The Physicochemical Properties of Biochar from Oil Palm Residues in Southeast Asia

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Abstract

The recent IPCC 6th Assessment Report has mentioned that the nature-based solutions for carbon dioxide removal are less costly, closer to deployment, and more amenable to reversal, compared to technology-based ones. Biochar, produced from biomass through pyrolysis process, is one such nature-based solution that can help reducing greenhouse gas emissions via soil carbon sequestration. Oil palm biomass residues, namely, empty fruit bunches, mesocarp fiber, oil palm frond, oil palm trunk, and palm kernel shell, are abundant in Southeast Asian countries, especially in Indonesia, Malaysia, and Thailand. These residues can be used to produce biochar through thermochemical conversion, so called pyrolysis. This study aims to provide a literature review on the physicochemical properties of biochar production from the palm oil residues mentioned above in the Southeast Asia region. There are ten parameters reviewed such as yield, physical properties (i.e., moisture content, volatile content, fixed carbon content, and energetic value), as well as chemical properties (i.e., C, H, O, N, and ash content) under different temperatures for all palm oil residues. Future research is field application of biochar for soil carbon sequestration and life cycle assessment of biochar production and field application. It is expected that the study could give information to relevant stakeholders on the potential of biochar from oil palm residues in Southeast Asia as one of nature-based solutions to reduce GHG emissions.

Keywords: *carbon dioxide removal, palm oil residues, pyrolysis, biochar, Southeast Asia.*

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1. INTRODUCTION

The notion of ‘nature-based solutions’ has been echoed by conservation Non-Governmental Organizations (NGO) such as The Nature Conservation (TNC) to that harness the power of nature in the fight against climate change [1]. Figure 1 depicts the taxonomy of carbon dioxide removal (CDR) by using natural and technological pathways that have been published in the recent IPCC 6th Assessment Report [2]. It has been shown that natural CDR pathways are less costly, closer to deployment, and more vulnerable to reversal compared to technological CDR pathways.

Biochar is considered as one of the most affordable negative emissions technologies (NETs) for the future large-scale deployment of carbon dioxide removal [3]. The biochar system interacts with the climate system in complex and highly case specific ways. In terms of greenhouse gas (GHG) emissions, biochar aims at mitigating climate change by capturing and storing atmospheric carbon in recalcitrant form, while the combined effort of increased soil organic carbon (SOC) stability and biomass yield after biochar application may also lead to an increase in stock of carbon soil in agroecosystems. The most common process of biochar production is slow pyrolysis while the fast pyrolysis and gasification processes are less fit for the climate change mitigation and applications to soil due to lower yield and carbon content, energy costs during pretreatment, and higher risk of contamination [3].

Agriculture is one of the dominant sectors for Southeast Asian countries, with a high overseas demand for their food and agricultural products such as rice, sugar, coconut, palm oil, and corn. Consequently, these countries produce high amounts of agricultural residues from both harvesting and the food processing industries. It was estimated that there are more than 500 million tons/year of residues produced from the agricultural and forest sectors of SEA countries [4]. Indonesia, Malaysia, and Thailand in the Southeast Asia region are the major oil palm production base which exceeds 80% of the world annual yield. Oil palm is one of the most productive oil crops in the world in terms of oil yield per area. Palm oil is used in a wide range of processes, from fast food, chocolate spread and cereals to toothpastes and animal feed [5]. Since there are abundant biomass residues in the oil palm plantation area such as empty fruit bunch (EFB), oil palm frond (OPF), palm kernel shell (PKS), mesocarp fiber (MF), and Oil Palm Trunk (OPT), there is high potential to utilize those residues as the feedstock to be processed into biochar. Biochar from oil palm residues could act as carbon sink by storing carbon over a long period. Several works [6-8] have shown that biochar is an effective way for soil carbon sequestration and has GHG abatement potential. The result of the study from Lefebvre et al [8] shows a potential increase in soil C stocks by 2.35 ± 0.4 t C /ha/year in sugarcane fields across Brazil at application rates of 4.2 t biochar/ha/year. This study aims to provide literature review on the physicochemical properties of the biochar from oil palm residues focusing on the

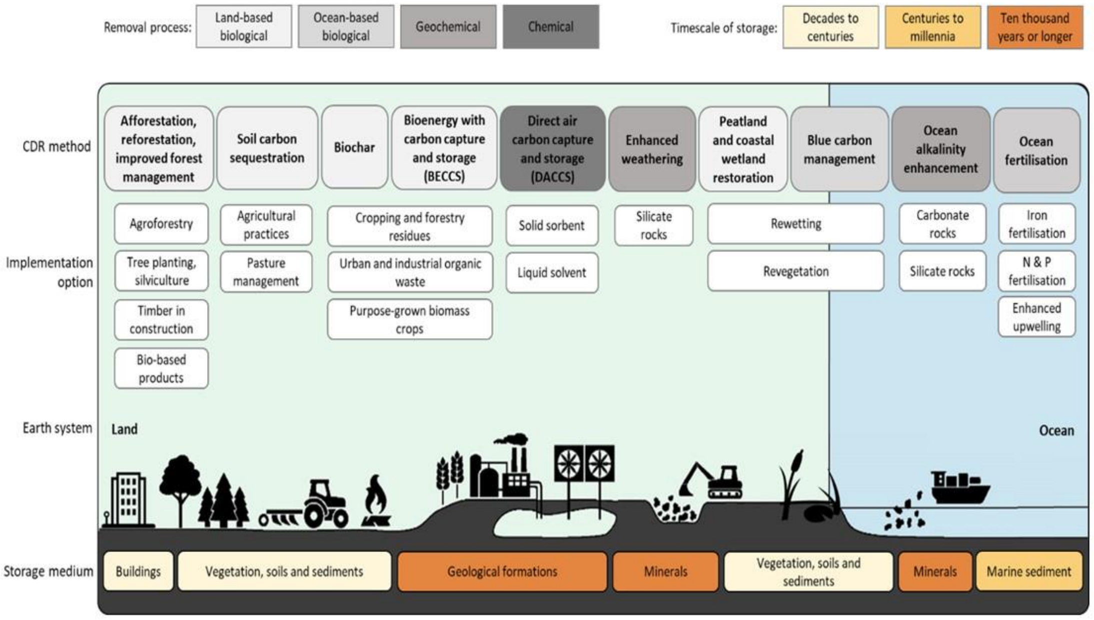

Figure 1. The taxonomy of carbon dioxide removal (CDR)[2]

Southeast Asian region. Understanding the properties could help to assess the potential of each biochar residue to remove CO_2. The biochar output from pyrolysis is obtained from lignin and cellulose; hence, the feedstock should have high contents of those components.

This study has several research questions:

1. How much is the yield of the biochar from palm oil residues?
2. What are the physical properties, i.e., moisture content, volatile matter, fixed carbon, and energetic value (gross calorific value), of the biochar from palm oil residues?
3. What are the chemical properties, i.e., C, H, O, N, ash content of the biochar from palm oil residues?

2. METHODS

The methodology for this study is through literature review. A keyword search for literature was conducted by using Scopus and Google Scholar search engines with the keywords: “biochar, oil palm residue, and Southeast Asia”. The residues of oil palm consist of the Mesocarp Fiber (MF), Empty Fruit Bunch (EFB), Palm kernel Shell (PKS), Oil Palm Trunk (OPT), and Oil Palm Frond (OPF). Existing studies on the biochar production from these feedstocks by using thermochemical conversion, i.e., slow, and fast pyrolysis. The other outputs from pyrolysis process such as bio-oil and biogas were not considered in this study owing to their limited contribution to soil carbon sequestration. The biochar was produced with feedstocks from oil palm residues. While the main products from oil palm are Crude Palm Oil (CPO) and Palm Kernel Oil (PKO), the rest of the products are considered as residues. OPT is obtained only once at the end of oil palm lifetime while the other residues are obtained throughout the lifetime (25¬30 years). Among all residues, the wastewater at the palm oil mill, Palm Oil Mill Effluent (POME), constitutes about ~45% of the weight of Fresh Fruit Bunches (FFB). However, POME is not qualified as biochar feedstock due to lack of the lignin and cellulose content. There are ten parameters in this study with temperature ranging from 250 °C to 900° C across the five types of palm oil residues. Apart from the biochar yield, there are nine physicochemical parameters that were collected as the results of proximate analysis and elemental analysis. There are four parameters from proximate analysis: moisture content, volatile matter, fixed carbon, and gross calorific value (GCV). There are also five parameters from the elemental analysis: carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and ash contents.

3. RESULTS AND DISCUSSION

There were 29 studies (95 experiments) gathered from the literature via searching through Google Scholar and Scopus as shown in **Table 1**. The oldest reference was from 2006 while the latest one was in 2020. Most of the papers are from Malaysia, Indonesia, and Thailand. Among the 29 studies, 3 are conference proceedings and 26 are peer reviewed journal publications.

3.1. Biochar yield

The yields of all residues are generally in the band of 0.36%-83% in temperature range 250°C - 800°C for all residues, whereas the highest yield of PKS at 250°C reaches a value of 83% [9] and the lowest yield of PKS at 700°C reaches the lowest value 0.36% [10]. The effect of pyrolysis temperature on the biochar yield is shown in **Figure 2**. As the temperature increased from 250° C to 750° C, the yield of PKS gradually decreased from 83% to 31.4% [9]. It is shown that higher pyrolysis temperature would strengthen the degradation behaviors of the three major components (cellulose, hemicellulose, and lignin) in the biomass residue PKS, and a large proportion of the residue is converted into other lower molecular components, namely bio-oil and non-condensable gases. The lowest yield 0.36% was obtained due to the CO2 activation process was applied soon after the slow pyrolysis /carbonization process [10]. The average biochar yield from all the biomass residues is about 30%.

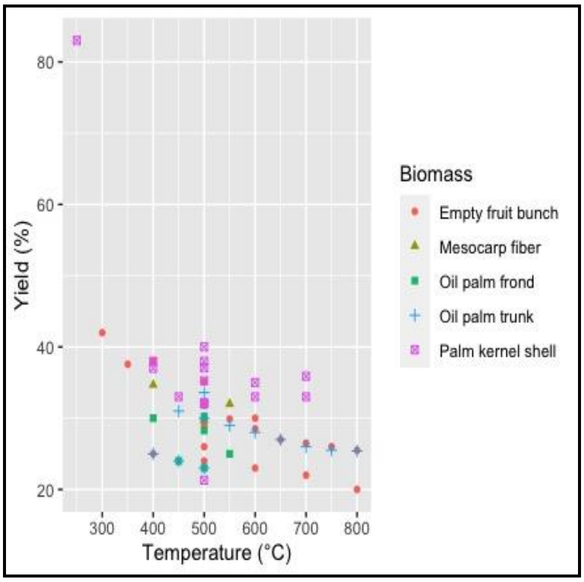

Figure 2. The biochar yield from pyrolysis process.

Table 1. Literature references for this study

No	Title	Author	Year
1	Bio-Oil and Biochar Derived from the Pyrolysis of Palm Kernel Shell for Briquette [11]	Abdullah et al.	2017
2	Characteristics of oil palm shell biochar and activated carbon prepared at different carbonization times [10]	Hamza et al.	2015
3	Characterization of oil palm empty fruit bunch (EFB) biochar activated with potassium hydroxide under different pyrolysis temperature [12]	Bahtiar et al.	2019
4	Temperature Effect on the Characterization of Pyrolysis Products from Oil Palm Fronds [13]	Rahman et al.	2014
5	Biochar potential evaluation of palm oil wastes through slow pyrolysis: Thermochemical characterization and pyrolytic kinetic studies [14]	Lee et al.	2017
6	Pyrolysis of oil palm mesocarp fiber and palm frond in a slow-heating fixed- bed reactor: A comparative study [15]	Kabir et al.	2017
7	Utilization of oil palm tree residues to produce bio-oil and bio-char via pyrolysis [16]	Abnisa et al.	2013
8	Improved yield and higher heating value of biochar from oil palm biomass at low retention time under self-sustained carbonization [17]	Idris et al.	2015
9	Characterization of industrially produced oil palm kernel shell biochar and its potential as slow release nitrogen-phosphate fertilizer and carbon sink [18]	Dominguez et al.	2020
10	Oil palm waste: An abundant and promising feedstock for microwave pyrolysis conversion into good quality biochar with potential multi-application [19]	Liew et al.	2018
11	Characterization and potential use of biochar from gasified oil palm wastes [20]	Mahmood et al.	2015
12	Pilot scale biochar production from palm kernel shell (PKS) in a fixed bed reactor [21]	Haryati et al.	2018
13	Investigation of yields and qualities of pyrolysis products obtained from oil palm biomass using an agitated bed pyrolysis reactor [22]	Palamanit et al.	2019
14	Characterization of Bio-oil and Bio-char from Pyrolysis of Palm Oil Wastes [23]	Abnisa et al.	2013
15	Potential Application of Oil Palm Wastes for Coal Replacement [24]	Abdullah et al.	2016

Table 1. Literature references for this study (continued)

No	Title	Author	Year
16	Optimization of pyrolysis of oil palm empty fruit bunches [25]	Sukiran et al.	2009
17	Biochar production from palm oil mill residues and application of the biochar to adsorb carbon dioxide [26]	Promraksa et al.	2020
18	Laboratory-scale Pyrolysis of Oil Palm Trunks [27]	Khor et al.	2010
19	Pyrolysis of Oil Palm Trunk (OPT). In: Som, M.A., Veluri, M.V.P.S., Savory, R.M., Aris, M.J. and Yang, Y.C. (Ed.).[28]	Deris et al.	2006
20	Biochar from oil palm biomass: A Review of its potential and challenges [29]	Kong et al.	2014
21	Comparing Characteristics of Oil Palm Biochar Using Conventional and Microwave Heating [30]	Abas et al.	2014
22	Slow Pyrolysis of Oil Palm Empty Fruit Bunches [31]	Khor et al.	2008
23	Simultaneous production of biochar and thermal energy using palm oil residual biomass as feedstock in an auto-thermal prototype reactor [32]	Salgado et al.	2020
24	Biochar and bio oil mixture derived from the pyrolysis of mesocarp fibre for briquettes production [33]	Safana et al.	2018
25	Effect of pyrolysis temperature on product yields of palm fibre and its biochar characteristics [34]	Selvarajoo et al.	2020
26	Temperature Effect on the Characterization of Pyrolysis Products from Oil Palm Fronds [13]	Rahman et al.	2014
27	Effects of pyrolysis temperature on the physicochemical properties of empty fruit bunch and rice husk biochars [35]	Claoston et al.	2014
28	Evolution of the chemical composition, functional group, pore structure and crystallographic structure of bio-char from palm kernel shell pyrolysis under different temperatures [9]	Ma et al.	2017
29	Production of bio-based phenolic resin and activated carbon from bio-oil and biochar derived from fast pyrolysis of palm kernel shells [36]	Choi et al.	2015

3.2. Physical properties of the biochar

There are four parameters in the physical properties in this study as shown in **Figure 3a-3d**. The proximate analysis in this study revealed the moisture content, volatile matter, fixed carbon, and gross calorific value (GCV). The moisture content was range from 1% to 13.8%. Higher temperature will reduce moisture content except for MF [25]. This study shows that while the moisture content increased in correspondence with temperature increase, but there is not much variation in moisture content for all biochar. The range of moisture content in all biochar are from 3% to 5% weight. Most of the moisture content are in the band 4% 5% as depicted in **Figure 3a.** Pyrolysis temperature has an influence on the structure of biochar due to the release of volatiles and the formation and volatilization of intermediate melts. The volatile matter reduces while temperature increases in all palm oil residues as depicted in **Figure 3b**. Increased carbon content (ranging from 3.2 to 86.3%) with an increase in pyrolysis temperature occurs due to a higher degree of polymerization leading to a more condensed carbon structure in the biochar.

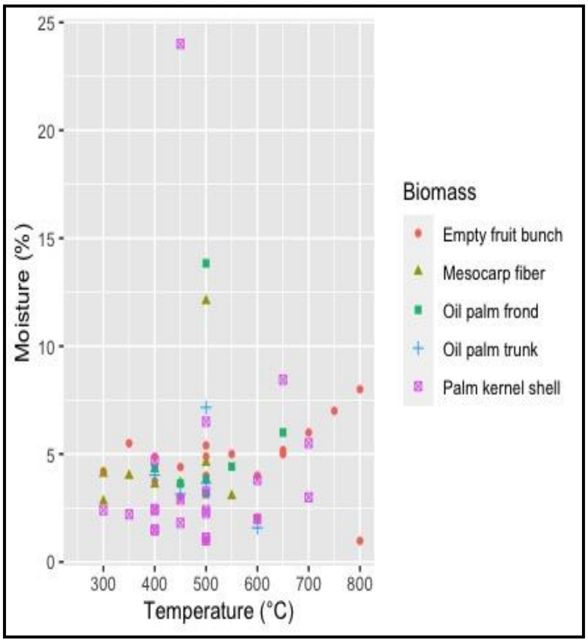

Figure 3a. Moisture content (%)

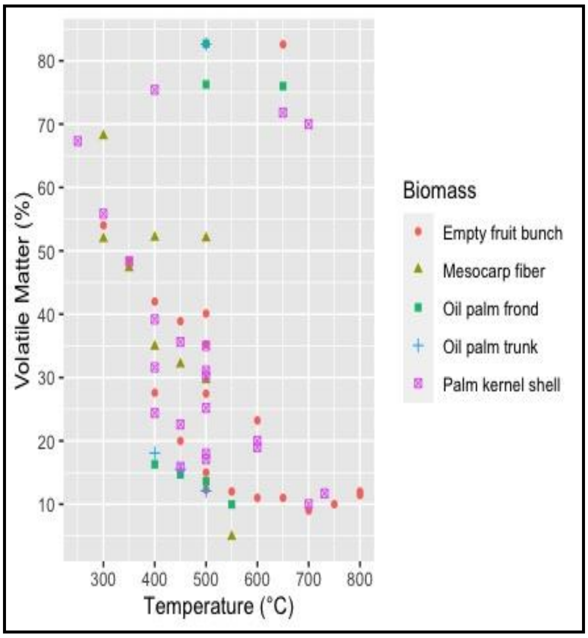

Figure 3b. Volatile matter content (%)

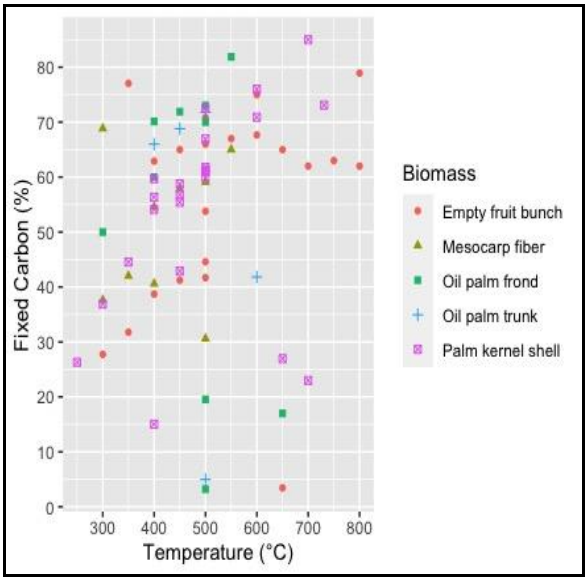

Figure 3c. Fixed carbon content (%)

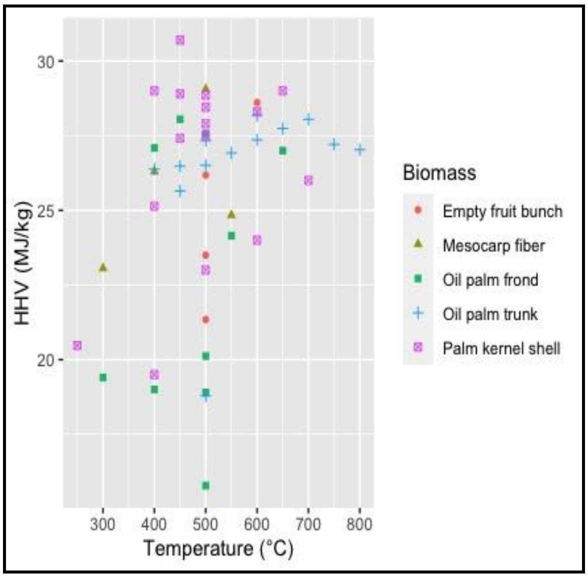

Figure 3d. Gross calorific value (MJ/kg)

Figure 3c shows that higher temperature pyrolysis will lead to higher fixed carbon in all palm oil residues. Organic carbon in biochar can be either labile or fixed/stable. The pattern of breakdown of organic matter in soil and associated release of CO_2 is well understood; the labile fractions decompose rapidly over one to five years. Fixed carbon or the more stable organic matter fractions could break down over decades to centuries, while the most recalcitrant fractions turn over in several hundred to a few thousand years. There are several studies on biochar for in-field soil C sequestration [7-8]. The higher heating value of the biochar are in the range 15.8 MJ/kg to 31.6 MJ/kg. It was observed that the energetic value (higher heating value) of the biochar increased as pyrolysis temperature increased; however, the increment of energetic value is not significant with the increment of the temperature. This showed that production of biochar at low temperatures might be more beneficial in an energy point of view as opposed to higher temperatures [24]. The average value for moisture, volatile matter, fixed carbon, and gross calorific value contents are: 4.4%, 33.6%, 54.1%, and 26.1 MJ/kg, respectively.

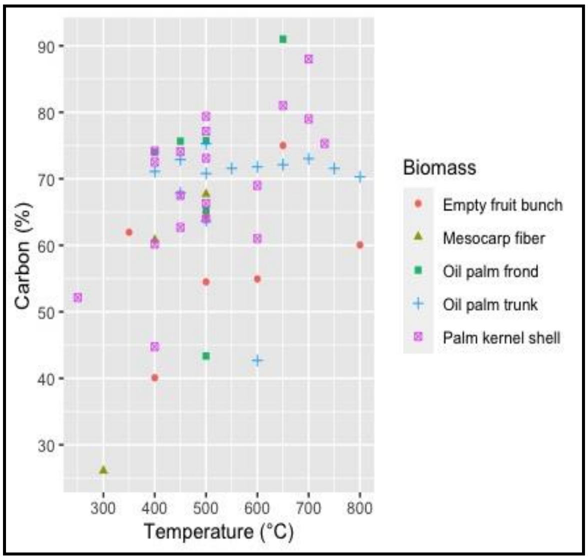

Figure 4a. Carbon content (%)

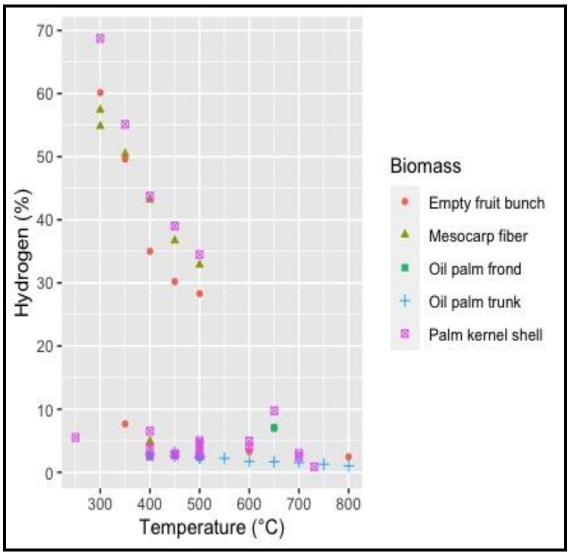

Figure 4b. Hydrogen content (%)

3.3. Chemical properties of the biochar

There are five parameters in the physical properties in this study as depicted in **Figures 4a-4e**. The parameters in this study are carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and ash. The carbon content increases corresponding to the temperature for all residues as depicted in **Figure 4a**, except for MF [24]. As pyrolysis temperature increased from 300 to 500 °C, an increase in carbon content was observed and as the temperature was further raised to 700 and 900 °C, there was a slight decrease in carbon content. The variation in carbon content in the biochar is not much as the difference is only 3 %. The hydrogen value decrease from 68.7% into 0.9% along with temperature increase from 250°C to 800°C for all residues. **Figure 4b** shows the hydrogen content on palm oil residues under different temperatures. Similarly, the oxygen also decreases from 51.2% to become 6% along with temperature increase from 250°C to 800°C for PKS and all residues as depicted in **Figure 4c**. The nitrogen content was in the band as shown in **Figure 4d**. All shown the increment values of carbon due to pyrolysis temperature except for the Hydrogen (H), and Oxygen (O). The declining of H and O content during temperature increment was due to breaking of oxygen containing functional groups (such as carboxyl, carbonyl, and methoxyl) from their polymerics backbone as well as formation of fixed carbon (aromatic) that are thermally stable. The nitrogen content was in the band of 0.3 to 3% under temperature range 250°C to 800°C for all biomass residues as shown in **Figure 4d**. The ash content was in the band 0.2% to 27% under temperature range 250°C to 800°C as depicted in **Figure 4e**. The increase in the ash content due to increasing pyrolysis temperature was resulted from progressive concentration of inorganic constituents and organic matter combustion residues. The average value for C, H, O, N, and ash contents are: 64.3%, 15.3%, 26.5%, 0.9%, and 9.9%, respectively.

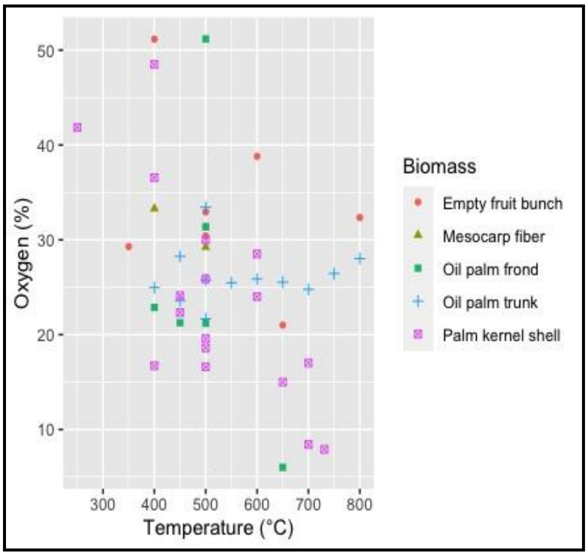

Figure 4c. Oxygen content (%)

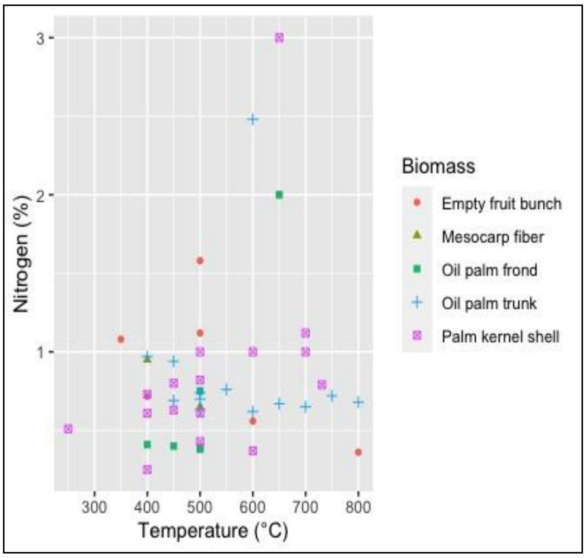

Figure 4d. Nitrogen content (%)

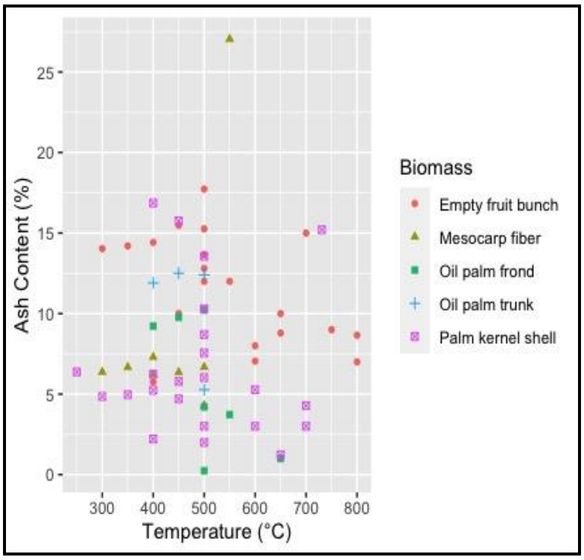

Figure 4e. Ash content (%)

Table 2. Summary of the physicochemical properties of the biochar in ASEAN.

No	Physico-chemical properties	Unit	EFB		MF		OPF		OPT		PKS		Overall	
			Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
1	Biochar yield	% w/w	**20**	42	29.8	34.7	23	30.2	23	33.6	**0.36**	**83**	**0.36**	**83**
	Physical properties													
2	Volatile content	% w/w	9	**82.6**	**4.9**	68.1	10	76.3	12.1	**82.6**	5.3	75.4	**4.9**	**82.6**
3	Moisture content	% v/v	**1**	8	3.1	12.1	3.2	**13.8**	1.6	7.1	**1**	8.44	**1**	**13.8**
4	Fixed carbon content	% w/w	3.5	**86.3**	30.6	74	**3.2**	81.9	5	71.8	15	85	**3.2**	**86.3**
5	Energetic value (Gross calorific value)	MJ/kg	21.3	28.6	23.1	29.1	**15.8**	28.1	18.8	28.2	19.5	**31.6**	**15.8**	**31.6**
	Chemical properties													
6	C content	% w/w	40.1	75	**19.1**	67.7	43.4	**91**	42.7	73	44.8	80	**19.1**	**91**
7	H content	% w/w	2.5	60.1	2.4	57.4	2.6	7.1	1	3.2	**0.9**	**68.7**	**0.9**	**68.7**
8	O content	% w/w	21	**51.2**	29.2	33.3	**6**	**51.2**	21.7	33.4	8.4	48.5	**6**	**51.2**
9	N content	% w/w	0.36	1.12	0.7	1	0.4	2	0.6	2.5	**0.3**	**3**	**0.3**	**3**
10	Ash content	% w/w	5.8	17.7	4.3	**27**	**0.2**	10.2	5.3	12.5	2	17.4	**0.2**	**27**

3.4. Chemical properties of the biochar

There are five parameters in the physical properties in this study as depicted in **Figures 4a-4e**. The parameters in this study are carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and ash. The carbon content increases corresponding to the temperature for all residues as depicted in **Figure 4a**, except for MF [24]. As pyrolysis temperature increased from 300 to 500 °C, an increase in carbon content was observed and as the temperature was further raised to 700 and 900 °C, there was a slight decrease in carbon content. The variation in carbon content in the biochar is not much as the difference is only 3 %. The hydrogen value decrease from 68.7% into 0.9% along with temperature increase from 250°C to 800°C for all residues. **Figure 4b** shows the hydrogen content on palm oil residues under different temperatures. Similarly, the oxygen also decreases from 51.2% to become 6% along with temperature increase from 250°C to 800°C for PKS and all residues as depicted in **Figure 4c**. The nitrogen content was in the band as shown in **Figure 4d**. All shown the increment values of carbon due to pyrolysis temperature except for the Hydrogen (H), and Oxygen (O). The declining of H and O content during temperature increment was due to breaking of oxygen containing functional groups (such as carboxyl, carbonyl, and methoxyl) from their polymerics backbone as well as formation of fixed carbon (aromatic) that are thermally stable. The nitrogen content was in the band of 0.3 to 3% under temperature range 250°C to 800°C for all biomass residues as shown in **Figure 4d**. The ash content was in the band 0.2% to 27% under temperature range 250°C to 800°C as depicted in **Figure 4e**. The increase in the ash content due to increasing pyrolysis temperature was resulted from progressive concentration of inorganic constituents and organic matter combustion residues. The average value for C, H, O, N, and ash contents are: 64.3%, 15.3%, 26.5%, 0.9%, and 9.9%, respectively.

3.5. Summary

This review includes 29 studies in total that have been conducted on the biochar based on pyrolysis from oil palm residues that are highly potential for soil carbon sequestration. The summary of the review is shown in **Table 2.** A wide range was observed in biochar yield as well as all the physicochemical properties of biochar. This is mostly caused by the pyrolysis process and the feedstock preparation beforehand. Wide range of data occurs due to differences in pyrolysis process and feedstock preparation. Several studies on application of biochar for soil carbon sequestration has been done and show promising results whereas increasing of soil carbon stock that could lead to negative emissions in the soil [8, 37].

4. CONCLUSIONS

The study on the physicochemical properties of the biochar from oil palm residue in Southeast Asia region has been done within period 2006-2020. There are 29 studies from the literature including three conference proceedings and 26 peer reviewed articles. The parameters considered in this study are biochar yield, physical i.e.: proximate analysis (volatile matter, moisture content, fixed carbon content, and energetic value) and chemical i.e.: elemental analysis (C, H, O, N, and ash contents). The variables are temperature ranging from 250°C to 900° C and the oil palm residue types: empty fruit bunch (EFB), mesocarp fiber (MF), oil palm frond (OPF), oil palm trunk (OPT), and palm kernel shell (PKS).

The biochar yield ranged from 0.36% to 83%. The physical properties such as volatile, moisture and fixed carbon contents ranged from 4.9% into 82.6, 1% to 13.8%, and 3.2% to 86.3%, respectively. Furthermore, the calorific values ranged from 15.8% to 31.6%. The chemical properties such as C, H, O, N and ash contents value ranged between 19.1% to 91%, 0.9% to 68.7%, 6% to 51.2%, 0.3% to 3%, and 0.2% to 27%, respectively. Wide range of data occurs due to differences in pyrolysis process and feedstock preparation. While this preliminary study aimed to review the physicochemical of oil palm residues, the next study should be conducted on the soil carbon sequestration due to biochar field application and the life cycle assessment (LCA) conducted to assess the net GHG emissions during the production process and field application of the biochar. It is expected that this study would be useful for overall assessment on the feasibility of the biochar from oil palm residues as one option for carbon dioxide removal (CDR).

5. ACKNOWLEDGEMENT

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