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Carbonization Characteristics of Juvenile Woods from Some Tropical Trees Planted in Indonesia

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The objective of this study was to evaluate the characteristics of charcoals from juvenile woods of albizia (*Paraserianthes falcataria*), gmelina (*Gmelina arborea*), mindi (*Melia azedarach*), and mangium (*Acacia mangium*). Carbonization was performed at 400, 600, and 800°C for 10 min with a heating rate of 6°C/min. The physical, bioenergetic, and chemical properties were evaluated. Maximum char yield was obtained at 400°C and the increase of carbonization temperature resulted in a decrease of char yield. At the same carbonization temperature, char yield was higher in wood with greater initial density, i.e. ordered from the highest to the lowest: mangium, mindi, gmelina, and albizia. The heating values in all woods increased after carbonization, with maximum values at 600°C. Maximum energy densification ratio and energy yield were obtained at carbonization temperature of 600°C and 400°C, respectively. Char yield of 23.62–39.03%, heating value of 25.16–33.85 kJ/g, energy densification ratio of 1.45–1.72, energy yield of 39.09–60.10%, ash content of 0.80–3.94%, volatile matter of 14.61–38.69%, and fixed carbon of 58.58–83.27% were obtained in all charcoals from juvenile woods and were comparable with those of mature woods, showing suitability for the production of charcoal fuel.

Key words: carbonization, juvenile wood, tropical species, heating value, proximate analysis

INTRODUCTION

The demand for forest products continues to rise as world population and incomes grow (FAO, 2014). These demands will have to be met from a static or declining resource. Countries deal with this challenge in many different ways, including the application of a mix of approaches aiming at broadly promoting sustainable forest management and land use planning. In addition, there have been improvements in harvesting and processing technologies and increases in plantation establishment.

Planted forests play a very important role in providing wood supply in Indonesia. In 2013, 19.55 million m3 out of the total 23.23 million m^3 of wood supplied came from planted forests (Ministry of Forestry, Republic of Indonesia, 2014). In Indonesia, planting fast growing tree species has been widely established in industrial, state–owned enterprise, and community planted forests.

Albizia (*Paraserianthes falcataria*), gmelina (*Gmelina arborea*), mindi (*Melia azedarach*), and mangium (*Acacia mangium*) are promising fast growing tree species to be developed for industrial planted forests and community forests. Albizia is one of the most important pioneer multipurpose tree species, and it is preferred for industrial forest plantations in Indonesia due to its very fast growth, ability to grow on various soil conditions, and its favorable silvicultural characteristics (Krisnawati *et al*., 2011). Gmelina is indigenous to India and neighboring countries and planted in many tropical countries. Moreover, it can adapt to various soil conditions and is known to improve soil through nitrogen fixation (Allen and Allen, 1981). Mindi has been introduced in commercial plantations in Indonesia, particularly in state–owned enterprises plantation areas and community forests, as it is well adapted to warm climates, poor soils, and seasonally dry conditions (Harrison *et al*., 2003). Mangium has become the most abundant tree species in forestry plantation programs in Southeast Asia. In Indonesia, the total area of mangium tree plantations reached more than 1 million ha (Yamashita *et al*., 2008). Mangium is characterized as a fast growing species, adaptable to a wide range of acidic soils (pH 4.5–6.5), with a tolerance for low fertility and impeded drainage in devastated sites (Awang and Taylor, 1993).

In our previous studies, we have reported on the properties of those four tropical species including their anatomical characteristics (Kim *et al*., 2012), physical and mechanical properties (Kim *et al*., 2014), combustion properties (Park *et al*., 2015), natural durability properties (Febrianto *et al*., 2015), and weathering (ultraviolet radiation) properties (Park *et al*., 2016). The results showed that those four species have relatively low density, low durability, and low mechanical properties that are not suitable for structural timbers. Forest industry sectors should be encouraged to adapt to the use of the species from planted forests. One of the technologies that might be suitable for this is carbonization.

Carbonization is defined as the pyrolysis process in inert atmosphere by which high carbon content solid resi-

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dues are formed from organic material (McNaught and Wilkinson, 1997). During the thermal decomposition process, moisture and volatiles are removed, leaving a solid residue (charcoal), liquids (condensable vapors), and permanent gases (Lohri *et al.*, 2016).

Charcoal can be utilized for a broad range of applications including as an alternative source of domestic and industrial energy for briquettes, firewood, gas, coal, and electricity. Charcoal can be manufactured from various lignocellulosic materials. However, not all species can produce good quality charcoal due to variability in physical properties (*e.g.*, density, moisture content, ash content, and volatile matter) and chemical composition (*i.e.*, cellulose, hemicelluloses, and lignin) (Kumar and Chandrashekar, 2013; Collard and Blin, 2014; Lohri *et al.*, 2016). In addition, charcoal quality is affected by process parameters such as carbonization temperature, heating rate, residence time, sample size, and reactor pressure (Antal *et al.*, 2000; Kim and Hanna, 2006; Kwon *et al.*, 2009; Yan *et al.*, 2009). Comprehensive study on carbonization of juvenile woods from fast–growing tree species is very limited (Fuwape, 1996; Pereira *et al.*, 2013; Marques *et al.*, 2015). In this context, the objective of this study is to evaluate the charcoal characteristics of juvenile woods from four different tropical fast–growing tree species, after carbonization at different temperatures.

MATERIALS AND METHODS

Materials

Juvenile woods of four tropical fast growing species i.e., albizia, gmelina, mindi, and mangium were obtained from experiment plots in the plantation sites of Perum Perhutani, a state–owned enterprise in Indonesia. The first experiment plot, located in Purwakarta consists of mix plantation of albizia and mindi. The second experiment plot, located in Bogor consists of mix plantation of gmelina and mangium. To provide optimal growth, 30 trees of each species were planted with a spacing of 3 m × 3 m in both experiment plots. The trees of the four species were felled and disks of 70 mm thickness were obtained at the diameter at breast height (DBH). Wood disks were air–dried and kept in a conditioning room under the relative humidity of 65 ± 3% and a temperature of 25 ± 2°C before the experiment. Disks were cut into small blocks of 40 mm (length) × 20 mm (width) × 20 mm (thickness). The obtained blocks were oven dried at 105°C for 24 h prior to carbonization process. General information about the four species used in this study is shown in Table 1.

Methods

Carbonization of Woods

Wood samples were carbonized in an electric furnace (HT 16/16, Supertherm, Germany) using nitrogen gas with a concentration of 1 kg/cm². The carbonization was performed with a heating rate of 6°C/min from ambient temperature to the target temperatures of 400, 600, and 800°C. After the target temperature was attained, it was maintained for 10 min and the charcoal samples were rapidly taken out of the furnace and buried in a sand container until it cooled down.

Charcoal Characterization

To evaluate the bioenergy property, char yield, energy densification ratio, and energy yield were determined using the following equations (Yan *et al.*, 2009):

$$\text{Char yield} = \frac{\text{Oven dried weight of carbonized wood}}{\text{Oven dried weight of origin wood}} \times 100\% \quad (1)$$

$$\text{Energy densification ratio} = \frac{\text{Heating value of carbonized wood}}{\text{Heating value of origin wood}} \quad (2)$$

$$\text{Energy yield} = \text{Char yield} \times \text{Energy densification ratio} \quad (3)$$

The heating value of wood before and after carbonization was measured in an oxygen bomb calorimeter (Parr 6300 calorimeter, Parr Instrument) according to Korean Standard KS E 3707 (KSA 2011). Powder samples of 0.4–0.6 g after 60 mesh sieving were oven dried

Table 1. General information of the woods used in this study

Wood species	DBH[a] (cm)	Age (year)	Density[b] (g/cm³)	Origin
Albizia (*P. falcataria*)	16.5 (1.72)	7	0.22 (0.01)	Purwakarta, Indonesia (6°29'59" S, 107°21'37" E)
Gmelina (*G. arborea*)	16.1 (1.82)	6	0.34 (0.02)	Bogor, Indonesia (6°20'21" S, 106°33'58" E)
Mindi (*M. azedarach*)	15.4 (2.01)	7	0.48 (0.03)	Purwakarta, Indonesia (6°29'59" S, 107°21'37" E)
Mangium (*A. mangium*)	17.7 (1.17)	6	0.56 (0.02)	Bogor, Indonesia (6°20'21" S, 106°33'58" E)

Numbers in parenthesis are standard deviations.
[a] means are average of three trees measurement.
[b] oven dry density = oven dried mass/oven dried volume, means are average of five replications.

at 105°C for 24 h and used for the analysis.

The pH was determined using a mixed solution of 1 g oven–dried wood charcoal powder and 100 ml distilled water in accordance with TAPPI 435 (TAPPI 2006). The solution was then boiled for 10 min and cooled down until reaching room temperature. pH was measured with a pH meter (InoLab pH Level 2).

For proximate analysis, volatile matter and ash content were evaluated in accordance with KS E ISO562 (KSA 2012a) and KS E ISO1171 (KSA 2012b), respectively. In addition, fixed carbon content was calculated using the equation:

$$\%FC = 100 - (\%Ash + \%VM) \quad (4)$$

where %FC, %Ash, and %VM, mean the mass percentages of fixed carbon, ash, and volatile matter of the sam- respectively. Char yield, heating value, pH, volatile matter, ash content, and fixed carbon content were measured in five replications.

Changes of the surface chemical properties during carbonization were evaluated with FTIR spectroscopy. FTIR spectra of wood and charcoal samples were measured by direct transmittance using a KBr pellet. Pellets were made by intimately mixing 2 mg of wood or charcoal pov with 100 mg of dry KBr. Spectra were nned in the range of 4000–400 cm^{-1} using a Spectrum 0 FTIR spectrometer (PerkinElmer Inc., USA) at a spectral resolution of 4 cm^{-1} and 4 scans were taken per sample.

RESULTS AND DISCUSSION

Char Yield

The char yields of the four studied juvenile woods after carbonization at different temperatures are shown in Figure 1. The char yields at 400°C ranged from 31.22 to 39.03% and decreased gradually with increasing carbonization temperature, reaching the lowest char yields of 23.62–27.77% at 800°C in all species. The results showed differences in char yields among the four species. It was highest in mangium and in order of mindi, gmelina, and albizia. This may be due to the differences in the physical properties and chemical composition. For example, mangium has the highest density among the other species. Previous studies also reported that high–density wood species generally resulted in higher char yield compared to low–density wood (Fuwape *et al*., 1997; Cutter and McGinnes, 1981).

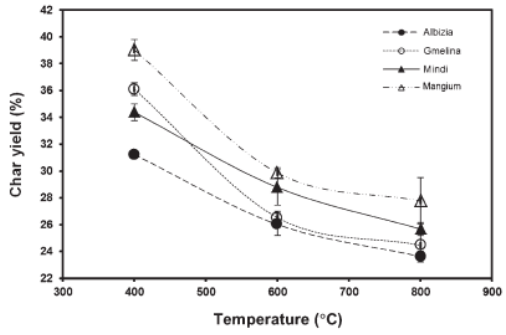

Fig. 1. Char yield of juvenile woods from four tropical wood species after carbonization at 400, 600, and 800°C.

The obtained char yields of the four juvenile woods in this study were similar to those of other juvenile woods (Fuwape, 1996; Pereira *et al*., 2013) and compa- with those of the mature woods reported by Kim and Hanna (2006) and Kwon *et al*. (2009). According to Fuwape (1996), the char yields of juvenile wood from gmelina (5–year–old) after carbonization at 400 and 600°C were 32.2 and 18.9%, respectively. Kim and Hanna (2006) reported on the carbonization of mature wood from *Quercus variabilis* and obtained char yields of 25.6, 18.7, and 16.6%, after carbonization at 400, 600, and 800°C, respectively.

A higher char yield at 400°C can be attributed to a limited decomposition and degradation of the main chemical constituents of wood (i.e., cellulose, hemicellulose, and lignin) in this temperature, when compared with that at 600 and 800°C. During thermal decomposition, hemicellulose was the first degraded component at a temperature of 220–315°C, followed by cellulose at 315–400°C, while lignin decomposed slowly, reaching maximum decomposition rate at above 900°C (Yang *et al*., 2007). The decrease of char yield may also be due to the highe agnitude of volatile matter removal from charcoal as the carbonization temperature increased (Table 2).

The overall results of char yield after carbonization at 400, 600, and 800°C with a range of 24–40% can be considered satisfactory. Generally, the average commercial char yield does not exceed 30% and is affected by the raw material and conversion process used (Antal *et al*., 2000).

Heating Value

Heating value expresses the energy content released when wood is burned in the air, which is very important in determining the potential of charcoal for bioenergy. Figure 2 shows the heating value before and after carbonization at different temperatures. The heating values for albizia, gmelina, mindi, and mangium before carbonization were quite similar, showing 19.12–19.78 kJ/g, which is higher than the heatin alue of gmelina (16.61 kJ/g). The variation in heating values can be attributed to the different chemical composition of the wood, especially in lignin content. Kaltschmitt *et al*. (2009) reported that lignin has a heating value of 27.0 kJ/g, remarkably higher than cellulose and hemicelluloses with values of 17.3 and 16.2 kJ/g, respectively. Therefore, the higher lignin content will result in a higher heating value (Demirbas, 2003; Kataki and Konwer, 2001). Previous studies reported that albizia, mindi, and mangium have lignin content of 26.8, 30.1, and 24.9%, respectively (Martawijaya *et al*., 1989; Awang and Taylor, 1993), whereas gmelina has a lower lignin content of 22.0% (Wu *et al*., 1992). This lower lignin content of gmelina may be one of the factors

Table 2. Proximate analysis of juvenile woods from four tropical wood species before and after carbonization at 400, 600, and 800°C

Wood species	Temp. (°C)	Ash Content (%)	Volatile Matter (%)	Fixed Carbon (%)
Albizia (*P. falcataria*)	Control	1.03 (0.11)	73.81 (3.04)	25.16 (3.05)
	400	2.49 (0.19)	33.50 (3.67)	64.01 (3.64)
	600	2.75 (0.08)	22.33 (2.02)	74.92 (3.00)
	800	3.42 (0.31)	18.82 (1.56)	77.76 (2.33)
Gmelina (*G. arborea*)	Control	0.61 (0.04)	76.82 (4.82)	22.57 (5.10)
	400	2.73 (0.04)	38.69 (3.15)	58.58 (3.22)
	600	3.03 (0.19)	26.14 (2.84)	70.83 (2.79)
	800	3.94 (0.28)	22.52 (2.18)	73.54 (2.33)
Mindi (*M. azedarach*)	Control	0.57 (0.08)	69.65 (1.86)	29.78 (2.04)
	400	0.80 (0.12)	28.84 (1.77)	70.36 (1.98)
	600	1.58 (0.10)	18.77 (4.28)	79.65 (3.67)
	800	2.12 (0.12)	14.61 (3.54)	83.27 (3.67)
Mangium (*A. mangium*)	Control	0.68 (0.11)	70.80 (3.18)	28.52 (2.95)
	400	1.42 (0.11)	30.52 (3.90)	68.06 (3.78)
	600	1.71 (0.16)	26.60 (2.51)	71.69 (2.45)
	800	1.91 (0.07)	16.72 (1.77)	81.37 (1.58)

Numbers in parenthesis are standard deviations. Means are average of five replications.

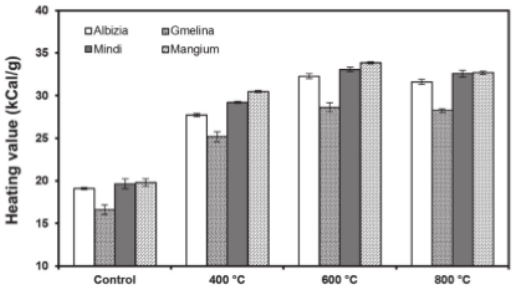

Fig. 2. Heating value of juvenile woods from four tropical wood species before carbonization (control) and after carbonization at 400, 600, and 800°C.

for the lower heating value compared to the other studied species.

The heating values at 400°C increased to 25.16–30.46 kJ/g, which are 42–54% higher than those of the control sample before carbonization. Its values further increased to 28.63–33.85 kJ/g with increase in carbonization temperature to 600°C, which are 11–16% higher than those at 400°C. However, the heating values at 800°C were similar or slightly lower compared with those at 600°C. This indicates that 600°C is the optimum carbonization temperature of the investigated temperature range regarding to heating values. The obtained heating values in this study were comparable to 24.70, 30.98, and 33.61 kJ/g of the charcoals from mature wood of *Q. variabilis* after carbonization at 340, 540, and 740°C respectively (Kwon *et al.*, 2013), even though the charcoal of the current study is from juvenile woods.

Based on the heating values, gmelina has a calorific value of 11–17% lower than the other juvenile woods. Overall, the heating values of the four juvenile woods carbonized at different temperatures meet the requirement (minimum heating value of 8 kJ/g) of the Indonesian Standard SNI 01–1506–1989 as the Standard of Wood Charcoal for Metal Smelting (BSN 1989).

In general, the heating value increases with carbonization showing a linear relationship with the increase of carbon content. During carbonization, volatile matter such as H_2O, CO, CO_2, and CH_4 are released, resulting in the increase of the fixed carbon content (Han and Kim, 2006; Kumar *et al.*, 2013; Liu *et al.*, 2014). Furthermore, increasing carbonization temperature resulted in the decrease of volatile matter and the increase of the fixed carbon content.

The present results of proximate analysis are in good agreement with the previous studies mentioned above. As summarized in Table 2, ash content and volatile matter were significantly increased and decreased respectively with increasing carbonization temperature, resulting in the increase of fixed carbon content. Similar to the heating values, the fixed carbon content of the control sample greatly increased as the temperature increased to 400°C, and slightly increased from 600°C to 800°C. The result of the proximate analysis in this study is similar to the previous study of Marquez *et al.* (2015) who reported that carbonization of 5–year–old *A. mangium* woods at 400°C resulted in ash content of 1.64%, vola-

tiles of 34.17%, and fixed carbon of 64.19%.

Table 3 summarizes energy densification ratio and energy yield. Energy densification ratio and energy yield after carbonization were determined from the heating value data. In all species, the increase in temperature caused a reduction in energy yields. On the other hand, energy densification ratio increased with increasing temperature. Energy densification ratio showed a similar trend with the heating value, and the highest ratio was obtained at carbonization of 600°C. For example, albizia yields a higher energy densification ratio and energy yield than mindi at all temperatures. Carbonization of albizia at 600°C had a char yield of 26.01%, resulting in an energy yield of 43.74%, while the char yield of mindi after carbonization at 800°C was 25.67%, resulting in energy yield of 42.55%.

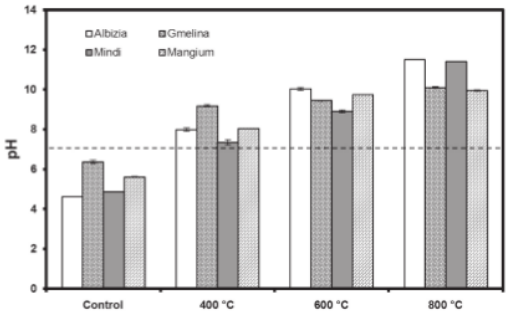

Fig. 3. pH of juvenile woods from four tropical wood species before carbonization (control) and after carbonization at 400, 600, and 800°C.

pH Change

Figure 3 shows pH values before and after carbonization at different temperatures. The pH increased with increasing carbonization temperatures. The pH of all samples was changed into basic after carbonization at a temperature higher than 400°C. Generally, the lower temperatures result in a lower pH, because the lower temperature may retain the carboxyl and hydroxyl groups in the char structure. Kwon *et al.* (2013) reported that pH value increased with increasing carbonization temperature, showing a pH of 5.5 and 9.1 at 300°C and 740°C, respectively. Luo *et al.* (2011) reported that pH became weakly basic (pH= 7.81) after carbonization at 350°C, whereas it turned to be strongly basic (pH= 10.80) at the higher temperature of 700°C.

Maximum pH in this study was obtained after carbonization at 800°C, showing pH values of 11.50, 10.10, 11.40, and 9.95, for albizia, gmelina, mindi, and mangium respectively. The basic pH of charcoal could positively influence the soil by increasing its cation exchange capacity (CEC). When charcoal is added to soil, it can neutralize the soil acidity, thus providing suitable conditions for microorganisms (Fowles, 2007; Luo *et al.*, 2011).

Change in Chemical Composition Investigated by FTIR

Figure 4 shows the FTIR spectra of the four juvenile woods before and after carbonization. The correspond-

Table 3. Effect of species and temperature on the energy densification ratio and energy yield

Wood species	Temp. (°C)	Energy densification ratio	Energy yield (%)
Albizia (*P. falcataria*)	Control	n/a	n/a
	400	1.45 (0.01)	45.25 (0.15)
	600	1.69 (0.00)	43.92 (1.45)
	800	1.65 (0.03)	39.09 (1.27)
Gmelina (*G. arborea*)	Control	n/a	n/a
	400	1.51 (0.03)	54.69 (1.95)
	600	1.72 (0.03)	45.72 (0.83)
	800	1.70 (0.01)	41.61 (1.47)
Mindi (*M. azedarac*)	Control	n/a	n/a
	400	1.49 (0.01)	51.12 (0.74)
	600	1.68 (0.01)	48.41 (1.84)
	800	1.66 (0.02)	42.56 (0.27)
Mangium (*A. mangiu*)	Control	n/a	n/a
	400	1.54 (0.01)	60.10 (1.33)
	600	1.71 (0.01)	51.10 (0.85)
	800	1.65 (0.01)	45.88 (3.09)

Numbers in parenthesis are standard deviations. Means are average of five replications.

ing assignments of bands are given in Table 4 based on Nishimiya *et al*. (1998), Muller *et al*. (2009), Chen *et al*. (2010), and Kwon *et al*. (2013). Carbonization at 400°C and 800°C drastically changed the chemical structure of the four tropical woods, as shown by the differences of absorption bands between woods and charcoals. For example, most of the bands in the original albizia wood were not found in the charcoal carbonized at 400°C, leaving only few bands. Most of the main bands assigned to cellulose and hemicellulose have disappeared, while some bands for lignin aromatic ring remained (Kwon *et al*., 2013).

The results in this study revealed that lignin was not completely degraded after carbonization at 400°C. However, the aromatic bands of lignin completely disappeared in the charcoal carbonized at 800°C. These results are in good agreement with a previous report (Nishimiya *et al*., 1998). They studied the chemical structure change of wood and charcoal carbonized at 300°C, 600°C, and 800°C and revealed that the aromatic modes associated with lignin were found in the charcoals carbonized at 300°C and 600°C, but disappeared completely in the charcoal carbonized at 800°C. A similar trend was found in gmelina, mindi, and mangium.

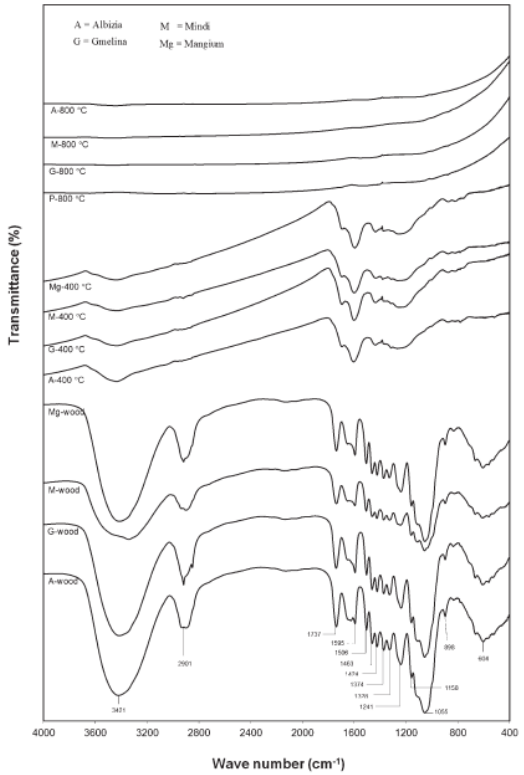

Fig. 4. FTIR spectra of juvenile woods from four tropical wood species before and after carbonization at 400 and 800°C.

CONCLUSION

The maximum char and energy yields were obtained at a carbonization temperature of 400°C, while the maximum heating value was obtained at a carbonization temperature of 600°C. Proximate analysis of the charcoals showed ash content of 0.80–3.94%, volatile matter of 14.61–38.69%, and fixed carbon of 58.58–83.27%. The obtained properties of charcoal from four juvenile tropical fast growing tree species were comparable with those of a mature wood, showing the suitability of these species for industrial (or commercial) production of charcoal.

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Table 4. Band positions and assignments in the infrared spectra of samples before and after carbonization at 400 and 800°C

Wave number (cm^{-1})												Band assignment
Wood				Carbonized at 400°C				Carbonized at 800°C				
A	G	M	Mg	A	G	M	Mg	A	G	M	Mg	
3421	3416	3341	3413	3433	3436	3429	3435					O–H stretching
2901	2918	2901	2919									C–H stretching in methyl– and methylene groups
	2851											C–H stretching in methyl– and methylene groups
1737	1741	1739	1739		1695							C–O stretching in unconjugated ketone, carbonyl and aliphatic groups xylan
1625												C–O stretching conjugated to aromatic ring
1595	1594	1595	1595	1605	1604	1603	1595					C–O stretching conjugated to aromatic ring
1506	1506	1508	1506									Aromatic skeletal stretching
1463	1463	1463	1463									CH2 deformation stretching in lignin and xylan
1424	1424	1426	1424	1435	1436	1436	1436					Aromatic skeletal combined with C–H in–plane deforming and stretching
1374	1373	1373	1373			1382		1368	1376		1376	Aliphatic C–H stretching in methyl and phenol OH
1328	1328	1327	1330									Condensation of guaiacyl unit and syringyl unit, syringyl unit and CH2 bending stretching
				1272	1256	1259	1253					Guaiacyl ring breathing with C–O stretching
1241	1238	1243	1240									C–C plus C–O plus C–O stretching
1158	1160	1161	1159									C–O–C stretching in pyranose rings, C–O stretching in aliphatic group
1055	1056	1057	1055									C–O deformation in primary alcohols, plus C–O stretch unconjugated plus aromatic C–H in–plane deformation
898	898	898	898									C–H stretching out of plane of aromatic ring
604	610	610	609									C–OH out of plane bending

A= Albizia; G= Gmelina; M= Mindi; Mg= Mangium

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