Fuel Properties of Indonesian Bamboo Carbonized at Different Temperatures

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Bamboo can be used in a variety of ways, including as fuel and as household and construction materials. Due to its versatility, the material is of high economic value. This study investigated the fuel properties of six bamboo species grown in Indonesia. Each bamboo sample was carbonized at different temperatures. Proximate and ultimate analyses were carried out on the bamboo samples. The thermal maturity of the bamboo samples as a solid fuel was investigated by the van Krevelen diagram. The efficiency of bamboo at each carbonizing temperature was determined based on the char yield, energy densification rate, energy efficiency, and calorific value. The results showed that the ash and fixed carbon contents of carbonized bamboo increased with an increasing carbonization temperature; while the volatile matter decreased. Significant changes in the fuel properties were observed between 200 °C and 400 °C. Carbonized bamboos showed lower sulfur contents in comparison to other fossil fuels. Ampel bamboo showed a calorific value of 18 MJ/kg to 32 MJ/kg, which was the highest value among the samples. Bamboo carbonized at temperatures above 600 °C showed a thermal maturity of coal grade. The results of this study can be used for utilizing Indonesian bamboo as a fuel source.

Keywords: Carbonization; Indonesian bamboo; Proximate and Ultimate analysis; van Krevelen diagram

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INTRODUCTION

Fossil fuels have been the main energy source for mankind since the invention of the internal combustion engine. The continued usage of fossil fuels should be regulated, as it is the main cause of global environmental pollution and climate change. Furthermore, an agreement was reached on the theme of reducing greenhouse gas (GHG) emissions through the Kyoto Protocol to the United Nations framework convention on climate change, and a binding reduction target was given to developed countries. Europe and North American countries have pursued improvements in energy efficiency and forestation, as well as the development of alternative energy, to solve this problem. The development of sustainable energy sources has been emphasized as it solves environmental problems and strengthens national energy independence (Sims 2004).

Biomass refers to plants that synthesize organic matter with solar energy that is then ingested by biological organisms such as animals and microorganisms. Biomass can be converted into chemical energy through pyrolysis or fermentation (Klass 1998). Charcoal, biogas, bioethanol, biodiesel, and methanol are produced through various processes and can be used for cooking, heating, and automobile fuel (Demirbaş 2003). In addition, biomass, unlike fossil fuels, can be produced in a relatively short time and produce less environmental pollution (Bial *et al*. 2013). However, like other alternative energy resources, the drawbacks of biomass that hinder its expansion across the market are its low efficiency and high manufacturing costs. For example, grain-based bioethanol, *i.e.*, first-generation bioethanol, puts pressure on food supplies and consumes a large-scale of land for its production. Similarly, wood-based bioethanol (second-generation) is not suitable due to the difficulty in crafting a sufficient supply and the inefficiency of the hydrolysis process. As a result, researchers have been trying to find new biomass resources from herbaceous, seaweed, and waste materials (Beer *et al*. 2009; Ahn *et al*. 2014; Bilal *et al*. 2017).

Bamboo, an herbaceous plant, is a highly valuable biomass resource in Indonesia because of its fast growth rate and the total gross area. Bamboo occupies 3.2% of the world's forest area, and approximately 65% of this bamboo is grown in Asia. Following India and China, Indonesia is 3rd in bamboo forest area (1.4 million ha, Table 1). In Indonesia, bamboo has been used for architecture, household goods, furniture, musical instruments, textiles, and mats after first simple physical processing. However, the use of bamboo has gradually decreased due to the development of alternative materials such as plastic. In addition, bamboo exports from Indonesia in 2015 (1.5 million US $) did not even reach half of the exported amount in 2007 (3.0 million US$, Park *et al.* 2018).

Indonesian bamboo species show distinctive characteristics that include larger volumes (greater diameters and heights) than other bamboo species such as Moso bamboo (*Phyllostachys edulis*), which is a common species in the Asia region. Indonesian bamboos exhibit sympodial growth, indicating that these bamboos can be harvested as a mass volume in one place. Sympodial growth type bamboo grows together like a bundle, but monopodial growth type bamboo grows individually (Fig. 1). Therefore, sympodial growth presents advantages in harvesting and workability. For these reasons, the Indonesian government regards bamboo as an important agroforestry product. Under the certain goal of promoting bamboo's usage in daily life and replacing wood resources, the bamboo industry has been developed around Central Java, West Java, East Java, Bali, and Yogyakarta (Hardiani and Dewy 2014). Despite the previously mentioned advantages, Indonesian bamboo is mainly used for simple products such as construction materials, musical instruments, and food stuffs (Yudodibroto 1985). Considering its versatility, the development of bamboo as a new renewable energy source is needed.

Many studies, primarily in East-Asia and North America, have been conducted on bamboo biomass for environmental carbon materials. The relationship between the carbonizing temperature of bamboo and the removal of harmful gases has been analyzed (Asada *et al*. 2002). An efficient process for the production of fuel ethanol from bamboo has been developed (Sun *et al*. 2011). Bamboo charcoal effectively adsorbs and removes cesium from wastewater (Khandaker *et al*. 2017). Although Indonesia has many bamboo resources, there is little research on the utilization of bamboo for energy resources.

This study was conducted to determine which Indonesian bamboo species are appropriate for use as a renewable energy raw material. The fundamental data for fuel properties were analyzed by species and carbonization temperatures. Furthermore, it is hoped that this data will support and encourage the Indonesian government, which is still a beginner with respect to the utilization of bamboo.

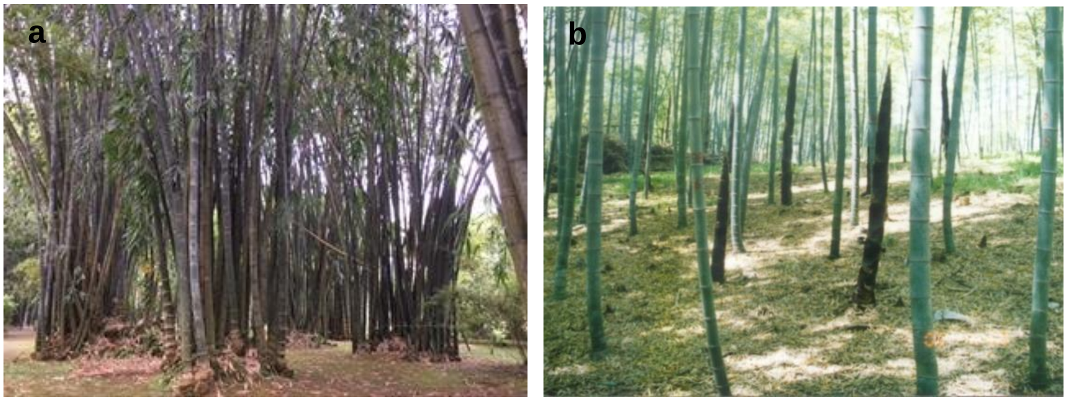

Fig. 1. Pictures of a) sympodial growth type bamboo (Andong, *Gigantochloa pseudoarundinacea* (Steudel) Widjaja) and b) monopodial growth type bamboo (Moso, *Phyllostachys edulis*)

EXPERIMENTAL

Materials

Six Indonesian bamboo species were used in this research: Andong (*Gigantochloa pseudoarundinacea* (Steudel) Widjaja), Hitam (*G. atroviolacea* Widjaja), Tali (*G. apus* Schult. & Schult. F.), Kuning (*Bambusa vulgaris* var. *striata*), Ampel (*B. vulgaris* Scharad), and Betung (*Dendrocalamus asper* Schult. F.). The above bamboo samples were collected at the second node from the ground at Bogor (6°20'21"S, 106°33'58'E). The bamboo samples were naturally dried for 3 months in ambient condition and then cut into 25 mm (width) x 40 mm (length) pieces. Detailed information for each species is given in Table 2.

Table 1. Distribution of Bamboo Forest in Indonesia

Province	No. of clump	Estimated area (ha)
West Java	10,651,743	343,604
Central Java	8,186,878	264,093
East Java	7,348,613	237,052
North Sumatra	818,593	102,324
South Sulawesi	1,397,941	53,767
Others	9,569,147	413,535
Total	37,972,9006	1,414,375

Table 2. General Information of Bamboo Species Used in This Study

Species	Scientific Name	Age (year)	Avg. Diameter * (cm)	Avg. Thickness (mm)	Avg. Density (g/cm^3)
Andong	*Gigantochloa pseudoarundinacea*	5	12.1	12.5	0.71
Hitam	*G. atroviolacea*	*5*	8.3	10.8	0.71
Tali	*G. apus*	*5*	8.1	9.7	0.60
Kuning	*Bambusa vulgaris* (var. *striata*)	5	7.9	17.3	0.67
Ampel	*B. vulgaris* (Scharad)	5	7.0	13.3	0.77
Betung	*Dendrocalamus asper*	*5*	14.0	22.4	0.56
* Diameter of second node from ground level					

Methods

Carbonization

The bamboo samples were wrapped in paper and aluminum foil and then placed in heat-resistant containers (Park and Park 2012). The prepared samples were carbonized in a laboratory electric furnace (TST BT-F724, Daeyang Ins., Yeoju, Korea). The heating rate was set at 50 °C/h and maintained at varied target temperatures of 200, 400, 600, 800, and 1000 °C for 2 h (Fig. 2). Carbonized specimens were ground, sieved to pass the 150 mesh, and then used for proximate and ultimate analyses.

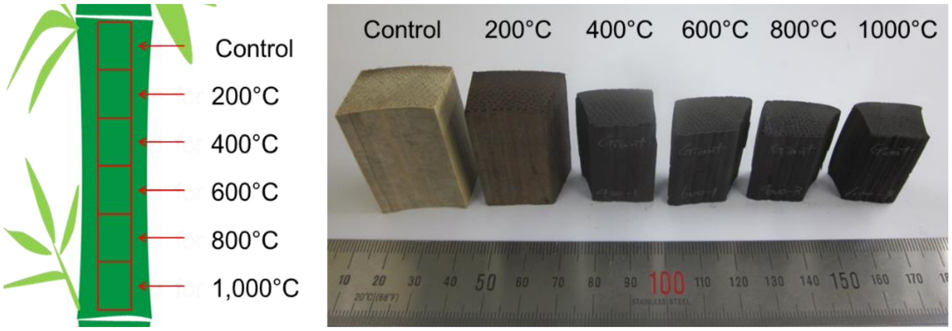

Fig. 2. Picture of the original and carbonized bamboo samples at different temperatures

Fuel properties

The fuel properties of original bamboo and carbonized bamboo were investigated by proximate analysis and ultimate analysis. The volatile matter and ash contents were measured according to KS E ISO 562 (KSA 2012a) and KS E ISO 1171 (KSA 2012b) for the proximate analysis. The fixed carbon content (FCC) was calculated based on the following formula,

$$FCC\ (\%) = 1 - M - VM - ASH \quad (1)$$

where M, VM, and ASH represent the moisture content (%), the volatile matter (%), and the ash content (%), respectively, of the specimens.

An elemental analyzer (Elementar Vario MACRO cube, Langenselbold, Germany) was used to determine the contents of carbon, hydrogen, nitrogen, and sulfur. Approximately 30 ± 5 mg of the sample was wrapped in silver foil and put in a sampler. Soil standard (certificate 133317; carbon 2.29% w/w, nitrogen 0.2% w/w, and sulfur 0.023% w/w) was used as an analytical reference material. During the analysis, the oxidation tube temperature and the reduction tube temperature of the elemental analyzer were maintained at 1050 °C and 830 °C, respectively. The oxygen content was calculated by subtracting the sum of carbon, nitrogen, hydrogen, and sulfur components. The calorific value was analyzed using a calorimeter (Parr 6300 calorimeter, Parr Instrument, Moline, IL, USA) according to Korean Standard KS E 3707 (2016).

Fuel efficiency

The char yield (Eq. 2), energy densification ratio (Eq. 3), and energy yield (Eq. 4) were calculated to evaluate the overall fuel efficiency (Hidayat *et al.* 2017),

$$Char\ yield\ (\%) = W_c/W_o \times 100 \quad (2)$$

$$Energy\ densification\ ratio = CV_c/CV_o \quad (3)$$

$$\textit{Energy yield}\ (\%) = (2) \times (3) \tag{4}$$

where W_c and W_o represent the oven-dried weight (%) of the carbonized and original specimens, and CV_c and CV_o represent the calorific value (MJ/kg) of the carbonized and original specimens.

In order to evaluate the thermal maturity of the original and carbonized bamboo samples as a solid fuel, a van Krevelen diagram by species and carbonization temperature was drawn for each sample according to the data from the equation below (Jones *et al*. 2006).

$$[H/C] = 1.412\ [O/C] + 0.5004 \tag{5}$$

where H, C, and O represent hydrogen, carbon and oxygen content (%) of samples.

RESULTS AND DISCUSSION

Fuel Properties of Original Bamboo

The fundamental properties of the original bamboo were analyzed to compare measurements with carbonized bamboo and determine the best way to use the material commercially (Table 3). The moisture contents (MC) of all species ranged from 7.1% to 10.2%. The Ampel bamboo showed a higher MC, while the Betung bamboo showed a lower MC. The moisture content of Indonesian bamboo is much higher than that of other bamboo that grows in Korea and Japan (less than 5%). This is a reasonable result considering the result of observing the high thickness of woody part and growing weather.

Table 3. Fuel Properties of Original Bamboo Samples

Species	Proximate analysis (%)				Ultimate analysis (%)					CV * (MJ/kg)
	MC	Ash	VMC*	FCC**	C	H	O	N	S	
Andong	8.4	2.08	78.0	11.5	49.0	6.09	44.4	0.40	0.05	18.65
Hitam	7.8	1.36	72.4	18.4	50.3	6.21	42.9	0.46	0.05	18.75
Tali	7.3	1.89	80.0	10.8	50.9	6.44	42.3	0.24	0.07	18.70
Kuning	7.6	2.68	75.4	14.3	48.2	6.08	45.2	0.39	0.05	18.84
Ampel	10.2	1.15	72.0	16.7	49.5	6.30	43.7	0.43	0.04	18.27
Betung	7.1	2.44	75.4	15.1	48.7	6.00	44.9	0.33	0.05	18.41

* CV: Calorific value
* VMC: volatile matter contents
** FCC: fixed carbon contents

In the proximate analysis of all bamboo species, the ash, volatile matter, and fixed carbon were in the range of 1.1% to 2.7%, 72% to 80%, and 10% to 18%, respectively. In the ultimate analysis of all the bamboo species, the carbon, hydrogen, oxygen, nitrogen, and sulfur contents were in the range of 48.2% to 50.9%, 6.00% to 6.44%, 42.3% to 45.2%, 0.24% to 0.46%, and 0.04% to 0.07%, respectively. The calorific value of all the bamboo species was 18.2 MJ/kg to 18.8 MJ/kg, and there was no significant difference among the species. The low calorific value of original bamboo was attributed to the high water content and the effect of VMC. These results were similar to those reported by Hernandez-Mena *et al*. (2014) and Kumar and Chandrashekar (2014) for the *Bambusa* and *Dendrocalamus* genus.

Fuel Properties of Carbonized Bamboo

The results of the proximate and ultimate analysis of bamboo after being carbonized at different temperatures are shown in Table 4. The ash contents of carbonized bamboo (c-bamboo) samples varied from 1.3% to 10.8% according to the carbonization temperatures. In general, biomass with a high ash content is not preferred because it negatively affects the calorific value and combustion quality. Ampel c-bamboo, which has a lower ash content than others, might be preferred for good fuel quality. The values of volatile matter of each sample ranged from 4.7% to 77.7%. The volatile matter of all the species decreased with an increasing carbonization temperature, especially at carbonization temperatures between 200 °C and 400 °C. Qian *et al*. (2004) reported that 80% of the total weight loss occurred due to volatilization of hydrogen and oxygen at 260 °C to 400 °C. Volatiles are closely related to rapid ignition, but high volatiles generate soot and smoke, which is a factor to be avoided during combustion.

Carbonized Ampel, Hitam, and Andong bamboo showed higher fixed carbon contents than other bamboo species at most of the carbonization temperatures. The fixed carbon, which represents the amount of carbon contained in solid fuel, is an important indicator in determining calorific value. The fixed carbon of Hitam showed the highest value at 200 °C and 1000 °C, while that of Ampel and Andong showed the highest value at 600 °C and 800 °C, respectively. Hidayat *et al*. (2017) reported that fixed carbon of Indonesian wood species, such as Albizia (*P. falcataria*), Gmelina (*G. arborea*), Mindi (*M. azedarach*) and Mangium (*A. mangium*), were in the range of 22 to 29% at control, 58 to 70% at 400 °C, 70 to 70% at 600 °C, and 73 to 83% at 800 °C. The bamboo species used in this study showed lower fixed carbon contents than Indonesian wood species. The fixed carbon of Hitam and Ampel bamboo, however, represented a somewhat close value to wood materials mentioned above.

In the ultimate analysis, the carbon, hydrogen, and oxygen contents of the c-bamboo samples varied depending on carbonization temperatures. Bamboo and other biomass showed a large difference depending on the content of moisture, lignin, and cellulose in the initial stage (below 400 °C) of the pyrolysis process, but as the carbonization temperature was increased, the results of ultimate analysis showed a similar trend. With an increasing carbonization temperature, carbon contents increased, while the oxygen and hydrogen contents decreased. During the carbonization, O, N, S, *etc*. bound to the initial C are dissociated, and the content of C is increased (Zuo *et al*. 2003). The major changes of carbon, oxygen, and hydrogen contents were observed between 200 °C and 400 °C. These changes were caused by mainly volatile emissions and the enrichment of residual charcoal matrices with aromatic compounds (Biagini *et al*. 2008). Exceptionally, unlike other elements, sulfur was detected in trace amounts. This is a major advantage of biomass materials when compared to fossil fuels. For example, conventional fuels such as lignite and anthracite coal generate a large amount of sulfur during combustion. Therefore, limestone should be used in large quantities to reduce sulfur emissions to the atmosphere (Pimchuai *et al*. 2010).

The calorific value refers to the amount of heat released when combustion fuel is completely burned. The measure represents an important criterion for the performance of fuel. The calorific value of carbonized bamboo at different temperatures is shown in Fig. 3. The calorific value of all species generally increased to a carbonization temperature of 600 °C due to decrease of volatile matter and increase of fixed carbon.

Table 4. Fuel Properties of Carbonized Bamboo Samples

Carbonization Temperature (°C)	Proximate Analysis (%)				Ultimate Analysis (%)				
	MC	Ash	VMC*	FCC**	C	H	O	N	S
Andong									
200	4.8	3.1	77.1	15.0	53.0	5.78	40.6	0.49	0.06
400	5.0	5.7	28.4	60.8	74.7	3.19	21.1	0.82	0.11
600	6.1	7.9	11.0	78.8	85.1	1.76	12.0	0.92	0.13
800	7.8	6.8	11.0	74.5	86.3	0.96	11.4	1.15	0.12
1000	6.6	7.7	10.4	75.4	88.4	0.69	9.9	0.85	0.10
Hitam									
200	4.3	2.7	71.4	21.6	53.7	5.77	39.8	0.55	0.05
400	4.4	4.0	32.0	59.6	73.3	3.34	22.2	0.95	0.06
600	3.2	4.4	15.9	76.5	83.8	2.74	12.3	1.06	0.06
800	4.3	4.9	5.3	85.6	91.5	0.74	6.5	1.17	0.06
1000	4.9	4.4	5.2	85.5	93.7	0.39	4.7	1.07	0.05
Tali									
200	3.9	2.9	77.7	15.5	53.6	5.82	40.0	0.36	0.07
400	4.6	4.0	32.4	59.0	78.2	3.13	17.8	0.59	0.14
600	4.6	4.6	19.3	71.5	91.8	2.08	5.2	0.67	0.16
800	7.2	6.0	12.7	74.1	93.6	0.97	4.3	0.86	0.17
1000	8.0	4.0	11.8	76.2	95.7	0.48	2.6	0.97	0.16
Kuning									
200	4.1	3.1	76.0	16.7	52.6	5.39	41.4	0.47	0.09
400	4.9	7.1	30.7	57.3	72.9	2.89	23.3	0.67	0.16
600	6.1	7.0	15.4	71.4	83.9	1.65	13.3	0.83	0.18
800	7.3	7.9	15.4	69.3	86.5	0.73	11.4	1.14	0.15
1000	7.3	8.3	8.0	76.3	87.9	0.40	10.5	0.99	0.10
Ampel									
200	3.9	1.3	74.6	20.1	56.0	5.73	37.6	0.50	0.04
400	4.6	3.0	26.7	65.7	78.8	3.41	16.7	0.87	0.06
600	4.3	3.0	15.2	77.5	89.5	2.41	6.9	1.01	0.08
800	6.7	3.3	4.7	85.3	92.6	1.11	5.1	1.04	0.07
1000	6.6	3.0	6.4	84.0	94.8	0.54	3.5	0.96	0.06
Betung									
200	4.0	3.7	71.8	20.4	53.8	5.71	40.0	0.41	0.04
400	5.2	6.8	28.7	59.2	71.0	3.05	25.1	0.71	0.04
600	4.6	7.7	14.9	72.7	85.2	1.81	12.0	0.85	0.05
800	4.9	9.7	10.4	75.0	90.5	0.87	7.5	0.99	0.03
1000	3.8	10.8	11.6	73.9	89.9	0.51	8.5	0.96	0.03

* VMC: volatile matter contents
** FCC: fixed carbon contents

Generally, the heat of combustion by carbon is higher than those by volatile substances such as oxygen or hydrogen (Jones *et al*. 2006). For carbonization temperatures at or above 600 °C, the calorific value slightly decreased due to higher ash contents that negatively affected the quality of combustion (Klass 1998). At the carbonization temperature of 600 °C, the calorific values of carbonized Andong, Hitam, Tali, Kuning, Ampel, and Betung bamboo were of 31.5, 32.6, 32.7, 30.9, 32.0, and 31.4 MJ/Kg, respectively. The calorific value of Ampel, Hitam, and Tali bamboos were higher than that of the others. Park *et al*. (1998) studied properties of carbonized Moso bamboo grown in South Korea, where the calorific value of the carbonized Moso bamboo was in the range of 30.3 MJ/kg to 33.1 MJ/kg. In the comparison of Indonesian bamboo and

Korean (Moso) bamboo, calorific values showed similar results, but the Indonesian bamboo had a bigger diameter than the Korean bamboo. Therefore, larger diameter would be a good advantage as it would imply longer combustion times.

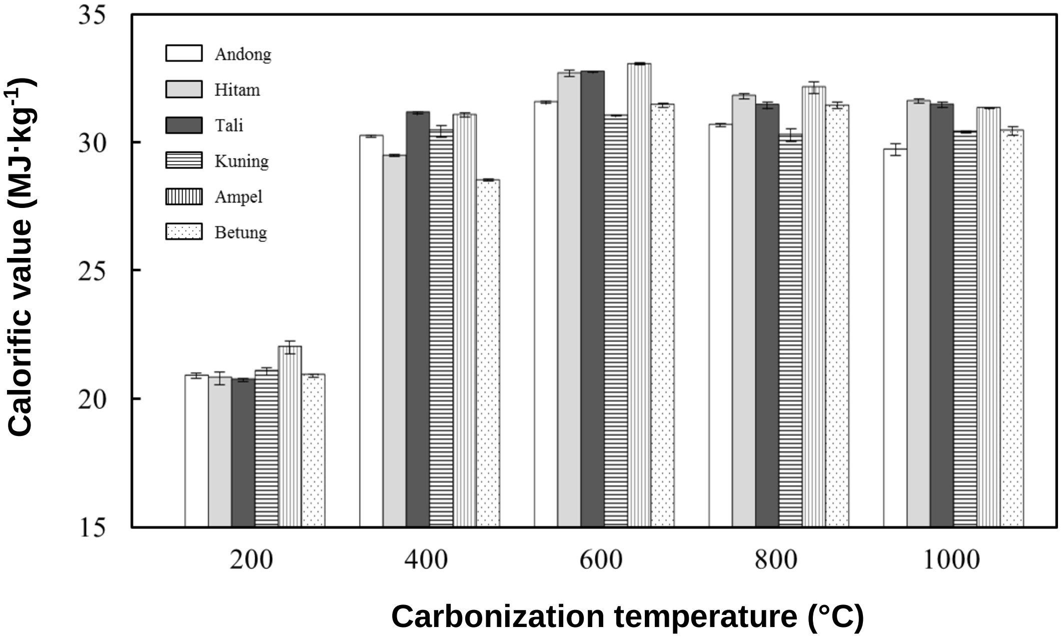

Fig. 3. Calorific value of bamboo samples carbonized at different temperatures

Fuel Efficiency

Due to its low calorific value in comparison to other solid fuels, biomass requires heat treatment processes such as gasification, semi-carbonization, and carbonization to reach the level required by the market. Calorific value of biomass increased with increasing of temperature, while those of mass and volume rapidly decreased (Bial *et al.* 2013). A quantitative process is needed to find the optimum carbonization condition of biomass use. Moreover, an energy efficiency analysis should be conducted to find out an appropriate application area. The energy density is calculated based on the calorific value, the main indicator of fuel, and the fuel efficiency is analyzed by comparing the char yields. The results are shown in Table 5.

The utilization of biomass depends on the amount of energy needed for the specific purpose. For example, a higher combustion heat value is needed for using charcoal, and the economic aspect is more important when using the material as pellets for households heating sources (Hidayat *et al.* 2017). In the general case of wood or biomass carbonization, the char yield decreased with increasing carbonization temperature. Char yield of bamboo also showed same results. No significant difference was observed among the c-bamboo speices. Kuning carbonized bamboo showed the lowest char yield (74.1%) at 200 °C carbonization than that of others. However, on the carbonization at 1000 °C, the highest char yield was observed on Kuning carbonized bamboo (28.0%).

The highest value of energy densification was observed on all c-bamboo samples carbonized at 600 °C and then remained or slightly decreased at 800 °C and 1000 °C. Based on energy densification ratio, the values of c-bamboo increased carbonization temperature from 200 °C to 600 °C and then started to decrease until 1000 °C. It is the same pattern with char yield, which means that with increasing carbonization temperature, the energy efficiency decreased. Energy yield of c-bamboos decreased with increasing carbonization temperature. In the bamboo species comparisons, Ampel bamboo carbonized at 200 °C showed significantly higher the energy yield than that of other bamboo species. As mentioned above, the utilization of biomass depends on specific purpose. Therefore, people who desire to use it as a house heating source, Ampel with 200 °C carbonization would be recommended, while as use of charcoal, Ampel with 600 °C carbonization is more suitable.

Table 5. Energy Efficiency of Original and Carbonized Bamboo Samples

	Species	200 °C	400 °C	600 °C	800 °C	1000 °C
Char yield (%)	Andong	80.3±2.1	33.9±1.3	29.5±0.1	26.2±1.7	26.6±1.4
	Hitam	80.9±2.2	34.7±1.1	29.7±3.3	28.2±1.2	27.6±1.0
	Tali	82.0±0.7	36.1±0.5	29.5±1.2	28.3±2.7	27.8±1.3
	Kuning	74.1±2.4	36.3±0.4	30.9±2.2	29.0±0.7	28.0±0.9
	Ampel	79.6±1.5	34.3±0.4	29.3±2.1	27.6±1.1	27.0±0.7
	Betung	82.3±3.9	35.0±0.7	30.8±0.7	28.4±2.5	27.6±2.1
Energy densification ratio	Andong	1.11±0.02	1.62±0.03	1.69±0.03	1.64±0.02	1.59±0.01
	Hitam	1.10±0.03	1.57±0.01	1.74±0.01	1.69±0.02	1.68±0.01
	Tali	1.10±0.01	1.66±0.01	1.75±0.01	1.68±0.02	1.68±0.02
	Kuning	1.11±0.03	1.61±0.03	1.64±0.03	1.60±0.02	1.61±0.03
	Ampel	1.19±0.03	1.70±0.01	1.80±0.01	1.75±0.03	1.71±0.01
	Betung	1.13±0.01	1.54±0.00	1.70±0.01	1.70±0.01	1.65±0.02
Energy yield (%)	Andong	89.2±3.8	54.8±2.6	49.8±0.7	43.0±3.2	42.2±2.0
	Hitam	89.0±0.3	54.4±2.1	51.8±5.8	47.7±1.5	46.6±2.2
	Tali	90.1±0.6	60.1±1.2	51.7±1.8	47.5±3.9	46.8±2.3
	Kuning	82.1±4.3	58.5±0.5	50.7±4.0	46.5±1.6	45.0±1.4
	Ampel	96.1±1.6	58.3±1.0	52.9±3.6	48.6±1.2	46.2±1.4
	Betung	92.8±5.3	54.0±1.2	52.5±0.6	48.5±1.4	45.7±3.2

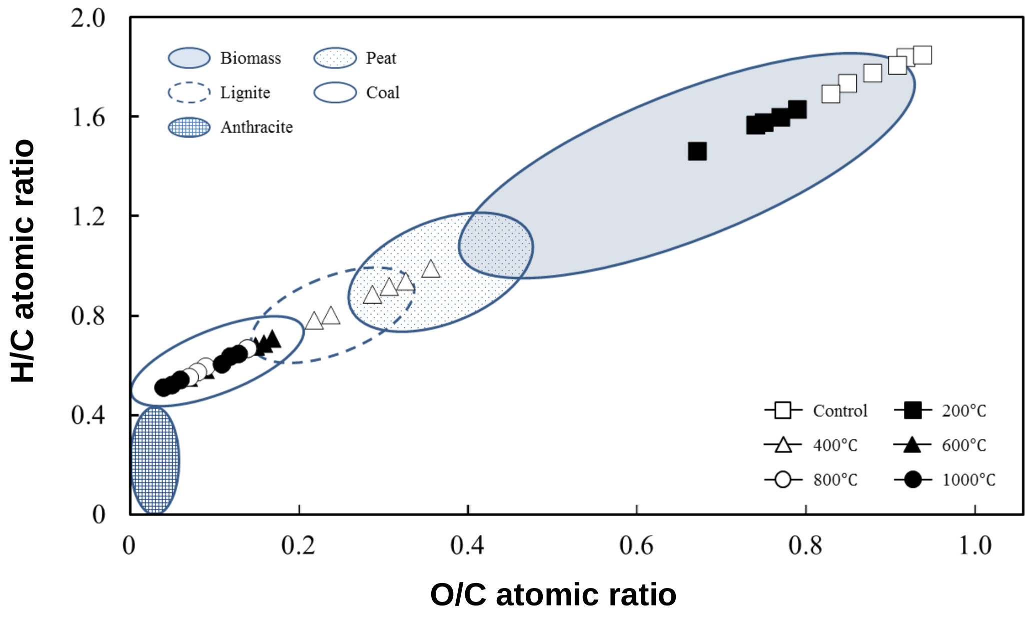

Fig. 4. Classification of the original and carbonized bamboo samples at different temperatures by hydrogen/carbon and oxygen/carbon ratios

The van Krevelen diagram was plotted by using [H/C] and [O/C] ratios to evaluate the thermal maturity of carbonized bamboo as a solid fuel (Fig. 4). The original bamboo and carbonized bamboo at 200 °C belonged to a biomass grade. Carbonized bamboos at 400 °C were affiliated with a peat grade. More specifically, carbonized Ampel and Tali bamboos above 400 °C reached a thermal maturity at a lignite grade. From a carbonization temperature at 600 °C, all bamboo samples showed thermal maturity at coal grade, but it was confirmed that the materials did not satisfy an anthracite grade. Jones *et al*. (2006) suggested that the oxygen contents should to be lower to produce higher quality liquid fuel, as oxygen reduces the calorific value and hinders the liquefaction of the fuel. In general, bamboo has a relatively high proportion of holocellulose in comparison to that of wood (Wahab *et al*. 2013). Therefore, to overcome limitations of biomass and replace other solid fuels, bamboo should be carbonized to at least 400 °C or higher due to the degradation of holocellulose.

CONCLUSIONS

1. The original bamboos showed 7.1% to 10.2% of moisture content (MC), 1.1% to 2.7% of the ash, 72% to 80% of volatile matter, and 10% to 18% of fixed carbon. The calorific value of all the bamboo species was 18.2 MJ/kg to 18.8 MJ/kg. No significant difference of calorific value among the species was evaluated.
2. The carbonized Ampel bamboo showed the highest calorific value among the samples due to lower ash and volatile matter contents and a higher fixed carbon. In contrast, the Betung bamboo had a lower value than the other samples.
3. While carbonization at 200 °C resulted in bamboo with higher fuel efficiency, it is not preferred for use as a fuel source due to its lower calorific value. On the other hand, carbonized bamboo above 400 °C showed better thermal maturity than the conventional solid fuels even with the lower fuel efficiency.
4. Indonesian bamboo biomass carbonized at 200 °C may be suitable for household heating source as wood pellets. For usage as charcoal, bamboo should be carbonized at least 400 °C with using Ampel bamboo. Carbonization above 800 °C may not be preferred due to lower efficiency.
5. Based on these results, major Indonesian bamboos could be utilized as a fuel source in different way with varying manufacture conditions.

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