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Biochar Quality During Slow Pyrolysis from Oil Palm Empty Fruit Bunches and Its Application as Soil Ameliorant

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Abstract

The optimal utilization of oil palm empty fruit bunch (OPEFB) waste holds significant potential for biomass bioconversion via slow pyrolysis, presenting a promising alternative for producing high-quality biochar as a soil ameliorant. This study investigates the effects of slow pyrolysis temperatures (≤ 300 °C) on the physicochemical properties of biochar derived from OPEFB and evaluates its efficacy as a soil ameliorant. This study utilized a completely randomized design (CRD) with three replications across two experiments. The first experiment assessed the effect of slow pyrolysis temperature on the quality of biochar derived from OPEFB, with treatments set at four temperatures (150, 200, 250, and 300 °C) levels. The second experiment evaluated the impact of the selected biochar on the surface charge of oil palm plantation soil, applying biochar at five different doses (0, 20, 40, 60, and 80 tons ha^{-1}). The potential temperature of 200 °C in slow pyrolysis had a significant effect on the quality of biochar from OPEFB with a yield ratio of 27.84% char; proximate (91.95% volatile matter and 0.81% fixed carbon), cation exchange capacity (CEC) [167.73 cmol(+) kg^{-1}], and macro and micronutrients (e.g., C, N, P, K, Ca, Si, Fe, Cu, Zn, and Mn). The potential of O-H, N-H, C-H, and C=O functional groups of biochar from OPEFB for nutrient availability and absorption efficiency proven by the effect of 40 tons ha^{-1} biochar from OPEFB which significantly increased 80% of soil surface charge [pH by 0.80; organic matter (OM) composition by 19.8%, CEC by 11 cmol(+) kg^{-1}] and nutrients [0.93% C; 0.04% N; 17.57 ppm P_2O_5; 0.65 cmol(+) kg^{-1} K] on Inceptisols.

Keywords: biochar; chemical properties; Inceptisols; nutrients; surface charge

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INTRODUCTION

Biochar production and application in agriculture present significant potential for promoting sustainable agriculture, especially in developing countries. Biochar supports long-term agricultural productivity and environmental health by improving soil quality and enhancing carbon sequestration. While its impacts depend on factors like production methods, soil conditions, and resource availability, biochar offers a promising approach to address challenges such as soil degradation and low fertility commonly found in developing regions (Owsianiak et al., 2021).

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Biochar, as an alternative ameliorant produced from the carbonization process of biomass, can improve soil fertility and quality for a long time. Biochar contains high stable carbon (Bo et al., 2023; Pandian et al., 2024) and nutrient composition required by the agricultural cultivation process and maintains the ecosystem against climate change (Singh et al., 2023; Khan et al., 2024). Biochar will be produced with different diversity from the type of biomass (Ravindiran et al., 2024), temperature (Tomczyk et al., 2020), time (Amalina et al., 2022), pyrolysis method (Kavan Kumar and Panwar, 2024), and size applied (Yaashikaa et al., 2020). Biomass carbonization through the principle of pyrolysis aims as a form of thermochemical modification of organic compounds. One potential organic material that continues to be developed is oil palm empty fruit bunch (OPEFB) waste.

The OPEFB is one of the main solid by-products generated from the processing of palm oil mills. The palm oil industry has to dispose of about 1.1 tons of OPEFB for every ton of palm oil produced with lignocellulose content such as cellulose (42.7 to 65%), hemicellulose (17.1 to 33.5%), and lignin (13.2 to 25.31%) (Samiran et al., 2016). The fundamental properties of OPEFB facilitate its efficient management and optimized resource utilization, particularly when available in substantial quantities. Basic properties of biomass, including moisture content, particle size, density, elemental composition, structural constituents, ash content, and volatile matter, are critical in determining the feasibility of OPEFB as a raw material (Hardianto et al., 2023). Proximate analysis reveals that OPEFB possesses a high moisture content, necessitating substantial thermal energy for drying, alongside elevated volatility, indicating its reactive nature (Nabila et al., 2023). Thus, the right method and temperature are needed to produce quality biochar using the principle of slow pyrolysis.

The production process for making biochar significantly impacts the diversity of biochar quality produced. Various forms of methods used are traditional (Soil Pit), conventional (Kon-Tiki), and modern (Reactors) (Herviyanti et al., 2022; Maulana et al., 2022), but the impact of the implementation of temperature is the main principle of concern in the biochar production process and is interesting to develop especially in slow pyrolysis (Selvarajoo and Oochit, 2020; Altıkat et al., 2024). The pyrolysis process can be divided into slow, fast, and flash pyrolysis (Al-Rumaihi et al., 2022). All of these processes are distinguished by the temperature difference during the pyrolysis process. Slow pyrolysis, operating at lower temperatures (≤ 300 °C), offers energy efficiency and controlled production of biochar with superior characteristics compared to fast and flash pyrolysis, which require higher temperatures (≥ 400 °C). Among available methods, slow pyrolysis has the advantage of not requiring a very large energy supply compared to other pyrolysis processes and average heating (5 to 7 K min^{-1}) by producing little liquid while more gas and charcoal to support various applications (Pahnila et al., 2023).

The biochar structure is unique and plays an important role in its various applications, especially for soil ameliorants (Ayaz et al., 2021; Darfis et al., 2023b; Ravindiran et al., 2024). Biochar produced from the pyrolysis process should prioritize the yield in the form of charcoal. The charcoal produced should have a lot of negative charge along with various functional groups that can interact with other compounds especially related to nutrients and pollutants. Biochar has a large specific surface area, which means it has a lot of surface available for interaction relative to its mass (Zhou et al., 2024). Biochar also has a large pore volume, creating spaces within its structure where other substances can be deposited, and its high cation exchange capacity (CEC). Cations are positively charged ions, and biochar’s ability to exchange these ions makes it valuable in soil improvement (Elkhlifi et al., 2023). Biochar can attract and hold important nutrients such as K, Ca, and Mg, thus preventing them from being washed away by water and making them available to plants (Nicholas et al., 2022; Chi et al., 2024). The OPEFB waste-based biochar shows great potential to support soil and crop productivity affected by the lignocellulosic composition of OPEFB on biochar quality and optimizing operational parameters of slow pyrolysis, such as temperature so that efficiency and product quality are not yet clearly defined.

Evaluation of the long-term impact of biochar on soil quality, such as nutrient retention and mitigation against organic and inorganic compound contamination, also needs to be developed. On the other hand, the mechanism of biochar interaction with soil, especially in nutrient retention and soil remediation in oil palm plantations are required to be identified. Therefore, this study aimed to assess the effect of slow pyrolysis temperature (≤ 300 °C) on the quality of biochar from OPEFB and its application as a soil ameliorant.

MATERIALS AND METHOD

This research was conducted from June to September 2024 at the Chemistry and Soil Fertility Laboratory, Department of Soil Science and Land Resources, Faculty of Agriculture, Central Laboratory of Universitas Andalas, and Chemistry Laboratory, Faculty of Mathematics and Natural Sciences, Universitas Negeri Padang, Indonesia.

Experimental design

This study utilized a completely randomized design (CRD) with three replications across two experiments. Experiment I investigated the impact of slow pyrolysis temperature on the quality of biochar derived from OPEFB, with the following temperature treatments: (a) 150, (b) 200, (c) 250, and (d) 300 °C. In experiment II, the effect of the selected biochar from OPEFB on changes in the soil surface charge and nutrients of oil palm plantations was examined, with varying application rates: (a) 0, (b) 20, (c) 40, (d) 60, and (e) 80 tons ha^{-1}. Experimental units for both experiments were randomly assigned within each treatment level to ensure unbiased and robust statistical analysis.

Biochar production

The primary raw material for biochar was OPEFB waste collected from Bina Pratama Sakato Jaya Inc. The OPEFB was sized into 5 to 10 cm segments and subjected to thorough cleaning with running water to eliminate any adhering impurities, followed by multiple soaking cycles until it was completely purified. The waste was baked at 70 °C for 2 x 24 hours to dry and weighed for the production process according to experiment I with a temperature difference of 150 to 300 °C for 30 minutes. Each batch of biochar production used 50 g of dry OPEFB waste for each sample with three replicates for consistency and standardization of the experiment. The pyrolysis process was carried out using a ceramic fiber muffle furnace LMF-10D. This instrument was chosen due to its precision in controlling temperature and its ability to maintain an oxygen-free environment, which is essential for producing high-quality biochar. The biochar produced was analyzed morphologically and characteristically in the laboratory.

Soil sampling

The soil samples used were obtained from the forest area of an oil palm plantation in Sijunjung-Dharmasraya, West Sumatra, Indonesia, within the coordinates 101°24'13.52" to 101°32'6.80" E and 0°47'48.97" to 1°2'39.73" S, classified under the order Inceptisols. Soil samples were taken compositely at a depth of 0 to 20 cm and then brought to the laboratory for preparation by (a) drying, (b) pulverizing and sieving with a 2 mm sieve, and (c) stirring homogeneously and weighing according to the experiment. Soil was used for experiment II to assess the effect of selected biochar on soil surface charge with different rates (0 to 80 tons ha^{-1}). Soil was weighed as much as 100 g absolute dry equivalent and OPEFB biochar was weighed according to the dose given. Soil samples and biochar from OPEFB following the dose were homogenized by adding the amount of water according to the field capacity of the soil in the experimental pot manually until well mixed. The samples were then incubated for one week and analyzed in the laboratory.

Biochar, soil, and statistics analysis

Biochar analysis used guidelines issued by the International Biochar Initiative (IBI) and followed the Minister of Agriculture of the Republic of Indonesia decree standard No. 261/KPTS/SR.310/M/4/2019 concerning minimum technical requirements for soil ameliorants, namely proximate analysis, pH (H_2O, KCl 1M, and point of zero charge (PZC)), electrical conductivity (EC), CEC, organic and inorganic C, total N, and oxide composition with PANalytical Epsilon 3XL Benchtop X-Ray Fluorescence (XRF) Spectrometer (Singh et al., 2017). Functional group analysis with IRT racer 100 Fourier Transform Infrared (FTIR) Shimadzu A217061 also supports the potential of biochar for application as a soil ameliorant. Soil analysis was focused on soil surface charge characteristics and nutrients namely % clay, pH (H_2O, KCl 1M, and PZC), EC, mineral and organic matter (OM) composition, CEC, and nutrients such as organic C, total N, available P and exchangeable K (Eviati et al., 2023). The results of soil analysis were subjected to statistical analysis using software (Microsoft Excel 2016 and SPSS 23). The statistical analysis used was the analysis of variance (ANOVA) and Duncan’s multiple range test (DMRT). After detecting a significant effect with ANOVA, DMRT was used as a post hoc test to identify which specific group means differ from each other. Significance levels were determined as follows: if F count > F table at the 5% level, the results are significant and marked with [*], and if F count > F table at the 1% level the results are very significant and marked with [**]. The [*]

and [**] annotations reflect the significance levels of these differences.

RESULTS AND DISCUSSION

Effect of slow pyrolysis temperature on the quality of biochar

Pyrolysis temperature significantly affected the biochar yield of OPEFB waste. The temperature of 150 °C produced the highest charcoal yield of 29.36% and the highest gas and liquid yield of 93.23% at 300 °C (Table 1). The decomposition of OM through combustion at different temperatures and times can produce conversion products with different yields of charcoal, gas, and liquid. Increasing the temperature affects all three components (Yan et al., 2005). The high content of cellulose and hemicellulose in OPEFB affects the quality of the biochar produced. Hemicellulose pyrolyzed at temperatures between 180 and 300 °C, and cellulose pyrolyzed at temperatures between 260 and 350 °C, while lignin pyrolysis occurred at temperatures of 300 °C or higher (Chen et al., 2021). The increase in gas and liquid composition resulting from higher temperatures was due to incomplete biomass decomposition, indicating that the pyrolysis process was not fully completed. The expected quality of biochar is adjusted to the needs of the application used as ameliorant material which requires more charcoal compared to gas and liquid composition. Elevating the pyrolysis temperature leads to a reduction in biochar yield, accompanied by a decline in the H/C and O/C ratios. Furthermore, the specific properties of the resulting biochar exhibit variability, influenced by both biomass type and pyrolysis temperature (He et al., 2024).

Proximate analysis is aimed to characterize the quality of biochar through the thermal decomposition method to determine moisture, volatile matter, ash, and fixed carbon (Chávez-García et al., 2020). Moisture refers to the physically adsorbed water both on the surface and contained within the pores. The increase in pyrolysis temperature was significant for the increase in moisture and ash content of biochar from OPEFB. The biochar obtained at 300 °C exhibited the highest moisture and ash content, at 64.15% and 19.45%, respectively, with both values decreasing at lower temperatures. The increase in temperature caused a large amount of water to evaporate during the pyrolysis process, reducing the water content of the biochar. Ash is the inorganic residue after combustion. The inorganic content comes from the conversion, oxidation, and possible evaporation of inorganic species (Vassilev et al., 2017).

Increasing the pyrolysis temperature affected the amount of volatiles produced, reducing it from 93.95% at 150 °C to 80.45% at 300 °C. The decrease in volatile matter content during pyrolysis is due to the progressive breakdown of cellulose, hemicellulose, and lignin. Biochar with volatile organic compounds (VOCs), consisting mostly of short-chain aldehydes, furans, and ketones, is produced at lower pyrolysis temperatures ($\leq$ 350 °C) (Darfis et al., 2023a). Most of the higher temperature (> 350 °C) biochar components are usually long-chain hydrocarbons and adsorbed aromatic compounds. The adsorbed VOCs are reduced due to the presence of oxygen during pyrolysis (Chen et al., 2021). A decrease in pyrolysis temperature usually results in a more amorphous biochar with decreased stable carbon. This result is similar to biochar from OPEFB. Accelerated decomposition of OM into volatile chemicals and synthesis gas at higher pyrolysis temperatures (400 to 600 °C) reduces the biochar yield (Suresh et al., 2024). The effect of pyrolysis temperature significantly influences the decrease in fixed carbon content. The decrease begins at temperatures of 150 and 200 °C, with reductions of 0.85% and 0.81%, respectively, and continues to drop further at 300 °C to 0.60%.

High temperatures cause VOC such as methane, hydrogen, and light hydrocarbons to evaporate more easily from the biomass, reducing the amount of carbon left in solid-form biochar. High temperatures can also trigger the breaking of chemical bonds in the carbon structure of the biomass, resulting in smaller and more easily oxidized carbon molecules. The carbon in the biomass can react with residual oxygen in the system, forming oxygenated compounds such as carbon monoxide (CO) and carbon dioxide (CO_2). These compounds are volatile and will escape into the atmosphere (Visser et al., 2024). The pyrolysis temperature significantly increased the pH H_2O and KCl of biochar, from 6.60 and 6.47 (200 °C) to 9.97 and 9.83 (300 °C) (Table 1). Meanwhile, the pH PZC of biochar from OPEFB was below the pH H_2O and KCl at each temperature. This result indicates that the biochar predominantly carries negative charges. An increase in temperature disrupts weak bonds within the biochar structure, such as hydroxyl groups, leading to their breakdown and contributing to the alkalinity of the biochar (Zhang et al., 2022).

Table 1. Effect of slow pyrolysis temperature on biochar quality from OPEFB waste

Slow pyrolysis temperature (°C)	Yield ratio		Proximate				pH			EC	LP	CEC	OC	IOC	Total N
	Char	Gas + Liquid	Moisture	Volatile matter	Ash	Fixed carbon	H_2O	KCl 1M	PZC						
	------ % ------		---------------- % ----------------				--------- unit ---------			dS m^{-1}	% $CaCO_3$	cmol(+) kg^{-1}	---------- % ----------		
150	29.36^{a}	70.64^{d}	27.00^{d}	93.95^{a}	5.95^{d}	0.85^{a}	6.60^{c}	6.47^{c}	6.33^{b}	0.14^{d}	1.25^{d}	304.67^{a}	3.66	1.67^{c}	1.19^{a}
200	27.84^{b}	72.16^{c}	29.00^{c}	91.95^{b}	7.95^{c}	0.81^{ab}	6.97^{b}	6.67^{b}	6.37^{b}	0.17^{c}	2.50^{c}	167.73^{b}	3.38	2.27^{c}	0.95^{a}
250	20.46^{c}	79.54^{b}	29.50^{b}	86.95^{c}	12.95^{b}	0.72^{b}	7.10^{b}	6.77^{b}	6.43^{b}	0.40^{b}	3.75^{b}	131.73^{c}	3.09	3.07^{b}	0.65^{b}
300	6.72^{d}	93.23^{a}	32.50^{a}	80.45^{d}	19.45^{a}	0.60^{c}	9.97^{a}	9.83^{a}	9.70^{a}	1.54^{a}	8.76^{a}	105.33^{d}	2.71	8.27^{a}	0.36^{c}
CV	2.51	0.67	0.17	0.06	0.43	6.71	1.07	0.78	0.98	1.26	12.20	4.04	11.53	10.26	18.61
Duncan's test	**	**	**	**	**	**	**	**	**	**	**	**	ns	**	**
SE	0.43	0.43	0.04	0.04	0.04	0.04	0.07	0.05	0.06	0.01	0.41	5.85	0.30	0.32	1.12

Note: Numbers in the same column followed by the same lowercase letter are not significantly (ns) different according to Duncan's test at the 5% (*) and 1% (**) level; PZC = Point of zero charge [(2*KCl) – H_2O]; EC = Electrical conductivity; LP = Liming potential; CEC = Cation exchange capacity; OC = Organic carbon; IOC = Inorganic carbon; CV = Coefficient of variation; SE = Standard error and n = 12 samples

Table 2. Effect of biochar produced at selected slow pyrolysis temperature (200 °C) from OPEFB waste and application rates on soil surface charge and nutrient availability of Inceptisols

Dose of biochar from OPEFB (tons ha^{-1})	Fraction	pH			EC	Composition		CEC	Nutrient			
	Clay	H_2O	KCl 1M	PZC		Mineral	OM		OC	Total N	Available P	Exchangeable K
	%	----------- unit -----------			dS m^{-1}	------ % ------		cmol(+) kg^{-1}	------ % ------		ppm P_2O_5	cmol(+) kg^{-1}
0	42.04	4.30^{d}	4.10^{c}	3.90^{c}	0.35^{d}	83.85^{a}	16.20^{e}	26.60^{d}	1.67^{d}	0.19^{d}	19.32	0.12^{e}
20		5.00^{c}	4.50^{b}	4.00^{b}	0.43^{c}	64.85^{b}	35.20^{d}	36.20^{c}	2.20^{c}	0.21^{c}	35.05	0.53^{d}
40		5.10^{b}	4.90^{a}	4.70^{a}	0.44^{b}	64.00^{c}	36.00^{c}	37.60^{b}	2.60^{b}	0.23^{b}	36.89	0.77^{c}
60		5.23^{ab}	5.00^{a}	4.77^{a}	0.46^{ab}	61.60^{d}	38.40^{b}	39.20^{ab}	3.35^{b}	0.25^{ab}	38.29	0.94^{b}
80		5.37^{a}	5.07^{a}	4.77^{a}	0.47^{a}	61.00^{e}	39.00^{a}	40.20^{a}	5.61^{a}	0.26^{a}	38.51	1.06^{a}
CV	-	2.31	3.19	6.28	2.54	0.07	0.15	2.78	15.89	6.29	36.77	0.84
Duncan's test	-	**	**	**	**	**	**	**	**	**	ns	**
SE	-	0.09	0.12	0.23	0.01	0.04	0.04	0.82	0.40	0.01	10.09	0.01

Note: Numbers in the same column followed by the same lowercase letter are not significantly (ns) different according to the Duncan's test at the 5% (*) and 1% (**) level; PZC = Point of zero charge [(2*KCl) – H_2O]; OM = Organic matter; EC = Electrical conductivity; CEC = Cation exchange capacity; OC = Organic carbon; IOC = Inorganic carbon; CV = Coefficient of variation; ** = SE = Standard error; and n = 15 samples

The pyrolysis temperature significantly increased the EC values from 0.14 to 1.54 dS m^{-1}. The increase in EC value represents the increasing salts in the biochar since the pyrolysis temperature also increases. The amount of salt dissolved in the biochar solution is important because the application of large amounts of biochar to the soil can adversely affect salt-sensitive crops. Solutions with higher salt concentrations have a greater ability to conduct electric current (Wang et al., 2020). The increase in EC is also affected by the increase of residue or ash concentration caused by the loss of volatile matter during the pyrolysis process.

The ratio of biochar to water in suspension affected the EC value, with the EC value decreasing through increasing dilution. High dissolved salt content and equilibration time also affect EC values, with longer equilibration times associated with higher EC values (Wang et al., 2024b). Meanwhile, the liming potential is also significant to the effect of pyrolysis temperature. The higher pyrolysis temperature used in producing biochar indicates an increase in biochar's clouding potential. This result is evident at a temperature of 350 °C, which has a potential clouding value of 8.76% $CaCO_3$. Parts of the biochar ash composition (e.g., basic oxides and carbonates) can provide a significant increase in alkalinity (Tusar et al., 2023). It depends on the raw materials and procedures that give biochar liming qualities, enabling it to be used as a liming agent on acidic soils. To make liming recommendations, it is necessary to understand biochar's liming potential and ability to balance soil pH (pH-biochar) before application.

The negative electrical charge of OM components causes cation exchange. The effect of slow pyrolysis temperature significantly reduced the CEC of biochar from OPEFB with the highest CEC at 200 °C of 304.67 cmol(+) kg^{-1}. CEC is a measure of the ability of biochar to absorb cations in exchangeable form. In biochar, most of the negative charge is a variable type (pH dependent) (Lago et al., 2021). This negative charge develops as a result of proton dissociation from oxygenated functional groups on the biochar surface. As pH increases, dissociation intensifies, leading to an increase in the negative charge of biochar. Consequently, the CEC of biochar also increases with the rising pH.

The majority of the variable charged hydroxyl groups on the biochar surface are organic acid functional groups that can be generally categorized into carboxylic, lactonic, and phenolic groups (Maulana et al., 2022). The distribution, concentration, and dissociation constants of these groups vary and degrade as the pyrolysis temperature increases. The CEC-pH dependence is specific to the biochar, with most of the carboxylic acid groups having pKa values between 2 and 4, while the phenolic groups have pKa values ranging from ~7 to 10, meaning they mostly dissociate at pH values above 5. These groups are expected to be available for cation exchange in the oil palm bunch biochar (Hailegnaw et al., 2019).

The temperature of slow pyrolysis plays a significant role in the reduction of organic carbon (OC) and total N. A decrease in OC and total N was observed at temperatures of 250 °C (3.09% C) for OC and 200 °C (0.95% N) for total N, primarily due to the degradation of organic compounds. As the temperature increases, the chemical bonds in organic compounds break, leading to the degradation of organic compounds into simpler ones. During the volatilization process, the degraded organic compounds evaporate in the form of gas (volatiles). This process causes a decrease in OC and N in the solid residue (biochar) with increased aromaticity at high temperatures. As the temperature rises, the carbon structure in biochar tends to become more aromatic (Bagheri et al., 2023).

This increase in aromaticity makes the carbon in biochar more stable and difficult to degrade, causing the OC content in biochar to be higher than in the original material. The formation of heterocyclic compounds affects the N content in organic materials and can form more stable heterocyclic compounds at high temperatures (Zhang et al., 2023). This causes some N to be retained in biochar and not released in gaseous form. At low temperatures, the degradation of organic compounds is slow, and most organic compounds remain in the biochar, leading to a small decrease in OC and total N. In contrast, most organic compounds are degraded and vaporized at very high temperatures. However, at too high a temperature, the risk of partial oxidation (partial combustion) becomes greater, thus reducing the biochar yield. Inorganic carbon (IOC) is part of the ash fraction in biochar such as calcite ($CaCO_3$) and/or dolomite [$CaMg(CO_3)_2$] (Wang et al., 2014). The effect of pyrolysis temperature is significant in increasing the IOC of biochar from OPEFB at 300 °C (8.27%). Mineral composition from biochar belonging to IOC tends to be very stable at high temperatures. The pyrolysis process is not strong enough to change the structure of these minerals. The increase in such salts may contribute to the liming properties and the nutrient value of the biochar (Nair et al., 2023).

The FTIR spectra and oxide composition of the best biochar made from OPEFB at 200 °C were identified using the XRF method (Figure 1). FTIR spectroscopy aimed to identify the changes in the functional groups of organic molecules in OPEFB and their biochar at 200 °C as a potential temperature. The identified functional group shifts showed O-H or N-H stretching at 3442.94 to 3464.15 cm^{-1}; C=O stretching at 1647.21 to 1701.22 cm^{-1}; and -C-H wrinkling at 1161.15 to 1236.37 cm^{-1}. The shift in wave numbers in the FTIR spectrum after the pyrolysis process occurs due to the heating process of organic materials in the absence of oxygen, resulting in thermal decomposition (Wang et al., 2024a). Significant changes in the organic molecular structure of OPEFB at 200 °C are thought to cause degradation, condensation, aromatization, and isomerization of organic molecules (Matin and Aydin, 2022). The oxide composition of biochar from OPEFB at 200 °C identified 34.24% K_2O, 20.25% SiO_2, 16.14% P_2O_5, 13.52% CaO, 8.40% Cl, 2.33% Fe_2O_3, and $\leq$ 0.2% ZnO; CuO and MnO (Figure 1). This oxide composition functions as a nutrient that can potentially contribute to the soil.

Effect of dosage of biochar on chemical properties of Inceptisols

The application of biochar produced at 200 °C was selected to investigate its effects on changes in soil surface charge and nutrient content in Inceptisols from oil palm plantations. The biochar application at 200 °C significantly increased soil pH, EC, OM content, CEC, and nutrient levels, including OC, total N, and exchangeable K. The pH of Inceptisols from oil palm plantations was measured using two solutions: H_2O (active pH) and 1M KCl (potential pH). The application of biochar at doses of 80 and 60 tons ha^{-1} significantly increased the pH H_2O by 1.07 and 0.93, respectively, compared to the control. The pH H_2O reflects the concentration of H^+ ions in the soil solution, whereas the pH KCl represents the H^+ charge on soil colloids (Wang et al., 2019; Karimah et al., 2024). The lower pH KCl compared to pH H_2O indicates that the soil in the oil palm plantation is predominantly negatively charged. The alkalinity of biochar contributes to its potential to reduce soil acidity (Geng et al., 2022). A strong relationship exists between soil pH and biochar alkalinity in soils treated with biochar, allowing for the evaluation of its liming effect. Most biochar exhibits pH values ranging from neutral to alkaline, making it highly effective in increasing soil pH and therefore enhancing CEC (Table 2). The EC value also increased with higher application rates of biochar from OPEFB. At doses of 60 and 80 tons ha^{-1}, EC significantly increased by 0.11 and 0.12 dS m^{-1}, respectively, compared to the control. The movement of singly charged ions is governed by a simple force balance involving the electric field and the viscous resistance of the solution. Exchangeable sodium percentage (ESP), CEC, soil-specific surface area (S), density (δ_o), electric potential (φ_o), and electric field strength (E_o) are key soil surface electrochemical parameters influencing soil behavior (Du et al., 2020).

The application of biochar from OPEFB induces a shift in the composition of minerals and OM in the soil of oil palm plantations. The shift in mineral and OM composition was due to the application of biochar which increased the OM at the rate of 80 tons ha^{-1} by 22.80%, compared to the control. Meanwhile, on the contrary, the composition of soil minerals decreased significantly due to the application of biochar from OPEFB. Biochar, with its high carbon content and chemical stability, can remain in the soil for extended periods, significantly enhancing the soil's OC content (Azzi et al., 2024). The application of biochar from OPEFB also significantly increased the CEC of the soil. Among the tested doses, the application of 60 and 80 tons ha^{-1} of biochar was most effective, increasing the CEC by 13.60 and 12.60 cmol(+) kg^{-1}, compared to the control. The interaction of minerals with biochar from OPEFB exhibits a high affinity for weak acids consisting of hydroxyl and carboxyl groups. Changes in the electrochemical properties of clays are closely related to the number of aluminum hydroxy complexes incorporated in clays and their chemical composition and charge properties (Prasetyo et al., 2023). The effect of the number of interlayers on the CEC of clay affects the zero charge point (Herviyanti et al., 2024).

The effect of the number of interlayers on the cation exchange increases pH, EC, CEC, and OM, leading to enhanced soil negative charge activity (PZC). The pH PZC showed a lower value than the pH H_2O. The effect of 40 to 80 tons ha^{-1} significantly increased the negative charge of soil by $\geq$ 80%. This increase supports the availability

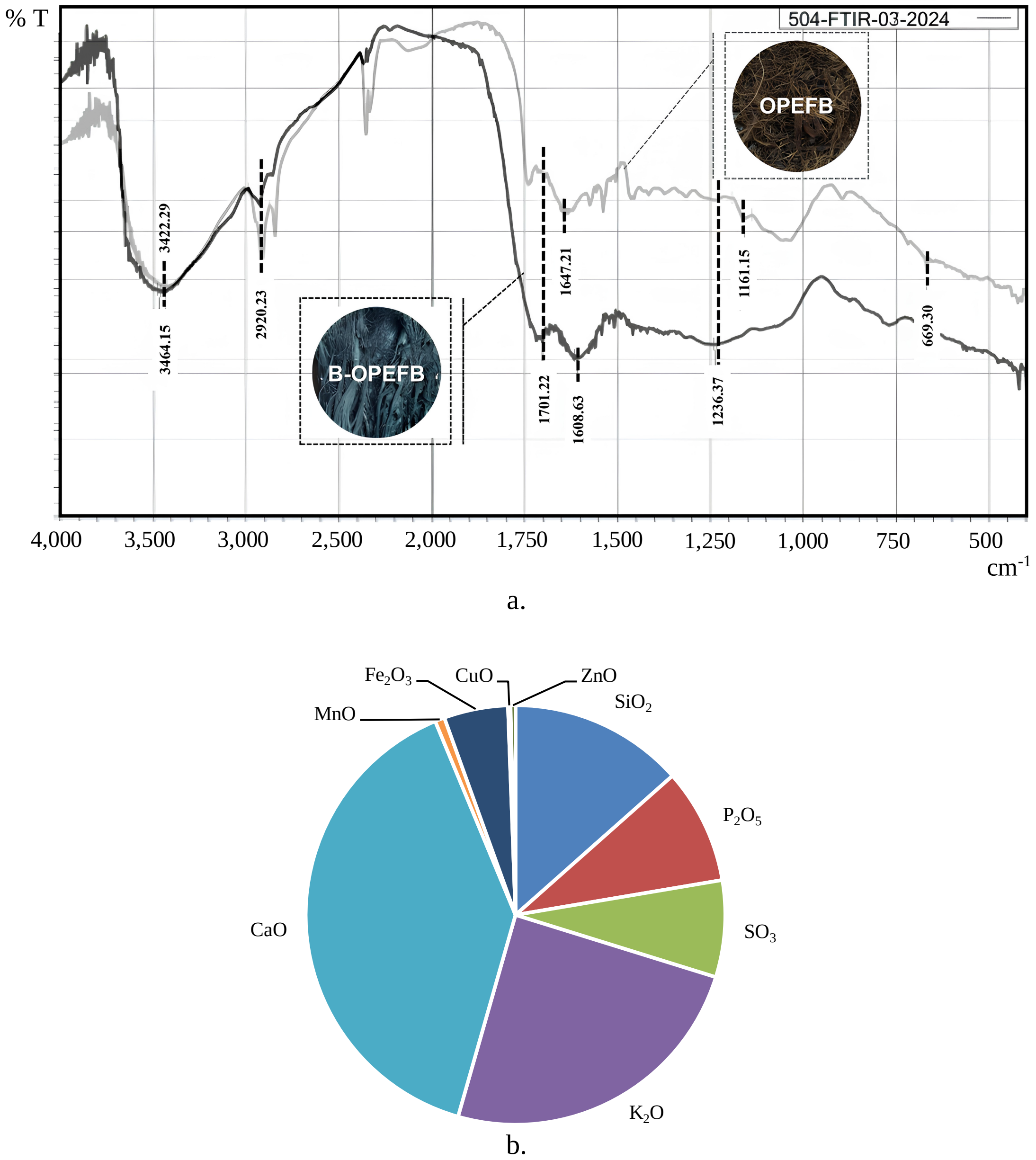

Figure 1. Characterization of functional groups by FTIR (a) and oxide composition by XRF on the selected slow pyrolysis temperature (200 °C) combustion of biochar from OPEFB waste (b)

of nutrients and the absorption of pollutants (organic and inorganic), especially in oil palm plantations. The use of amelioration technology with biochar from OPEFB increased the negative charge on the soil surface charge. Soil from oil palm plantations ameliorated with 40 to 80 tons ha^{-1} biochar from OPEFB exhibited a longer range of negative charge (ΔpH = pH KCl – pH H_2O) on the soil colloidal surface compared to the control. Higher negative charge activity is expected to increase nutrient availability and overcome pollution, such as pesticides, in oil palm plantations.

The description of surface charge on the soil usually consists of two types, permanent charge and variable charge. The permanent charge is formed during the process of soil formation or weathering through isomorphic substitution on clay minerals (Wen et al., 2020). Variable charge arises from the protonation or deprotonation process of surface functional groups. It is mainly found in clay minerals and metal oxides. The PZC is often included in surface charge characteristics and soil surface acidity or salinity properties. Hydroxyl functional sites serve as adsorption sites for protons and other inorganic and organic contaminants. The PZC is the state that occurs when the presence of positive and negative charges are equal (Kumari et al., 2022). This index is useful for identifying favorable soil properties. Evidence has shown an increase in nutrients, such as OC, total N, and exchangeable K in soils from oil palm plantations.

The effect of 80 tons ha^{-1} biochar from OPEFB significantly increased OC and exchangeable K, each by 3.94% C and 0.94 cmol(+) kg^{-1}. Meanwhile, the increase in total N occurred at the application of 60 and 80 tons ha^{-1} by 0.07 and 0.06% N, respectively, compared to the control. Biochar can bind carbon in a stable form, therefore, the carbon is not easily decomposed and released back into the atmosphere (Li and Tasnady, 2023). The pore structure of biochar protects the OC already in the soil, thus slowing down the mineralization process. On the other hand, biochar can be a living place for microorganisms that can fix nitrogen from the air. The fixated nitrogen is then available to plants through the denitrification process by adsorbing nitrate ions. Biochar also has a high CEC, so it can retain K ions and prevent them from being leached out by water (Tsolis and Barouchas, 2023). Thus, biochar from OPEFB at a slow pyrolysis temperature of 200 °C can potentially improve the soil quality and productivity of oil palm plantations.

CONCLUSIONS

The potential of a 200 °C temperature in slow pyrolysis significantly affects the biochar quality of OPEFB, with a yield ratio of 27.84% char and 72.16% gas and liquid. The proximate analysis revealed 91.95% volatile matter, 7.95% ash, and 0.81% fixed carbon. The biochar had a pH of 6.97, EC of 0.17 dS m^{-1}, CEC of 167.73 cmol(+) kg^{-1}, and macro-micronutrient content of 3.38% C, 0.95% N, 16.14% P, 34.24% K, 13.52% Ca, 20.25% Si, 2.33% Fe, 0.17% Cu, 0.20% Zn, and 8.40% Mn. The functional groups O-H, N-H, C-H, and C=O in the biochar play a significant role in the availability and absorption efficiency of nutrients and pollutants. The application dose of 40 tons ha^{-1} OPEFB biochar significantly increased pH (by 0.80), EC (by 0.09 dS m^{-1}), OM composition (19.8%), CEC (11 cmol(+) kg^{-1}), and nutrient e.g., 0.93% C; 0.04% N; 17.57 ppm P_2O_5; 0.65 cmol(+) kg^{-1} K. Thus, the potential of biochar from OPEFB with slow pyrolysis system in amelioration technology can also be recommended for fertilization efficiency and remediation of pollutants in oil palm plantations such as pesticides.

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