

Analysis of Variability in Making Wood Charcoal: Influence of Wood Type, Gas Fuel Consumption, and Efficiency on the Charcoal Produced

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Abstract- Charcoal is an extremely relevant (valuable) product for managing waste from wood offcuts or residues, because it can be used in a variety of applications, adding value to the material. This study aimed to investigate and compare the carbonization of three different types of wood, that is, teak (*Tectona grandis*) wood, matoa (*Pometia pinnata*) wood, and merbau (*Intsia bijuga*) wood, using a carbonization reactor. Each wood type had an initial weight of 2.15 kg and was processed for 4 hours. The study records the carbonization results, fuel gas consumption for each wood type, and the maximum temperature achieved during the process. The research findings indicate that *Tectona grandis* wood produces 0.75 kg of charcoal, utilizing 1.6 kg of fuel gas and reaching a maximum temperature of 374.07 °C. In contrast, *Pometia pinnata* wood yields 0.85 kg of charcoal, with 1.2 kg of fuel gas consumption, and a maximum temperature of 428.77 °C. *Intsia bijuga* wood generates 1.2 kg of charcoal, utilizing 1.3 kg of fuel gas and reaching a maximum temperature of 284.89 °C. Based on the data, it can be suggested that Teak wood charcoal has the highest charcoal content among the three types of wood, with a percentage of 79.02%. Meanwhile, Matoa wood charcoal has the lowest charcoal content, with a percentage of 44.56%, indicating that Teak wood is efficient for charcoal production.

Keywords EDX/EDS analysis; energy consumption; proximate analysis; wood type; variability of carbonization results.

1. Introduction

Charcoal is a versatile material that has a rich history of use. For centuries, it has been used as a remedy for poisonings [1], and as a source of energy for household heating and cooking, and for industrial applications such as iron smelting. Its potential as a tool for paleoenvironmental investigations has also been highlighted [2]. In the medical field, charcoal has been utilized for binding toxic substances [3]. The preservation of fossil charcoal, which provides detailed plant ultra-structure, has been noted as well [4].

Charcoal obtained from biomass, also known as biochar, is a valuable product for various applications. It is produced through the carbonization of lignocellulosic materials, such as

wood, coconut shells, and rice husks [5]. The production process involves the manipulation of pressure, moisture content, and gas flow, which can significantly affect the yield and properties of charcoal [6]. This process converts biomass into charcoal, a carbon-rich material known as charcoal. Sustainable production methods, such as the use of airtight ovens or retorts, are crucial for reducing negative environmental impacts [7]. There are numerous applications for the resulting biochar, including use as a clean solid fuel for cookstoves, in water purification, and as a catalyst [8]. The use of biochar for carbon sequestration is a promising application that can mitigate its environmental impact [9]. Charcoal is produced through a carbonization process, where wood is burned in a restricted oxygen environment [10–12]. Charcoal derived from biomass has several advantages, including its

abundance, low cost, reproducibility, and environmental friendliness. It can be used as an adsorbent because of its porous structure and abundant oxygen-containing functional groups [13]. Biomass briquettes, a form of biochar, are also being explored as alternative fuel sources, particularly in rural areas with abundant biomass feedstock [14].

Conventional and traditional technologies for making charcoal from biomass differ significantly in terms of energy efficiency and environmental impact. Traditional methods, such as earth mounds, pits, and brick kilns, rely on the principle of incomplete combustion [15]. They burn the biomass in conditions with restricted oxygen supply, generating the heat required for carbonization but with considerable energy loss. Often, up to 80 – 90% of the potential energy of the biomass is not captured as charcoal, as it is lost as heat or through the release of volatile compounds into the atmosphere. The major drawback of conventional production methods lies in the significant emissions of harmful carbon monoxide (CO) during the conversion of wood to charcoal, reaching 20 - 25%, with fixed carbon content at 60 - 65% under operating temperatures of 450 - 500 °C [16]. Additionally, these rudimentary methods emit greater quantities of greenhouse gases and other pollutants due to suboptimal combustion and absent or inadequate emissions control [14, 17]. According to Rajkumar [18], charcoal production entails emissions impact, including sulphur dioxide (SO₂), carbon dioxide (CO₂), nitrogen oxides (NO), carbon monoxide (CO), and particulate matter (PM2.5), with their formation occurring during the combustion stage, with average emission rates of 23.22, 45.45, 14.38, 40.66, and 14.30 g/kg, respectively.

In contrast, conventional technologies in charcoal production have evolved to increase carbonization efficiency and reduce environmental degradation. Improvements include better kiln designs that can recover and utilize the heat from carbonization to maintain the process, as well as systems that capture and combust off-gases, resulting in higher energy yield and less pollution. Some of these technologies can achieve carbonization efficiencies of up to 35% [19], while vertical furnaces with double layers, aimed at preventing heat loss, may reduce combustion time by 50% [20]. Furthermore, the implementation of emissions controls in advanced kilns can reduce potential environmental impacts by approximately 90%, offering a stark contrast to traditional methods and underscoring the importance of technology adoption in the charcoal industry [21]. These enhancements not only lead to a more sustainable production process but also contribute to a reduced ecological footprint, aligning with global efforts to combat climate change and promote sustainable resource utilization.

The research aims to evaluate the impact of wood species selection on the yield and efficiency of the carbonization process, with a special focus on the comparison between Merbau wood and Teak wood. Furthermore, this study aims to analyze the gas fuel consumption required to heat the carbonization reactor, with the aim of identifying differences in energy requirements based on wood type.

2. Experimental Method

2.1. Preparation of Materials and Tools

The carbonization reactor uses 12 kg LPG gas cylinders which are modified by adding 5 type K thermocouple holders with a distance of 15 cm between the points. The top of the tube is cut (Fig. 1). For testing materials, *Tectona grandis*, *Pometia pinnata* and *Intsia bijuga* wood chips were used, which were cut into squares measuring 5 cm x 5 cm x 5 cm from the remains of building construction (Fig. 2). The weight of materials and LPG gas fuel is measured using a digital scale with an accuracy of 100 g, and for real-time temperature measurements during the process, a 10-channel thermocouple data logger based on an Arduino Mega with an Adafruit MAX6675 sensor with an accuracy level of 1.10% (Fig. 3). The carbonization results of the three types of samples were further tested to determine their characteristics through proximate tests and component analysis (EDX/EDS) at the integrated Laboratory of the Center for Standardization of Sustainable Forest Management Instruments (PUSTARHUT), Bogor City, Indonesia.

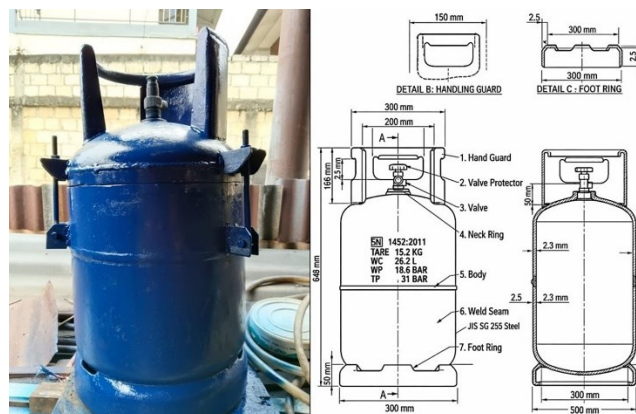


Fig. 1. Modification of a gas cylinder into a carbonization reactor.



Tectona grandis wood *Pometia pinnata* wood *Intsia bijuga* wood

Fig. 2. Wood chips prepared for the carbonization process.

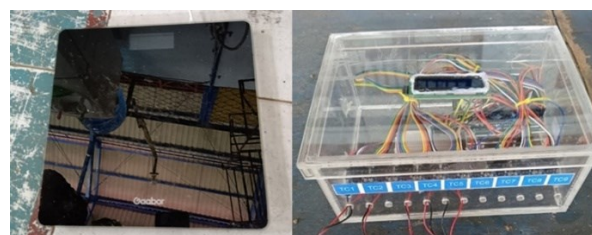


Fig. 3. Digital scale and type-K thermocouple data logger.

2.2. Testing

The process of producing activated charcoal from wood involves the initial preparation of materials and equipment, including a gas cylinder saw, gas stove, scales, stopwatch, and the wood that will be transformed into activated charcoal. Following this, any dirt and gravel from the wooden pieces was removed, followed by drying the wood under the sun. Then, a type K thermocouple probe onto the T₁, T₂, T₃, T₄, and T₅ holders in the reactor was installed. This probe was connected to a datalogger thermometer, enabling the continuous monitoring of temperature throughout the process. After placing each 2.15 kg piece of wood into the reactor, the safety clamp was tightened to ensure a secure closure. The gas stove and adjusting the flame pressure with the regulator was turned on, and the reactor was positioned on the prepared gas stove. Each material (wood) test required four hours to complete, as shown in Figure 4. At end of each test, the gas cylinder and the charcoal produced are reweighed. For additional varieties of wood, these procedures were duplicated.

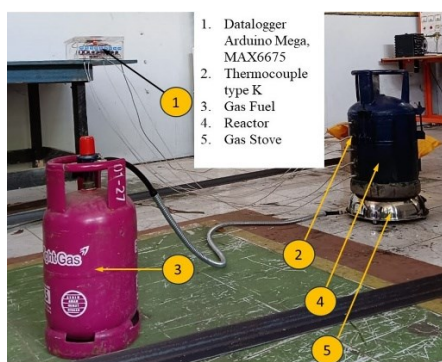


Fig. 4. Carbonization process.

3. Results and Discussions

3.1. Temperature Distribution

The temperature in the wood carbonization reactor, referred to as the carbonization reactor, is a critical factor in determining the final result of the process. The temperature distribution in the reactor chamber is a crucial factor that can greatly impact the properties of the activated charcoal product. Figure 5 shows a visualization of the temperature distribution that occurs during the carbonization process. This distribution is influenced by various factors such as the type of reactor, properties of the feedstock, and the surrounding environment.

In the initial phase, referred to as preheating, the wood is introduced into a reactor that initiates the process of heating. During this stage, the temperature rises gradually from the starting temperature of 29 – 47 °C (which is the initial temperature of the reactor before heating begins) until it reaches the specific temperature at which water vapor is released from the wood. These temperatures remain stable over time, i.e., 274.82 °C in 116.40 minutes for Merbau wood, 356.72 °C in 118.59 minutes for Teak wood, and 413.6 °C in 155.56 minutes for Matoa wood, respectively. After reaching the final temperature for releasing water vapor, the wood goes

through thermal decomposition in the following stage, known as the decomposition phase. Since the wood is releasing gases and steam that condense in the raw material, the temperature in the reactor increases more rapidly at this point. The decomposition phase exhibits variability in duration across different types of wood. For instance, Teak and Merbau requires an approximate range of 116 to 119 minutes. On the other hand, it takes precisely 155.56 minutes for Matoa wood to fully decompose. This suggests that the charcoaled wood exhibits a different water content at the beginning of the process.

The maximum temperature in the third stage occurs when the decomposition process reaches its peak. The maximum temperature varies with the reactor design and process parameters. Gas, steam, and active carbon products are efficiently produced during wood decomposition at this temperature, which peaks between 274.82 °C and 413.16 °C. Once the maximum temperature is reached, the reactor is regulated to maintain the temperature at the desired level in order to avoid excessive heat. The temperature decrease, also known as the cooling phase, happens when a specific time or stage is reached, and the fuel supply is reduced, or the air flow is adjusted. This temperature distribution fluctuates due to raw material and reactor operating conditions, temperature, and other factors.

3.2. Carbonization Results

Carbonization, a crucial chemical process involved in the conversion of biomass to sustainable fuel, garners interest regarding its application to three distinct wood species, i.e., *Tectona grandis*, *Pometia pinnata*, and *Intsia bijuga*. Carbonization is the thermal decomposition of organic fuels in the absence of oxygen and at high temperatures to produces bio-oil, bio-gas, and bio-carbon, all of which are alternative fuels or industrial raw materials. The data presented in Table 1 shows the carbonization results for all three types of wood based on an initial weight of 2.15 kg, ensuring a sufficient volume for carbonization analysis.

Table 1. Carbonization data for three types of wood

No	Process time (hours)	Weight (kg)			fuel consumptions weight (kg)	
		Type of Wood	First	Final	First	Final
1	4	<i>Tectona grandis</i>	2.15	0.75	10.8	9.2
2		<i>Pometia pinnata</i>	2.15	0.85	11.95	10.75
3		<i>Intsia bijuga</i>	2.15	1.2	12.5	11.2

The carbonization process was conducted for a duration of 4 hours, which was selected to ensure an adequate timeframe for the thermal conversion of *Tectona grandis* into carbonization products, while also maintaining the kinetic aspects of the chemical reactions involved. The carbonization weight differs for each wood type, with *Tectona grandis* wood weighing 0.75 kg, *Pometia pinnata* wood weighing 0.85 kg, and *Intsia bijuga* wood weighing 1.2 kg (Figure 6).

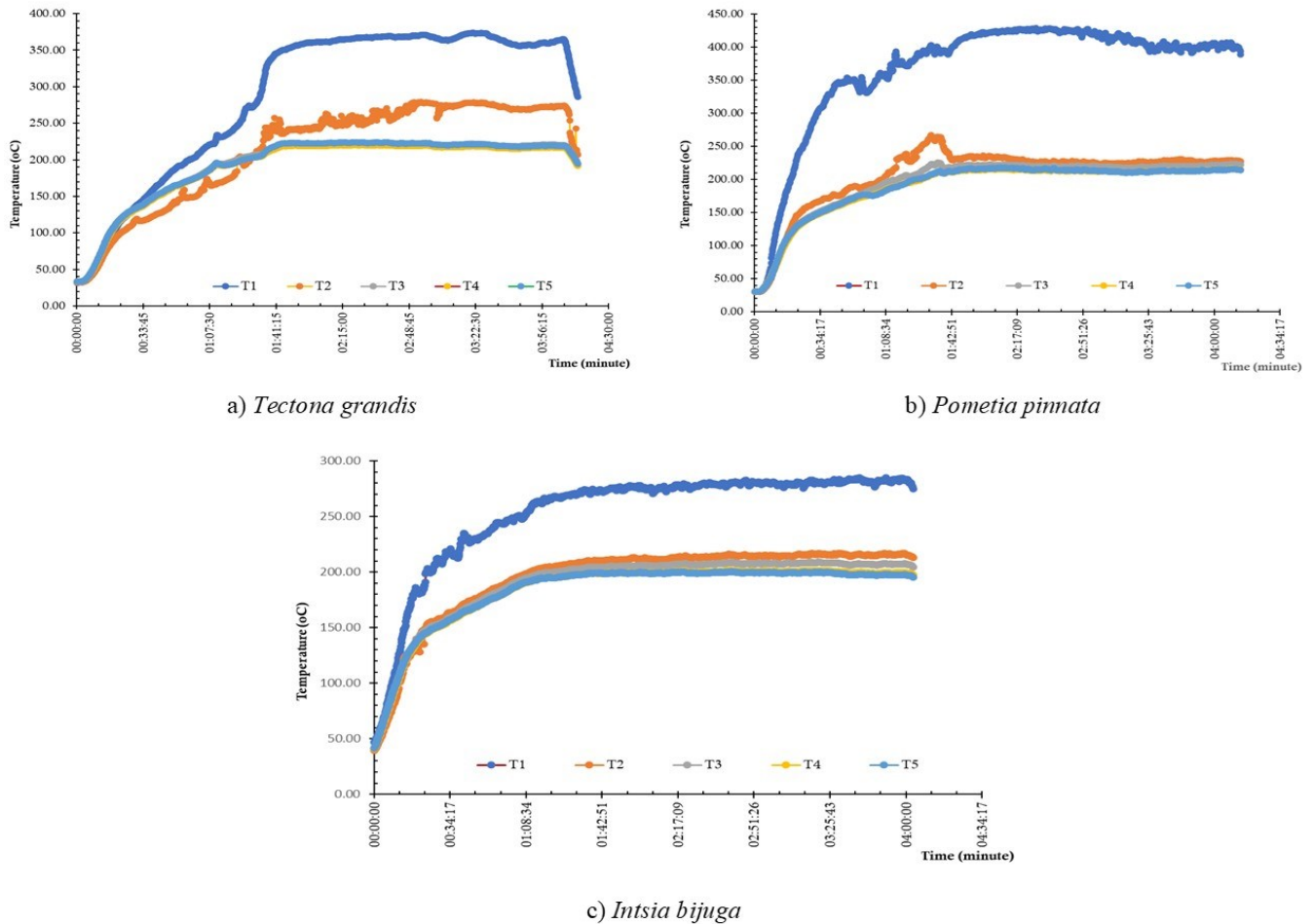


Fig. 5. Temperature distribution in the carbonization reactor.

Furthermore, the maximum temperatures reached during the carbonization process vary, influencing how much wood components decompose into carbonization process. Further analysis included the use of gas fuel to heat the carbonization reactor, which varies depending on the type of wood, as well as energy efficiency calculations. The carbonization process has an efficiency range of 46.88% for *Tectona grandis* wood, 70.83% for *Pometia pinnata* wood, and 92.31% for *Intsia bijuga*. This efficiency measures the rate at which organic fuel is converted into usable carbonization products.

In general, the maximum temperature reached during the carbonization process is a crucial factor in optimizing the efficiency and yield of carbonization products.

3.3. Characteristics of Charcoal

To provide comprehensive data and explanations about the carbonization process used in the three different types of wood samples, as well as an analysis of the charcoal components produced and approximate test results. Proximate analysis includes measurement of water content, volatile matter, fixed carbon, and ash content in carbonized charcoal. The data in Table 2 shows the physical properties of the charcoal that were produced through the proximate test on *Tectona grandis* wood charcoal. The results indicate that the charcoal contained approximately 2.9% water, 20.19% volatile matter, 79.02% fixed carbon, and 0.79% ash. *Pometia pinnata* wood charcoal contains approximately 3.54% water, 53.86% volatile matter, 44.56% fixed carbon, and 1.58% ash. Meanwhile, proximate test results for *Intsia bijuga* wood charcoal show a water content of around 2.42%, volatile matter of 31.43%, fixed carbon of 67.79%, and ash content of around 0.78%.



Fig. 6. Charcoal products from three wood species.

Carbonization products derived from three different types of wood show promising potential for use in a variety of applications, including fuel and raw materials in industrial

Table 2. Charcoal proximate test results

Charcoal sample	Test results	Test standards
<i>Tectona grandis</i> wood	Moisture content = 2,9%	SNI 1683:2001 point 7.1
	Ash content = 0,79%	SNI 1683:2001 point 7.2
	Volatile matter = 20,19%	SNI 1683:2001 point 7.3
	Fixed carbon = 79,02%	SNI 06-3730-1995 point 5.6
<i>Pometia pinnata</i> wood	Moisture content = 3,54%	SNI 1683:2001 point 7.1
	Ash content = 1,58%	SNI 1683:2001 point 7.2
	Volatile matter = 53,86%	SNI 1683:2001 point 7.3
	Fixed carbon = 44,56%	SNI 06-3730-1995 point 5.6
<i>Intsia bijuga</i> Wood	Moisture content = 2,42%	SNI 1683:2001 point 7.1
	Ash content = 0,78%	SNI 1683:2001 point 7.2
	Volatile matter = 31,43%	SNI 1683:2001 point 7.3
	Fixed carbon = 67,79%	SNI 06-3730-1995 point 5.6

Proximate parameters are critical in determining the potential energy content and burning behavior of wood [22]. Teak wood has a moisture content of only 2.9%, indicating that it is mature and suitable for efficient burning. Its high fixed carbon content of 79.02% means that when burned, it generates a lot of heat, making it ideal for applications that require a lot of energy, like charcoal manufacturing.

Meanwhile, Taun wood contains more water (3.54%) and less carbon (44.56%). This suggests that its combustion may be less efficient than Teak wood's, producing less heat per unit mass. However, the relatively high volatile matter content, 53.86%, suggests that this material is more flammable and suitable for applications that require rapid ignition, such as firewood. Merbau wood's composition falls between Teak and Taun, with a moderate water content of 2.42% and a fixed carbon content of 67.79%. This demonstrates that this material can strike a balance between heat output and ease of ignition, making it an adaptable option for a wide range of wood-based applications. The composition obtained is superior compared to charcoal derived from raw materials such as *Butyrosperum paradoxum*, *Combretum lamprocarpum*, *Pakia biglobosa*, *Ficus platyphylla* (*Ganji*), and *Anogeissus leiocarpus* (*Marke*), where ash content ranges from 5.35% to 16.91%, carbon content from 43.40% to 76.89%, and volatile matter from 13.59% to 34.59% [23]. On the other hand, charcoal obtained from jackfruit peel waste exhibits an ash content of 8.58% with the highest carbon content ranging from 58.12% to 61.42%, and volatile matter ranging from 16.88% to 25.31% [24].

According to Berrocal-Mendez and Moyan [25], charcoal in various countries of the European Union should possess specific characteristics. These include a moisture content ranging from 6 to 10%, fixed carbon content between 75 and 80%, volatile content between 5 and 16%, and ash content between 3 and 8%. Therefore, the test results indicate that the charcoal must be effectively managed to improve its moisture content, volatile matter, and ash content. Meanwhile, charcoal produced from rice straw, sugarcane leaves, sawdust, and coconut shells exhibits moisture content ranging from 5.67% to 9.23%, volatile matter ranging from 9.75% to 72.57%, ash content ranging from 2.58% to 11.27%, and fixed carbon varying from 8.92% to 78.04% [26].

Figure 7 shows the results of energy dispersive X-ray spectroscopy (EDX) analysis of charcoal samples obtained from Merbau wood. EDX serves as a method for determining the elemental composition of a substance by examining the distinct X-rays released by its atoms. The X-ray spectrum consists of peaks that correspond to the energy levels of the emitted X-rays. The energy is denoted on the horizontal axis of the graph in kilo electron volts (keV), whereas the intensity is represented on the vertical axis in units of amount per second. The elements in the charcoal sample are labeled along the curve based on their corresponding peaks.

The Merbau wood charcoal samples contained three primary elements, i.e., carbon (C), oxygen (O), and aluminum (Al). The presence of these elements is indicated by spectrum peaks at 0.25 keV for C, 0.52 keV for O, and 1.45 keV for Al, respectively. The relative height of the peak indicates how abundant each element is in the sample. Carbon has the highest weight percentage (49.05%) and atomic percentage (63.31%) among all the elements. Oxygen is the second most abundant element, with a weight percentage of 18.82% and an atomic percentage of 18.24%. Aluminum, with a weight of 32.12% and an atomic percentage of 18.45%, appears to be the least abundant element in the sample.

EDX analysis of Matoa wood charcoal samples also revealed the presence of carbon (C), oxygen (O), and aluminum (Al). The spectrum displays prominent peaks at energy levels of 0.25 keV for C, 0.52 keV for O, and 1.45 keV for Al, which indicate the relative abundance of these elements in the sample. The height of the peaks in the Matoa wood charcoal samples was directly linked to the abundance of each element. According to the spectrum analysis, charcoal samples obtained from Teak wood mainly contain carbon (C) and oxygen (O). The strong peak at approximately 0.25 keV corresponds to the K-alpha carbon X-ray line, while the smaller peak at around 0.52 keV corresponds to the K-alpha oxygen X-ray line. The inset table displays the weight percentage (wt.%) and atomic percentage (at. %) of each element in the Teak charcoal sample, indicating approximately 83.3 wt.% carbon and 16.7 wt.% oxygen.

Proximate analysis and EDX/EDS tests were conducted on wood charcoal from *Pometia pinnata*, *Intsia bijuga*, and *Tectona grandis*. The results revealed that the carbon conversion in some samples did not reach 100%. The

carbonization process of *Tectona grandis* wood resulted in complete conversion at a temperature range of 350 °C to 400 °C. On the other hand, *Pometia pinnata* wood has reached a conversion rate of 61.41% even though being heated to a higher temperature range of 400 °C to 450 °C. Further, the presence of 1.60% aluminum in the sample indicates

contamination, likely due to its origin from a construction waste project. This aluminum content is similar to that found in *Intsia bijuga* wood, which contains 18.45% aluminum. The complete conversion of *Intsia bijuga* wood into charcoal was achieved when the carbon content level reached 63.31% at a carbonization temperature ranging from 280 °C to 290 °C.

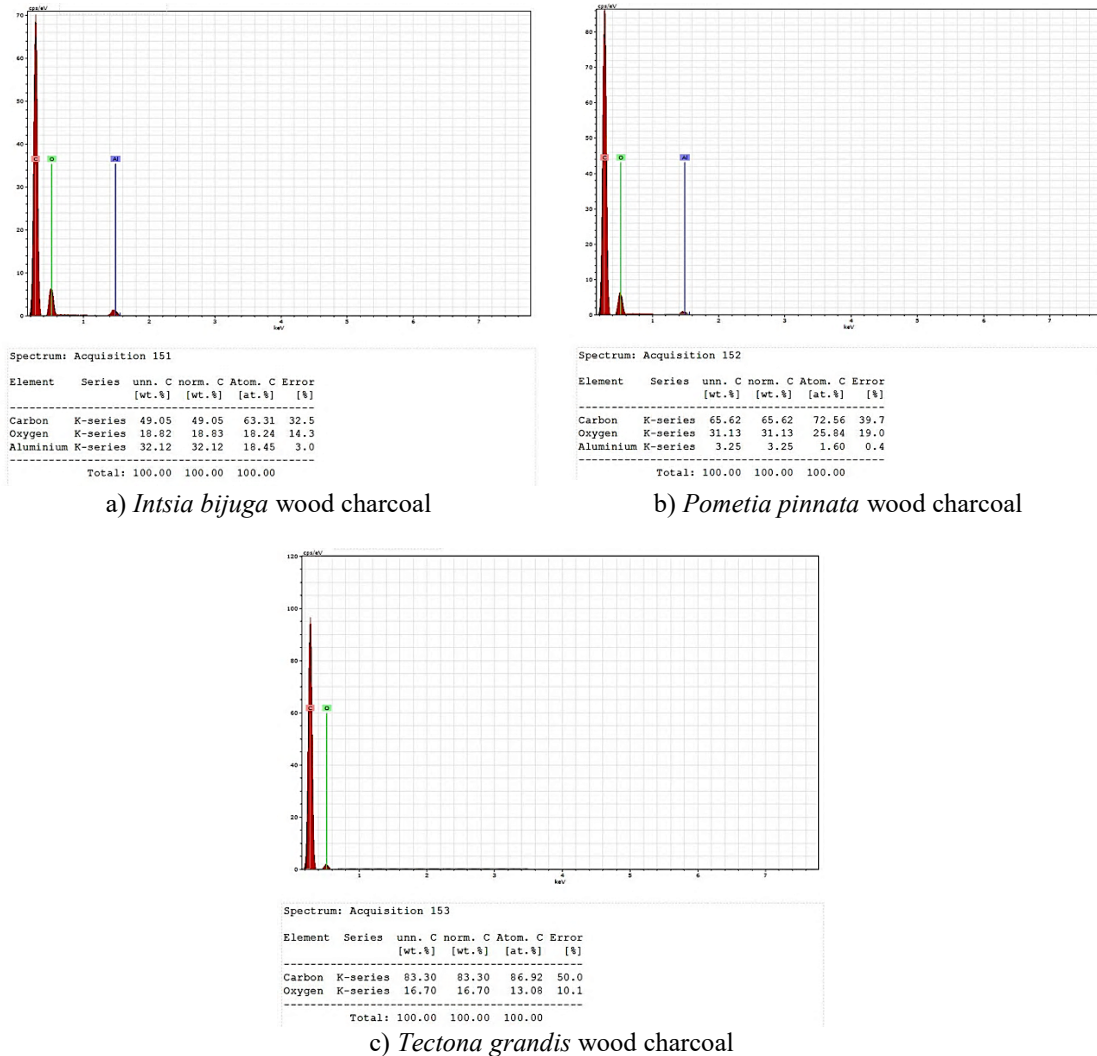


Fig. 7. Elemental analysis results (EDS/EDX).

4. Conclusion

The type of wood used in the carbonization process has a substantial impact on the variability of carbonization results and energy efficiency. According to the analysis, Merbau wood produces more carbonization products and has a higher energy efficiency than *Tectona grandis* wood. This variation emphasizes the importance of selecting the right wood type to achieve the best results and efficiency in the carbonization process. Furthermore, the use of fuel gas provides information about the energy differences required depending on the type of wood. *Intsia bijuga* wood necessitates lower fuel gas consumption (1.2 kg) to reach a maximum temperature of 284.89°C, while *Tectona grandis* wood requires a higher energy input (1.3 kg). The sustainability of the carbonization process and operational expenses may be influenced by these

differences. Hence, choosing the right wood type and managing fuel gas consumption become critical components of operational efficiency.

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Author Contributions

Joni Joni contributed to conceptualization, validation, resources, data curation, and project administration. Pither Palamba, Agustinus, and Johni Jonatan Numberi contributed

to methodology, formal analysis, investigation, writing-original draft preparation, writing-review and editing, visualization, and supervision. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

The authors declare no conflicts of interest regarding the research, authorship, and publication of this article.

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