Applicability Assessment of Oil Palm Trunk Biochar for Use as Soil Amendment: Morphology, Structure, and Chemical Properties

by Turnitin ©

P-ISSN 2586-9000
E-ISSN 2586-9027
Homepage : https://tci-thaijo.org/index.php/SciTechAsia
Science & Technology Asia
Vol.29 No.1 January - March 2024
Page: [256-270]
Original research article

Applicability Assessment of Oil Palm Trunk Biochar for Use as Soil Amendment: Morphology, Structure, and Chemical Properties

Ebsan Marihot Sianipar[1,2,*], Sumihar Hutapea[3], Ernitha Panjaitan[2], Siti Mardiana[3]

[1]*Program in Agriculture Science, Universitas Medan Area, Medan 20112, Indonesia*
[2]*Department of Agrotechnology, Faculty of Agriculture, Universitas Methodist Indonesia, Medan 20132, Indonesia*
[3]*Department of Agrotechnology, Faculty of Agriculture, Universitas Medan Area, Medan 20112, Indonesia*

Received 19 July 2023; Received in revised form 14 December 2023
Accepted 12 January 2024; Available online 31 March 2024

ABSTRACT

This study was conducted to investigate the quality of biochars derived from oil palm trunk (OPT) based on relative trunk height (bottom, middle, top). The OPT biochars were produced by drum retort kiln with a temperature range of 300-400°C (slow pyrolysis conditions). Morphology, structure, chemical properties and heavy metal content of the OPT biochars were measured in order to assess their suitability for use as a soil amendment. The synthesized carbon was analyzed by X-ray diffraction analysis (XRD). The morphology of the OPT biochars was analyzed by scanning electronic microscopy (SEM) coupled with an energy dispersive X-ray spectrometer (EDX) to identify mineral species on the OPT biochar surface. The analytical methods applied for biochar characterization were proximate analysis and elemental analysis. Characterization of surface functional groups of the OPT biochar was carried out using Fourier transform infrared spectroscopy (FTIR). According to the analysis results, the biochar derived from bottom OPT had the highest intensity peak measured by XRD; it contained 62.05% fixed carbon, 69.21% carbon, and it had the lowest oxygen content at 26.28%. The highest number of pores was found in biochar derived from top OPT. Overall, the biochars had rich macronutrients, numerous functional groups, and low heavy metal content. This study showed the applicability of oil palm trunk biochar for use as a soil amendment for agricultural applications.

Keywords: Carbon; Characterization; Drum retort kiln; Heavy metal; Pyrolysis

***Corresponding author:** ebsansianipar@methodist.ac.id

1. Introduction

Currently, biomass is one of the main renewable and sustainable bioenergy sources that is already widely used around the world [1]. Biomass can also be used to produce different chemicals and materials [2, 3] that can be converted into three distinct forms of bioenergy fuels, those being liquid (bio-oil), gaseous (syngas) and solid (biochar) forms [4-7]. However, the potentiality of biomass as feedstock in each country or region depends on a variety of factors, such as location, climate, weather, available local plantations, agricultural activity, and industrial processing. For example, Indonesia has many agro-industries, which has led to the production and use of various types of biomass.

Indonesia became the global leader in palm oil export, with the increase in the plantation area from 0.3 million hectares in 1980 to 14.62 million hectares in 2021 [8]. The expansion of oil palm plantations has been identified as a significant source of anthropogenic greenhouse gas (GHG) emissions [9]. Meanwhile, the harvesting, processing, and replanting of oil palm produces many forms of oil palm biomass (OPB), including empty fruit bunches (EFB), oil palm fronds (OPF), mesocarp fiber (MF), oil palm kernel shells (PKS), palm oil mild effluent (POME), and oil palm trunks (OPT) [10]. It has been estimated that by 2030, Indonesia will produce 54 million tons of EFB, 115 million tons of OPF, 31 million tons of MF, 15 million tons of PKS, 130 million tons of POME, and 59.7 million tons of OPT [11]. Utilization of oil palm biomass in all of these forms is a promising way to mitigate the negative impacts of oil palm plantations and to develop renewable and sustainable bioenergy sources.

Across Indonesia, there are 14.3 million hectares of oil palm plantations with a 4%/year rejuvenation rate [13]. In the context of commercial oil palm production, the life cycle of the oil palm plant requires that it be replaced every 20 to 25 years to maintain the desired level of oil production [12]. During the process of replanting oil palm trees, large quantities of OPT and OPF waste are produced. It has been estimated that the replanting generates, on a dry weight basis, 14.4 ton /ha of OPF and 66 ton/ha of OPT [14]. Further, there is about 40.0 million tons/year of trunk waste production. Oil palm trunk, a biomass source that possesses the desirable property of fast growth, is an alternative to native or reforested wood. OPT remains an underutilized byproduct of palm oil, which is often shredded in the field at the end of the productive lifetime of a plantation tree. Therefore, OPT is one of the most promising sources of feedstock biomass for biochar synthesis. Biochar is a carbon-rich byproduct of thermal degradation of organic materials under an oxygen-depleted environment (i.e., pyrolysis) and was recently recognized as an emerging technology and is distinguished from charcoal by its ability to be used as a soil amendment [15-18]. However, characteristics of biochar vary significantly, depending on feedstocks, production methods, and temperatures [19, 20].

OPT, is mainly composed of hemicelluloses, cellulose, and lignin and has a high potential for use in biochar applications in Indonesia [21]. In terms of sustainably, it is assumed that the conversion of OPT biomass into other forms of biochar is much more effective and useful than the direct burning of biomass. Direct burning produces a large amount of pollutants that are hazardous to both human health and the environment. At present, the use of OPT to produce biochar using pyrolysis-based processes is still a challenge as there have only been a few studies that have investigated this process as it relates to trunk height [22-29], necessitating further studies to obtain in-depth insights into the qualities of biochars derived from bottom, middle, and top sections of OPT. These three sections of OPT biomass were pyrolyzed using a drum retort kiln. It is crucial to verify the morphology, structure, chemical properties, and heavy metal content of OPT biochars based on trunk section. The different trunk sections of OPT (bottom, middle, top) were assessed for variations in composition as it relates to the suitability for use as a soil amendment. We performed a full characterization of the material based on the International Biochar Initiatif (IBI) Biochar Standards [30] and the European Biochar Community (EBC) Standards [31]. The purpose of this research was therefore to investigate the quality of biochars derived from bottom, middle, and top sections of OPT for the suitability of the biochar as a soil amendment.

2. Materials and Methods

2.1 Material

OPT was collected from oil palm plantation PTPN IV at Tanah Jawa, Simalungun District, North Sumatera Province, Indonesia. OPT was harvested at the oil palm plantation, selecting mature stem samples at 23 years of age, taking cylinder logs approximately 15 min length and 59 cm in diameter. OPT is fibrous, bulky, and has a high moisture content of about 76%. OPT sampling was conducted by sectioning the trunk into three parts: bottom, middle and top. The boundaries of the three trunk sections were 0-30%, 30-60%, and 60-100% of the total height, corresponding to bottom, middle, and top, respectively. First, the OPT was chipped by heavy-duty chipper into pieces about 10-15 cm thick (Fig. 1). The OPT was then sun-dried for 6 hours a day for ten days to reduce the moisture content to around 15% by weight (Fig. 2). The higher the water content of the feed-stock, the more combustion energy is needed to evaporate the water and to heat the feedstock to pyrolysis temperatures (300-400°C).

Fig. 1. OPT chipped by heavy equipment.

Fig. 2. Sun dried of OPT chipp.

2.2 Pyrolysis

Pyrolysis was carried out using a drum retort kiln with a 200 liters drum reactor system. The center of the drum had a hole at top (cap) and bottom (floor) where a 6 in diamter pipe was placed. The pipe had holes about 10 cm from its bottom to allow smoke to escape. Dried OPT biomass was placed in the drum retort. The biomass was heated directly by burning wood in the kiln. The drum was sealed by heat isolation fabric (Fig. 3) which allowed the drum to form the necessary gas-tight seal required for carbonization to take place.

Fig. 3. The drum retort kiln.

The kiln was fired and the biomass was heated for 7 hours, reaching temperatures of 300°C to 400°C. The temperature reading was shown on digital infrared thermometer (BNQ, BN 1000) (Fig. 4). After cooling for 12 hours, the drum was opened and the biochar was removed.

Fig 4. The temperature reading.

Fig. 5. OPT biochar.

2.3 Characterization of biochar

The biochar (Fig. 5) were ground to particle size < 20 mess and three representative samples (bottom, middle, and top OPT biochar) were taken for analysis. The crystallography of OPT biochar was characterized using X-ray diffraction analysis (XRD) SHIMADZU Lab X 6100 Japan. X-ray pattern was equipped with Cu Kα radiation (λ = 1.5406 Å) with a targeted voltage of 45 kV and a current of 40 mA. The scans were collected from 5-70° and used a step size of 0.02° 2θ and a scan speed of 1.0° 2θ/min. The morphology and the mineral species of the biochar were identified using scanning electron microscopy (SEM) (ZEISS EVO MA 10 Germany) and energy dispersive X-ray spectroscopy analysis (EDX) (BRUKER 129 eV Germany), with 15 kV and 180 Pa for acceleration voltage and beam current, respectively, in a vacum of 25 Pa with an Au coating. The analytical methods applied for biochar characterization were proximate analysis and elemental analysis. The proximate analysis for moisture (Carbolite minimum free space oven), ash (Carbolite Horizontal Muffle Furnace), and volatile contents (Ishizuka Denki Muffle Furnace) were determined according to the ASTM D1762-84 standard method. Fixed carbon was determined according to ASTM D3172-17. The elemental analysis (CHN) was performed in duplicate using an Elemental Analyser (Leco CHN 628 USA), and element S using Leco 144-DR. The organic functional chemical groups of biochar were identified using the fourier transform infrared spectroscopy (FTIR), Nicolet IS 10 ATR USA (38/IKA/MT). The chemical functional groups in biochar are vital to understanding the chemical characteristics of the biochar produced. The spectra were recorded with a 4 cm^{-1} resolution between wave numbers of 4000^{-1} and 500 cm^{-1}. The graph is drawn using Origin 8 pro, Excel. Heavy metal content analysis was performed using HNO_3 digestion (CEM Mars 6) and followed by determination with Atomic Absorption Spectrophotometry (Hitachi ZA 3000, Japan).

3. Results and Discussion

3.1 XRD analysis

The result of the XRD measurement of the synthesized carbon of the OPT biochars is shown in wide-angle range (5° to 70°) (Fig. 6). In the case of the carbon, it demonstrated a broad peak at 2θ value of 21-22°, which corresponds to the amorphous plane of (002) carbonaceous materials [32]. The spectra of the C-OPT biochars presented characteristic peaks at 21.92°, 44.12°, and 64.62° for the biochar derived from bottom OPT. As for the biochar derived from middle OPT, the characteristic peaks were at 21.72°, 44.3° and 64.22°. While the characteristic peaks were at 22.5°, 44.08°, and 64.22° for the biochar derived from top OPT corresponding to the (002), (200) and (220) planes of carbon, respectively. The highest intensity of the peaks was shown by biochar derived from the bottom OPT, followed by middle OPT, indicating that the bottom OPT biochar has the highest degree of graphitization [33], and the broad peaks of OPT biochar also suggest that the synthesized carbon from OPT is amorphous [34]. The thermal pyrolysis enabled the trans-formation of biomass to biochar by condensation of smaller organic molecules into conjugated aromatic rings, meanwhile producing massive defective edges along the biochar boundaries terminated with hydrogen atoms and oxygen functionalities [35, 36]. The quality of biochar is determined by its fixed carbon content and biochar composition is crucial to define its application [37]. One identified option for sustainable soil management practice is to increase soil organic carbon levels, especially with recalcitrant forms of carbon (e.g., biochar application) [38].

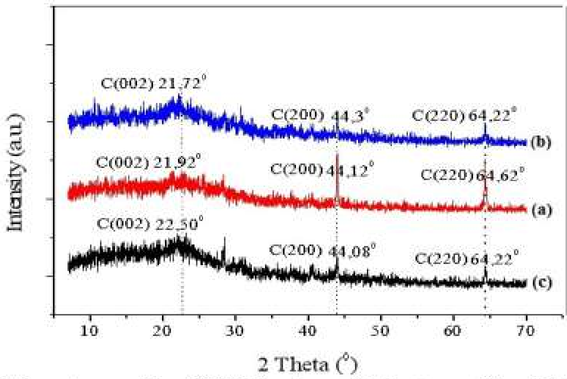

Fig. 6. XRD pattern of the OPT biochars: (a) bottom; (b) middle; (c) top.

3.2 Morphological analysis

The SEM-EDX analysis of OPT biochar is presented in Fig. 7. The morphology of top-OPT biochar had relatively more pores on its surface. In the case of bottom-OPT biochar, the pore size was smaller and the number of pores was fewer (Fig 7a). This is because the bottom-OPT biochar contained the highest level of lignin, giving it a high density structure that was hard and solid. Consequently, the pyrolysis of the bottom OPT did not completely devolatilize most of lignin, and the pores were not fully develoved. The formation of pores and an increase in surface area were mostly due to the removal of moisture and certain volatile matter due to the elimination of hemicelluloses and cellulose. Further increase in pore size, pore volume, and surface area was observed as mostly the major constituents of lignocelluloses, i.e., lignin, cellulose, and hemicelluloses, were broken down as depicted in previous studies [39]. As a result, the highest number of pores was observed in the top-OPT biochar (Fig. 7c). Porous channels and a higher amount of mesopores were observed on the surface of the OPT biochar produced in this study, similar to previous results [40-42]. The synthesis and release of volatile molecules from OPT throughout the carbonization process is indicated by porous channels. The remaining non-volatile components are subsequently converted into biochar, which has pores of various sizes and shapes visible on the surface.

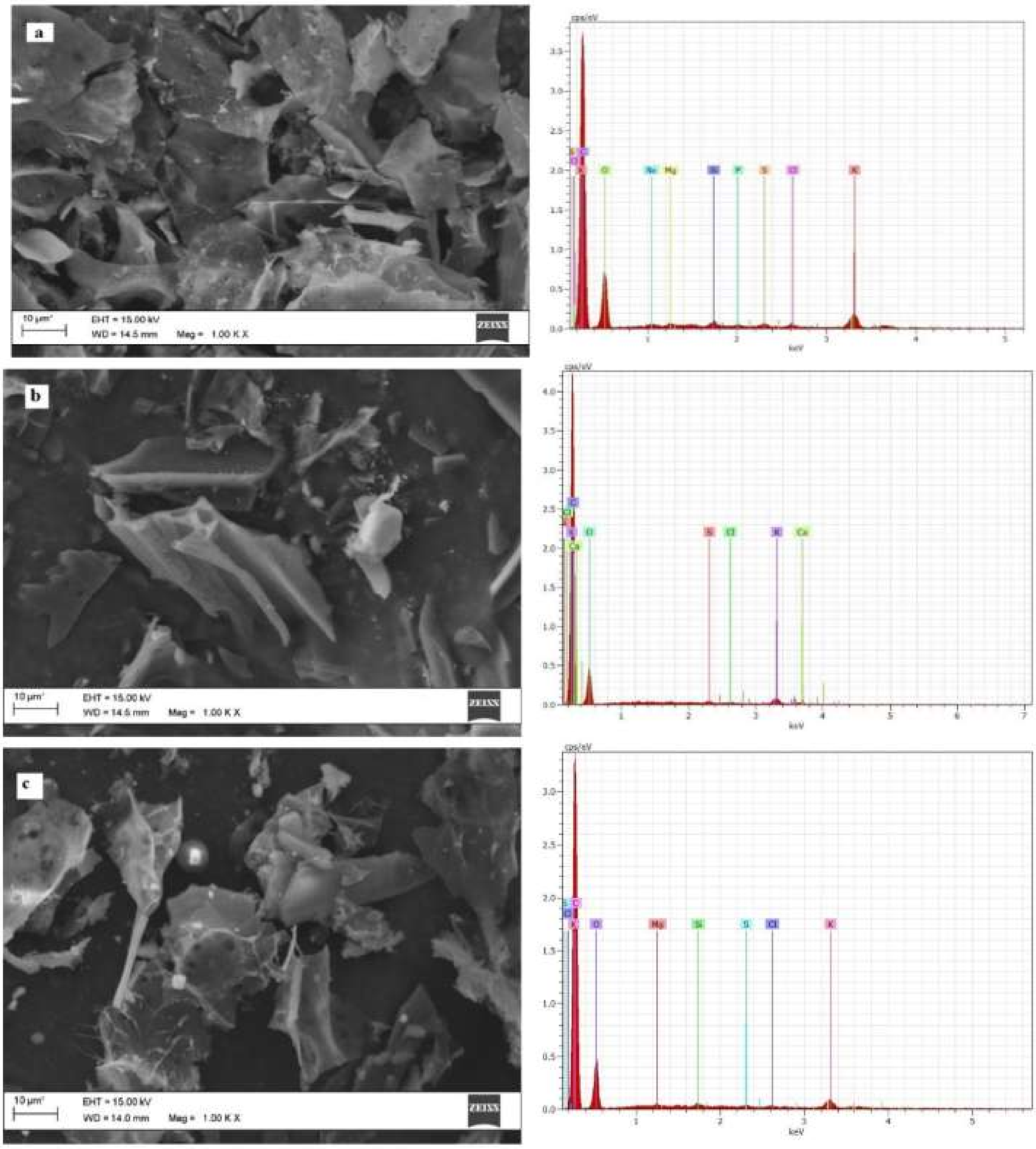

Fig. 7. SEM photographs at 1,000X and EDX analysis of the surface of the biochar: a. bottom; b. middle; c. top.

The large pores are caused by the progressive degradation of the lignocellulosic components including cellulose, hemicelluloses, and lignin. At higher temperatures, these pores also facilitate the release of volatile materials resulting in larger pore size [40]. Furthermore, the highly porous structure of biochar may be beneficial for biofilter applications and soil mixing [44]. This highly porous structure increases water holding capacity by increasing the total porous space of the soil, in addition to its benefits as a soil amendment [45].

On the surface of the OPT biochars, EDX examination demonstrated the coexistence of elements C, O, K, Ca, Mg, Si, Cl, S, and P. This is because the feedstock (OPT) contains bioavailable elements that have an impact on the soil environment. Carbon and oxygen are prominent on all surfaces, with carbon constituting almost the entire surface composition. Minor peaks were also observed for Mg, K, Si, Cl, S, and P on all surfaces. Low pyrolysis biochars showed higher concentrations of Ca, Mg, K, Fe, Mn, and Zn than fast pyrolysis biochars did [46]. This is in agreement with another study, which reported that K, Ca and Mg appeared to be retained in low pyrolysis temperatures of 400°C [47]. The biochar ash mineral content includes inorganic constituents such as oxides, carbonates, silicates, sulfates, chlorides, and phosphates of some metals [48]. The macronutrients P, K, S, Ca, and Mg are among those found in OPT biochars. The type of feedstock and the processing conditions have a significant impact on the nutritional content of biochar. One of the main oxides found in OPT is K_2O, along with CaO, SiO_2, P_2O_5, and MgO [49]. Nutrient availability is related to the nature of the chemical compounds in which the key elements occur [50].

3.3 Proximate and elemental analysis

The proximate and elemental analysis results of OPT biochar are summarized in Table 1. The relative standard deviation for the proximate analysis was < 4%, while it was < 2% for the ultimate analysis. The proximate analysis showed that the moisture content, fixed carbon content, volatile matter, and ash content of the OPT biochar derived bottom to top trunk were in the ranges of 4.54-6.07, 62.05-54.34, 30.12-33.32, and 7.83-12.34 (wt.%), respectively. The data suggest that there is a small difference between the biochar derived from bottom, middle and top OPT. The highest fixed carbon content was found in bottom-OPT biochar (62.05%), followed by middle-OPT biochar (57.93%), and the lowest content in top-OPT biochar (54.34%). However, the volatile matter of the bottom-OPT biochar was the lowest of the three, at 30.12 wt.%.

Table 1. Proximate and ultimate analyses of OPT biochar produced by drum retort kiln.

Property	Bottom	Middle	Top	Average±St.Dev
Proximate Analysis (% dry basis)				
Moisture	4.54	5.22	6.07	5.28 ± 0.77
Fixed Carbon	62.05	57.93	54.34	58.11 ± 3.86
Volatile Matter	30.12	31.23	33.32	31.56 ± 1.62
Ash	7.83	10.84	12.34	10.34 ± 2.30
Elemental Analysis (% dry basis)				
C	69.21	67.31	65.49	67.34 ± 1.86
H	4.42	4.79	4.43	4.55 ± 0.21
N	0.06	0.05	0.05	0.05 ± 0.01
S	0.03	0.04	0.04	0.04 ± 0.01
O*	26.28	27.49	29.99	27.92 ± 1.89
Bulk atomic ratios				
H/C	0.76	0.84	0.81	0.80 ± 0.04
O/C	0.38	0.41	0.46	0.42 ± 0.04
(N + O)/C	0.38	0.41	0.46	0.42 ± 0.04

The remaining volatile matter in biochar includes oxygenated compounds such as acetic acid, furans, phenols, and 2-Propanone,1-hydroxy- [40]. In the present study, it was observed that the moisture content of biochar samples was not zero after pyrolyzing, which is similar to results from previous studies [40, 41].

The quality of biochar is determined by its fixed carbon content and the composition of biochar is crucial in determining its potential applications [20]. The proportion of fixed carbon was related to the presence of stable aromatic carbon in the biochar [51]. Taking into account the recalcitrant nature of carbon contained in the biochar (high resistance to mineralization due to the microbial action), the above result suggests that the pyrolysis of OPT is an effective way to increases the turnover time of the carbon contained in the biomass. The high fixed carbon content of biochar is favorable for use as a soil amendment [40, 52]. The high fixed carbon content of biochar also helps improve soil carbon sequestration that results in an increase in soil organic carbon content [53]. Biochar soil management systems could deliver tradable carbon emissions reduction as the carbon sequestered could be the basis for sustainable oil palm cultivation, even with the impacts of climate change in Indonesia. This could combat desertification, sequester atmospheric CO_2 in the long term, and help to maintain biodiversity in tropical rainforests [54]. However, the volatile matter of the biochar remained between 30.12-33.32 wt.%, indicating incomplete pyrolysis of the biomass under the investigated pyrolysis temperatures and time. This is because the biomass samples contained some lignin, which only decomposes at high temperatures. The lower volatile matter led to a higher fixed carbon content in the biochar. The ash content of OPT was 7.83-12.34 wt.%. The ash in biochar is non-volatile and non-combustible. The increase in ash content of biochar resulted from the destructive volatilization of lignocellulose components at higher temperatures [55]. Lignin, with its greater chemical stability, can be only partially degraded during pyrolysis. Correspondingly, the original skeleton of the particles is mostly preserved [56] and the particles retain the cellular appearance of the raw materials [57].

The elemental composition of the OPT biochar in regards to C, H, N, S, and O content derived from bottom to top trunk were in the ranges of 69.21-65.49; 4.42-4.79; 0.05-0.06, 0.03-0.04 and 26.28-29.99 wt.%, respectively. The results show that carbon and oxygen are the most abundant elements present in the OPT biochar, whereas hydrogen, nitrogen, and sulphur were detected at low concentrations. It should be noted that the feedstock (oil palm) has been found to store an estimated 37.8 to 42.1 t C ha^{-1} in its above-ground biomass [58]. Biochar is graded based on its carbon content, split into three classes. Class I has a carbon content of 60% and higher, class II has a carbon content of 30 to 60%, and class III has a carbon content of 10 to 30% [30]. According to IBI biochar standards, the organic carbon content of the OPT biochars in this study were all > 60 %, placing them in class I. The results of ultimate analysis were consistent with the proximate analysis results as indicated by the relation between fixed carbon content and volatile matter, and carbon and hydrogen content. These results clearly showed that the pyrolysis of biomass produced biochar with a high carbon content and a low oxygen content, which is similar to the results from previous studies [40]. This biochar product is suitable to be used as a soil amendment to improve soil fertility [59].

As one of the roles of biochar is to store carbon, the C yield and H/C ratio is more important than the biochar yield in regards to carbon sequestration [60]. Generally, the H/C molar ratio can be used as an indicator of the degree of aromaticity and carbonization. Combustion analysis H/C ratios of 0.76 (bottom), 0.84 (middle) and 0.81 (top) OPT biochar indicate similar aromaticities. An H/C ratio > 0.6 indicates the possibly of not being fully carbonised [52]. This means that a low H/C ratio indicates a biochar that highly carbonised, exhibits a highly aromatic structure, and has a generally high stability for storing carbon [61]. Furthermore, the H/ C and O/C ratios are essential parameters for stability and degree of oxidation in the biochar structure. Biochar produced at low temperatures will have O/C and H/C ratios that are larger than those of biochar produced at high temperatures [62].

Biochars with low H/C and O/C ratios are graphite-like materials or charcoal which are highly stable compared to their original biomass feedstock having higher H/C and O/C ratios [31]. The polarity index ((O + N)/C), an indication of the surface hydrophilicity and polar group content, was similar for bottom-OPT biochar (0.38), middle-OPT biochar (0.41) and top-OPT biochar (0.46) indicating similar hydrophilicities. Essentially, every carbon-rich solid often consists of two parts: hydrophobic core (a highly aromatic nucleus) and hydrophilic shell (outer layer; a high concentration of reactive oxygen functional groups like hydroxyl/phenolic, carbonyl, or carboxylic groups) [63].

3.4 FTIR analysis

FTIR analysis was conducted to determine the functional groups in OPT biochars (Fig. 8).

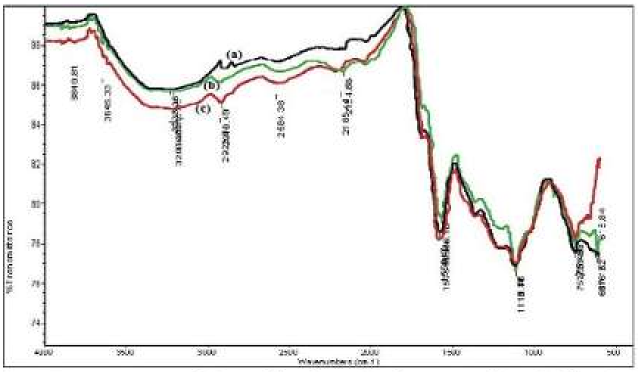

Fig. 8. FTIR spectra of OPT biochar: (a) bottom, (b) middle, (c) top.

Fig. 8 showed that the classification of chemical compounds present in the biochar can be derived from the functional groups that were detected as vibrational modes (or transmittance peaks) observed at different ranges of wavenumber (Table 2). The OPT biochars had several bends which indicates that they had a high level of functional groups present at the surface.

Table 2. The FTIR results for OPT biochar.

Frequency range (cm^{-1})	Functional groups	Bottom	Middle	Top
3200-3500	O–H stretching	3233	3215	3207
2800-2950	C–H stretching	2892	2918	2919
2500-2700	Carboxylic O–H	2601	2575	2577
2200-2500	C≡C stretching	2089	2164	2229
1600-1700	Aldehid C=O	1697	1695	1694
1583-1464	C=C stretching	1581	1568	1583
1371-1250	C–O stretching	1363	1371	1371
1100-1212	C–H bending	1212	1112	1114
750-600	C–H in plane benching	752	751	754

This is because the biochar still contained structures of carbon, hydrogen, and oxygen, which mostly remained in the form of lignin. The results of FTIR analysis are consistent with the proximate and ultimate analysis results discussed previously. The spectra of the three OPT biochars did not differ because their elemental compositions were relatively similar as indicated by the content of carbon, hydrogen, and oxygen. The peaks can be explained as follows. The first peak appeared at 3200-3600 cm^{-1} and was attributed to the stretching of an O-H group [63, 64]. It is also attributed to the acceleration in the dehydration reaction of biomass. The small peaks at 3208 cm^{-1} were associated with the C-H stretching vibration of aliphatic and aromatics structures. The carboxylic O-H occurred in the range 2500-2700 cm^{-1} [65]. The observed peak at 1694-1697 cm^{-1} is attributed the presence of a carbonyl group in carbohydrate [66]. The aromatic C = C ring stretching vibration occurred at 1568-1583 cm^{-1} [43, 65]. At 1371 cm^{-1}, the peak is assigned mainly to stretching vibrations of aliphatic C–H and CH2 bending in biochar. The band in the range of 1115 cm^{-1} represents the stretching of aromatic C–O and phenolic OH. The weak vibrations of the C-H bond in aromatic and heteroaromatic compounds are visible as a band between 604-754 cm^{-1} [66, 67]. Among these, the carboxylic and phenolic groups were the primary acidic functional groups. These groups provide an opportunity for application in the immobilization of heavy metals in the soil [68].

Table 3. Heavy metal content of OPT biochar.

Element	Bottom	Middle	Top	Average ± St.Dev	(EBC Standards)[31]	(IBI Biochar Standards) [30]
				mg kg^{-1}		
As	0.03	0.10	0.10	0.08 ± 0.04	< 13	12-100
Cd	nd	nd	Nd		< 1.50	1.4-39
Cr	6.10	4.90	8.60	6.53 ± 1.89	< 90	64-1200
Co	1.20	1.70	4.20	2.37 ± 1.61	-	40-150
Cu	84.00	87.00	26.00	65.67 ±34.39	< 100	63-1500
Pb	1.10	1.10	6.00	2.73 ± 2.83	< 120	70-500
Hg	0.01	0.01	0.01	0.01 ± 0.00	< 1.00	1-17
Mo	nd	5.30	15.00	10.15 ± 6.86	-	5-20
Ni	0.90	1.20	2.30	1.47 ± 0.72	< 50	47-600
Se	0.60	0.40	0.40	0.47 ± 0.12		2-36
Zn	177.00	477.00	410.00	354.67 ± 157.47	< 400	200-7000

3.5 Heavy metal content

Heavy metal content and maximum allowed thresholds of IBI Biochar Standards are listed in Table 3. These thresholds were used as a reference to understand the levels of heavy metals in OPT biochars for soil amendment. Considering the heavy metals contained in the biochars, Zn had the highest concentration at 177-477 mg kg^{-1}, followed by Cu with a concentration of 26-84 mg kg^{-1}. Other heavy metal concentrations were below 15 mg kg^{-1}. According to the standards of IBI biochar thresholds [30] and the European biochar certificate [31], these results indicate that the heavy metal contents are acceptable and the biochar product is clean. Heavy metal contamination is a worldwide problem and anthropogenic activities are to blame for the increased concentrations of heavy metals in soils [70]. High concentrations of heavy metals adversely affect soil quality and biological functions due to their toxicity and persistence after entering the soil [69]. The content of heavy metals in biochar is greatly influenced by the source biomass [71]. Overall, heavy metal content in OPT biochars do not pose threats to the environment when biochar is used as a soil amendment.

4. Conclusion

The biochar derived from the bottom section OPT provided the highest intensity of peaks and amount of fixed carbon (62.05%). Overall, each of the OPT biochars had an average carbon content > 60% making them all class I biochars, indicating that they are conducive to carbon sequestration when used as a soil amendment. The biochars all had an H/C ratio > 0.6 which indicates the possibly of not being fully carbonized. The biochars also had a porous structure, and contained macronutrients such as P, K, S, Ca, and Mg for plant growth, and oxygen containing functional groups present on the suface for the immobilization of heavy metals in the soil. Most concentrations of heavy metals in the OPT biochars were still up to the European biochar certificate and the IBI biochar threshold standards. Based on these results, it can be concluded that OPT biochar possesses suitable properties for its use as a soil amendment for agricultural applications. Still, the research on OPT biochar as a soil amendment is scarce and more research should be conducted to further validate the benefits of it as a soil amendment on oil palm plantations.

Acknowledgements

The authors would like to aknowledge Universitas Methodist Indonesia for funding this research. We are also very grateful to The Indonesia Customs Laboratory Office Medan, The Laboratory of Indonesia Soil Research Institute Bogor, State University of Medan (The Laboratory of Physics) and The Laboratory Test of Underground Mining Education and Training Unit, Sumatera Barat-Indonesia.

References

[1] WBA: World Bioenergy Association. Global bioenergy statistics 2022 [Internet]. [cited 2023 May 2]. Available from: https://www.world-bioenergy.org› *uploads›22.*

[2] Chum HL, Overend RP. Biomass and renewable fuels. Fuel Processing Technology. 2001;71:187-95.

[3] McKendry P. Energy production from biomass (part 2): conversion technologies. Bioresource Technology. 2002;83:47-54.

[4] Nizamuddin S, Jayakumar NS, Sahu JN, Ganesan P, Bhutto AW, Mubarak NM. Hydrothermal carbonization of oil palm shell. Korean Journal Chemical Engineering. 2015;32:1789-97.

[5] Fan L, Sun P, Yang L, Xu Z, Han. Facile and scalable synthesis of nitrogen-dope ordered mesoporous carbon for high performance supercapsitors. Korean Journal Chemical Engineering. 2020;(37)1: 166-75.

[6] Kim S, Tsang YF, Kwon EE, Lin KYA, Lee J. Korean Journal Chemical Engineering. 2019;(36)1: 1.

[7] Lehmann J. A Handful of Carbon. Nature. 2007;447: 143-4.

[8] BPS-Statistics Indonesia. Indonesia oil palm statistics 2021. Directorate of Food Crop, Horticulture and Estate Crop Statistics. 2022.

[9] Lam WY, Kulak M, Sim S, King H, Huijbregts M, Chaplin-Kramer R. Greenhouse gas footprints of palm oil production in Indonesia over space and time. Science of The Total Environment. 2019;688:827-37.

[10] Nabila R, Hidayat W, Haryanto A, Hasanudin U, Iryani DA, Lee S, Kim S. *et al.* Oil palm biomass in Indonesia: Thermochemical upgrading and its utilization. Renewable and Sustainable Energy Reviews. 2023;176:13193

[11] Hambali E, Rivai, M. The potential of palm oil waste biomass in Indonesia 2020 and 2030. IOP Conference Series: Earth and Environmental Science. 2017;65:012050.

[12] Corley RHV, Tinker PB. The Oil Palm. Oxford: Blackwell Scientific Publications; 2003.

[13] Directorate General of Estate Crops Ministry of Agriculture. Tree Crop Estate Statistics of Indonesia 2018-2020. Palm Oil. Jakarta: Directorate General of Estate Crops; 2019.

[14] Khor K, Lim K, Zainal ZA. Laboratory-scale pyrolysis of oil palm trunks. Energy Sources: Recovery, Utilization and Environmental Effects. 2010;32(6):518-31.

[15] Lehmann J. A Handful of Carbon. Nature Publishing Group. 2007;447:143-4.

[16] Lehmann J, Joseph S. Biochar for environmental management: An Introduction. In: Lehmann J, Joseph, S, editors. Biochar for environmental management. London, Earthscan: Science and Technology; 2009. p. 1-12.

[17] Ok YS, Chang SX, Gao B, Chung HJ. SMART biochar technology— a shifting paradigm towards advanced materials and healthcare research. Environmental Technolology and Innovation. 2015;4:206-9.

[18] El-Naggara A, Lee SS, Rinklebed J, Farooqf M, Songe H, Sarmahh AK, Zimmermani AR, Ahmadj M, Shaheend SM, Oka YS. Biochar application to low fertility soils: A review of current status, and future prospects. Geoderma. 2019;337:536-54.

[19] Sun Y, Gao B, Yao Y, Fang J, Zhang M, Zhou Y, Chen H, Yang L. Effects of feedstock type, production method, and pyrolysis temperature on biochar and hydrochar properties. Chemical Engineering Journal. 2013;240:574-8.

[20] Weber K, Quicker P. Properties of biochar. Fuel. 2018;217:240-61.

[21] Qureshi SS, Premchand, Javed M, SaeedS, Abro R, Mazari SA, Mubarak NM, Siddiqui MTH, Baloch HA, Nizamuddin S. Hydrothermal carboni-zation of oil palm trunk via taguchi method. Korean Journal of Chemical Engineering. 2021;38(4):797-806.

[22] Lim KO, Lim KS. Carbonisation of oil palm trunks at moderate temperatures. Bioresource Technology. 1992;40:215-9.

[23] Abnisa F, Arami-Niya A, Wan Daud WMA, Sahu JN, Noor IM. Utilization of oil palm tree residues to produce bio-oil and bio-char via pyrolysis. Energy Conversion and Management. 2013;76:1073-82

[24] Yakub MI, Abdalla AY, Feroz KK, Suzana Y, Ibraheem A, Chin SA. Pyrolysis of oil palm residues in a fixed bed tubular reactor. Journal of Power and Energy Engineering. 2015;3(4):185-93.

[25] Abdullah H, Jie WS, Yusof N, Isa IM. Fuel and ash properties of biochar produced from microwave-assisted carbonisation of oil palm trunk core. Journal of Oil Palm Research. 2016;28(1):81-92.

[26] Loh SK. The potential of the Malaysian oil palm biomass as a renewable energy source. Energy Conversion and Management. 2017;141:285-98.

[27] Nudri NA, Bachmann RT, Ghani WAWAK, Sum DNK, Azni AA. Characterization of oil palm trunk biocoal and its suitability for solid fuel applications. Biomass Conversion and Biorefinery. 2020;10:45-55.

[28] Sakulkit P, Palamanit A, Dejchanchaiwong R, Reubroycharoen P. Characteristics of pyrolysis products from pyrolysis and co-pyrolysis of rubber wood and oil palm trunk biomass for biofuel and value-added applications. Journal Environment and Chemical Engineering. 2020;8(6):104561.

[29] Shrivastava P, Khongphakdi P, Palamanit A, Kumar A, Tekasakul, P. Investigation of physicochemical properties of oil palm biomass for evaluating potential of biofuels production via pyrolysis processes. Biomass Conversion and Biorefinery. 2021;11:1987-2001.

[30] IBI. Standardized product definition and product testing guidelines for biochar that is used in soil. International Biochar Initiative 2015. [Internet] [cited 2021 Des 21] Available from: https://biochar-international.org/wp-content/uploads/2019/01/IBI_Biochar_Standards_V2.1_Final1.pdf.

[31] EBC 'European Biochar Certificate - Guidelines for a sustainable production of biochar.' Carbon Standards International (CSI), Frick, Switzerland. 2012 - 2023.

[Internet] [cited 2023 May 15] Available from: http://european-biochar.org. (Version 10.3 from 5th April 2022)

[32] Oh WK, Yoon H, Jang J. Size control of magnetic carbon nanoparticles for drug delivery. Biomaterials. 2010;31(6):1342-48.

[33] Chen CP, Cheng CH, Huang YH, Chen CT, Lai CM, Menyailo OV, Fan LJ, Yang YW. Converting leguminous green manure into biochar: changes in chemical composition and C and N mineralization. Geoderma. 2014;232-234:581-88.

[34] Selvamani V, Ravikumar R, Suryanarayanan V, Velayutham D, Gopukumar S. Garlic peel derived high capacity hierarchical N-doped porous carbon anode for sodium/lithium ion cell. Electrochimica Acta. 2016;190:337-45.

[35] Keiluweit M, Nico PS, Johnson MG, Kleber M. Dynamic molecular structure of plant biomass-derived black carbon (Biochar). Environmental Science Technology. 2010;44(4):1247-53.

[36] Guizani C, Haddad K, Limousy L, Jeguirim M. New insights on the structural evolution of biomass char upon pyrolysis as revealed by the Raman spectroscopy and elemental analysis. Carbon. 2017;119: 519-21.

[37] Karlsson Weber K, Quicker P. Properties of biochar. Fuel. 2018;217:240-61.

[38] Hou D, Bolan NS, Tsang DCW, Kirkham MB, O'Connor D. Sustainable soil use and management: An interdisciplinary and systematic approach. Science of The Total Environment. 2020;729:138961.

[39] Brebu M, Vasile C. Thermal degradation of lignin—a review. Cellulose Chemistry and Technology. 2010; 44(9):353-63.

[40] Palamanit A, Khongphakdi P, Tirawanichakul Y, Phusunti N. Investigation of yields and qualities of pyrolysis products obtained from oil palm biomass using an agitated bed pyrolysis reactor. Biofuel Research Journal. 2019;6(4):1065-79.

[41] Bensidhom G, Hassen-Trabelsia AB, Alper K, Sghairoun M, Zaafouri K, Trabelsi I. Pyrolysis of date palm waste in a fixed-bed reactor: characterization of pyrolytic products. Bioresource Technology. 2018;247:363-69.

[42] Sianipar EM, Hutapea S, Mardiana S. Characterization of oil palm trunk biochar as soil amendment produced by using drum retort kiln. International Journal of Chemical and Biochemical Sciences. 2022;22:10-14.

[43] Bhattacharjee N, Biswas AB. Pyrolysis of *Alternanthera philoxeroides* (alligator weed): Effect of pyrolysis parameter on product yield and characterization of liquid product and biochar. Journal of The Energy Institute. 2018;91(4):605-18.

[44] Shariff A, Hakim R, Abdullah N. Rubber wood as potential biomass feedstock for biochar via slow yrolysis. International Journal of Chemical Moleculer Engineering. 2016;10(12):1415-20.

[45] Mukherjee A, Lal R. Biochar Impacts on Soil Physical Properties and Greenhouse Gas Emissions. Agronomy 2013;3(2):313-339.

[46] Gezahegn S, Sain M, Thomas SC. Phytotoxic condensed organic compounds are common in fast but not slow pyrolysis biochars. Bioresource Technology Reports. 2020;13:100613.

[47] Liu WJ, Li WW, Jiang H, Yu HQ. Fates of chemical elements in biomass during its pyrolysis. Chemical Reviews. 2017;117(9):6367-98.

[48] Raveendran K, Ganesh A, Khilar KC. Influence of mineral matter on biomass pyrolysis characteristics. Fuel. 1995;74(12):1812-22.

[49] Umar HA, Sulaiman1 SA, Ahmad RK, Tamili SN. Characterisation of oil palm trunk and frond as fuel for biomass thermochemical. IOP Conference Series: Material Science and Engineering. 2020;863:012011.

[50] Camps Arbestain M, Amonette JE, Singh B, Wang T, Schmidt HP. A biochar classification system and associated test methods. In: Lehmann J, Joseph S, editors. Biochar for environmental management – science and technology. 2nd ed. New York: Routledge; 2015. p.165-94.

[51] Wu W, Yang M, FengQ, McGrouther K, Wang H, Lu H, Chen Y. Chemical characterization of rice straw-derived biochar for soil amendment. Biomass and Bioenergy. 2012;47:268-76.

[52] Kabir G, Din ATM, Hameed BH. Pyrolysis of oil Palm mesocarp fiber and palm frond in a slow-heating fixed-bed reactor: A comparative study. Bioresource Technololgy. 2017;241: 563-72.

[53] Powlson DS, Whitmore AP, Goulding KWT. Soil carbon sequestration to mitigate climate change: A critical re-examination to identify the true and the false. European Journal soil science. 2011;62:42-55.

[54] Paterson RRM, Lima N. Climate change affecting oil palm agronomy, and oil palm cultivation increasing climate change, requires amelioration. Ecolology and Evolution. 2018;8:452-61.

[55] Calvelo Pereira R, Kaal J, Camps Arbestain M, Pardo Lorenzo R, Aitkenhead W, Hedley M, Maci´a-Agull´o JA. Contribution to characterisation of biochar to estimate the labile fraction of carbon. Organic Geochemical. 2011;42:1331-42.

[55] Sevilla M, Maciá-Agulló JA, Fuertes AB. Hydrothermal carbonization of biomass as a route for the sequestration of CO2: Chemical and structural properties of the carbonized products. Biomass and Bioenergy. 2011;35(7):3152-9.

[57] Sevilla M, Fuertes AB, Mokaya R. High density hydrogen storage in superactivated carbons from hydrothermally carbonized renewable organic materials. Energy and Environmental Science. 2011;4(4):1400.

[58] Khasanah N, Noordwijk V, Ningsih H. Aboveground carbon stocks in oil palm plantations and the threshold for carbon-neutral vegetation conversion on mineral soils. Cogent Environment Science. 2015;1(1):1119964.

[59] Lehmann J, Rillig MC, Thies J, Masiello CA, Hockaday WC, Crowley D. Biochar effects on soil biotaea : Review. Soil Biology Biochemistry. 2011;43:1812-36.

[60] Masek O, Brownsort P, Cross A, Sohi S. Influence of production conditions on the yield and environmental stability of biochar. Fuel. 2013;103:151-55.

[61] Kong SH, Lam SS, Yek PNY, Liew RK, Ma NL, Osman MS, Wong CC. Self-purging microwave pyrolysis: an innovative approach to convert oil palm shell into carbon-rich biochar for methylene blue adsorption. Journal Chemical Technolology and Biotechnolology. 2019;94(5):1397-1405.

[62] Sakhiya AK, Anand A, Aier I, Vijay VK, Kaushal P. Suitability of rice straw for biochar production through slow pyrolysis: Product characterization and thermodynamic analysis. Bioresource Technology Reports. 2021;15:100818.

[63] Tran HN, You SJ, Chao HP. Insight into adsorption mechanism of cationic dye onto agricultural residues-derived hydrochars: Negligible role of π-π interaction. Korean Journal Chemical Engineering. 2017;34:1708-20.

[64] Liang M, Zhang K, Lei P, Wang B, Shu CM, Li B. Fuel properties and combustion kinetics of hydrochar derived from co-hydrothermal carbonization of tobacco

residues and graphene oxide. Biomass Conversion and Biorefinery. 2020;10(1):189-201.

[65] Khan SA, Khan SB, Khan LU, Farooq A, Akhtar K, Asiri AM. Fourier transform infrared spectroscopy: Fundamentals and application in functional groups and nanomaterials characterization. In: Sharma SK editor. Handbook of Materials Characterization, Chapter 9. Springer International Publishing AG. 2018;p. 317-44.

[66] Bavariani MZ, Ronaghi A, Ghasemi R. Influence of pyrolysis pemperatures on FTIR analysis, nutrient bioavailability, and agricultural use of poultry manure biochars. Communications in Soil Science and Plant Analysis. 2019;50(4):1-10.

[67] Elnour YA, Alghyamah AA, Shaikh HM, Poulose AM, Al-Zahrani SM, Anis A, Al-Wabel MI. Effect of pyrolysis temperature on biochar microstructural evolution, physicochemical characteris-tics, and its influence on biochar/ polypropylene composites. Applied Sciences. 2019;9(6):1-20.

[68] Mandal S, Pu S, He L, Ma H, Hou D. Biochar induced modification of graphene oxide & nZVI and its impact on immobilization of toxic copper in soil. Environmental Pollution. 2020;259:113851.

[69] Yua H, Zouc W, Chene J, Chenf H, Yug Z, Huangh J, Tanga H, Weij X, Gao B. Biochar amendment improves crop production in problem soils: A review. Journal of Environmental Management. 2019;232:8-21.

[70] Wang M, Li S, Li X, Zhao Z, Chen S. An overview of current status of copper pollution in soil and remediation efforts in China. Earth Science Frontiers. 2018;25(5):305-13.

[71] Liu Z, Singer S, Tong Y, Kimbell L, Anderson E, Hughes M, Zitomer D, McNamara P. Characteristics and applications of biochars derived from wastewater solids. Renewable and Sustainable Energy Reviews. 2018;90:650-64.

Applicability Assessment of Oil Palm Trunk Biochar for Use as Soil Amendment: Morphology, Structure, and Chemical Properties

ORIGINALITY REPORT

17%	7%	15%	1%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	jopr.mpob.gov.my Internet Source	1%
2	Sandip Mandal, Shengyan Pu, Lingling He, Hui Ma, Deyi Hou. "Biochar induced modification of graphene oxide & nZVI and its impact on immobilization of toxic copper in soil", Environmental Pollution, 2020 Publication	1%
3	repository.lppm.unila.ac.id Internet Source	1%
4	Thambiraj S., Ravi Shankaran D.. "Green synthesis of highly fluorescent carbon quantum dots from sugarcane bagasse pulp", Applied Surface Science, 2016 Publication	1%
5	Lam, Su Shiung, Rock Keey Liew, Xin Yi Lim, Farid Nasir Ani, and Ahmad Jusoh. "Fruit waste as feedstock for recovery by pyrolysis technique", International Biodeterioration & Biodegradation, 2016. Publication	1%

6	Sevilla, M.. "The production of carbon materials by hydrothermal carbonization of cellulose", Carbon, 200908 Publication	1 %
7	cyberleninka.org Internet Source	1 %
8	Haowei Yu, Weixin Zou, Jianjun Chen, Hao Chen, Zebin Yu, Jun Huang, Haoru Tang, Xiangying Wei, Bin Gao. "Biochar amendment improves crop production in problem soils: A review", Journal of Environmental Management, 2019 Publication	1 %
9	Nadia Razali, Nurhanim Zulaikha Kamarulzaman. "Chemical characterizations of biochar from palm oil trunk for palm oil mill effluent (POME) treatment", Materials Today: Proceedings, 2020 Publication	1 %
10	Sandro Lucio Silva Moreira, Hewlley Maria Acioli Imbuzeiro, Colby Silvert, Otto Herbert Schuhmacher Dietrich et al. "Above- and below-ground carbon accumulation in cultivated macauba palm and potential to generate carbon credits", Journal of Cleaner Production, 2020 Publication	1 %
11	Goutam Kishore Gupta, Pavan Kumar Gupta, Monoj Kumar Mondal. "Experimental	1 %

process parameters optimization and in-depth product characterizations for teak sawdust pyrolysis", Waste Management, 2019
Publication

12	Shishu Zhu, Xiaochen Huang, Fang Ma, Li Wang, Xiaoguang Duan, Shaobin Wang. "Catalytic Removal of Aqueous Contaminants on N-Doped Graphitic Biochars: Inherent Roles of Adsorption and Nonradical Mechanisms", Environmental Science & Technology, 2018 Publication	1 %
13	Jianghong Zhang, Bing Huang, Liang Chen, Yang Li, Wei Li, Zhuanxi Luo. "Characteristics of biochar produced from yak manure at different pyrolysis temperatures and its effects on the yield and growth of highland barley", Chemical Speciation & Bioavailability, 2018 Publication	1 %
14	nmbu.brage.unit.no Internet Source	1 %
15	opus.lib.uts.edu.au Internet Source	1 %
16	scholar.sun.ac.za Internet Source	1 %
17	Nadly Aizat Nudri, Robert Thomas Bachmann, Wan Azlina Wan Abdul Karim	1 %

Ghani, Denny Ng Kok Sum, Atiyyah Ameenah Azni. "Characterization of oil palm trunk biocoal and its suitability for solid fuel applications", Biomass Conversion and Biorefinery, 2019
Publication

18	onlinelibrary.wiley.com Internet Source	1 %
19	journalarticle.ukm.my Internet Source	1 %
20	Mokhtar Zolfi Bavariani, Abdolmajid Ronaghi, Reza Ghasemi. "Influence of Pyrolysis Temperatures on FTIR Analysis, Nutrient Bioavailability, and Agricultural use of Poultry Manure Biochars", Communications in Soil Science and Plant Analysis, 2019 Publication	1 %
21	thaiscience.info Internet Source	1 %
22	Muhammad Bilal Khan, Xiaoqiang Cui, Ghulam Jilani, Lin Tang et al. "New insight into the impact of biochar during vermi-stabilization of divergent biowastes: Literature synthesis and research pursuits", Chemosphere, 2020 Publication	1 %
23	Sitti Fatimah Mhd Ramle, Othman Sulaiman, Rokiah Hashim, Zubaidah Aimi	1 %

Abdul Hamid et al. "Chemical characterization from parenchyma and vascular bundle at different parts of oil palm trunk", AIP Publishing, 2019

Publication

Exclude quotes	Off	Exclude matches	Off
Exclude bibliography	Off		