Proximate Analysis of Bamboo Culm and Wood Carbonized at Low Temperatures: A Comparative Study

Go Un Yang,[a,†] Byantara Darsan Purusatama,[b,†] Jong Ho Kim,[a] Denni Prasetia,[a] Alvin Muhammad Savero,[a] and Nam Hun Kim [a,*]

To obtain basic data for further use of bamboo culms and wood as eco-friendly bioenergy resources, the proximate analysis of *Dendrocalamus giganteus*, *D. asper*, *Bambusa vulgaris*, *Gigantochloa apus*, *Phyllostachys pubescens*, *Pinus densiflora*, and *Quercus variabilis* carbonized at 200 to 320 °C at 40 °C intervals was undertaken. Proximate analysis of moisture content, ash content, volatile matter, and fixed carbon content was performed according to JIS M 8812 (2004) with 60-mesh carbonized powder. Carbonized bamboo showed higher ash and volatile content than carbonized wood, whereas carbonized wood had a higher fixed carbon content than carbonized bamboo. At all temperatures, giant bamboo had the highest ash content. In bamboo and wood, the ash and fixed carbon contents increased with increasing carbonization temperature, whereas the volatile substances decreased.

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Keywords: Indonesian bamboo; Low temperature carbonization; Proximate analysis; Giant bamboo; Betung bamboo; Kuning bamboo; Tali bamboo; Moso bamboo; Carbonized wood; Korean red pine

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INTRODUCTION

Woody resources are eco-friendly materials and are expected to become one of the main bioenergy resources. Bamboo is eco-friendly material that can be considered as alternative for wood as an energy source. Compared with wood, it has various advantages, including rapid growth, short rotation age, and high tensile strength (Febrianto *et al*. 2015; Jeon *et al.* 2018a, 2018b). Bamboo is widely distributed worldwide in the range of 51° N to 47° S, including in Asia, the Atlantic and Pacific countries, Africa, the South of the United States, and Central and South America. There are 60 to 90 genera of bamboo and 1,100 to 1,500 bamboo species, which are distributed over 22 million hectares worldwide (Korea Forest Research Institute 2005). Bamboo is abundant in South Asia and Southeast Asia, which represents approximately 80% of the world's total bamboo.

Giant bamboo (*Dendrocalamus giganteus*), betung bamboo (*D. asper*), kuning bamboo (*Bambusa vulgaris*), and tali bamboo (*Gigantochloa apus*) from Indonesia are widely used in construction, household articles, furniture, particleboard reinforcement, oriented strand boards, and paper (Papadopoulos *et al.* 2004; Wahab *et al.* 2009; Li *et al.* 2012; Febrianto *et al.* 2012; Zaia *et al*. 2015; Krause *et al*. 2016; Maulana *et al.* 2021). Besides, charcoal derived from wood and bamboo has been used as fuel, fertilizer, humidity control, adsorbents, wastewater purification, and catalysts (Hoshi 2001; Asada *et al*. 2002). In Korea, wood charcoal has long been used as a traditional medical treatment

(Lee *et al.* 2019).

Many studies have been conducted on the characteristics of bamboo carbonized at various temperatures. Yang *et al.* (2010) found that andong and betung bamboo that had been carbonized at 600, 700, 800, and 900 °C had larger specific surfaces at higher temperatures. Subyakto *et al*. (2012) evaluated carbonization properties such as char yield, fixed carbon, volatile matter, and ash content in betung bamboo (*Dendrocalamus asper*) carbonized at 700, 800, and 900 °C for 45, 60, and 90 min, respectively. The authors confirmed that the char yield and volatile matter content decreased with increasing temperature, while the fixed carbon and ash content increased with increasing temperature. Park *et al*. (2021) investigated morphological and chemical properties of *Dendrocalamus asper*, *Gigantochloa pseudoarundinacea*, *Gigantochloa atroviolacea*, *Gigantochloa apus*, *Bambusa vulgaris* var. *striata*, and *Bambusa vulgaris* that had been carbonized from 200 to 1,000 °C. Cracks in the fiber bundle were observed and became more visible with increasing carbonization temperature, and the pH of all species increased with increasing temperature. Significant changes in the chemical structure of the carbonized bamboo were observed between 400 and 600 °C. In the authors' previous study (Yang *et al.* 2022), weight loss, pH, and calorific value of *D. giganteus*, *D. asper*, *Bambusa vulgaris*, *Gigantochloa apus*, and *Phyllostachys pubescens* carbonized at low temperatures of 200, 240, 280, and 320 °C increased with increasing temperature. Using Fourier transform infrared spectroscopy, all the bamboo species examined showed a considerable change in hemicellulose peaks at 280 °C and a substantial change in cellulose peaks at 320 °C.

The characteristics of carbonized wood at different carbonization temperatures have been examined in several studies. Kim and Hanna (2005) investigated the morphological characteristics of *Quercus variabilis* wood that had been carbonized at 400, 600, 800, and 1,000 °C. Most of the morphological characteristics changed above 400 °C, and the crystals displayed a sponge-like appearance at 800 and 1,000 °C. Kwon *et al.* (2009) examined structural changes in the cell wall and crystalline cellulose of *Quercus variabilis* wood that had been carbonized at 250, 300, 350, 400, 450, and 500 °C. Collapsed vessels and amorphous-like cell wall structures were observed in wood carbonized above 350 °C, and crystalline substances were not detected at 350 °C. Kwon *et al.* (2014) investigated dimensional changes in *Quercus variabilis*, *Q. dentata*, *Q. mongolica*, *Pinus koraiensis*, and *Larix kaempferi* that had been carbonized at low temperatures of 300 to 350°C at intervals of 10 °C. Considerable changes in cell dimensions were found for all species, even though there was a relatively low range of carbonization temperatures. Qi *et al.* (2016) reported that the ash and fixed carbon content in compression wood of *Pinus densiflora* and tension wood of *Paulownia tomentosa* carbonized at various temperatures at 400, 600, and 800 °C increased with increasing temperature, while the volatile matter decreased as the temperature increased. Hidayat *et al.* (2017) evaluated the charcoal characteristics of the juvenile wood of *Paraserianthes falcataria*, *Gmelina arborea*, *Gmelina arborea*, and *Acacia mangium* carbonized at 400, 600, and 800 °C. The maximum char and energy yields were obtained in the wood samples that had been carbonized at 400 °C, whereas the maximum heating value was obtained at 600 °C. The ash and fixed carbon content for all species increased with increasing temperature, whereas the volatile matter decreased as the temperature increased.

In the authors' previous study, there were differences in the physical and chemical characteristics between bamboo species and between bamboo and wood that had been carbonized at low temperatures (Yang *et al.* 2022). However, further study was needed on the proximate analysis of bamboo and wood carbonized at low temperatures to establish a baseline dataset on the carbonization mechanism from raw materials to charcoal for further use as an eco-friendly biomass resource. Therefore, in this study, a comparative study on the proximate analysis of bamboo and wood was performed using samples carbonized at low temperatures of 200, 240, 280, and 320 °C for giant bamboo (*Dendrocalamus giganteus*), betung bamboo (*Dendrocalamus asper*), kuning bamboo (*Bambusa vulgaris*), tali bamboo (*Gigantochloa apus*) from Indonesia and moso bamboo (*Phyllostachys pubescens*), red pine (*Pinus densiflora*), and cork oak (*Quercus variabilis*) from Korea to provide basic for further utilization of bamboo culms and wood as an eco-friendly biomass resource.

EXPERIMENTAL

Materials

The bamboo and wood materials that were used in this study were obtained from samples that had been used in a previous study (Yang *et al*. 2022). Three bamboo culms each from three-year-old Indonesian bamboo, giant bamboo (*Dendrocalamus giganteus*), betung bamboo (*D. asper*), kuning bamboo (*Bambusa vulgaris*), and tali bamboo (*Gigantochloa apus*), were obtained from the bamboo arboretum at the IPB University, West Java, Indonesia (6°20'21" S, 106°33'58" E). Three bamboo culms from 3-year-old moso bamboo (*Phyllostachys pubescens*) were harvested from Damyang-gun, Jeollanam-do, Republic of Korea (35°18' N, 126°54' E). One tree each of fifty-year-old Korean red pine (*Pinus densiflora*) and 35-year-old cork oak (*Quercus variabilis*) were harvested from the research forest of Kangwon National University, Gangwon-do, Republic of Korea (37°77' N, 127°81' E). The diameter at breast height of the Korean red pine and the cork oak were 47.3 cm and 17.2 cm, respectively.

The bamboo culm was divided into three parts, namely the top, middle, and bottom, and only the bottom parts were used. Key information on the bamboo culms and wood is shown in Table 1. The dimensions of the base of the bamboo culms are shown in Table 2.

Table 1. Key Information on the Bamboo and Wood Samples

<table>
<tr><th>Species</th><th>Location</th><th>Age</th><th>Height (m)</th><th>Oven-dried Density (g/cm³)</th></tr>
<tr><td>Giant bamboo (Dendrocalamus giganteus)</td><td rowspan="4">IPB University, West Java, Indonesia, (6°20'21" S, 106°33'58" E)</td><td rowspan="5">3 years old</td><td>25 to 35</td><td>0.61 ± 0.04</td></tr>
<tr><td>Betung bamboo (D. asper)</td><td>20 to 30</td><td>0.67 ± 0.03</td></tr>
<tr><td>Kuning bamboo (Bambusa vulgaris)</td><td>10 to 20</td><td>0.61 ± 0.04</td></tr>
<tr><td>Tali bamboo (Gigantochloa apus)</td><td>8 to 22</td><td>0.67 ± 0.04</td></tr>
<tr><td>Moso bamboo (Phyllostachys pubescens)</td><td>Damyang-gun, Jeollanam-do, Rep. of Korea (35°18' N, 126°54' E)</td><td>10 to 20</td><td>0.63 ± 0.05</td></tr>
<tr><td>Korean red pine (Pinus densiflora)</td><td rowspan="2">The research forest of Kangwon National University, Gangwon-do, Rep. of Korea (37°77' N, 127°81' E)</td><td>50 years old</td><td>15</td><td>0.51 ± 0.06</td></tr>
<tr><td>Cork oak (Quercus variabilis)</td><td>35 years old</td><td>12</td><td>0.77 ± 0.03</td></tr>
</table>

Table 2. Key Information on the Base of the Bamboo Culms

	Giant Bamboo	Betung Bamboo	Kuning Bamboo	Tali Bamboo	Moso Bamboo
Diameter (mm)	146.6 ± 1.5	131.3 ± 6.5	79.9 ± 3.5	86.3 ± 1.1	83.1 ± 2.1
Thickness (mm)	17.2 ± 0.5	23.7 ± 1.2	14.1 ± 1.2	11.6 ± 0.4	9.7 ± 4.2

Carbonization Method

Carbonization was performed as described by Yang *et al*. (2022). Samples of bamboo culm and wood with dimensions of 20 mm (longitudinal) × 10 mm (radial) × 10 mm (tangential) were carbonized in an electric furnace (Supertherm, HT 16/16, Germany) at 200, 240, 280, and 320 °C. The carbonization was conducted at a 6 °C/min heating rate from 40 °C to the target temperatures of 200, 240, 280, and 320 °C. After reaching the target temperature, the samples were kept at the target temperature for 10 min and then removed from the furnace after cooling. The carbonized samples were stored in a room at 20 ± 3 °C and relative humidity (RH) 50 ± 5% for further measurements.

Proximate Analysis of Carbonized Bamboos

Proximate analyses, such as moisture content (MC), ash content (AC), volatile matter content (VMC), and fixed carbon content (FCC), were performed according to JIS M 8812 (2004) using 60-mesh carbonized powder. All the measurements for each sample were repeated thrice.

Measurement of moisture content

The MC was measured from 1 g of carbonized powder. The crucible with carbonized powder was weighed before and after drying in an oven at 105 ± 3 °C for 60 min. Prior to being weighed, the oven-dried samples were placed in a desiccator for 1 h. The moisture content was calculated using Eq. 1,

$$\text{MC (\%)} = \frac{W_1 - W_2}{W_2}\ X\ 100 \tag{1}$$

where W_1 is the weight of the crucible and sample before drying (g) and W_2 is the weight of the crucible and sample after drying (g).

Measurement of ash content

The AC was measured using 1 g of carbonized powder. The carbonized powder was placed in a crucible that had been previously weighed, and then the crucible and samples were weighed. The samples in the crucible were incinerated in a furnace (Supertherm, HT 16/16, Germany) at 815 °C for 150 min. After cooling to room temperature, the samples were removed and placed in a desiccator for 2 h before their weights were measured. The ash content was calculated using Eq. 2, as follows,

$$\text{AC (\%)} = \frac{M_2 - M_3}{M_2 - M_1}\ X\ 100 \tag{2}$$

where M_1 is the weight of the crucible before incineration (g); M_2 is the weight of the crucible and sample before incineration (g); and M_3 is the weight of the crucible and sample after incineration (g).

Measurement of volatile matter

The VMC was measured using 1 g of carbonized powder. The carbonized powder was placed in a crucible that had been previously weighed, and then the crucible and samples were weighed. The samples in the crucible were incinerated in a furnace (Supertherm, HT 16/16, Germany) at 900 °C for 7 min. The samples were then placed in a desiccator and weighed. The VMC was calculated using Eq. 3,

$$\text{VMC (\%)} = \frac{M_2 - M_3}{M_2 - M_1}\ X\ 100 - MC \tag{3}$$

where M_1 is the weight of the crucible before incineration (g); M_2 is the weight of the crucible and sample before incineration (g); and M_3 is the weight of the crucible and sample after incineration (g).

Measurement of fixed carbon

The FCC is the portion of charcoal that remains after deduction of MC, AC, and VMC, as presented in Eq. 4:

$$\text{FCC(\%)} = 100 - (MC + AC + VMC) \tag{4}$$

Statistical Analysis

The significant differences in proximate analysis between the species and between temperatures were statistically examined using analysis of variance (ANOVA) and *post-hoc* Duncan's multiple range tests. The statistical analyses were performed using SPSS software (SPSS ver. 24, IBM Corp., Armonk, NY, USA).

RESULTS AND DISCUSSION

Moisture Content

The MC of all the samples that had been carbonized at low temperatures are summarized in Table 3. The MC of the untreated bamboo species was 7.97 to 9.10%, whereas that of the Korean red pine and cork oak was 9.23 ± 2.74% and 10.52 ± 0.39%, respectively. All the species showed a comparable MC following treatment at each temperature, as 5.1 to 5.6% at 200 °C, 5.8 to 6.5% at 240 °C, 5.9 to 6.8% at 240 °C, and 6.7 to 6.9% at 320 °C. The MC values for the carbonized samples were significantly lower than those of the control samples. There were no significant differences in moisture content between the species.

The MC of betung bamboo, kuning bamboo, tali bamboo, moso bamboo, and both wood species significantly increased at 240 °C, whereas that of giant bamboo showed a significant difference at 280 °C. The MC became constant from 280 °C for giant bamboo and moso bamboo, whereas the MC of betung bamboo, kuning bamboo, tali bamboo was constant at 240 to 280 °C, and then it significantly increased at 320 °C. The MC of the Korean red pine and cork oak showed no increasing tendency between 240 to 320 °C.

Several studies have been conducted on the MC of bamboo and wood that have been carbonized at various temperatures, supporting the results of the current study. Liu *et al.* (2014) reported that the MC of bamboo biochar was lower than that of raw bamboo, predominantly due to water evaporation during the carbonization process. The hydroxyl groups were destroyed due to thermal decomposition of the organic components, leading to a decrease in water absorption of biomass materials. Park *et al.* (2019) found that the MC of andong, tali, kuning, ampel, and betung bamboo carbonized at 200 to 1,000 °C was lower than the untreated samples and increased with increasing carbonization temperature. Park *et al.* (2020) highlighted that the MC of the control bamboo samples was 7 to 10% and decreased to less than 6% after carbonization, and the MC of carbonized bamboo increased as the carbonization temperature increased. The fine pores and cracks in the carbonized bamboo could adsorb water molecules and increase the MC. Kwon *et al.* (2012) reported that the MC of *Quercus variabilis* wood carbonized at 400 to 1,000 °C increased as the temperature increased from 3.1 to 7.0%. The variation in moisture content between species could be related to the surface properties and the cellulose crystalline structure of each species. As mentioned by Wang *et al.* (2010), the adsorption property correlates to physical and chemical properties of adsorbents, such as grain size, exchangeable cation capacity, pore diameter and quantity, specific surface area, and surface chemical characteristics. Kim *et al*. (2001) reported that the d-spacings of cellulose crystal in wood steadily increased by thermal expansion, which may facilitate the moisture adsorption of the wood.

Table 3. Moisture Content of Samples Carbonized at Different Temperatures

Species	Moisture Content (%)				
	Control	200 °C	240 °C	280 °C	320 °C
Giant bamboo	8.85 ± 0.38^{Ad}	5.6 ± 0.1^{Aa}	5.8 ± 0.7^{Aa}	6.7 ± 0.1^{Bb}	6.7 ± 0.3^{Ab}
Betung bamboo	7.97 ± 1.07^{Ad}	5.3 ± 0.2^{Aa}	6.1 ± 0.5^{Ab}	6.4 ± 0.4^{ABbc}	6.9 ± 0.3^{Ac}
Kuning bamboo	8.07 ± 1.41^{Ad}	5.4 ± 0.2^{Aa}	6.0 ± 0.6^{Aab}	6.5 ± 0.4^{Bb}	6.9 ± 0.6^{Ab}
Tali bamboo	8.71 ± 0.78^{Ad}	5.1 ± 0.6^{Aa}	6.1 ± 0.4^{Ab}	5.9 ± 0.4^{Ab}	6.9 ± 0.2^{Ac}
Moso bamboo	9.10 ± 2.20^{Ad}	5.1 ± 0.5^{Aa}	5.8 ± 0.3^{Ab}	6.7 ± 0.2^{Bc}	6.7 ± 0.1^{Ac}
Korean red pine	9.23 ± 2.74^{Ad}	5.3 ± 0.2^{Aa}	6.3 ± 0.8^{Ab}	6.8 ± 0.2^{Bab}	6.7 ± 0.3^{Ab}
Cork oak	10.52 ± 0.39^{Ad}	5.6 ± 0.2^{Aa}	6.5 ± 0.2^{Ab}	6.7 ± 0.1^{Bb}	6.8 ± 0.5^{Ab}

Note: The same superscript uppercase and lowercase letters beside the mean values denote insignificant outcomes at the 5% significance level for comparisons between species and among temperatures, using Duncan's multiple range tests, respectively.

Ash Content

The AC of the carbonized samples at different temperatures are presented in Table 4. The untreated giant bamboo had the highest AC of 5.42 ± 0.04% among the bamboo samples. Betung bamboo, kuning bamboo, tali bamboo, and moso bamboo showed AC ranging from 1.85 to 2.36%. The AC of the Korean red pine and cork oak was lower than that of the bamboo species at 0.18 ± 0.02 for Korean red pine and 0.70 ± 0.03 for cork oak.

The carbonized giant bamboo yielded the highest AC among the carbonized bamboos, ranging from 6.60 to 11.28%. Meanwhile, tali bamboo had the lowest AC among the carbonized bamboos, ranging from 2.03 to 3.75%. The AC of carbonized Korean red pine and cork oak was 0.25 to 0.67% and 0.88 to 2.84%, respectively. At all carbonization temperatures, bamboo had a significantly higher AC than wood, and there was a significant difference in AC between the bamboos. The AC of giant bamboo and tali bamboo significantly increased at 200 to 280 °C and became constant above 280 °C. Meanwhile, that of betung bamboo, kuning bamboo, moso bamboo, Korean red pine, and cork oak constantly increased with increasing temperature.

Many studies on the variation in AC in bamboo and wood carbonized at various temperatures support the results of this study. Rousset *et al*. (2011) reported that the AC of *Bambusa vulgaris* torrefied at 220, 250, and 280 °C increased with increasing temperature. As reported by Liu *et al.* (2014), the inorganic ash content in bamboo biochar carbonized at 200, 250, and 300 ℃ was higher than that of untreated bamboo, and the AC increased with increasing carbonization temperature and residue time. The AC variation was caused by the removal of absorbed water and the degradation of the chemical compositions under different carbonization conditions. Kwon *et al*. (2012) reported that the AC of *Quercus variabilis* carbonized at approximately 400 to 1,200 ℃ increased with increasing carbonization temperature. Qi *et al.* (2016) reported that the AC of *Pinus densiflora* carbonized at 400 to 800 ℃ increased with increasing temperature. Wahyu *et al.* (2017) also found that the AC of *Paraserianthes falcataria*, *Gmelina arborea*, *Melia azedarach*, and *Acacia mangium* carbonized at 400, 600, and 800 °C increased as the temperature increased. The ash content of Mi *et al.* (2016) revealed that the inorganic ash content of untreated and torrefied *Phyllostachys praecox* was higher than that of mason pine. The difference in AC between the carbonized bamboo and wood could be attributed to the presence of inorganic substances in bamboo. Park *et al.* (2021) reported that the inorganic substances, such as potassium, silica, magnesium, and calcium were observed in the carbonized bamboo at 200 to 1,000 ℃ and that inorganic substances increased with increasing carbonization temperature.

Table 4. Ash Content of Samples Carbonized at Different Temperatures

Species	Ash Content (%)				
	Control	200 °C	240 °C	280 °C	320 °C
Giant bamboo	5.42 ± 0.04^{Fa}	6.60 ± 0.42^{Fb}	8.10 ± 0.29^{Fc}	10.92 ± 0.22^{Fd}	11.28 ± 0.10^{Fd}
Betung bamboo	2.36 ± 0.15^{Da}	3.25 ± 0.17^{Eb}	4.00 ± 0.02^{Dc}	4.68 ± 0.01^{Dd}	5.40 ± 0.07^{De}
Kuning bamboo	2.36 ± 0.13^{Da}	2.67 ± 0.28^{Da}	4.43 ± 0.29^{Eb}	5.12 ± 0.03^{Ec}	5.70 ± 0.01^{Ed}
Tali bamboo	1.85 ± 0.10^{Ca}	2.03 ± 0.11^{Ca}	2.31 ± 0.11^{Cb}	3.65 ± 0.22^{Cc}	3.75 ± 0.04^{Fc}
Moso bamboo	2.62 ± 0.28^{Ea}	3.32 ± 0.01^{Eb}	4.26 ± 0.12^{DEc}	4.55 ± 0.02^{Dd}	5.40 ± 0.05^{De}
Korean red pine	0.18 ± 0.02^{Aa}	0.25 ± 0.01^{Aa}	0.35 ± 0.04^{Ab}	0.47 ± 0.05^{Ac}	0.67 ± 0.06^{Ad}
Cork oak	0.70 ± 0.03^{Ba}	0.88 ± 0.05^{Bb}	1.32 ± 0.03^{Bc}	2.13 ± 0.02^{Bd}	2.84 ± 0.17^{Be}

Note: The same superscript uppercase and lowercase letters beside the mean values denote insignificant outcomes at the 5% significance level for comparisons between species and among temperatures using Duncan's multiple range tests, respectively.

Volatile Matter Content

The VMC of the samples carbonized at 200 to 320 ℃ are summarized in Table 5. Moso bamboo showed the lowest VMC among untreated bamboo species as 77.62 ± 1.48% compared with 84.01 ± 1.66% for giant bamboo, 80.85 ± 1.50% for betung bamboo, and 83.90 ± 1.56% for tali bamboo. The untreated bamboo had a higher VMC than the untreated wood species.

The VMC of the carbonized bamboos at 320 ℃ was 41.57 ± 1.26% for giant bamboo, 32.16 ± 1.64% for betung bamboo, 34.75 ± 2.15% for kuning bamboo, 29.58 ± 0.82% for tali bamboo, and 36.44 ± 1.23% for moso bamboo. Tali bamboo carbonized at 320 ℃ yielded the lowest VMC among the bamboos, whereas giant bamboo showed the highest VMC. The VMC of Korean red pine and cork oak was 26.79 ± 1.96% and 27.20 ± 0.92%, respectively, which were lower than those of the carbonized bamboos. There were significant differences in the VMC of the carbonized samples at each temperature. The carbonized bamboo and wood samples showed significantly lower VMC values than the untreated samples. In bamboo, the VMC gradually decreased with increasing temperature, whereas the VMC of Korean red pine and cork oak rapidly decreased.

Many studies have been conducted on the VMC of carbonized bamboo and wood at various carbonization temperatures that support the current findings. Rousset *et al*. (2011) reported that the VMC of untreated *Bambusa vulgaris* torrefied at 220, 250, and 280 °C was 79.86%, 74.78%, 68.09%, and 57.71%, respectively, showing a decrease with increasing torrefaction temperature. As reported by Liu *et al.* (2014), the VMC of bamboo-biochar decreased as the carbonization temperature increased to 78.60% at 200 °C, 61.81% at 250 °C, and 41.34% at 300 °C. Park *et al.* (2019, 2020) reported that the VMC of Indonesian bamboos carbonized at 200 °C to 1,000 °C showed a significant decrease at 200 °C to 400 °C and became constant after 600 °C. Kwon *et al*. (2012) found that the VMC of *Quercus variabilis* wood carbonized at 400 °C to 1,200 °C decreased with increasing carbonization temperature. Qi *et al.* (2016) showed that the VMC of *Pinus densiflora* decreased as the temperature decreased. Wahyu *et al.* (2017) also reported that the VMC of *Paraserianthes falcataria*, *Gmelina arborea*, *Melia azedarach*, and *Acacia mangium* carbonized at 400, 600, and 800 °C decreased with increasing temperature.

Table 5. Volatile Matter of Samples Carbonized at Different Temperatures

Species	Volatile Matter Content (%)				
	Control	200 °C	240 °C	280 °C	320 °C
Giant bamboo	84.01 ± 1.66^{Ce}	78.36 ± 1.45^{Dd}	61.11 ± 1.10^{Fc}	48.55 ± 1.53^{Db}	41.57 ± 1.26^{Fa}
Betung bamboo	80.85 ± 1.50^{BCe}	74.41 ± 1.95^{Cd}	53.81 ± 1.04^{Dc}	42.91 ± 1.96^{Bb}	32.16 ± 1.64^{CDa}
Kuning bamboo	83.90 ± 1.56^{Ce}	71.73 ± 0.94^{Cd}	61.56 ± 0.96^{Fc}	43.68 ± 2.38^{ABb}	34.75 ± 2.15^{DEa}
Tali bamboo	82.20 ± 1.53^{Ce}	71.48 ± 2.87^{Cd}	58.71 ± 1.78^{Ec}	43.18 ± 1.77^{Bb}	29.58 ± 0.82^{BCa}
Moso bamboo	77.62 ± 1.48^{ABe}	67.04 ± 0.74^{Bd}	50.98 ± 0.62^{Cc}	46.39 ± 1.74^{CDb}	36.44 ± 1.23^{Ea}
Korean red pine	73.97 ± 2.86^{Ae}	53.58 ± 2.32^{Ad}	42.96 ± 1.49^{Bc}	41.88 ± 1.25^{Bb}	26.79 ± 1.96^{Aa}
Cork oak	74.86 ± 3.96^{Ae}	54.93 ± 1.78^{Ad}	40.02 ± 0.51^{Ac}	34.86 ± 1.30^{Ab}	27.20 ± 0.92^{ABa}

Note: The same superscript uppercase and lowercase letters beside the mean values denote insignificant outcomes at the 5% significance level for comparisons between species and among temperatures, using Duncan's multiple range tests, respectively.

Fixed Carbon Content

Table 6 lists the FCC of the samples carbonized at 200 to 320 °C. The FCC of untreated bamboo was 7.02 ± 1.07% for giant bamboo, 12.61 ± 1.77 for betung bamboo, 10.30 ± 1.56 for kuning bamboo, 12.07 ± 1.85 for tali bamboo, and 16.24 ± 1.74 for moso bamboo. Giant bamboo yielded the lowest FCC among the untreated bamboo types, whereas moso bamboo showed the highest value. Betung bamboo, tali bamboo, and kuning bamboo showed a comparable FCC. The FCC of the untreated woods was higher than that of the bamboos at 22.00 ± 2.79% for Korean red pine and 21.13 ± 3.81% for cork oak.

The FCC of bamboo and wood carbonized at 320 °C was 40.18 ± 1.09% for giant bamboo, 55.57 ± 1.51% for betung bamboo, 52.67 ± 2.14% for kuning bamboo, 59.80 ± 0.91% for tali bamboo, 51.46 ± 1.25% for moso bamboo, 65.80 ± 1.65% for Korean red pine, and 63.12 ± 1.24% for cork oak, with higher FCC than the untreated samples. At all carbonization temperatures, the wood samples had significantly higher fixed carbon content than the bamboo samples, and there was a significant difference between bamboo samples. The FCC for bamboo steadily increased as the carbonization temperature increased. In wood, the FCC significantly increased at 200 °C and then gradually increased until reaching 320 °C.

Several studies on FCC in bamboo and wood carbonized at various temperatures have been conducted. Rousset *et al*. (2011) showed that the fixed carbon content of *Bambusa vulgaris* torrefied at 220, 250, and 280 °C increased with increasing temperature, whereas the VMC decreased as temperature increased. According to Kumar and Chandrashekar (2014), the higher FCC value in charcoal prepared at higher temperatures may be caused by VMC removal from the wood during the pyrolytic process. Kwon *et al*. (2012) reported that the fixed carbon content of cork oak carbonized at 400 to 1,200 °C increased as the carbonization temperature increased. Qi *et al*. (2016) also mentioned that the fixed carbon content of *Paulownia tomentosa* and *Pinus densiflora* carbonized at 400 to 800 °C increased with increasing temperature. Wahyu *et al.* (2017) also found that the FCC of *Paraserianthes falcataria*, *Gmelina arborea*, *Melia azedarach*, and *Acacia mangium* carbonized at 400, 600, and 800 °C increased with increasing temperature, which may be due to the decrease in VMC. More volatile matter, such as H_2O, CO, CO_2, and CH_4, was released as the carbonization temperature increased during the carbonization process, resulting in an increase in FCC and a decrease in VMC (Liu *et al.* 2014; Qi *et al*. 2016; Wahyu *et al.* 2017).

Table 6. Fixed Carbon Content of Samples at Different Temperatures

Species	Fixed Carbon Content (%)				
	Control	200 °C	240 °C	280 °C	320 °C
Giant bamboo	7.02 ± 1.07^{Aa}	9.50 ± 1.88^{Ab}	24.96 ± 0.98^{Ac}	33.80 ± 1.49^{Ad}	40.18 ± 1.09^{Ae}
Betung bamboo	12.61 ± 1.77^{BCa}	17.01 ± 1.98^{Ba}	36.08 ± 1.35^{Db}	45.97 ± 2.38^{Cc}	55.57 ± 1.51^{Cd}
Kuning bamboo	10.30 ± 1.56^{ABa}	20.17 ±0.97^{BCb}	27.97 ± 1.29^{Bc}	44.71 ±2.19^{BCd}	52.67 ± 2.14^{Be}
Tali bamboo	12.07 ± 1.85^{Ba}	21.45 ±3.48^{CDb}	32.90 ± 2.21^{Cc}	47.24 ± 1.53^{Cd}	59.80 ± 0.91^{Ee}
Moso bamboo	16.24 ± 1.74^{Ca}	24.57 ± 1.23^{Db}	38.94 ± 0.91^{Ec}	42.39 ± 1.61^{Bd}	51.46 ± 1.25^{Be}
Korean red pine	22.00 ± 2.79^{Da}	40.92 ± 2.39^{Eb}	50.37 ± 1.61^{Fc}	50.86 ± 1.45^{Dc}	65.80 ± 1.65^{Fd}
Cork oak	21.13 ± 3.81^{Da}	38.65 ± 1.91^{Eb}	52.17 ± 0.41^{Fc}	56.32 ± 1.38^{Ed}	63.12 ± 1.24^{Ee}

Note: The same superscript uppercase and lowercase letters beside the mean values denote insignificant outcomes at the 5% significance level for comparisons between species and among temperatures using Duncan’s multiple range tests, respectively.

CONCLUSIONS

The proximate analysis of bamboo culms and woods carbonized at low temperatures in the range of 200 to 320 ℃ at the intervals of 40 ℃ was examined and compared, and the results were as follows:

1. The moisture content (MC) values of the carbonized samples were significantly lower than those of the control samples. In carbonized bamboo, the MC constantly increased with increasing temperature, whereas carbonized wood showed constant MC after 240 ℃.
2. The ash content (AC) and fixed carbon content (FCC) of the carbonized samples were higher than those of the control samples, and they continuously increased as the temperature increased. The volatile matter content (VMC) of carbonized bamboo gradually decreased with increasing temperature, whereas that of carbonized wood rapidly decreased with increasing temperature.
3. There were significant differences in AC, VMC, and FCC between the bamboo species. Giant bamboo had the highest AC and VMC among the bamboo species, whereas tali bamboo had the lowest. The FCC of giant bamboo was lowest at each temperature.
4. The carbonized bamboo showed significantly higher AC and VMC than the carbonized wood, whereas FCC was significantly higher in the carbonized wood than in the carbonized bamboo.

In summary, the difference in proximate analysis among bamboo species and between bamboo and wood carbonized at low temperatures was determined, and the results of this study may be used for the further use of bamboo and wood as eco-friendly biomass resources.

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REFERENCES CITED

Asada, T., Ishihara, S., Yamane, T., Toba, A., Yamada, A., and Oikawa, K. (2002). "Science of bamboo charcoal: Study on carbonizing temperature of bamboo charcoal and removal capability of harmful gases," *Journal of Health Science* 48(6), 473-479.

Febrianto, F., Hidayat, W., Bakar, E. S., Kwon, G. J., Kwon, J. H., Hong, S. I., and Kim, N. H. (2012). "Properties of oriented strand board made from Betung bamboo (*Dendrocalamus asper* (Schultes. f) Backer ex Heyne)," *Wood Science and Technology* 46(1), 53-62.

Febrianto, F., Jang, J. H., Lee, S. H., Santosa, I. A., Hidayat, W., Kwon, J. H., and Kim, N. H. (2015). "Effect of bamboo species and resin content on properties of oriented strand board prepared from steam-treated bamboo strands," *BioResources* 10(2), 2642-2655. DOI: 10.15376/biores.10.2.2642-2655

Hidayat, W., Qi, Y., Jang, J. H., Febrianto, F., Lee, S. H., Chae, H. M., Kondo, T., and Kim, N. H. (2017). "Carbonization characteristics of juvenile woods from some tropical trees planted in Indonesia," *Journal of the Faculty of Agriculture* 62(1), 145–152.

Hoshi, T. (2001). "Growth promotion of tea trees by putting bamboo charcoal in soil," in: *Proceedings of the 2001 International Conference on O-cha (Tea) Culture and Science*, Shizuoka, Japan, pp. 147-150.

Jeon, W. S., Kim, Y. K., Lee, J. A., Kim, A. R., Darsan, B., Chung, W. Y., and Kim, N. H. (2018a). "Anatomical characteristics of three Korean bamboo species," *Journal of the Korean Wood Science and Technology* 46(1), 29-37. DOI: 10.5658/WOOD.2018.46.1.29

Jeon, W. S., Byeon, H. S., and Kim, N. H. (2018b). "Anatomical characteristics of Korean *Phyllostachys pubescens* by age," *Journal of the Korean Wood Science and Technology* 46(3), 231-240. DOI: 10.5658/WOOD.2018.46.3.231

JIS M 8812 (2004). "Coal and coke-Methods for proximate analysis," Japanese Standards Association, Tokyo, Japan.

Kim, D. Y., Nishiyama, Y., Wada, M., Kuga, S., and Okano, T. (2001). "Thermal decomposition of cellulose crystallites in wood," *Holzforschung* 55(5), 521-524. DOI: 10.1515/HF.2001.084

Korea Forest Research Institute (2005). "All things of bamboo (in Korean)," 7, 8-21.

Kumar, R., and Chandrashekar, N. (2014). "Characterization of charcoal from some promising bamboo species," *Journal of the Indian Academy of Wood Science* 11(2), 144-149.

Krause, J. Q., de Andrade Silva, F., Ghavami, K., Gomes, O. D. F. M., and Toledo Filho, R. D. (2016). "On the influence of *Dendrocalamus giganteus* bamboo microstructure on its mechanical behavior," *Construction and Building Materials* 127, 199-209. DOI: 10.1016/j.conbuildmat.2016.09.104

Kwon, S. M., Kim, N. H., and Cha, D. S. (2009). "An investigation on the transition characteristics of the wood cell walls during carbonization," *Wood Science and Technology* 43(5), 487-498. DOI: 10.1007/s00226-009-0245-6

Kwon, S. M., Kwon, G. J., Jang, J. H., and Kim, N. H. (2012). "Characteristics of charcoal in different carbonization temperatures," *Journal of Forest and Environmental Science* 28(4), 263-267. DOI: 10.7747/JFS.2012.28.4.263

Kwon, S. M., Jang, J. H., and Kim, N. H. (2014). "Dimensional change of carbonized woods at low temperatures," *Journal of Forest and Environmental Science* 30(2), 226-232. DOI: 10.7747/JFS.2014.30.2.226

Lee, H. S., Jeon, W. S., Kim, Y. K., Purusatama, B. D., Kim, A. R., Cho, J. I., Kim, W. J., Kim, H. C., and Kim, N. H. (2019). "Design of a modified charcoal production kiln for thermal therapy and evaluation of the charcoal characteristics from this kiln," *BioResources* 14(3), 7275-7284. DOI: 10.15376/biores.14.3.7275-7284

Li, M. F., Sun, S. N., Xu, F., and Sun, R. C. (2012). "Microwave-assisted organic acid extraction of lignin from bamboo: Structure and antioxidant activity investigation," *Food Chemistry* 134(3), 1392-1398. DOI: 10.1016/j.foodchem.2012.03.037

Liu, Z., Fei, B., and Jiang, Z. (2014). "Combustion characteristics of bamboo-biochars," *Bioresource Technology* 167, 94-99. DOI: 10.1016/j.biortech.2014.05.023

Mi, B., Liu, Z., Hu, W., Wei, P., Jiang, Z., and Fei, B. (2016). "Investigating pyrolysis and combustion characteristics of torrefied bamboo, torrefied wood and their blends," *Bioresource Technology* 209, 50-55. DOI: 10.1016/j.biotech.2016.02.087

Papadopoulos, A. N., Hill, C. A. S., Gkaraveli, A., Ntalos, G. A., and Karastergiou, S. P. (2004). "Bamboo chips (*Bambusa vulgaris*) as an alternative lignocellulosic raw material for particleboard manufacture," *Holz als Roh-und Werkstoff* 62(1), 36-39. DOI: 10.1007/s00107-003-0447-9

Park, S. H., Jang, J. H., Wistara, N. J., Ferianto, F., and Lee, M. (2019). "Fuel properties of Indonesian bamboo carbonized at different temperatures," *BioResources* 14(2), 4224-4235. DOI: 10.15376/biores.14.2.4224-4235

Park, S. H., Wistara, N. J., Febrianto, F., and Lee, M. (2020). "Evaluation of Sembilang bamboo (*Dendrocalamus giganteus*) charcoal for potential utilization," *BioResources* 15(1), 6-19. DOI: 10.15376/biores.15.1.6-19

Park, S. H., Lee, M., Febrianto, F., and Wistara, N. J. (2021). "Effects on morphology and chemical properties of indonesian bamboos by carbonization," *Jurnal Sylva Lestari* 9(2), 190-201. DOI: 10.23960/jsl29190-201

Qi, Y., Jang, J. H., Hidayat, W., Lee, A. H., Lee, S. H., Chae, H. M., and Kim, N. H. (2016). "Carbonization of reaction wood from *Paulownia tomentosa* and *Pinus densiflora* branch woods," *Wood Science and Technology* 50(5), 973-987. DOI: 10.1007/s00226-016-0828-y

Rousset, P., Aguiar, C., Labbé, N., and Commandré, J. M. (2011). "Enhancing the combustible properties of bamboo by torrefaction," *Bioresource Technology* 102(17), 8225-8231. DOI: 10.1016/j.biortech.2011.05.093

Subyakto, S., Budiman, I., and Pari, G. (2012). "Effects of temperature and time of carbonization on the properties of bamboo (*Dendrocalamus asper*) carbon," *Wood Research Journal* 3(2), 68-73. DOI: 10.51850/wrj.2012.3.2.68-73

Yang, W., Kim, H. Y., Chae, T. Y., Ibik, K., and Pohan, H. G. (2010). "A study on carbonization characteristics of Indonesian and Korean bamboo for production of bamboo charcoal and vinegar," *Journal of the Korean Society of Combustion* 15(1), 30-37.

Yang, G. U., Purusatama, B. D., Kim, J. H., Suri, I. F., Prasetia, D., Hidayat, W., Febrianto, F., Lee, S. H., and Kim, N. H. (2022). "Physical and chemical characteristics of the bamboo culm and wood carbonized at low temperature," *BioResources* 17(3), 4837-4855. DOI: 10.15376/biores.17.3.4837-4855

Zaia, U. J., Cortez-Barbosa, J., Morales, E. A. M., Lahr, F. A. R., Nascimento, M. F. D., and Araujo, V. A. D. (2015). "Production of particleboards with bamboo (*Dendrocalamus giganteus*) reinforcement," *BioResources* 10(1), 1424-1433. DOI: 10.15376/biores.10.1.1424-1433

Wahab, R., Mohamed, A., Mustafa, M. T., and Hassan, A. (2009). "Physical characteristics and anatomical properties of cultivated bamboo (*Bambusa vulgaris* Schrad.) culms," *Journal of Biological Sciences* 9(7), 753-759. DOI: 10.3923/jbs.2009.753.759

Wang, F. Y., Wang, H., and Ma, J. W. (2010). "Adsorption of cadmium (II) ions from aqueous solution by a new low-cost adsorbent-Bamboo charcoal," *Journal of Hazardous Materials* 177(1-3), 300-306. DOI: 10.1016/j.jhazmat.2009.12.032

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