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The Influence of Pyrolysis Time and Temperature on the Composition and Properties of Bio-Oil Prepared from Tanjong Leaves (*Mimusops elengi*)

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Abstract: This research aims to evaluate the influence of pyrolysis time and temperature on the composition and properties of bio-oil derived from *Mimusops elengi*. Experiments were conducted by varying the pyrolysis temperature and time from 400 to 600 °C and 30 to 120 min, respectively. Both pyrolysis temperature and time were found to significantly influence the bio-oil composition. At enhanced pyrolysis temperatures, the bio-oil yield increased while the ash and gas yields decreased. In addition, extended pyrolysis time produced a greater bio-oil yield, indicating that higher temperatures and longer durations promote additional decomposition of biomass. Functional groupings, including alcohols, phenols, ketones, esters, and aromatic compounds in the bio-oil, were identified via FT-IR analysis, indicating that the bio-oil's diversified chemical properties make it a potential alternative feedstock. GC-MS analysis identified 26 chemical compounds in the bio-oil, of which phenol was the most abundant. However, a high phenol content can diminish bio-oil quality by enhancing acidity, decreasing heating value, and encouraging engine corrosion. Temperature and pyrolysis time are crucial factors in producing bio-oil with the desired chemical composition and physical properties. The maximum yield, 34.13%, was attained after 90 min of operation at 500 °C. The characteristics of the *Mimusops elengi* bio-oil produced, namely density, viscosity, pH, and HHV were 1.15 g/cm^3, 1.60 cSt, 4.41, and 19.91 MJ/kg, respectively, in accordance with ASTM D7544. Using *Mimusops elengi* as a pyrolysis feedstock demonstrates its potential as an environmentally friendly energy source for a variety of industrial and environmental applications. The yield of bio-oil produced is not optimal due to the formation of tar, which results in the blockage of the output flow during the pyrolysis process.

Keywords: bio-oil; *Mimusops elengi*; pyrolysis; pyrolysis temperature; pyrolysis time

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1. Introduction

In a period of globalization, along with rapid growth in population and developing technology, energy demands and the number of energy sources are increasing daily. Actual statistics and severe forecasts on the future demand for fossil resources (even though their usage has led to environmental concerns) testify to the need for more sustainable energy, industrial, and agricultural policies, prompting researchers to seek cleaner energy sources [1–3]. The primary objective of the renewable energy program is to increase environmentally favorable energy production by applying innovative technology [4–6]. As the demand for renewable energy increases, biomass has emerged as a crucial renewable energy source with a good reputation due to its availability and carbon neutrality. Among the numerous varieties of biomass, agricultural waste (crop residue) is gaining increasing prominence as a potential source of bioenergy in an agro-economy, as it consists predominantly of leaves and stems, constitutes a lignocellulosic biomass, and is a suitable feedstock for biorefineries to generate value-added biomaterials and bioenergy (sustainability fuels) [7].

Several valuable plants grow naturally in Southeast Asian nations; most dwell in suburbs, cities, and agricultural areas [8]. *Mimusops elengi* is one of the sources of agricultural residue biomass in Banda Aceh (Aceh, Indonesia). These plants are native trees from India, Myanmar, and Sri Lanka that have been in the archipelago for centuries [9–11]. Banda Aceh (Indonesia) currently has around 6500 *Mimusops elengi* plants across an area of 28.2 ha [12]. According to the literature, these types of plants have been used widely for various purposes, with encouraging outcomes. All parts of the *Mimusops elengi* plant have been studied for medical purposes, including the roots, skin, foliage, flowers, and leaves, and it may even be used as biodiesel (bioenergy) [13–16]. The *Mimusops elengi* biomass residues, particularly the leaves, can be utilized as an alternative energy source if handled appropriately. This residual biomass (leaves) could be used for energy or converted into liquid via a pyrolysis process due to it containing carbon (38.50%), hydrogen (5.23%), cellulose (33.17%), and lignin (10.24%) [17]. It is also noted in the literature that biomass with high cellulose content has the potential to be used as raw material in bioenergy production [18–21]. To the best of our knowledge, there is a limited number of reports on utilizing and converting *Mimusops elengi* leaves (waste) via thermal pyrolysis into value-added compounds (bio-oils). However, it is crucial to emphasize that the potential of agricultural residues (waste) for bioenergy must be observed locally, depending on the environmental factors in a particular location.

Pyrolysis is a thermochemical process (300–700 °C) that makes it possible to convert biomass to bio-oil, biochar, and non-condensable gases [22,23]. Generally, bio-oil is a dark brown liquid fuel with a smoke-like stench that comes from condensing lignin-rich pyrolysis vapor, cellulose, and other carbon compounds [24]. Bio-oil contains alcohol, phenols, organic acids, and carbonyls as its principal organic compounds. It has a slightly lower fuel value than diesel and other light fuel oils but a slightly higher fuel value than other oxygen-based fuels (such as methanol). Even though the pyrolysis of biomasses has been investigated with numerous categories of biomass, such as wood [25,26], agricultural waste [19,27–31], and domestic and industrial waste [32], until now, no prior research has been conducted on the pyrolysis of *Mimusops elengi* for producing bio-oil. Therefore, in this research, the *Mimusops elengi* biomass (leaves) is investigated as a raw material for producing bio-oil as a renewable energy source.

In most previous investigations, different parameters (reaction times and temperatures) were altered to identify the optimal range of bio-oil results. The most suitable temperature for each experiment was 400–600 °C, with reaction durations ranging from 20 min to 3 h [23,33,34]. Even now, few studies have defined the phenomena and issues most commonly associated with the product distribution behavior (functional groups and chemical composition) of bio-oil products at various temperatures and reaction times in the pyrolysis process, particularly regarding *Mimusops elengi* residues (leaves). The objectives of this study were to gain a deeper comprehension of the product distribution behavior in bio-oils derived from *Mimusops elengi* leaves (waste) during the thermal-pyrolysis process (temperature = 300–500 °C; time = 30–120 min) through gas chromatography–mass spectroscopy (GC-MS) and Fourier-transform infrared spectroscopy (FT-IR) analyses. For the purpose of obtaining an understanding of the *Mimusops elengi* biomass's (leaves') characteristics, the material's properties, such as volatile matter, moisture, fixed carbon, and ash, as well as the amounts of carbon (C), hydrogen (H), nitrogen (N), and oxygen (O), are examined via proximate and ultimate analyses. Along with this issue being discussed, the bio-oil's properties, such as pH, density, viscosity, and calorific value (HHV), were extensively examined.

2. Materials and Methods

2.1. Material and Sample Preparation

The biomass used was *Mimusops elengi*, which was obtained from around Darussalam and Banda Aceh (5.565547 N and 95.367807 E). *Mimusops elengi* was first cleaned under running water and dried in the sun for about three days. The dried *Mimusops elengi* was cut into small pieces. It was then put in the oven at 105 °C for 24 h with the aim of removing the water content from the *Mimusops elengi*. The *Mimusops elengi* that had been dried in the oven was ground and sieved to a mesh size of 40. The proximate analysis consisted of the determination of ash, moisture, and fixed carbon content in accordance with ASTM standards (D1102-84, D2016-74, D3178-89, and D3175-07 for ash, moisture, fixed carbon, and volatile matter [35–38], respectively). Employing an elemental analyzer using Unicube Organic Matter Analyzer, United States, the C, N, H, and S of *Mimusops elengi* biomass samples were calculated. Using Equation (1), the oxygen content of the biomass samples was determined, and the results are presented in Table 1.

$$O\ (\%) = 100 - (\text{ash} + \text{sulfur} + \text{nitrogen} + \text{hydrogen} + \text{carbon}) \quad (1)$$

Table 1. The proximate and ultimate analyses of *Mimusops elengi*.

Characteristics	Value
Proximate Analysis (wt%)	
Moisture content	12.00
Volatile matter	62.35
Fixed carbon	21.16
Ash	5.49
HHV (MJ/kg)	18.886
LHV (MJ/kg)	16.41
Ultimate Analysis (wt%)	
C	45.91
H	6.42
O	40.28
N	1.64
S	0.26
Component Analysis (wt%) [17]	
Cellulose	33.17
Hemicellulose	-
Lignin	10.2
Others	-

The heating value was obtained using the elemental analysis results. High calorific value (HHV) and low calorific value (LHV) are the two primary calorific value categories. The difference between HHV and LHV is equal to the water vaporization heat produced by fuel combustion. Mott and Spooner's modification of the Dulong-type formula was used to derive the high heating value of bio-oil [39–41]. Generally, the HHV and LHV formulations are employed when the oxygen concentration exceeds 15%, which is shown in Equations (2) and (3).

$$\text{HHV (MJ/kg)} = 0.3417\ C + 0.1232\ S + 1.3221\ H - 0.1198\ (O + N) - 0.0153\ A \quad (2)$$

$$\text{LHV (MJ/kg)} = \text{HHV} - (0.218 \times H) \quad (3)$$

where C, H, O, N, S, and A are the mass percents of carbon, hydrogen, oxygen, nitrogen, sulfur, and ash in the material, respectively.

2.2. Pyrolysis Process

The pyrolysis apparatus consists of a fluidized bed reactor, a condenser, and a furnace with a temperature controller. The reactor is made of stainless steel and has a biomass raw material capacity of 40 g. The biomass-filled reactor is placed in the furnace, the furnace is sealed, and inert gas is injected into the reactor for approximately 10 min before being turned off [42]. Nitrogen is utilized as an inert gas. Nitrogen's function is to eliminate confined air in the reactor, leaving the reactor devoid of air.

Experiments were conducted with varying temperatures of 300, 350, 400, 450, and 500 °C and pyrolysis durations of 30, 60, 90, and 120 min. The yields of bio-oil, biochar, and gas can be calculated using the formulas % bio-oil yield (% dry weight), % biochar yield (% dry weight), and % gas yield (% dry weight) [43–45]. The pyrolysis employed in this experiment is depicted in Figure 1.

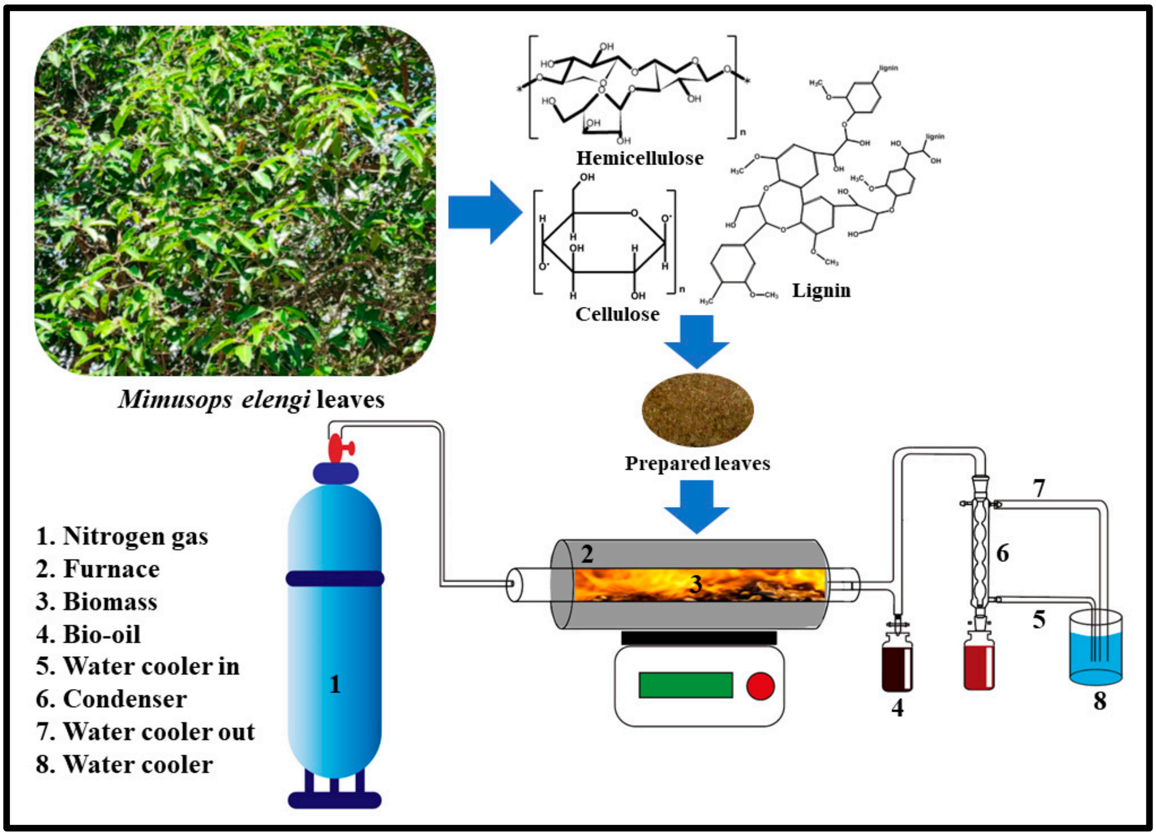

Figure 1. Schematic illustration of the pyrolysis of *Mimusops elengi*.

2.3. Bio-Oil Characteristics

Biomass from *Mimusops elengi* is pyrolyzed to produce bio-oil, a liquid with a reddish-black hue. As shown in Table 2, the bio-oil's characteristics were analyzed in accordance with ASTM 7544-12 to ascertain its physical properties [38]. According to ASTM D240, the heating value measurement was conducted using a bomb calorimeter [46]. The GC-MS Shimadzu QP 2010 Plus (Kyoto, Japan) was used to determine the chemical composition of *Mimusops elengi* bio-oil, and the FT-IR Shimadzu IRPrestige-21 (Kyoto, Japan) was used to identify the bio-oil's functional groups. Meanwhile, the decomposition of *Mimusops elengi* caused by heat was investigated using thermogravimetric analysis and differential thermogravimetric analysis (TGA-DTG Perkin Elmer STA 6000) (Waltham, MA, USA).

Table 2. Characteristics of bio-oil (ASTM 7544-12) [38].

Property	Test Method	Specification	Units
Density at 20 °C	D4052	1.1–1.3	kg/m^3
Kinematic viscosity at 40 °C	D445	125 max	cSt
pH	E70-07	report	

3. Results

3.1. Characterization of *Mimusops elengi*

3.1.1. Proximate and Ultimate Analyses

The proximate and ultimate analyses of *Mimusops elengi* provide a deeper understanding of the characteristics of this biomass and how these characteristics affect the pyrolysis process and the quality of the bio-oil produced. The proximate analysis revealed that the *Mimusops elengi* biomass had a moisture content of 12%, a volatile matter content of 62.35%, a fixed carbon content of 21.16%, and an ash content of 5.49%. High water content can affect the quality of the bio-oil produced because high water content in bio-oil can cause a low heating value [47,48]. However, excess moisture content can also help reduce the viscosity of bio-oil and reduce NO_x emissions [49].

Furthermore, volatile components of the *Mimusops elengi* biomass have a major effect on the bio-oil yield produced via pyrolysis. The greater the proportion of volatile components in biomass, the greater the bio-oil yield. This volatile component can be broken down by heat into vapor, which is then condensed into bio-oil [43,50,51]. In addition, the fixed carbon and ash content of the *Mimusops elengi* biomass additionally affect bio-oil production. High fixed carbon can increase char production, whereas high ash content can decrease bio-oil yield [51]. Therefore, the *Mimusops elengi* biomass, which has low fixed carbon and ash content, is suitable for bio-oil production via the pyrolysis process.

The ultimate analysis of the *Mimusops elengi* biomass revealed carbon, nitrogen, hydrogen, sulfur, and oxygen content of 45.91%, 1.64%, 6.42%, 0.26%, and 40.28%, respectively. The high carbon and hydrogen content indicates the potential for high calorific value in the bio-oil produced [52]. During the pyrolysis process, oxygen binds to hydrocarbon molecules and forms oxygenated compounds that can degrade the quality of the bio-oil. Therefore, a *Mimusops elengi* biomass with low oxygen content produces bio-oil with better quality. In addition, the low nitrogen and sulfur content in the *Mimusops elengi* biomass indicates that the bio-oil produced has a low potential for the formation of NO_x and SO_x, which are harmful to the environment.

By comparing the results of the proximate and ultimate analyses of the *Mimusops elengi* biomass, it can be deduced that this biomass has excellent prospects for bio-oil production via pyrolysis. The biomass of *Mimusops elengi* has a moderate water content, a high volatile material content, and a low fixed carbon and ash content, suggesting that it can produce bio-oil yields of a high quality and quantity. Moreover, the hydrogen content and high carbon content of the *Mimusops elengi* biomass imply that it could be harnessed to produce bio-oil with a high calorific value. By reducing the oxygen, nitrogen, and sulfur content of the biomass, it is possible to ensure that the bio-oil produced is of higher quality and less damaging to the environment.

3.1.2. Thermogravimetric Analysis

Figure 2 depicts the mass change and mass change rate of *Mimusops elengi* as a function of temperature with TGA and DTG graphs. At the beginning of the test, the mass of the *Mimusops elengi* leaves decreased gradually over a low temperature range (28–222 °C) and a short time (0–270 s). This decrease is due to the evaporation of the moisture content and light volatile matter present in the biomass. Then, in the intermediate temperature range (192–497 °C) with a longer time (271–658 s), lignocellulose decomposition occurred in the *Mimusops elengi*. It was seen that there was a significant increase in the rate of mass change at a given temperature, which indicated a more intense decomposition reaction. Furthermore, at temperatures within 250 and 350 °C, hemicellulose decomposition occurred, followed by cellulose decomposition at 350 to 450 °C. At this temperature range, levoglucosan was formed as the main pyrolysis product. It was seen that the rate of mass change reached its peak at a specific temperature, indicating a peak in decomposition activity. At higher temperatures (300–900 °C) [29,30], lignin decomposition occurred in the *Mimusops elengi*. The graph shows that the rate of mass change decreases significantly at these high temperatures, signaling slower decomposition of lignin.

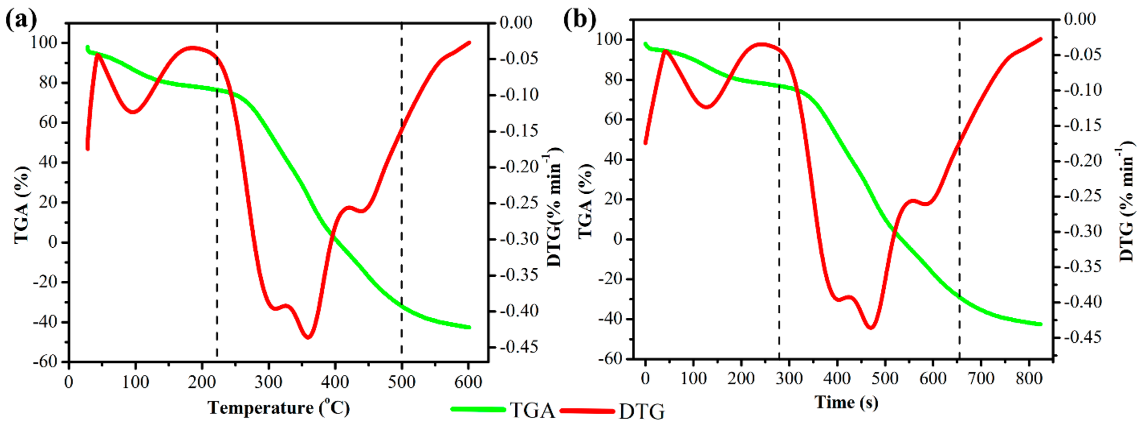

Figure 2. Thermogravimetric analysis of *Mimusops elengi* relative to (**a**) temperature and (**b**) time.

From Figure 2, it can be seen that the decomposition of *Mimusops elengi* reaches its peak at a temperature of about 470 °C and a time of 359.11 s, where the most significant mass change occurs. This temperature can be regarded as the optimum temperature for the decomposition of the *Mimusops elengi* biomass in the pyrolysis process. The TGA and DTG analyses provide a deeper understanding of the *Mimusops elengi* biomass's decomposition patterns. This information can be used to optimize pyrolysis parameters, such as temperature and time, to achieve efficient biomass decomposition and produce bio-oil of the desired quality.

3.1.3. Influence of Pyrolysis Temperature

The influence of pyrolysis temperature on the biomass of *Mimusops elengi* was investigated, and the results are depicted in Figure 3. The graph depicts the variations in the percentages of bio-oil, char, and gas products at various pyrolysis temperatures (300, 350, 400, 450, and 500 °C). At 300 °C, the lowest pyrolysis temperature, the decomposition process is slow and char is the primary by-product. The bio-oil yield at 300 °C was 18.32%, while the char yield was high at 46%. However, as the temperature rose from 300 °C to 500 °C, the yield of condensable bio-oil increased until a maximum of 34.14% was attained. Higher pyrolysis temperatures enhance the heating rate and lignin degradation, thereby increasing bio-oil production. In addition, with the increase in the temperature, the biochar produced decreased from 46% down to 25%. However, the yield of bio-oil decreases when the temperature exceeds the optimal range. This decrease is due to the decomposition of volatile substances into gases and tar into gases and char. The bio-oil yield increased from 18.32% at 300 °C to 34.13% at 500 °C. This can be attributed to the decomposition of lignin at 250–500 °C, which is the main contribution of bio-oil in the pyrolysis process [23,33].

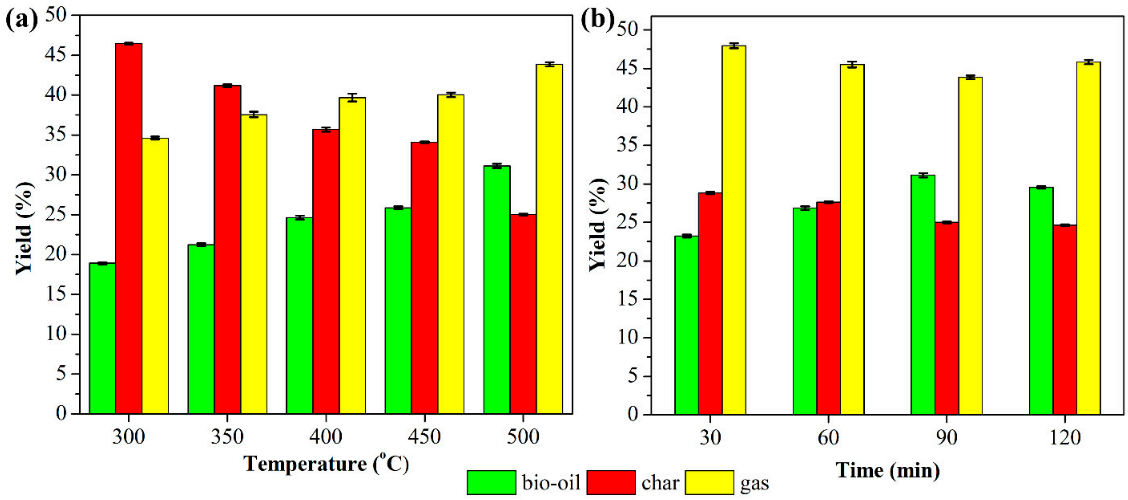

Figure 3. Pyrolysis yield of *Mimusops elengi*; (**a**) the influence of pyrolysis temperature; (**b**) the influence of pyrolysis time.

In contrast, as the temperature rises, the yield of char decreases. Rises in temperature lead to a reduction in char yield due to the increased degradation of *Mimusops elengi* and char residues. Conversely, gas yield increases as the temperature increases. The spike in gas production is expected to be caused primarily by the secondary breakdown of pyrolysis vapor at elevated temperatures.

In addition to the percentages of bio-oil, char, and gas products, it is also necessary to pay attention to the quality of the products produced, which is affected by the pyrolysis temperature. At lower pyrolysis temperatures, bio-oil tends to have a higher moisture content and a lower viscosity. Conversely, at higher temperatures, bio-oil has a lower moisture content and a higher viscosity. In addition, pyrolysis temperature can also affect the chemical composition of the bio-oil produced. At lower temperatures, bio-oils tend to have higher levels of fatty acids and aldehydes. However, at higher temperatures, aromatic components such as phenol and catechol tend to increase.

3.1.4. Influence of Pyrolysis Time

In addition to the influence of temperature, the pyrolysis time also has a significant impact on the pyrolysis yield of *Mimusops elengi*. At a pyrolysis process time of 30 min, the yields of bio-oil, char, and gas products were 23.23%, 28.83%, and 47.94%, respectively. It can be seen that at this relatively short pyrolysis time, the biomass decomposition process is not entirely complete. However, when the pyrolysis process time was extended to 90 min, the yields of bio-oil, char, and gas increased to 34.13%, 21.04%, and 44.83%, respectively. This also happened in the previous study, which used palm shell biomass. At 20 min, the yields of bio-oil, char, and gas products were 61%, 30%, and 7% wt., respectively, while at 30 min, the yields of bio-oil, char, and gas products increased. This increase in yield can be explained by the length of the secondary reaction time, which allows the decomposition of lignin into hydrocarbons to be maximized [53].

The increase in bio-oil yield along with the increase in pyrolysis time show that a longer pyrolysis time provides an opportunity for the chemical reaction to last longer, resulting in better conversion of biomass into bio-oil. The longer pyrolysis process also allows for more efficient decomposition of lignin into hydrocarbon compounds. In addition, it should be noted that the effect of time on gas yield does not show significant changes. Although there are slight fluctuations in gas yield, the difference is not very noticeable between 30 and 120 min. This suggests that reaction time appears to have little effect on gas yield in a given time frame. In the context of longer pyrolysis times, it is also necessary to pay attention to the possibility of excessive thermal degradation, which may reduce the quality of bio-oil products and lead to the formation of unwanted by-products. Therefore, optimization of the pyrolysis time becomes an important factor in achieving maximum bio-oil yield with the desired quality.

3.2. Characterization of Bio-Oil from Mimusops elengi

The bio-oil produced by the pyrolysis of Tanjung leaves has a distinctive reddish-black hue and an acrid odor, as shown in Figure 4. It possesses the characteristics enumerated in Table 3. Viscosity is a measurement of a fluid's resistance to flow, and is affected by variables such as temperature, pressure, and impurities. The viscosity of a substance increases with increasing temperature and reaction time, which indicates that the substance becomes more resistant to flow as it is subjected to reactions at a higher temperature and for a longer time. This can be attributed to the fact that increasing temperature and reaction time can cause the molecules of a substance to become closer together and have more difficulty moving past one another, resulting in a higher viscosity [44]. Viscosity is an important property of fluids that can affect their behavior in various applications, such as lubrication, mixing, and pumping. For example, fluids with high viscosity may require more energy to pump or mix, while fluids with low viscosity may not provide sufficient lubrication or protection in certain applications. Therefore, understanding the viscosity of a substance under different conditions can be important for optimizing its use in various applications. *Mimusops elengi* bio-oil has a viscosity between 1.31 and 1.60 cSt at 40 °C. As a consequence of the bio-oil's high water content, its viscosity is reduced. The water content of the bio-oil is affected by the lignin content of the Tanjung biomass. The rise and fall in viscosity may be due to component degradation. During pyrolysis, the components of bio-oil may undergo thermal degradation. This is also caused by the uneven water content in the biomass. Bio-oil's energy content depends on its density. The density of bio-oil at 15 °C ranges between 1.1 and 1.3 kg/m^3. At 15 °C, the density of *Mimusops elengi* bio-oil ranges from 1.12 to 1.15 kg/m^3. Bio-oil's density depends on its composition [45]. The pH value of *Mimusops elengi* bio-oil at room temperature ranges from 4.0 to 4.4. The pH of the bio-oil obtained is similar to the pH of the bio-oil from previous studies [53,54]. Bio-oil's low pH is a result of the acidity of its composition. Bio-oil is acidic because of its breakdown of hemicellulose and cellulose from the biomass, resulting in a high oxygen content. In terms of direct use or application, the high acidity of bio-oil is detrimental to the product, as it can cause the crushing of constituents during crushing and application [55]. This must be considered in the storage process and production system for the materials used [27].

Figure 4. Bio-oil from pyrolysis of *Mimusops elengi*.

Table 3. Physical properties of bio-oil from *Mimusops elengi*.

Operating Conditions	Density (kg/m^3) @20 °C	Viscosity (cSt) @40 °C	pH	HHV (MJ/Kg)
[a] Temperature (°C)				
300	1.12 ± 0.026	1.31 ± 0.036	4.00 ± 0.053	16.80 ± 0.062
350	1.13 ± 0.026	1.32 ± 0.026	4.11 ± 0.061	17.44 ± 0.087
400	1.13 ± 0.026	1.40 ± 0.036	4.12 ± 0.043	17.59 ± 0.124
450	1.13 ± 0.043	1.42 ± 0.036	4.22 ± 0.078	18.14 ± 0.213
500	1.15 ± 0.043	1.60 ± 0.062	4.41 ± 0.046	19.91 ± 0.081
[b] Reaction time (min)				
30	1.13 ± 0.061	1.56 ± 0.088	4.06 ± 0.111	19.77 ± 0.121
60	1.13 ± 0.070	1.37 ± 0.092	4.00 ± 0.055	16.76 ± 0.079
90	1.15 ± 0.078	1.60 ± 0.026	4.41 ± 0.053	18.14 ± 0.141
120	1.15 ± 0.026	1.44 ± 0.070	4.33 ± 0.061	19.42 ± 0.026

[a] *Mimusops elengi* pyrolysis at 90 min. [b] *Mimusops elengi* pyrolysis at 500 °C.

Calorific value is a crucial consideration in determining a bio-oil's application. The chemical composition of the material itself also influences the HHV value. A composition with a higher concentration of high-energy or combustible organic compounds will have a greater HHV. The HHV of *Mimusops elengi*-derived bio-oil ranges between 6.76 and 19.91 MJ/kg. The HHV of biomass samples complies with the findings of the proximate and ultimate tests based on these results. In addition, previous research has demonstrated that biomass with high levels of cellulose and lignin has an averagely higher HHV value [56]. According to [47,56], lignin has a higher HHV than either cellulose or starch. During pyrolysis, the calorific value of biomass does not always alter the calorific value of bio-oil. This is due to the fact that different forms of biomass with the same calorific value contain different quantities of lignocellulose, volatile matter, and fixed carbon. As a result, under different pyrolysis and biomass conditions, the lignocellulose turns into condensed vapor (bio-oil) [57–59].

3.3. Chemical Composition Based on FT-IR Analysis

Figure 5 and Table 4 show the FT-IR spectra of the bio-oil obtained from the pyrolysis of *Mimusops elengi* at 500 °C and 90 min, which are the best pyrolysis parameters, with wavelengths between 4000 and 500 cm^{-1}. Based on the results of the FT-IR analysis, several functional groups can be identified in the *Mimusops elengi* bio-oil. In the frequency range between 3584–3700 cm^{-1} and 3300–3400 cm^{-1}, there is O-H stretching of the hydroxyl groups of alcohol, phenol, methanol, and ethanol, which are carboxyl groups that bind to aromatic rings in bio-oil. In addition, the occurrence of C-H stretching in the frequency ranges 2850–3000 cm^{-1} and 2815–2880 cm^{-1} indicates the presence of alkanes. The absorption band between 2815 and 2850 cm^{-1} is most likely due to the overlapping C-H bands of ethanol and methanol. The peaks detected between 2100 and 2140 cm^{-1} are indicative of C≡C stretching vibrations that form alkyne compounds, whereas the peaks between 1700 and 1790 cm^{-1} can be attributed to the strong C=O stretching of aldehydes and ketones. The peak between 1620 and 1680 cm^{-1} indicates the presence of variable C=C and moderate vibrational stretching in alkenes and aromatic compounds. Strong stretching vibrations between 1250 and 1310 cm^{-1} indicate the presence of ether (O=C–O–C). The peak at 1035–1085 cm^{-1} indicates the presence of primary and tertiary alcohols due to the elongation of the strong C-O bond. The alkenes' C–H vibrations could elicit an absorbance peak between 610 and 700 cm^{-1}. These functional groups are also present in bio-oils from other types of biomasses [60–63].

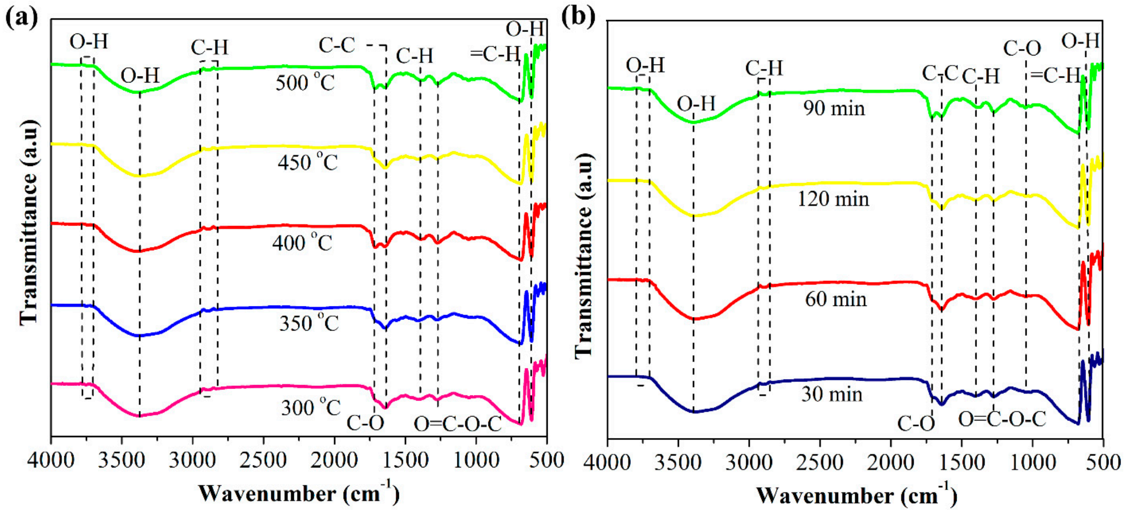

Figure 5. FT-IR spectra of the bio-oil from *Mimusops elengi*; (**a**) FT-IR spectra of bio-oil at different temperatures; (**b**) FT-IR spectra of bio-oil at different times.

Based on the FT-IR spectra of the bio-oil, it can be seen that the *Mimusops elengi* bio-oil contains various functional groups that are typical in chemical compounds. The content of alcohols, phenols, alkanes, methyl, ketones, aldehydes, carboxylic acids, aromatic derivatives, and other compounds can be detected through this FT-IR analysis. By knowing the composition of the functional groups, information about the types of chemical compounds contained in the bio-oil can be obtained. These data are vital in evaluating the quality of bio-oil produced from the pyrolysis process of *Mimusops elengi*.

3.4. Chemical Composition Based on GC-MS Analysis

The bio-oil derived from the pyrolysis of *Mimusops elengi* is a complex mélange of phenols, ketones, alcohol, nitrogen-containing compounds, ethers, aromatic hydrocarbon acids, furans, and esters. Table 5 shows the composition of edible oil from the pyrolysis of *Mimusops elengi*, with the following chromatography conditions: oven temp: 31 °C, injection temp: 270 °C, injection mode: split, flow control mode: linear, and total flow: 71.2 mL/min. A total of 26 chemical compounds were identified in the bio-oil from *Mimusops elengi*. In Figure 6, the predominant compound identified in the bio-oil from the pyrolysis of *Mimusops elengi* is phenol, which is derived from the decomposition of lignin [64]. In all bio-oils from energy crops, phenol is the most abundant compound in bio-oils obtained from lignin decomposition [65]. Phenol compounds contain 42% methoxy, 35% benzenediol, and 21% alkyl phenols. The lignin content in *Mimusops elengi* is 10.24%. However, the lignin content in *Mimusops elengi* is lower than in rice husk at 33.7% [66,67]. Bio-oil derived from *Mimusops elengi* contains 64.2% phenol. As a fuel, the elevated phenol content has several negative effects. High levels of phenolic compounds can increase the acid number, decrease the heating value, lower the pH level, and increase the engine corrosion value.

Table 4. FT-IR results and functional group compositions of the bio-oil.

Absorption (cm^{-1})	Wavenumber (cm^{-1})									Type of Vibrations	Class of Compounds
	[a] Reaction Time (min)				[b] Temperature (°C)						
	30	**60**	**90**	**120**	**300**	**350**	**400**	**450**	**500**		
3584–3700	-	-	3699	3699	3699	3699	3699	3699	3699	O-H stretch	Alcohols
	-	-	3390	-	-	-	-	-	3390		
3300–3400	3379	-	-	-	3379	-	-	-	-	O-H stretch	Alcohols
		3377	-	3377	-	3377	3377	3377	-		
2850–3000	2900	-	-	-	-	-	-	-	-	C-H stretch	Alkanes
	-	2891	-	-	-	-	-	-	-		
	-	-	2889	2889	2889	2889	2889	2889	2889		
2815–2850	-	2835	-	-	-	-	-	-	-	C-H stretch	Esters
	-	-	-	-	2833	2833	2833	2833	-		
	-	-	-	-	2382	-	-	-	-		
	-	-	-	-	-	-	-	2380	-		
2300–2400	-	2376	-	-	-	-	2376	-	-	C≡N	Nitrile stretch
	-	-	2349	-	-	-	-	-	2349		
	-	-	-	2347	2347	2347	-	-	-		
2100–2140	-	2119	-	-	-	-	-	-	-	C≡C	Alkynes
	2112	-	-	-	-	2112	-	2112	-		
	-	-	-	2100	-	-	2100	-	-		
1660–2000	-	-	1867	-	-	-	-	-	1867	Aromatic combination bands	Aromatic
	-	-	-	-	-	-	-	1865	-		
	-	1766	-	1766	1766	1766	1766	-	-	C=O stretch	Aldehydes ketones
1700–1790	-	-	-	-	-	-	-	1764	-		
	1762	-	-	-	-	-	-	-	-		
	-	-	1708	-	-	-	-	-	1708	C=C stretch	Alkenes
	-	-	-	-	-	-	-	1647	-		
1620–1680	-	-	1643	1643	1643	1643	1643	-	1643		
	1641	-	-	-	-	-	-	-	-	C-H blend	Aromatics
	-	1637	-	-	-	-	-	-	-		

Table 4. *Cont.*

Absorption (cm^{-1})	Wavenumber (cm^{-1})									Type of Vibrations	Class of Compounds
	[a] Reaction Time (min)				[b] Temperature (°C)						
	30	60	90	120	300	350	400	450	500		
1450–1600	-	-	-	-	-	1566	-	1566	-		
	-	-	-	1560	1560	-	1560	-	-		
	1516	1516	-	1516	1516	1516	1516	1516	-		
	-	-	1514	-	-	-	-	-	1514		
	-	-	-	-	1452	1452	-	-	-	C-H	Alkenes
	-	-	-	-	-	-	-	1450	-		
1410–1420	-	-	-	1413	-	1413	1413	-	-	O-H blend	Alcohols
	-	-	-	-	-	-	-	1411	-		
1310–1410	1409	-	-	-	-	-	-	-	-		
	-	1404	-	-	-	-	-	-	-		
	-	-		-	1402	-	-	-	-	O=C-O-C	Esters
	-	-	1370	-	-	-	-	-	1370		(aromatics)
1250–1310	-	-	-	1276	1276	1276	1276	1276	-		
	1274	1274	-	-	-	-	-	-	-	C-O stretch	Alcohols
	-	-	1271	-	-	-	-	-	1271		
1035–1085	-	-	1082	-	-	-	-	-	1082		
	-	-	1051	-	-	-	-	-	1051		
	-	1049	-	-	-	-	-	-	-		
	1047	-	-	-	1047	-	1047	1047	-		
990–1050	1016	-	1016	1016	-	-	1016	1016	1016	P-O-C stretch	Phosphorus
	-	-	-	-	1014	1014	-	-	-		
610–700	680	680	680	680	680	680	680	680	680	≡C-H stretch	Alkynes
	607	607	607	607	607	607	607	607	607		

[a] *Mimusops elengi* pyrolysis at 500 °C. [b] *Mimusops elengi* pyrolysis at 90 min.

Table 5. Concentrations of some compounds in *Mimusops elengi* bio-oil from pyrolysis.

No	Compound	Formula	Area (%)	Groups
1	Phosphonic acid	$C_6H_7O_4P$	4.89	Acid
2	2-cyclopentene-1-one, 2-hydroxy-3-methyl	$C_6H_8O_2$	0.97	Ketone
3	Oxiranecarboxamide, 2-ethyl-3-propyl	$C_8H_{15}NO_2$	4.31	Acid
4	p-cresol	C_7H_8O	1.73	Phenol
5	1,2,3-Propanetriol, 1-acetate	$C_5H_{10}O_4$	1.37	Acid
6	3-pyridinol	C_5H_5NO	2.01	Aromatic
7	Glutarimide	$C_5H_7NO_2$	2.22	Acid
8	Guanosine	$C_{10}H_{13}N_5O_5$	1.26	Acid
9	1,4;3,6-Dianhydro-alpha-d-glucopyranose	$C_6H_8O_4$	0.93	Hydrocarbon
10	1,4;3,6-Dianhydro-alpha-d-glucopyranose	$C_6H_8O_4$	7.02	Hydrocarbon
11	3,4-Anhydro-d-galactosan	$C_6H_8O_4$	1.09	Ester
12	Catechol	$C_6H_6O_2$	36.63	Phenol
13	5H-Cyclopentapyrazine	$C_9H_{12}N_2$	2.47	Pyrazine
14	2-Butanone, 4-hydroxy-3,3-dimethyl	$C_6H_{12}O_2$	0.93	Ester
15	1,2-Benzenediol, 3-methoxy	$C_7H_8O_3$	3.31	Phenol
16	1,2-Benzenediol, 3-methyl	$C_7H_8O_2$	3.85	Phenol
17	1,4-Benzenediol	$C_6H_6O_2$	5.61	Phenol
18	Beta-d-Ribopyranoside, methyl, 3-acetate	$C_8H_{14}O_6$	1.29	Ester
19	1,2-Benzenediol, 4-methyl	$C_7H_8O_2$	6.46	Phenol
20	Phenol	$C_8H_{10}O_3$	2.35	Phenol
21	4,6-Dimethyl (1H) pyrid-2-one	$C_{14}H_{13}N_3O_3$	2.99	Ketone
22	1,4-Benzenediol, 2,6-dimethyl	$C_8H_{10}O_2$	1.05	Phenol
23	1,3-Benzenediol, 4-ethyl	$C_8H_{10}O_2$	1.59	Phenol
24	2,5-Dimethoxybenzyl alcohol	$C_9H_{12}O_3$	0.38	Alcohol
25	D-Allose	$C_6H_{12}O_6$	1.65	Hydrocarbon
26	4-Oxo-beta-isodamascol	$C_{13}H_{20}O_2$	1.66	Phenol

The study of the chemical composition of bio-oil derived from the pyrolysis of *Mimusops elengi* is facilitated by the discovery of these compounds. Various properties and qualities of bio-oils, such as acid value, thermal stability, calorific value, and combustion properties, can be altered by these compounds. For the evaluation and development of the prospective use of bio-oil as an alternative energy source, a comprehensive understanding of the compounds contained in bio-oil is essential.

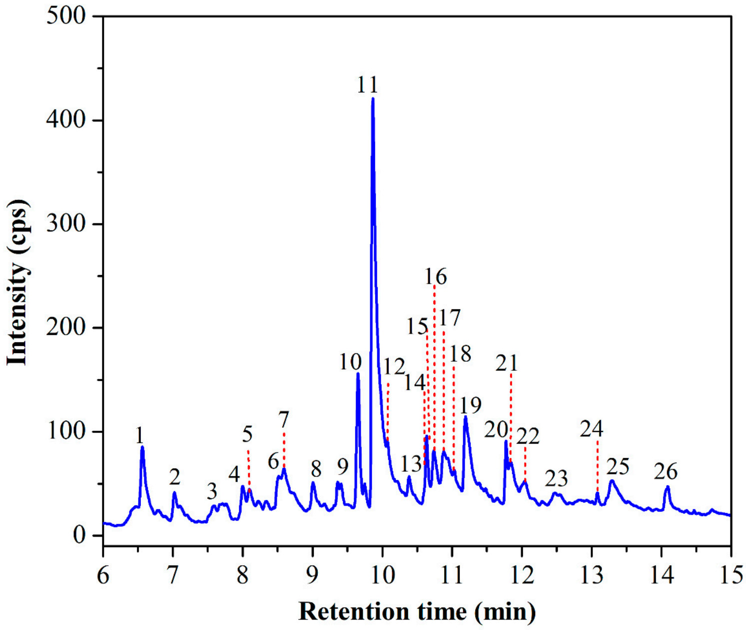

Figure 6. GC-MS spectra of bio-oils from *Mimusops elengi* at optimal temperature and time (T = 500 °C and t = 90 min).

4. Conclusions

In this study, the pyrolysis of *Mimusops elengi* was carried out at a temperature of 300–500 °C and a time of 30–120 min, and the resulting bio-oil was characterized. The optimum conditions for the pyrolysis of *Mimusops elengi* were 500 °C for 90 min at 34.13%, which were relatively similar to bio-oil yield conditions from other agricultural residues. The bio-oil's physical properties as a vegetable oil, such as density, viscosity, pH, and HHV—1.15 g/cm^3, 1.60 cSt, 4.41, and 19.91 MJ/kg, respectively—conform to the bio-oil standard. The resulting bio-oil had a wide range of functional groups, including phenols, acids, carbonyls, and hydrocarbons, which were detected via FT-IR and GC-MS analysis. FT-IR and GC-MS additionally showed that phenolic compounds are the predominant component of bio-oil derived from the pyrolysis of *Mimusops elengi*, indicating that the *Mimusops elengi* biomass is suited to being used as a source of renewable energy. Further research to explore the potential of *Mimusops elengi* in the fields of energy and the environment can be performed by adding catalysts.

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