KOH Activated-Biochar from Oil Palm Solid Wastes Via Pyrolysis for Energy Storage Application

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ABSTRAK

Sebagai negara eksportir minyak sawit terbesar di dunia, Indonesia menghadapi isu lingkungan terkait dengan besarnya jumlah limbah padat kelapa sawit. Untuk memanfaatkan limbah lignoselulosa ini menjadi material berbasis karbon yang murah, *biochar* dari tandan kosong sawit, cangkang sawit, pelepah sawit, dan batang sawit dihasilkan melalui pirolisis lambat menggunakan KOH sebagi agen aktivator. Proses pirolisis lambat dilakukan pada suhu 600°C dengan laju pemanasan 10°C/menit, dan ditahan selama 30 menit pada tekanan atmosferis. Kajian ini mengulas karakteristik fisiko-kimia dari limbah padat sawit beserta biochar yang dihasilkan meliputi analisis ultimat, kadar air dan abu, spektrometer FTIR, luas area permukaan menggunakan Brunauer-Emmet-Teller (BET), serta morfologi permukaan menggunakan Scanning Electron Microscope (SEM). *Yield* biochar yang lebih tinggi diperoleh pada cangkang sawit dan tandan kosong sawit yaitu sebesar 30% dan 35,79%, yang berkaitan dengan kandungan abu, lignin, serta padatan char residual yang lebih tinggi. Biochar dari batang sawit dan cangkang sawit memiliki luas area yang tinggi, masing-masing sebesar 467.49 m^2/g and 386.85 m^2/g, serta kandungan karbon yang tinggi, masing-masing sebesar 75.64% and 70.22%. Kinerja elektrokimia dari *biochar* batang sawit dan cangkang sawit juga dievaluasi dan menunjukkan respon. *Biochar* dari batang sawit dan cangkang sawit menunjukkan hasil yang menjanjikan sebagai *bio-carbon black* yang memiliki struktur morfologi yang baik, serta luas area permukaan dan kandungan karbon yang tinggi.

Kata kunci: biochar, limbah padat kelapa sawit, aktivasi KOH, pirolisis, penyimpanan energi

ABSTRACT

As the leading exporter of the oil palm in the world, Indonesia has an environmental issue regarding to the increasing oil palm solid wastes. In order to utilize this lignocellulosic wastes into an inexpensive supply of carbon-based material, biochar from empty fruit bunch (EFB), palm kernel shell (PKS), oil palm frond (OPF), and oil palm trunk (OPT) was produced via slow pyrolysis with KOH as activation agent. The slow pyrolysis was conducted with a temperature of 600ºC, a heating rate of 10ºC/min, held for 30 min, and atmospheric pressure. This study examines the physico-chemical characterization of all oil palm solid wastes and biochars by using ultimate analysis, water and ash content, Fourier Transform Infrared (FTIR) spectrometer, surface area using Brunauer-Emmet-Teller (BET), and surface morphology using Scanning Electron Microscope (SEM). The higher biochar yields were obtained by PKS and EFB with 30% and 35.79% which have a higher ash content, lignin content, and residual solid char. OPT and PKS biochars exhibit high surface area (467.49 m^2/g and 386.85 m^2/g) with a high carbon content of 75.64% and 70.22%, respectively. Electrochemical performances of OPT and PKS biochar were also evaluated and the cyclic voltammogram showed the response of current to potential. The results of OPT and PKS biochars had shown a promising raw materials as bio-carbon black which have a well-developed structure of morphology, high surface area, and high carbon content.

Keywords: Biochar, Oil Palm Solid Wastes, KOH activation, Pyrolysis, Energy Storage

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INTRODUCTION

A new trend currently developed is energy storage from clean energy sources (Shaker et al., 2021). Batteries, regular capacitors, and supercapacitors are currently used in energy storage systems. Supercapacitors primarily have three significant benefits over other energy storage devices, such as batteries and regular capacitors: high specific power, a long cycle life, and quick charge and discharge cycles that take only a few seconds (Bi et al., 2019). The capacitance a supercapacitors is highly dependent on the material utilized in the electrodes (Wang et al., 2017). The most common electrode materials for supercapacitors are carbon-based materials because of their substantial specific surface area, high electrical conductivity, and exceptional chemical stability. Carbon with pores is frequently used as an electrode in supercapacitors. Due to its abundance, affordability, recyclability, sustainability, simple of preparation, and environmental friendliness when compared to activated carbons made conventionally, porous carbon generated from biomass has attracted enormous attention as an electrode material (Miller et al., 2018; Ehsani and Parsimehr, 2020; Zhu et al., 2020).

Indonesia is leading in oil palm production industry in the world. Oil palm is a prominent sector in Indonesia because it is the largest export commodities. By 2021, the area of palm oil will reach 14.663 million ha and produce 46.223 million tons of oil palm (BPS, 2021). By the growth of oil palm plantations and oil palm production, it leads to increase in oil palm biomass waste. Oil palm processing only produce 10% of oil palm and palm kernel oil, with 90% of the remaining in the form of biomass wastes (Dungani et al., 2018). Oil palm biomass, which is also waste from the oil palm industry, is typically produced during activities on palm oil plantations and the processing of crude palm oil (Thomas and Andres, 2021). Oil palm processing generates solid waste such as empty fruit bunches (EFB), palm kernel shells (PKS), and mesocarp fiber. It also generates liquid waste in the form of palm oil mill effluent (POME). Meanwhile, the operational activities of palm oil plantations generate solid waste such as palm oil fronds (OPF) and trunks (OPT). These solid wastes have not been fully utilized. Furthermore, most of the palm oil biomass waste is still being disposed of by burning or dumping it in the fields which can cause an environmental risk (Jafri et al., 2021). Utilization of oil palm biomass as value-added product such as biochar can solve the environmental problem by the increasing oil palm industries.

Pyrolysis of biomass is a thermal degradation process that uses limited oxygen to transform biomass into solid (biochar), gas (syngas), and liquid (bio-oil, tar) products. During the reaction, several processes, including cross-linking, de-polymerization, and disintegration of the cellulose, hemicellulose, and lignin components, take place and produce either solid, liquid, or gaseous products (Saravanan and Kumar, 2022). Pyrolysis can be divided into three categories: slow, intermediate, and fast pyrolysis, depending on the residence time and heating rate (Haryanto et al., 2021). Generally, slow pyrolysis is employed to create solid biochar or charcoal products because slow pyrolysis is typically used to maximize the yield of solid products, while fast pyrolysis is typically used to maximize the yield of liquid products.

Many researchers use KOH as activating agent to produce bio-activated carbon (Luo et al., 2022). Alkali activation is one of the oldest, most popular, and most efficient chemical activation processes. When compared to other activating agents, KOH, a common alkali activating agent, produces the best results. The first step in the KOH activation is the reduction of KOH to free metals K. The network then expands as a result of the intercalation inside the carbon network. When these metals are removed destructively at high temperatures, the resulting graphitic layers in the bio-waste network tend to form, and it creates many pores (Sundriyal et al., 2021). The better energy storage performance is commonly affected by the increase surface area of activated carbon on the electrode which is important for the ions of the electrolyte to charge and discharge processes for storing charges. Therefore, the activated carbons with large surface area, high porosity, and high conductivity were preferred for energy storage material.

There is not much research related to the biochar processing of palm oil biomass waste on frond and trunk especially for energy storage applications. Therefore, in this study, all parts of oil palm solid wastes such as EFB, PKS, OPF, and OPT will be evaluated as the precursor for producing biochar via slow pyrolysis. Moreover, this study examines the physico-chemical characteristics of biochar from the various type of oil palm solid wastes via slow pyrolysis with KOH activation. Then, electrochemical performance analysis of electrodes from biochar products are assessed for supercapacitor application use.

MATERIALS AND METHODS

Materials Preparation and Pyrolysis

Oil palm solid wastes such as EFB, PKS, OPF, and OPT were obtained from PTPN VIII Cikasungka. These samples were chopped into coarse powder and dried at 105°C for 24 hours to eliminate the moisture and to get the exact weigh of biomass samples. The oil palm solid wastes were pretreated with KOH or impregnation procedure was carried out by soaking about 1:2.5 ratio of biomass:KOH in 250 ml distilled water and stirred 200 rpm at a temperature of 80°C for 24 hours. Then, the impregnated biomass was dried in the oven at a temperature of 105°C for 48 hours.

The pyrolysis procedure was performed using a furnace, Carbolite^{TM} CWF12/23. The impregnated biomass samples were put into closed-porcelain dishes at atmospheric pressure and temperature of 600°C for an hour with a heating rate of 10°C/min. Thereafter, the KOH-activated biochars were washed with HCl 0.1 M until the pH of those biochars altered to be neutral. The washed biochars were dried at 105°C for 24 hours. The pyrolysis experiments were carried out in duplo.

Feedstock and Biochar Products Characterization (Ultimate Analysis, Water and Ash Contents)

Each oil palm solid waste was evaluated the lignocellulosic composition by the gravimetric method (Ayeni et al., 2015). Water content of samples were figured out by dried the samples at 105°C for 1 hours according to ASTM D-3173-03. Ash content of samples were discovered by ASTM D3174-04. Ultimate analysis in the form of chemical composition such as levels of Carbon (C), Hydrogen (H), Oxygen (O), Nitrogen (N) and Sulfur (S) were determined using LECO CHN 628 with EDTA standard burned at 950°C and LECO Sulfur 632 with coal standard burned at 1350°C. The oxygen content was determined as a difference (C +H +N +O +S +Ash =100%).

Thermogravimetric Analysis

Thermogravimetric analysis (TGA) of palm oil solid wastes (EFB, OPF, PKS, and OPT) were executed using a Shimadzu DTG-60H TGA Analyzer. The biomass samples were heated from 30 to 900°C at a heating rate of 20°C/min. Nitrogen gas at 20 ml/min was used to induce an inert atmosphere for the pyrolysis process

Fourier Transform IR

FTIR (Fourier Transform IR) spectrophotometer was conducted to characterize the chemical function groups in the bulk phase and on the carbon surface. A Bruker Tensor 27 FTIR spectrophotometer was used at 25°C with wave number in the range of 4000–600cm^{-1}. The samples were examined as ATR Germanium

Surface Area and Pore Characteristics of KOH Activated Biochar

The specific surface area (SSA), pore-size distribution, and total pore volume of KOH activated biochar were observed using Novatouch LX2 instrument. Total pore volume and pore-size distribution were obtained using the Barrett–Joyner–Halenda (BJH) method. A certain amount of samples was prepared, and then vacuum degassed at 300°C for 2 hours preceded with heating at rate of 10°C/min. The analysis was conducted after degassing process in the different port in the instrument. Nitrogen was used as the adsorbate with bath temperature at 77.35 K.

Scanning Electron Microscope (SEM)

The morphology of biochars were characterized by SEM (Model: Jeol JSM-IT200) at vacuum 15 kV. The biochar specimens were prepared by Au coating. The magnification performed on the SEM analysis is 2500× and 10,000×.

Electrochemical Performances of KOH Activated Biochar

Electrochemical performance testing was carried out using a Cyclic Voltammetry (CV) instrument. This CV instrument is carried out by Metrohm PGSTAT302N with a 3-electrode system (reference, working, and counter/auxiliary). The working electrode consist of gold wire (99.99% Au) and biochar sample paste. The biochar sample paste consists of paraffin oil/white oil and biochar mixture with a ratio of paraffin oil:biochar (from EFB, PKS, OPF, and OPT) = 40 wt%:60 wt%. CV parameter settings are adjusted to the scan rates ranging between 5 and 150 mVs^{-1} along with the potential window of -1.5 to +1.5 V. Each of working electrode was tested as working electrode in 3 M KOH solution. Specific capacitance can be calculated using the equation (1).

$$C_s = \frac{\int IdV}{V \times m \times \Delta V} \quad (1)$$

where: C_s is specific capacitance (F), $I.dV$ is integrated area under the curve, m is mass of active material on the surface of the electrode (grams), ΔV is potential difference (Volt), and V is potential scan rate (mVs-1).

RESULTS AND DISCUSSION

Characterization of Palm Oil Solid Wastes

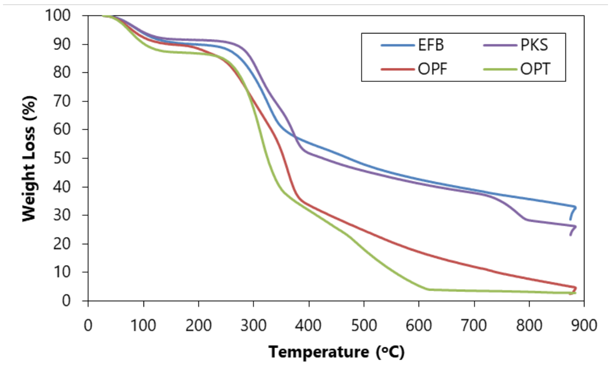
Elemental analysis, moisture, and ash content of raw palm oil solid wastes are revealed in Table 1.

Table 1. Elemental analysis, moisture, and ash content of raw palm oil solid wastes

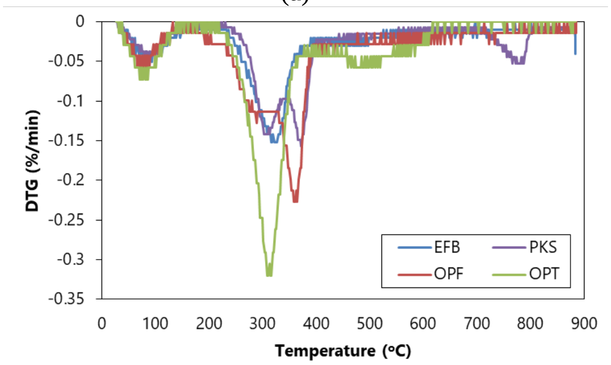
Feedstock	Elemental Analysis (%)							Moisture (%)	Ash (%)
	C	**H**	**N**	**O**	**S**	**H/C**	**O/C**		
EFB	41.35	5.17	1.75	32.29	0.21	0.13	0.78	10.60	19.43
PKS	42.44	4.43	1.56	35.14	0.05	0.10	0.83	9.01	16.94
OPF	46.02	5.81	0.23	45.01	0.15	0.13	0.98	11.04	2.93
OPT	47.07	2.57	2.46	45.36	0.18	0.05	0.96	11.99	2.54

The lignocellulosic biomass mainly comprised 40 – 50% carbon, 2 – 7% hydrogen, 0.5 – 2% nitrogen, and the remaining oxygen (Rafatullah et al., 2013) of which the initial elemental analysis results are similar to this study. Based on initial elemental analysis, OPF and OPT have higher carbon content than EFB and PKS. The atomic ratio of H/C describes the degree of carbonization. The H/C ratio of oil palm solid wastes is in the amount of 0.05 – 0.13 which shows that the degree of carbonization is low. The atomic ratio of O/C can be used to define the hydrophilicity of raw materials. The O/C ratio of raw oil palm is relatively high around 0.78 – 0.98 which is still hydrophilic. The low nitrogen and sulfur content in oil palm biomass indicates low NOx and SOx gases formation during the pyrolysis reaction.

Thermo-gravimetric analysis and derivative thermo-gravimetric profile of palm oil solid wastes (EFB, PKS, OPF and OPT) exposed that primary thermal decomposition occurred around 220 – 400°C as shown in Figure 1.



(a)



(b)

Figure 1. (a) Thermo-gravimetric and (b) Derivative thermo-gravimetric plots (DTG) profiles of palm oil solid waste (EFB, PKS, OPF, and PKS)

The TGA profiles of raw palm oil solid waste indicated that EFB-PKS and OPF-OPT have similar profiles. OPF and OPT have low residual solid char with yield of 2.48% and 2.69%, respectively. On the other hand, the yield residual solid char of EFB and PKS were 28.58% and 23.15%, respectively. Biomass with a high ash content is not preferred for the production of bio-oil or biochar via pyrolysis because it can cause a low yield of the bio-oil liquid product and a high content of inorganic elements in the biochar product (Palamanit et al., 2019).

Generally, the temperature range of pseudo-cellulose, pseudo-hemicellulose, and pseudo-lignin takes place at 205-375, 330-450, and 140-700°C, respectively (Stefanidis et al., 2014; Diez et al., 2020). From the derivative thermo-gravimetric curves as shown in Figure 2b, the peaks below 150°C represent the surface and bound moisture removal. The peaks between 220 – 400°C corresponds to the degradation of cellulose and hemicelluloses. As can be seen in OPT and OPF with a downward sharp curve in contrast to other feedstocks, the decrease in the graph indicates that OPT and OPF has a high cellulose and hemicellulose content which is confirmed by Table 2. The OPF and PKS curves show a significant decrease at 330 – 450°C, which shows that the hemicellulose component is quite the majority in the composition.

Table 2. Lignocellulosic content of oil palm biomass (%)

Component	EFB	PKS	OPF	OPT
Cellulose	6.59	19.86	25.40	23.24
Hemicellulose	29.27	21.44	33.18	28.84
Lignin	42.20	36.32	28.34	29.55
Extractive	17.80	21.55	17.00	12.22

The OPF and OPT contains higher cellulose and hemicellulose components compared to EFB and PKS. The high extractives were found in the EFB and PKS which is in line with their ash content in Table 1. The EFB and PKS have a high lignin content. The high lignin content of EFB was also reported by Prasetyo et al. (2022) which was in line with the experiment result of 42.2% lignin in EFB. A high cellulose and hemicellulose content generates higher yield of bio-oil or liquid product because they are easily decomposed by thermal. In contrast, biomass with a high content of lignin, which needs higher temperature to decompose, therefore promotes higher yield of biochar.

Pyrolysis Yields

The biochar yields from various lignocellulosic oil palm solid waste are shown in Figure 2.

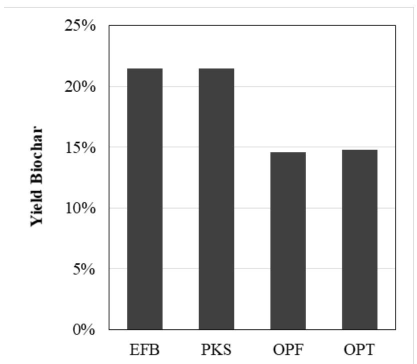


Figure 2. Yield of biochar from various lignocellulosic oil palm solid wastes with KOH activation via slow pyrolysis

The yield of biochars from EFB and PKS are higher than the others. This result is consistent with the characteristics of feedstock that EFB and PKS have high ash content that can lead to a higher yield of char. It is also confirmed by the TGA profile on EFB and PKS which have a high residual solid char at a temperature of 900°C. Moreover, EFB and PKS have higher lignin content which may generate char formation during the carbonization.

Table 3 presented elemental analyses of biochar with KOH activation. These results elemental analysis for all biochar with KOH activation were relatively similar to the previous study (Bakhtiar et al., 2019; Andas et al., 2017) with the range carbon content of 52 – 84.39%.

Table 3. Elemental analyses of biochar products

Feedstock	Elemental Analysis (%)					
	C	**H**	**N**	**O**	**H/C**	**O/C**
EFB	52.00	2.76	1.52	24.30	0.05	0.47
PKS	75.64	2.30	0.66	4.97	0.03	0.07
OPF	84.39	2.85	0.92	8.91	0.03	0.11
OPT	70.22	3.60	0.36	23.28	0.05	0.33

EFB biochar has the lower carbon content among the others, particularly the raw composition of EFB contains low level of cellulose and hemicellulose (see in Table 2). The H/C atomic ratio of biochar is relatively lower than that of raw biomass because the high temperature of pyrolysis leads to the dehydration reaction. De-oxygenation also followed during pyrolysis as the O/C atomic ratio of biochar was about 0.07 – 0.56, while that of raw palm oil solid wastes ranged from 0.78 to 0.98. The O/C atomic ratio of biochar was lower than raw biomass which means all biochars were more hydrophobic.

Surface Chemical Analysis of Biochar

The functional groups of biochar with KOH activation were analyzed by FTIR shown in Fig. 3.

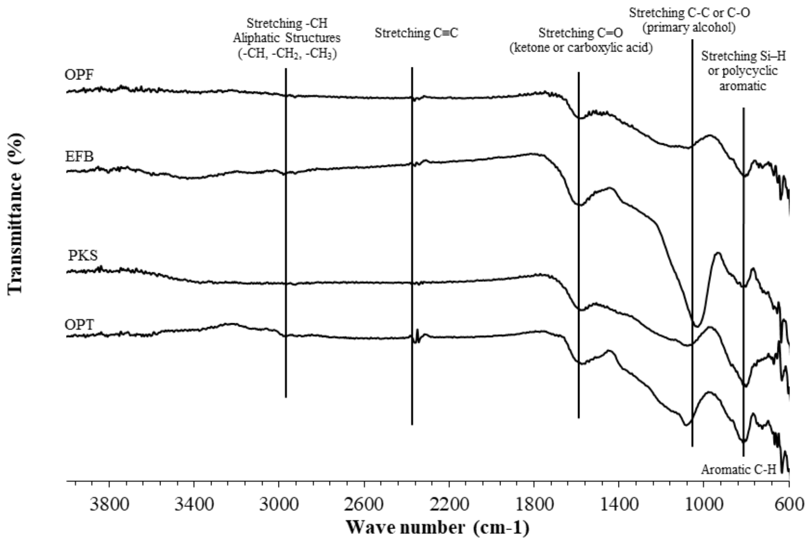


Figure 3. FTIR Spectra of biochar with KOH activation

All the spectra of biochar from raw biomass exhibits several bands: stretching vibration of aliphatic $-CH_2$ at 2920 cm^{-1}; -C≡C at 2343 cm^{-1}; –C=O (ketone or carboxylic acid) at 1600 cm^{-1}; a vibration band of C-O (alcohol, phenol, and carboxyl groups) at 1600 cm^{-1}; and C-C or C-O (primary alcohol) at 1035 cm^{-1}.

The spectra of OPT shows increase of transmittance at the wave number of 2343 cm-1 which represents the presence of the – C≡C – stretch. Based on this observation, the spectra of EFB show a dramatic C-C or C-O stretching vibration band than the others. This is affected because EFB has the largest lignin composition of 46.71% which the majority of lignin forms C-C and C-O aromatic groups.

Morphology and Pore Structure of Biochar

Table 4 summarizes the comparison of surface area and pore volume of biochar from palm oil solid wastes with KOH activation. At 600°C, the micropore and mesopore volume of various types biochars are almost the same amount.

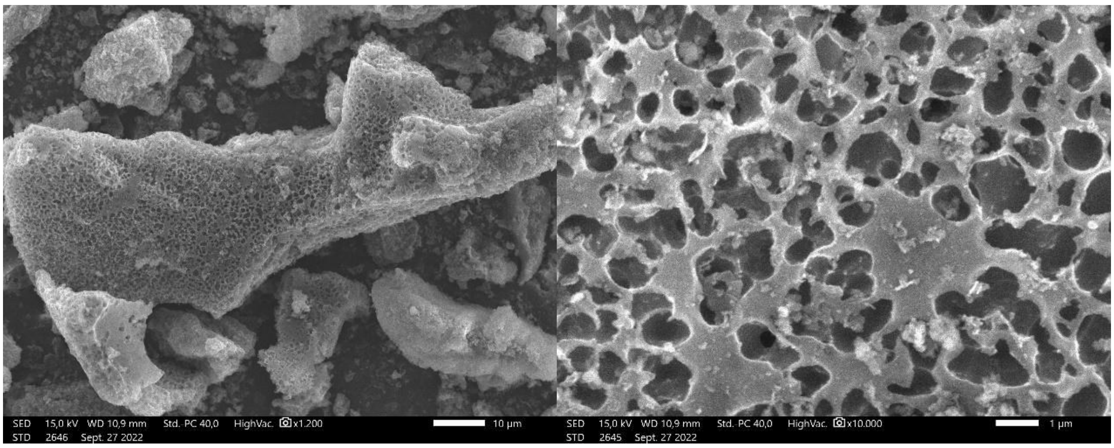
Table 4. BET parameters of biochar from oil palm solid wastes

Biochar sample	SA (m^2/g)	V micro (cc/g)	V meso (cc/g)	Pore volume (cc/g)
EFB	317.93	0.006	0.137	0.253
PKS	386.85	0.007	0.120	0.239
OPF	268.32	0.009	0.146	0.167
OPT	467.49	0.006	0.148	0.293

It has been reported that the capacitance may not influence by the volume of micropore because electrolyte ions have a poorly accessibility to the porous (Kumar et al., 2018). However, the high volume of mesopore promotes the excellent electrochemical performances due to the electrolyte accessibility (dos Reis et al., 2020).

The specific surface area (SSA) of oil palm solid wastes are ranged from 268.32 to 467.49 m^2/g. Other studies showed that an increase in KOH leads to larger pores which has lower the surface area of biochars (Liu et al., 2019; Bag et al., 2020). The SSA of biochars with KOH activation were better than those of the study from Liew et al. (2018) with an OPT SSA of 467.49 m^2/g. The high SSA of biochar indicates that the chemical reaction between the activating agent and the biomass precursor during activation process (the carbonization).

The surface morphology of biochars obtained from oil palm solid wastes were examined using SEM to portray the surface characteristic of each biochar due to KOH activation. Fig. 4 (a) illustrates the SEM of EFB biochar has limited pores as well as the structure is slightly deformed. Its surface appears not to have fully developed due to high amount of lignin, the pores underwent incomplete devolatilize of the lignin (Palamanit et al., 2019). In addition, the SEM image of OPF with KOH activation shows some largest pores (±3.3 µm) compared to the other biochars. These appearances lead to its low surface area and pore volumes confirmed by BET analyses (Table 4).



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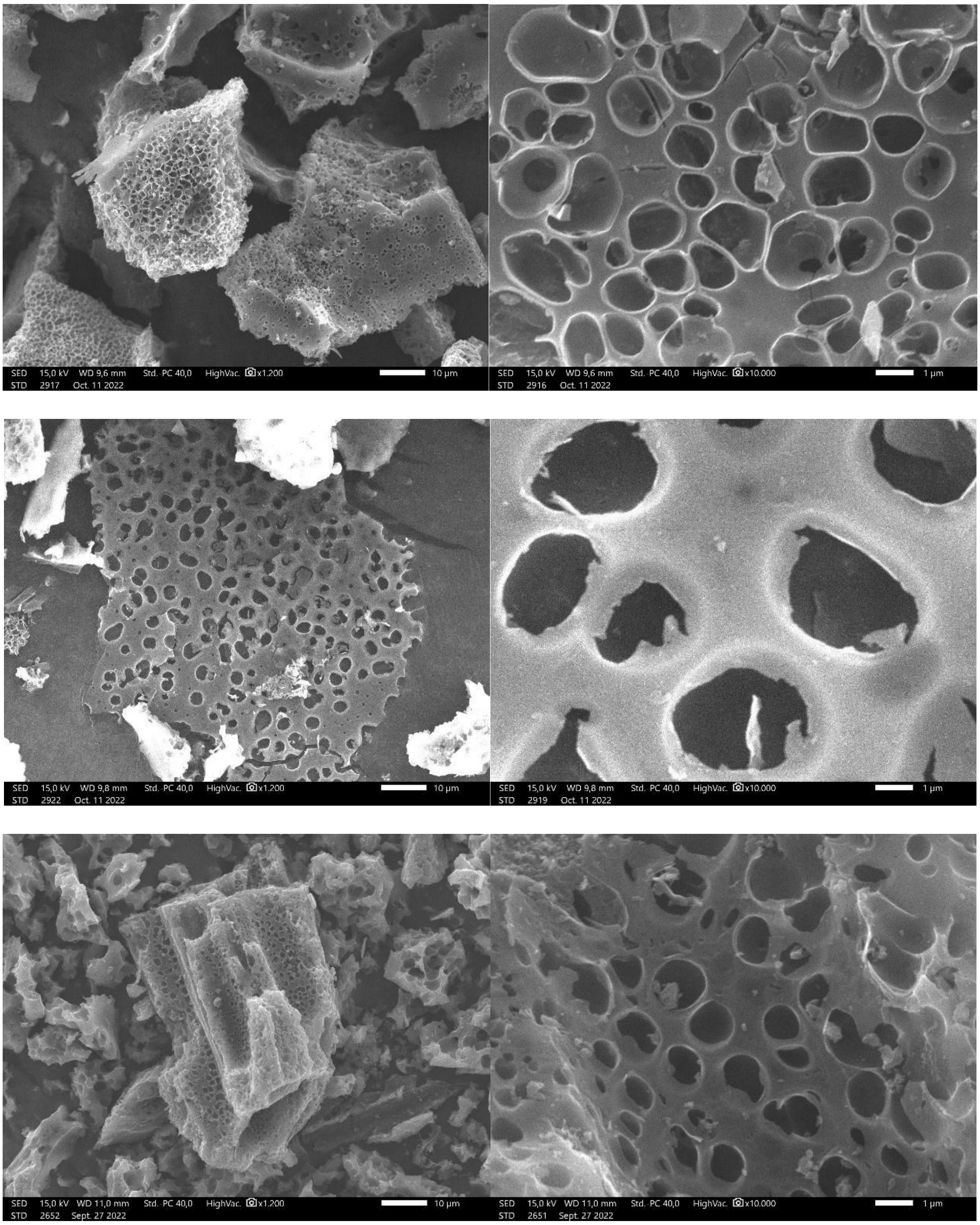


(b)

(c)

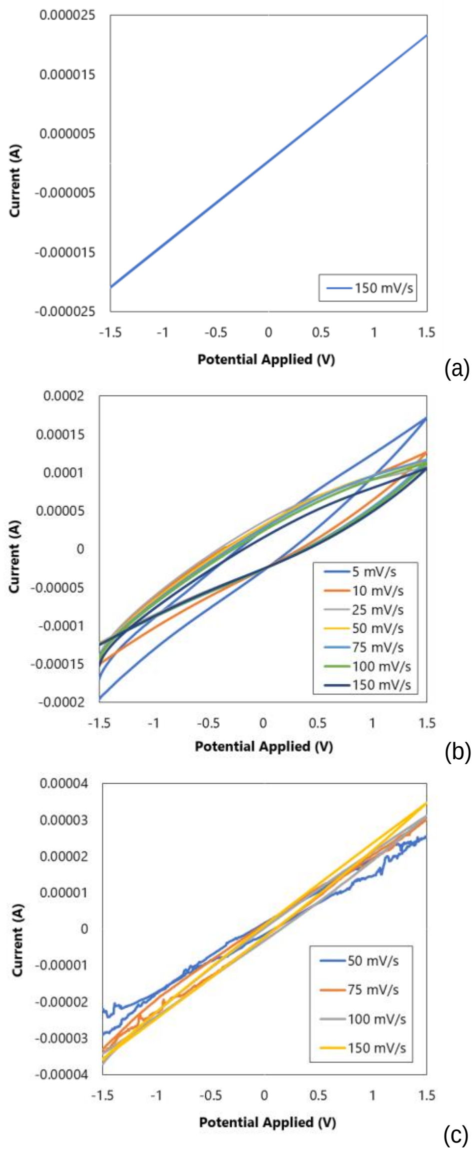
(d)

Figure 4. SEM images of (a) EFB; (b) PKS; (c) OPF; (d) OPT biochars pretreated with KOH

On the other hand, the SEM images of PKS and OPT biochars pretreated with KOH show theirs surface seem homogeneous with medium pores structures (±1.59 and ±1.19 µm, respectively) which gives higher surface area. Due to the larger surface area of the OPT, it can facilitate electrolyte penetration and ion transportation with less resistance (Kumar et al., 2018). Contrarily, the initial EFB morphology had already the small size of pores and then EFB biochar surface underwent rupture and break at 600^{o}C (Bakhtiar et al., 2019). The collapse of EFB biochar structures has limited pore sizes which can be hindered access on electrolyte penetration and ion transportation.

Electrochemical Properties of Biochar Products

This research focuses on producing the biochar that can be applied in the energy storage area, more specific is supercapacitor, as an electrode material. Therefore, the electrochemical properties of biochar have to be investigated along with the specific surface area of the material. The cyclic voltammetry (CV) curves of the biochar products from EFB, PKS, OPT, and OPF with KOH activation were shown in Fig. 5.



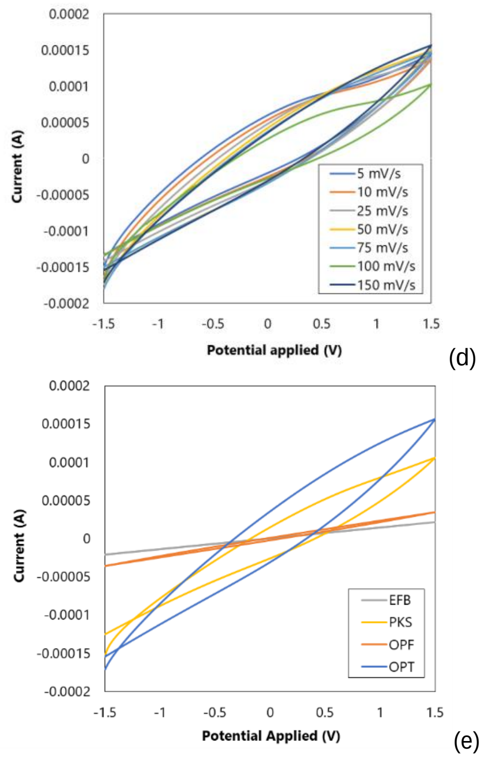


Figure 5. Cyclic voltammograms of solid palm waste-based biochar with KOH activation. CV of (a) EFB, (b) PKS, (c) OPF; and (d) OPT at different scan rate 5 – 150 mV/s, and (e) comparison of CV current for different feedstock with KOH activation at 150 mV/s

At a given scan rate (see in Fig. 5), biochars from PKS and OPT (4.35 F/g and 4.29 F/g at 5 mV/s, respectively) give a better response than those from EFB and OPF. OPT and PKS show higher current (A) at the same potential applied (V) compared to OPF and EFB, and they provide higher area under CV curves that indicate the more extensive stored charge.

The better performance of OPT and PKS is related to their higher SSA of 467.49 m^2/g and 386.85 m^2/g, respectively. Their pore volumes are also higher with 0.293 cc/g and 0.239 cc/g, respectively. The higher value of SSA and pore volume of the biochar give easier access and transportation for the electrolytes, better ion diffusion, and a higher number of sites that could trap the ion, resulting in high charge storage capability (Wang et al., 2017).

OPF shows a much lower response compared to OPT and PKS, linear with the characteristics of lower SSA and pore volume of this biochar which are 268.32 m^2/g and 0.167 cc/g, respectively. The SEM images also confirmed the more elevated pore size in OPF compared to other raw resources of biochar. However, EFB exhibits a different result of the CV curve. EFB exposes no response in the electrochemical performance since it indicates by the straight line in the CV curve, although EFB has higher SSA and pore volume compared to OPF. This result can be related to either the presence of higher primary alcohol or lower carbon content (52%) in EFB. Larasati et al. (2019) also reported the low capacitances of $ZnCl_2$ and $CaCl_2$ activated biochar from EFB were 2.45 and 4.3 F/g, respectively. These lower specific capacitance performances were because of poor interphase connection system.

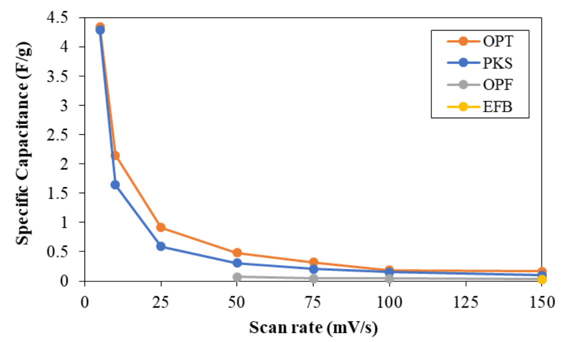


Figure 6. Specific capacitance trends of biochar activated by KOH with variation in scan rate

The specific capacitance of both OPT and PKS declined significantly with an increase in scan rate. The specific capacitance of PKS, for example, was dropped from 4.35 F/g at 5 mV/s to 2.15 F/g at 10 mV/s, approximately decreasing up to 51%. This phenomenon is related to the time needed by the electrolyte ions to infiltrate into the pores of biochar. At a higher scan rate, the electrolyte ions have insufficient time to penetrate the pores which lead to the accumulation of the ions on the outer surface of biochar. The hindrance of the ion movement will result in less specific capacitance (Liu et al., 2017). The specific capacitance of OPF biochar was only recorded for scan rate above 50 mV/s. The stability of the biochar in electrochemical performances has to be examined in further research.

However, the specific capacitance of PKS and OPT biochar is related to their carbon content and specific surface area. The carbon content of OPT and PKS biochar are 70.22% and 75.64%, respectively, and the specific surface areas (SSA) are 467.49 m^2/g and 386.85 m^2/g, respectively. The pore structure of PKS and OPT is also still dominated by mesoporous and macroporous structures. This pore structure may be caused by the pyrolysis process that is needed to be improved, for example, the setup of inert atmospheric for the process and optimization of process parameters including heating rate and operating temperature.

CONCLUSION

Oil palm solid waste-based biochar, i.e. oil palm trunk (OPT), oil palm frond (OPF), palm kernel shell (PKS), and empty fruit bunch (EFB), has been produced as an alternative source of the biomass precursor for the electrode material. The PKS and OPT biochars is superior to yield biochar with high specific surface area which lead to higher capacitive performances. OPT and PKS exhibit high surface area (467.49 m^2/g and 386.85 m^2/g, respectively), high carbon content (70.22% and 75.64%, respectively) and better electrochemical performances (4.35 F/g and 4.29 F/g at 5 mV/s, respectively). OPF and EFB, unfortunately, do not appear to be promising for further use as electrode materials. EFB has low carbon content (52 %) and deformed structure of biochar. OPF has the highest carbon content (84.39%) but it has the lowest SSA (268.32 m^2/g) among the others.

This research, however, has successfully screened the most potential of oil palm solid waste as a source of biochar since OPT and PKS have very low ash content and extractives allow to produce high yield carbon with low impurity. OPT and PKS biochars offer promises for further examination of high capacitance value, while OPF and EFB biochars may be more appropriate for other applications deodorize and decolorize waste-water treatment, air purification, and catalyst support.

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