ca^{2+}, Mg^{2+} and Na^+. According to Weber and Quicker (2018), biochar produced at relatively lower temperatures has a higher cation exchange capacity compared to that produced at higher pyrolysis temperatures, due to the effect of the combination of charged surface functional groups with the surface area of biochar. The type of biomass raw material used also impacts the CEC differences in biochar, consistent with Pituya *et al*. (2017), who stated that characteristics such as surface area, C, O, pH, CEC, and water retention capacity of biochar are greatly determined by the type of biomass from the raw materials used for biochar.

This research shows that the type of biochar raw materials, temperature, and duration of pyrolysis produce different biochar characteristics for soil amendment materials, indicated by varying ash content for each type of raw material, temperature, and duration of pyrolysis. This aligns with research by Pituya *et al*. (2017), which reported that the type of biomass from raw materials for biochar and pyrolysis conditions impacts the physicochemical characteristics of biochar.

The application of biochar in soil, particularly as a soil amendment, has high potential because it can increase the soil's negative charge from the generated functional groups. As a result, the soil's capacity to adsorb nutrients is enhanced, along with its ability to retain water. Biochar has a number of functional groups on its surface that can improve its adsorption properties, such as Carboxylates (COOH), Hydroxyl (OH), amines, and amides (Yaashikaa *et al*., 2020). The negative charge present on the surface of biochar also has the potential to enhance bonding with other materials in the soil, such as soil particles, organic soil material, and interactions between biochar and certain soil microbes. According to Tan *et al*. (2022), the physicochemical properties of biochar such as specific surface area, porous nature, ion exchange capacity, and pH help in altering soil environmental conditions and aid in enhancing the growth of microbes beneficial for soil and plants. Achieving optimal physicochemical characteristics of biochar as a soil amendment material depends not only on the raw material, temperature, and duration of pyrolysis but also significantly influences the quality of production. This aligns with Wang *et al*. (2020b), who state that pyrolysis temperature is a determining factor for biochar characteristics such as its physicochemical properties and molecular structure, as the process of pyrolysis involves depolymerization and dehydration with increasing temperature, producing compounds like cellulose, lignin, aldehydes, carboxyls, and ketones. Production of biochar at higher pyrolysis temperatures and longer durations results in a reduction of functional groups such as CO, OH, and aliphatic CH, with an increase in aromatic bonds on the biochar surface, leading to increased basicity and decreased acidity.

Conclusion

Biochar derived from palm oil and cocoa raw materials produced at different pyrolysis temperatures and durations significantly impacted improving the physicochemical properties of the biochar produced. Increasing the temperature and duration of pyrolysis in biochar production tends to have an impact on increasing various biochar properties such as pH, ash content, moisture content, organic carbon, total nitrogen, total phosphorus, total potassium, total calcium, total magnesium and Cation Exchange Capacity (CEC), but decreases the Carbon to Nitrogen ratio (C/N) of biochar.

Additionally, different temperatures and durations of pyrolysis in palm and cacao biochar result in changes to the functional groups and surface morphology of the biochar. The optimal biochar for soil amendment is obtained at a pyrolysis temperature of 550°C with a duration of two h for Palm Kernel Shells (PKS) biochar ($T_3D_2B_1$), a pyrolysis temperature of 450°C with a duration of four h for Palm Oil Empty Bunches (POEB) biochar ($T_2D_2B_2$) and a pyrolysis temperature of 450°C with a duration of two h for Cacoa Pod Husks (CPH) biochar ($T_2D_1B_3$), as well as mixed biochar from PKS: POEB: CPH ($T_2D_1B_4$).

These conditions provide the best characteristics for enhancing soil quality, supporting plant growth, and improving environmental sustainability through effective soil management practices.

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Author's Contributions

Iwan Saputra: Preparation of the journal manuscript, which include field and laboratory research, data analysis, and the drafted of the journal manuscript, as well as its subsequent publication.

Sugeng Prijono, Soemarno and Retno Suntari: Preparation of the journal manuscript.

Ethics

The author is solely liable for any consequences that may arise from the publication of this journal manuscript.

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