Characterization of Lignocellulosic Biomass as Raw Material for the Production of Porous Carbon-based Materials

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Lignocellulosic biomass is a potential raw material that can be used in the synthesis (manufacture) of porous carbon stuffs. The properties of such porous carbon products are affected by the species of the raw material and the manufacturing process, among other things. This paper scrutinizes the related characteristics of lignocellulosic raw materials that indicate potential for the production of porous carbon. Three species were used: pine (*Pinus merkusii*) wood, mangium (*Acacia mangium*) wood, and candlenut (*Aleurites moluccana*) shells, representing softwoods, hardwoods, and non-wood stuffs, respectively. Analyses of their chemical compounds and proximate contents were carried out. Additionally, nano scale scrutiny of the lignocellulosic biomass was also conducted using the nano capable instruments, which consisted of SEM, EDS, XRD, FTIR, and DSC. Results revealed that pine wood had the most potential to produce porous carbon. Morphologically, pine wood afforded the best permeability, whereby at the structure of monoclinic cellulose crystals, there were cellulose-I_α structures, which contained less cellulose-I_β structures. Furthermore, pine wood exhibited greater volatile matter content, as confirmed through the FTIR, which greatly assisted the forming of porosity inside its corresponding carbon.

Keywords: Characteristic; Biomass; Pinus merkusii; Acacia mangium; Candlenut shell; Porous carbon

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INTRODUCTION

Raw materials used to produce activated carbon are mostly derived from petroleum, coal, and their derivative products. Coal can be made into activated carbon with a micro-porous structure (pore diameter < 2 nm), high surface area, and wide porous volume (Ahmadpour and Do 1996). The coal-derived carbon can therefore be categorized as porous carbon. Being based on non-renewable materials, their availability is limited and is being continually depleted. Consequently, other alternative materials with potential for the production of activated carbon with high porosity should be proposed, and among these alternatives is lignocellulosic biomass (Chuenklang *et al.* 2002; Ishida *et al.* 2004; Adebowale and Adebowale 2008; Choi *et al.* 2012).

Lignocellulosic biomass usually contains as much as 50% of its overall compounds in the form of carbon; it can be regarded as a renewable resource that is abundantly available and environmentally friendly (Sharon *et al.* 2007; Bin *et al.* 2008; Hu *et al.* 2008).

Lignocellulose biomass consists of three main components that constitute its cell wall, *i.e.*, cellulose, hemicellulose, and lignin. Each component has its own different characteristics. Cellulose has high crystallinity, whereas hemicellulose and lignin are amorphous. Cellulose consists of repeating units of the β-D-glucopyranose monomer with higher polymerization degree in a linear chain.

Hemicellulose consists of several kinds of pentose and hexose as monomer units, such as xylose, mannose, glucose, and galactose in a branched, amorphous, and irregular arrangement with a lower degree of polymerization. Therefore, hemicelluloses are more easily degraded at lower temperatures, and by using diluted acid or base solution, compared to cellulose. Lignin consists of principally three kinds of phenyl propane units, shaping a three-dimensional polymer in the form of a branched structure with aromatic rings; it has a wide range of degradation temperatures depending on lignin-source origin (Pettersen 1984; Yang *et al.* 2006).

Lignin has more carbon elements compared to the other main compounds in the lignocellulosic biomass, *i.e*., 61%, while cellulose and hemicellulose have 42% and 40%, respectively (Cao *et al.* 2014). The amounts of other components in biomass, other than those constituting the cell wall (such as the extractive and inorganic or mineral content), are very small. Extractives contain sugar components (mainly glucose and fructose), as well as tannins, resins, and starches that are susceptible to heat degradation at relatively low temperature. Meanwhile, minerals are generally more chemically stable than the sugar components (Garrote *et al.* 1999; Knezevic *et al.* 2009; Reza *et al.* 2013a,b).

Natural cellulose contains cellulose with the so-called I_α and I_β structures. The composition of cellulose I_α and I_β in biomass varies, depending on the type of biomass (Wada *et al.* 2001). Cellulose I_β with monoclinic crystal structure is rather resistant to heat, whereas cellulose I_α, which has a triclinic structure, is not (Wada *et al.* 2010). In most hardwood species, the crystal structure is dominated by cellulose I_β (Wada *et al.* 2001). Biomass stuffs with high cellulose and low lignin contents have great potential to produce activated carbon with a micro-porous structure (Simon and Burke 2008; Doménech-Carbo 2010). This finding confirms the research of Petrov *et al.* (1999) who carried out the simulation on the synthesis of porous carbon from several species of biomass, which varied in the composition of cellulose and lignin contents.

In this research, three different species (kinds) of biomass, *i.e*., pine wood (*Pinus merkusii*), mangium wood (*Acacia mangium*), and candlenut shells (*Aleurites moluccana*), were used as raw material for the manufacturing of porous carbon. Pine is classified as a conifer; mangium wood is hardwood; and candlenut shell is considered a non-timber forest product residue.

The characteristics of each biomass were investigated to determine their potency as a raw material for producing porous carbon. Instruments that were used for biomass analysis included a scanning electron microscope (SEM) with energy dispersive X-ray spectroscopy (EDS), differential scanning calorimeter (DSC), Fourier transform infra-red (FTIR) spectrometer, and X-ray diffractometer (XRD).

EXPERIMENTAL

Materials

Lignocellulosic biomass that consisted of pine wood, mangium wood, and candlenut shell was procured, shaped into powder form, and then strained using 40-60 mesh sieves. The powder (from each species) that passed through the sieve was examined for its chemical contents, *e.g.*, lignin, cellulose, hemicellulose, and extractives. The lignin content was determined based on TAPPI 222 om-88 standard (TAPPI 1988a). Acid-soluble lignin was determined using the ultraviolet spectrophotometer method at 205 nm wavelength; alcohol-benzene soluble content was found using TAPPI 204 om-88 (TAPPI 1988b); and cellulose was evaluated using TAPPI T17m-55 (TAPPI 1955). Proximate analysis was carried out based on Indonesia National Standard Number 1-3730, related with the activated carbon aspects for the determination of fixed carbon, ash, and volatile matter (INS 1995).

Methods

SEM and EDS analysis

In order to visually observe the surface morphology of the biomass, a scanning electron microscope (SEM) Zeiss EVO 50 (Germany) was used at an energy of 10 kV. As such, the slice of biomass was coated by gold. Determination of the content of the element was done with energy dispersive X-ray spectroscopy (EDS), which was carried out in tandem with SEM imaging.

X-Ray analysis (XRD)

Analysis of the crystalline structure present in lignocellulosic biomass and in the cellulose as derived from the biomass was carried out using a Shimadzu (Japan) 7000 X-ray difractometer (XRD) instrument, with copper (Cu) as the radiant source. Analysis was performed at an energy of 40 kV, electric current of 30 mA, scanning speed of 2°/minute, recording every 0.02°, and scanning angle 10 to 80°. The observed parameters during the XRD analysis were comprised of the crystallinity degree, the value of Z (to determine which was the more dominant between cellulose I_α and cellulose I_β), and the comparison between cellulose I_α and I_β. The Z value was determined using the lateral distance between the cellulose polymer chains *i.e.*, d_1 (100 and 010) and d_2 (110 and 1-10), using the following equation (Wada *et al.* 2001) (Eq. 1):

$$Z = 1693d_1 - 902d_2 - 549 \tag{1}$$

If the Z value was greater than 0, it indicated the domination of cellulose I_α, while $Z < 0$ implied the domination of cellulose I_β. The value of d_1 0.613 nm and d_2 0.529 nm would result if the I_α/I_β ratio is 10:0 (pure I_α). On the other hand, d_1 0.602 nm and d_2 0.535 nm would result if the I_α/I_β ratio is 0:10 (pure I_β). When the I_α/I_β ratio is x/y (where x + y = 10, and as integers), d-spacings d_1 and d_2 can be represented as follows (Eqs. 2 and 3):

$$d_{1x/y}\,(\text{nm}) = 0.613(x/10) + 0.602(y/10) \tag{2}$$

$$d_{2x/y}\,(\text{nm}) = 0.535(y/10) + 0.529(x/10) \tag{3}$$

FTIR analysis

FTIR analysis done by mixing the test sample as much as 4 mg with 200 mg KBr, then made pellets measuring 1.3 cm in diameter and a thickness of 0.5 cm. The absorptions were measured using infrared spectrum (FTIR) Bruker Tensor. The data was taken in the form of transmission at wave number range 400 to 4000 cm^{-1} with a resolution of 16 cm^{-1} and 5 scans.

DSC analysis

Differential scanning calorimetry of the biomass samples was analyzed using a Shimadzu TA 60 (Japan) with detector DSC-60A within the temperature range from 30 to 300°C, a heating rate of 5°C/min in a nitrogen atmosphere, and a flow rate of 30 mL/min. The mass of each sample was 3.10 mg.

RESULTS AND DISCUSSION

Chemical Components

The chemical components, as analyzed in the three biomass materials, were decidedly different from each other. The most unique results were revealed to be for the candlenut shell (Table 1). The highest cellulose content occurred with mangium wood, followed by pine wood and candlenut shell.

Meanwhile, the candlenut shells exhibited the highest lignin content, and pine wood and mangium wood were the second and third highest. The high lignin content in candlenut rendered a correspondingly high yield for its activated carbon as well (Cagnon *et al.* 2009; Peters 2011). In general, as previously described, the carbon content in lignin is greater than that in cellulose and hemicellulose (Cao *et al.* 2014). It follows that lignin is more resistant to heat than the latter two compounds (Poletto *et al.* 2012). Consequently, because candlenut exhibited the highest lignin content, it also had the highest yield of its resulting activated carbon. Furthermore, the high yield could also be attributable to the high fixed carbon content in candlenut shell (Table 2). Fixed carbon is the solid combustible residue that remains after a sample is heated at 900°C for a period of 7 min and the volatile matter is expelled.

Table 1. Analysis Results of the Chemical Components in Biomass

Components	Kinds of biomass		
	Pine wood	Mangium wood	Candlenut shell
Cellulose (%)	43.74	44.69	25.77
Hemicellulose (%)	16.20	22.39	28.73
Total lignin (%)	29.14	27.91	36.02
- Klason	28.99	27.76	36.00
- Acid-soluble lignin	0.15	0.15	0.02
Alcohol-benzene solubility (%)	3.20	5.55	8.53

However, the rigid lignin structure, coupled with the low content of volatile matter in candlenut shells, may have contributed to its difficulty in producing activated carbon with high porosity. Cellulose would have contributed positively to the forming of micropores in the resulting activated carbon, while lignin would have had the contrary effect (Cagnon *et al.* 2009; Peters 2011). In order to be suitable for activated carbon with high porosity, activation of candlenut shell should be in strenuous condition, compared to those for mangium or pine wood. The presence of high ash or mineral contents, as occurred in the candlenut shells (Table 2), could also inhibit the formation of carbon porosity.

It is strongly indicated that pine and mangium woods had a similar opportunity to produce activated carbon with high porosity, as they exhibited comparable lignin and cellulose contents. However, the mangium wood had slightly more opportunity than pine, since the former contained more cellulose and lower lignin. In addition, such phenomena were also supported by the higher content of hemicellulose in mangium wood. This is because hemicellulose, being of lower molecular weight and having shorter polymer chains than cellulose, could take part in the formation of volatile matter or gaseous compounds, particularly during the processing (carbonization) of mangium wood into activated carbon (Cagnon *et al.* 2009; Peters 2011).

Proximate analysis for the three kinds of biomass revealed surprising results that were inconsistent with those of chemical components, especially when comparing pine wood with mangium wood. Volatile matter in pine wood was higher than in mangium (Tables 1 and 2). However, the results of the proximate analysis of candlenut shell showed consistency with the chemical analysis. This phenomenon was presumably affected by the morphology and crystallography of wood, which differed significantly from those of non-wood stuffs (candlenut shells), which would be explained later in the discussion related to using SEM and XRD devices.

This volatile matter would greatly contribute to the porosity formation in the ultimate product (active carbon) during the carbonization of biomass stuffs (Manocha 2010). Pine wood had a slightly higher volatile matter content than mangium wood but exceedingly greater than candlenut shells. This indicated that pine wood had the most potential to produce activated carbon with high porosity. The partial release of carbon in the form of CO_2 and CO into the air during carbonization and activation will increase porosity and concurrently decrease the yield of activated carbon.

Table 2. Proximate Analysis of Biomass

Parameters	Pine wood	Mangium wood	Candlenut shell
Fixed carbon (%)	15.64	17.47	28.30
Volatile matter (%)	84.05	82.01	65.39
Ash content (%)	0.31	0.52	6.31

Morphology and Elemental Analysis (SEM and EDS)

Related observations were conducted to determine the surface morphology, especially the porosity inside, as well as throughout the biomass. In the radial and tangential directions, pine wood was more porous than mangium wood. The cavities (particularly void spaces in the wood cells) of pine wood were more open and elongated (Fig. 1). This characteristic is typical for coniferous wood, which has long fibers that are mostly composed of tracheid cells and hence afford good permeability. The fibers in mangium wood, which consist of true fibers and hardwood tracheids, are shorter and smaller. The cavities inside were less open and the surface of the fiber wall maintained the lateral integrity among fibers, forming the so-called xylem tissue. The presence of cavities in tangential direction inside mangium wood created void spaces, which were interconnected between the wood fibers. Meanwhile, the structure of the candlenut shells was very different from that of wood. High lignin content made candlenut shells look very dense, such that only very minute pores existed.

The cavities would act to distribute heat evenly throughout the biomass, and the volatile matter was regarded as condensable matter (condensate) when the carbonization process takes place. Inside the structure and throughout the morphology of wood, its porosity caused the condensate to be trapped and to be gradually converted into solid carbon. Therefore, increased porosity could reduce the amount of volatilized matter during the biomass carbonization/activation that otherwise escaped free to the air.

During the activation process, the cavities will act as media to distribute the activator into the carbon structure (impregnation) and concurrently release water vapor as well as gaseous matter. This condition will facilitate the porosity formation. According to the biomass structure and morphology, pine wood had the largest opportunity to produce activated carbon with high porosity, followed in decreasing order by consecutively mangium wood and candlenut shell.

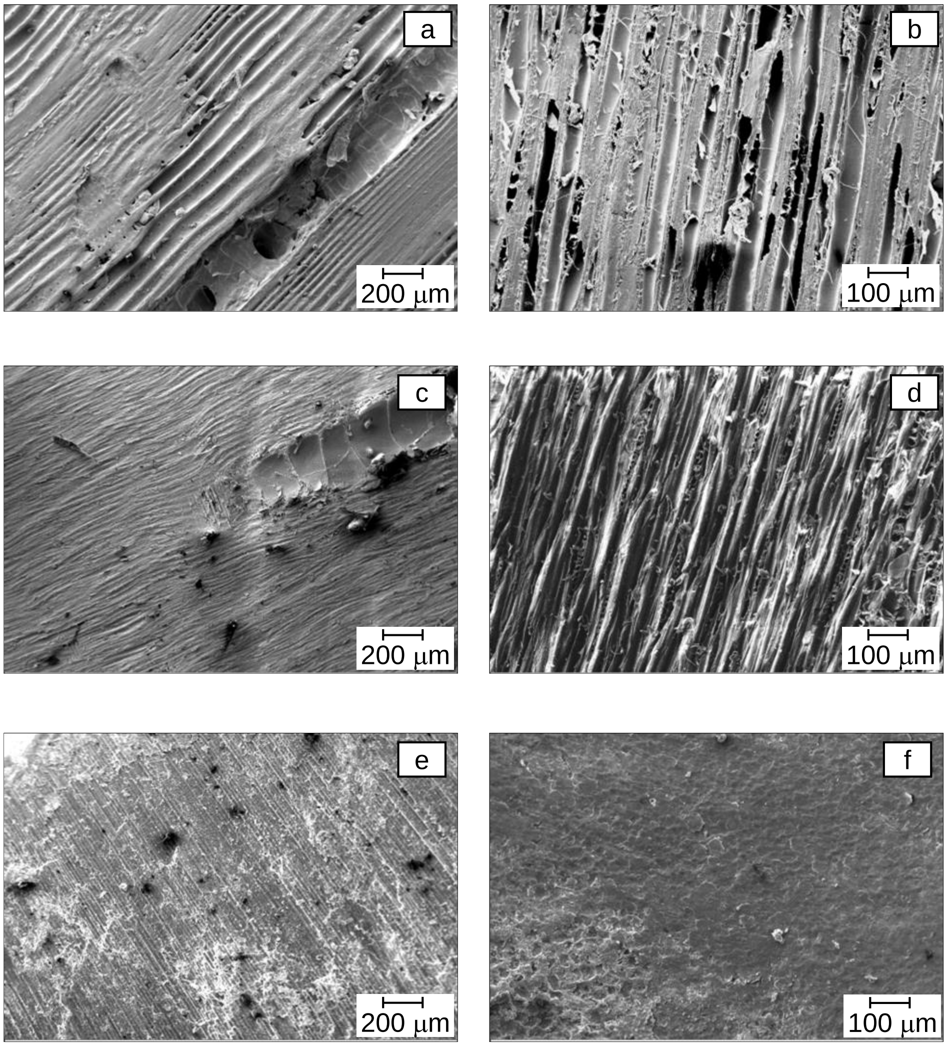

Fig. 1. Surface morphology of biomass: a) Pine, radial view, b) Pine, tangential view, c) Mangium, radial view, d) Mangium tangential view, e) Candlenut shell, side view, and f) Candlenut shell, inner view.

The content of chemical elements (in relative amount) in biomass can each be rapidly determined using an EDS instrument. However, this method cannot detect several light-weight elements such as hydrogen, helium, lithium, and beryllium. Therefore, the results as obtained in this research could not detect the hydrogen content of biomass. The results of the EDS analysis are shown in Table 3.

Theoretically, and according to the results found by Cao *et al.* (2014), lignin contains the highest proportion of the carbon element, followed by hemicellulose and cellulose. However, based on the percentage of chemical compounds, the lignin content in the experimented biomass for this research was far lower compared to the cellulose content (Table 1). Consequently, not only was the carbon content determined by the lignin but also by the whole body of each biomass, which also incorporated hemicellulose and cellulose (Table 3). Pine wood had a higher lignin content but exhibited lower carbon content compared to mangium wood. Further, mangium wood exhibited the highest content of carbon element of the three biomass species. In this regard, the highest cellulose and second highest hemicellulose contents for mangium wood contributed to its high carbon content. The third highest content of carbon occurred with candlenut shell, which was indicatively brought about by the percentage of its cellulose content (which was by far the lowest), despite its high lignin and hemicellulose contents compared to mangium and pine wood.

The carbon content that resulted from the EDS analysis (Table 3) was consistent with the results from the proximate analysis (Table 2). The consistent results also occurred with respect to the oxygen content (EDS) and volatile matter (proximate). The higher carbon content will increase the potency towards high fixed carbon. Additionally, oxygen in biomass will influence the volatile matter. Higher oxygen will result in a higher amount of gas released, as the oxygen could usually bond with other elements in the volatile matter. The results of EDS also detected the presence of calcium (Ca) in the candlenut shell. Therefore, the ash content in candlenut shell, which was exceedingly higher than that in two other biomasses (Table 2), consisted of predominantly the Ca element (Table 3).

Scrutinizing the results of SEM and EDS analysis, it can be judged that pine wood could potentially produce carbon with high porosity, followed by consecutively mangium wood and candlenut shell.

Table 3. Relative Amounts of Elements in Biomass using EDS

Elements	Pine wood	Mangium wood	Candlenut shell
C (%)	48.84	49.46	47.52
O (%)	51.16	50.54	44.49
Ca (%)	-	-	7.99

XRD Analysis

In general, the diffractogram feature of the three biomasses showed cellulose identifier (Fig. 2) as strongly justified by the presence of a peak at 2θ angle values around 16.5^o and 22.6^o (Poletto *et al.* 2012). However, among the three kinds of biomass, the diffractogram had different intensities and curve widths. Mangium wood exhibited the highest intensity and the least narrowing curve width, followed in proper order by pine wood and candlenut shell. This pattern could describe regularity in the formation of the crystalline structure of cellulose.

Mangium wood had the highest crystallinity degree, as it contained a high amount of cellulose (Table 1 and 4). Cellulose is composed of glucose monomer units in the form of linear chains, which make up the polycrystalline structure. Meanwhile, hemicellulose (with branched as well as straight polymer chains) and lignin (with three-dimensional polymer) are amorphous (Cagnon *et al.* 2009).

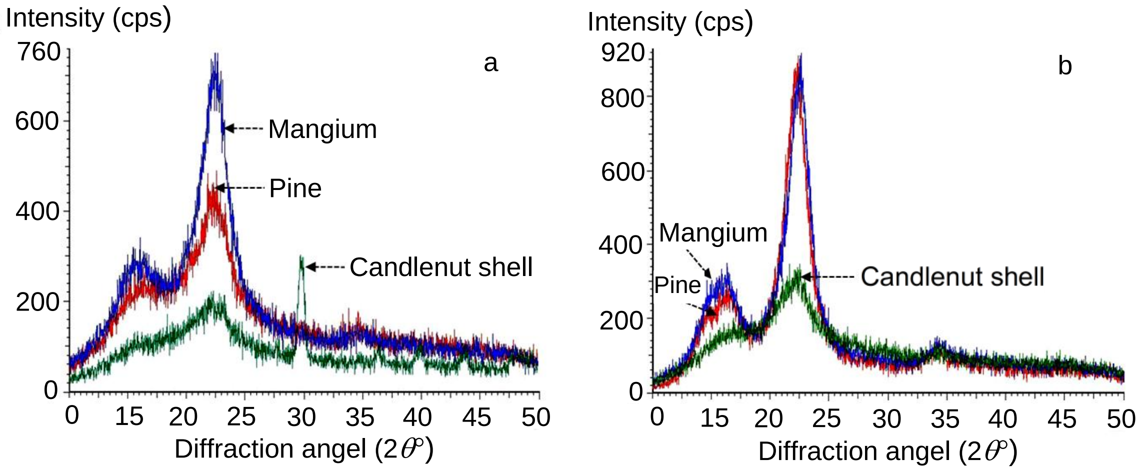

Fig. 2. X-ray diffraction of: a) lignocellulosic biomass and b) pure cellulose

A high crystallinity degree strongly indicated that the biomass had a more regular structure. Cellulose with high crystallinity degree is more resistant to decomposition by heating compared to cellulose with low crystallinity degree. Therefore, mangium wood had less volatile matter than pine wood. The crystallinity degree of cellulose inside all the varieties of biomass ranged from 43 to 65% (Moon *et al.* 2011).

The diffractogram of candlenut shell showed other peaks at around 23°, 29°, 37°, and 39°, which is presumably judged as an identifier of calcium carbonate. Based on the elemental analysis using EDS previously, calcium (Ca) was also identified. Accordingly, it can be justified that the XRD peak was undoubtedly a calcium identifier. In the formation of porous carbon, the mineral content will disturb porosity formation as well as the carbon purification process (Carrott *et al.* 2008).

The diffractogram of pure cellulose (Fig. 2b) showed a similar pattern to that of the overall lignocellulosic biomass (Fig. 2a), which comprised mangium, pine, and candlenut shell. However, significant differences still occurred, as indicated by the different intensities and curve widths between both patterns, with respect to particular biomass and its corresponding cellulose. Pine wood, mangium wood, and candlenut shell can be regarded as natural biocomposites, composed primarily of cellulose, hemicellulose, and lignin.

In pure cellulose, the diffractogram between pine wood and mangium wood looked relatively similar to each other, especially at the peak at approximately 22.6°. This angle was a reflection on a [200] lattice plane, which showed the cellulose crystal length at one chain of its polymer. This area could imply the polymerization degree. The progressive increase in intensity will result in an increase in the degree of cellulose polymerization (Terinte *et al.* 2011). The cellulose identifier appeared at an angle around 14.5° and 16.6°. Those two angles reflected cellulose I_α (triclinic) and I_β (monoclinic) structure (Wada *et al.* 2010). At this angle, the three biomass samples showed different patterns.

The crystallinity degree for mangium wood was higher than that of the other biomass types (Table 4). These properties, however, did not correlate with the amount of fixed carbon (Fig. 3). The crystallinity degree seemed strongly affected by the chemical components that compose the biomass. Accordingly, cellulose contributed to a positive correlation on the crystallinity degree, while lignin affected the crystallinity negatively. These phenomena correlated strongly with crystallography characters of cellulose, as well as lignin.

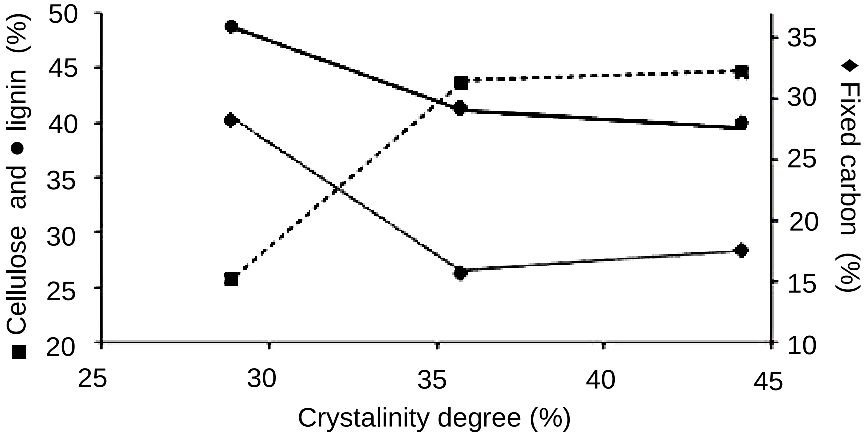

Fig. 3. Correlation of crystallinity degree with consecutively (■) cellulose, (●) lignin, and (♦) fixed carbon

The crystal structure of cellulose in pine wood, mangium wood, and candlenut shell was dominated by cellulose I_{β} (monoclinic) with Z value < 0 (Table 4). Further experiments showed that mangium cellulose was rich in I_{β} crystal structure, with a ratio of I_{α}/I_{β} equal to 0/10, while the ratios for pine wood and candlenut shell cellulose were 2/7 and 1/9, respectively (Fig. 4).

Table 4. Crystal Structure of Cellulose in Raw Materials (Biomass Origins) and Corresponding Pure Cellulose

Types of biomass / pure cellulose	Crystallinity Degree (%)	d_1 (nm)	d_2 (nm)	Z	Dominant Structure
Pine wood	35.73	0.6069	0.5377	-6.57	Monoclinic
Pine cellulose	47.81	0.6089	0.5397	-5.00	Monoclinic
Mangium wood	44.10	0.6057	0.5381	-8.92	Monoclinic
Mangium cellulose	53,28	0.5956	0.5410	-28.70	Monoclinic
Candlenut shell	28.85	0.6072	0.5441	-11.74	Monoclinic
Candlenut shell cellulose	24.28	0.6031	0.5349	-10.41	Monoclinic

The lateral distance (d_1 plane) between the cellulose polymer chains in mangium cellulose was denser (closer) compared to that in pine cellulose and candlenut shell cellulose. Therefore, the cellulose bonds in the lateral direction were stronger. Judging from the monoclinic structure, the distance of d_1, and crystallinity degree in mangium wood cellulose, indicated that the cellulose in mangium wood's lignocellulosic biomass was more difficult to decompose by heating compared to pine wood and candlenut shell cellulose. Accordingly, it lessened the release of volatile matter.

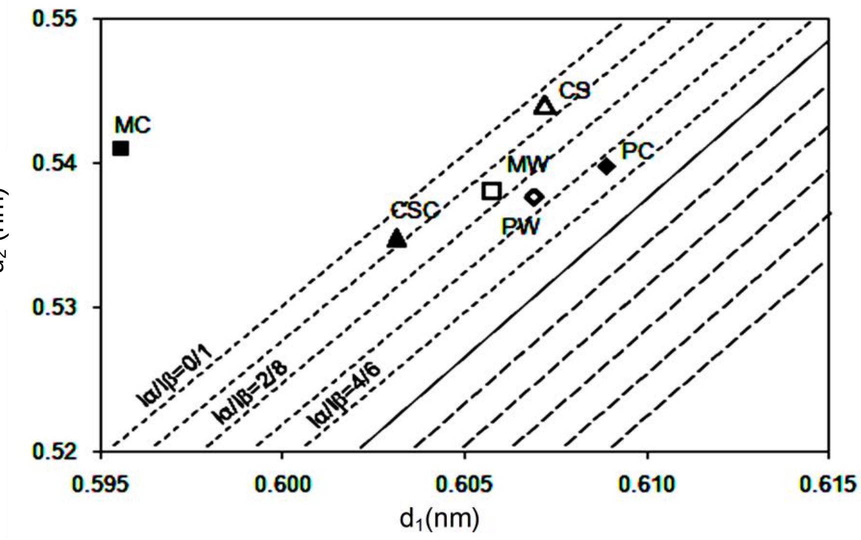

Fig. 4. Z plot of cellulose in raw material (MW=mangium wood, PW=pine wood, CS=candlenut shell=CS) and pure cellulose (MC=mangium cellulose, PC=pine cellulose, CSC=candlenut shell cellulose)

FTIR Analysis

Infra-red spectral analysis of pine wood, mangium wood, and candlenut shell is shown in Fig. 5. The presence of polysaccharides was identified by the appearance of the C=O (carbonyl) and O-H functional groups at wave numbers around 1740cm^{-1} and 3000 to 3700cm^{-1}; further, C-O-C at 1168cm^{-1}, C-H alkyl and aromatic at 2929cm^{-1}, and C-O at 1164cm^{-1} and 1068cm^{-1} indicate the presence of polysaccharides as well (Owen and Thomas 1989; Bilba and Ouensanga 1996; Parshetti *et al.* 2013). Lignin was identified based on the benzene spectrum C=C at 1650cm^{-1}, aromatic carbon skeleton at 1604cm^{-1}, CO deformation at 1056cm^{-1}, O-H stretching at 3000 to 3700cm^{-1}, CH deformation at 810cm^{-1} and 1434cm^{-1} and carbonyl groups include aldehydes at 1760 to 1720cm^{-1} and ketones at 1700 to 1670 cm^{-1} (Owen and Thomas 1989; Bilba and Ouensanga 1996; Li and Ding 2007; Parshetti *et al.* 2013).

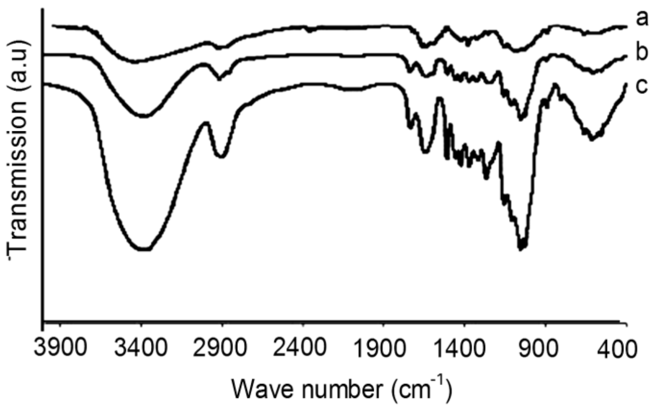

Fig. 5. FTIR spectrum of biomass: a) Candlenut shell, b) Mangium, and c) Pine

The intensities of OH, C=O, and C-O-C for pine wood were higher than those for mangium wood and candlenut shells, which again indicated that the former biomass contained a larger portion of volatile matter. This characteristic supported the arrangement of carbon elements, such that they formed more highly porous structure inside as well as throughout the structure of activated carbon from pine wood. These results were consistent with those of the proximate analysis and elemental analysis, as shown in Table 2 and Table **3**.

DSC Analysis

During pyrolysis the characteristic decomposition of biomass depends on the composition and concentration of the main components *i.e.,* hemicellulose, cellulose, and lignin. DSC curve at a temperature below 160°C showed an endothermic reaction with slow heating rate for all of biomass (Tarrío-Saavedra *et al.* 2013; Yang *et al*. 2007). Changes in this region can be attributed mainly to the removal of moisture, especially free-water. While at the temperature 160 to 200°C occurred to release the bound water. Greater energy was required to remove bound water as showed on the high heating rate; this could be seen from the high peak on the Fig. 6. The greatest energy (endothermic) to evaporate bound water was needed by mangium wood followed by pine wood and candlenut shell *i.e.,* 78.96, 49.43, and 31.55 mcal, respectively. Mangium wood had the highest degree of crystallinity or more orderly arrangement of polymers (high cellulose content) as compared to the others. These results support the previous results that mangium wood would be difficult to decompose generate vaporized as compared to pine wood. Meanwhile candlenut shell had high lignin content that would be produce volatile less than mangium and pines wood (Tarrío-Saavedra *et al*. 2013; Gasparovic *et al.* 2010).

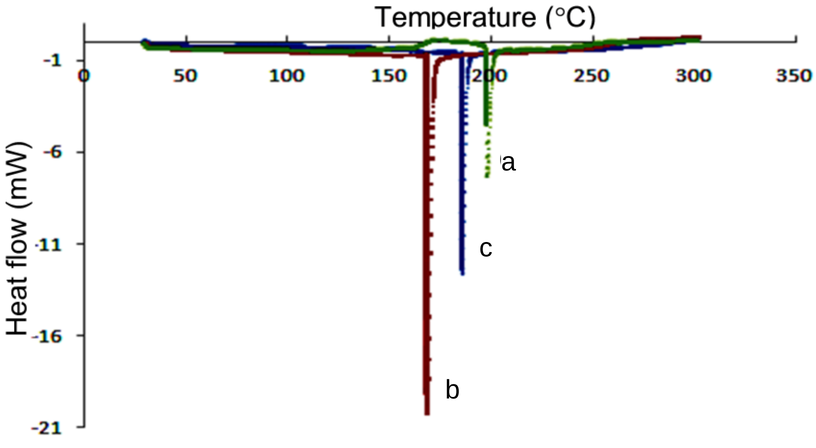

Fig. 6. DSC curves of: a) Candlenut shell, b) Mangium, and c) Pine

CONCLUSIONS

1. High cellulose content in lignocellulosic biomass, such as in pine wood, mangium wood, and candlenut shells, did not always result in high volatile matter. The typical morphology, functional groups, and crystal structure of cellulose contributed significantly to the forming of volatile matter and their subsequent release, thereby creating specific porosity of the corresponding porous carbon with high porosity.

2. According to the characterization and analysis of the related biomass, pine wood afforded the highest potency and the greatest prospect as a raw material in the production of porous carbon with high porosity, followed in decreasing order by mangium wood and candlenut shells.

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