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A Study of the Holding Time Effect on Char Yield Production in Hydrothermal Carbonization Behavior

Widya Wijayanti[1,*], Purnami[1], Lilis Yuliati[1], Mega Nur Sasongko[1], Elvinda Sangkilang[1], Yafi Dwi Saputra[1], Rizky Kusumastuti[2]

1 Department of Mechanical Engineering, Faculty of Engineering, Brawijaya University, Indonesia
2 Department of Mechanical Engineering, National Central University, Taiwan

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ABSTRACT

This study investigates the energy conversion process of biomass into solid fuel, focusing on hydrothermal carbonization as the chosen method. The aim of study is to produce char with a higher energy yield compared to conventional combustion and pyrolysis methods. By manipulating the holding time in the hydrothermal process, this research examines the energy yields and their relationship with the storage and release of energy, thus impacting the heating values of the resulting char. The study establishes the optimal processing time critical for energy savings in hydrothermal energy conversion. Using mahogany wood as the initial biomass at a pressure of 5 atm and T = 200°C, the experiment involved a 200 g biomass with a 1:4 biomass to water ratio. The holding times varied at intervals of 30, 60, 90, and 120 minutes, respectively. The results indicate a direct proportionality between energy yields and heating values. The highest heating value of char, recorded at 5560.9088 kcal/kg, was achieved at a holding time of 60 minutes, while the lowest value, 2911.501 kcal/kg, was observed at 30 minutes. This suggests that a 60-minute duration in the carbonization process yields maximum energy output. Proximate analysis further supports this, indicating elevated levels of fixed carbon and volatile matter in the hydrothermal process. Then, the comparative analysis demonstrates that the heating value of the char exceeds that of char produced by pyrolysis and even surpasses raw mahogany wood. This study highlights the efficiency of a 60-minute hydrothermal carbonization process in maximizing energy yield, emphasizing its potential in biomass energy conversion.

1. Introduction

In conventional combustion, wood is one of the popular biomasses which is most often used as fuel. Before undergoing thermochemical process, all wood species have almost the same chemical compositions, where proximate analysis of wood identifies 70% to 75% volatile matter, 20% fixed carbon, 0.5% ash content, and has heating values that range from 2000 to 4000 kcal/kg with different densities and water content [1,2]. Therefore, if woods are treated with the appropriate

* *Corresponding author.*
E-mail address: widya_dinata@ub.ac.id

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thermochemical process, it can improve the properties of the wood as desired, which has a great potential as an environmentally-friendly alternative fuel [3,4].

Hydrothermal processing is an energy conversion process of biomass in a state similar to the pyrolysis process. However, the biomass is treated with water. It is processed thermochemically at a high temperature and pressure [5]. This process is intended to provide a way to convert wet biomass without drying in its initial process, as opposed to pyrolysis. In other words, the temperature is sufficient to initiate the pyrolytic mechanisms to decompose biomass feedstock while the pressure is enough to maintain the liquid water processing phase. Meanwhile, hydrothermal carbonization is the process of converting raw biomass into solid products, such as coal—or char—which has the characteristics of high carbon content and high heating value. This type of thermochemical conversion is also referred to as wet pyrolysis (or wet torrefaction), which can be applied to various non-traditional sources, such as the organic fraction from municipal solid waste, wet agricultural residues, sewage sludge, algae, forests, agricultural wastes, household wastes, plantations and industries, and other cultivation residues [6-8].

There are many craft producing biomass wastes in Indonesia, and hydrothermal carbonization is appropriate to be implemented because of the abundant sources of available feedstock. Mahogany is one of the biomass types often used in this country and like in other tropical countries, mahogany has high wettability. This is the reason why this biomass is suitable to be processed using hydrothermal carbonization. The advantage of this hydrothermal process over other processes is that it can use biomass that has a high humidity level without the need to dry it previously.

Hydrothermal carbonization has been extensively studied for the valorization of biomass and organic waste [9,10]. However, there is limited research on the detailed impact of hydrothermal carbonization on the energy properties of high-moisture biomass, such as mahogany, which is prevalent in tropical countries like Indonesia. The potential of hydrothermal carbonization in utilizing mahogany and its effect on the energy properties of the resulting char remain relatively unexplored. Studies have focused on the general benefits of hydrothermal carbonization for various biomass types and its potential in waste conversion, but there is a need for more specific investigations into the energy properties of char derived from high-moisture biomass like mahogany. Further research is required to understand the potential of hydrothermal carbonization in converting mahogany into a valuable energy resource and to evaluate the impact of this process on the energy properties of the resulting char.

Something that is expected from the hydrothermal carbonization product besides the waste processing matter is the amount of energy produced from which it produces char that at least resembles coal with low calorific value i.e., lignite. Therefore, the products of the hydrothermal carbonization process will be observed in the form of the quality which will be identified by the char's physical properties (heating value) and the quantity (the mass and volume of produced char), as well as the constituent elements of the char—specifically, fixed carbon—volatile matter, moisture, and ash content.

In the hydrothermal carbonization process, there are many factors that influence this biomass decomposition process. One of them is the holding time. The significance of holding time in influencing the hydrothermal carbonization process has been acknowledged. Prior research has delved into the effects of holding time on the reaction rates and carbon content of hydro-char. However, there is a lack of detailed comparative analysis under controlled conditions, particularly concerning energy yields and product characteristics [11]. Extensive empirical comparisons between different studies are challenging due to various influencing factors such as temperature, pressure, and reactor design [12]. The hydrochar yield decreases with increasing holding time and temperature, primarily due to the loss of organic volatile matter and functional groups [13]. Under optimum conditions, a maximum energy yield and a high heating value can be achieved. The hydrochar obtained from hydrothermal carbonization has energetic properties close to sub-bituminous coals. Further research is needed to provide a detailed comparative analysis of holding time on energy yields and product characteristics in hydrothermal carbonization. As the pyrolysis process that raises the temperature enriches carbon content, the holding time is also expected to influence the char product related to O/C atomic ratio and H/C atomic ratio [9]. The holding time will provide an opportunity to decompose the biomass molecules at a certain time and at a certain temperature. Each of the biomass' constituent compounds has a different range of temperature decomposition and holding time, so the treatment temperature and holding time greatly affect the product. Because the effect of temperatures has been widely studied, especially on the pyrolysis process, this research will focus on observing hydrothermal carbonization by considering the holding time at a constant temperature [14-16].

Many researchers have investigated the effect of holding time on hydrothermal processes [17-19]. In fact, the holding time can affect the reaction time in order to determine the product compositions and overall yields of the biomass conversion. Since the hydrothermal process and decomposition rates are relatively fast in supercritical processes, a short residence time is expected to degrade biomass effectively [20]. According to Hwang *et al.,* [10] and Lu *et al.,* [21], the carbon content of hydro-char produced by the hydrothermal carbonization process is highly dependent on each particle. Because hydrothermal research still resulted in empirical data, it is very difficult to compare the changes in each carbon particle in each study with different experimental conditions. The reason is that it is determined by various influencing factors, such as temperature, pressure, reaction time, holding time, reactor design, and the ratio of biomass to water.

This study aims to bridge this gap by focusing specifically on the impact of holding time on hydrothermal carbonization while maintaining a constant temperature. By resembling pyrolysis conditions but with water-embedded feedstock and an initial pressure of 5 atm, this research will closely observe the behavior and energy potential of char yields. This approach will provide comprehensive insights into how holding time influences the energy characteristics of the produced char, thereby contributing to a deeper understanding of effective biomass energy conversion processes.

Afterward, this research lies in its specific focus on the detailed impact of holding time within the hydrothermal carbonization process while maintaining a constant temperature. While prior studies extensively explore hydrothermal carbonization's application for biomass valorization and waste conversion, there is a notable gap in understanding its effects on high-moisture biomass. By meticulously studying the relationship between holding time and the resulting char's energy characteristics in hydrothermal carbonization, this research endeavors to bridge gaps in existing knowledge, providing insights into effective biomass energy conversion processes, specifically in utilizing high-moisture biomass like mahogany.

This research lies in several focus on hydrothermal carbonization for enhanced energy yield, optimization of processing time for energy efficiency, utilization of mahogany wood, quantitative analysis of energy properties, and efficiency in biomass energy conversion. The study also aims to explore the impact of holding time on hydrothermal carbonization, specifically focusing on energy yields and char properties while determining the optimal processing parameters. The primary objectives encompass investigating hydrothermal carbonization, identifying the ideal holding time, comparing outcomes with pyrolysis, and evaluating resulting char properties. However, the study faces limitations due to fixed experimental conditions (constant temperature and pressure), sole reliance on mahogany wood as the biomass source, and a narrowed parameter scope that omits variations in process conditions and influential factors like reactor design or water-to-biomass ratio.

Additionally, the need for further replication and exploration to ensure result robustness and broader applicability remains acknowledged within the study's scope.

2. Methodology

The feedstock for the hydrothermal processing was mahogany wood biomass, a craft waste abundant in Indonesia. The properties of mahogany wood can be listed in Table 1, including the compositions of mahogany wood. In this work, we conducted both pyrolysis and hydrothermal experiments in which the experimental device of hydrothermal is illustrated in Figure 1. The pyrolysis process was conducted as a previous work by Wijayanti and Sasongko [22] by using a setting temperature of 200 °C, the same as this recent work for a period of two hours.

Table 1
Mahogany wood properties

Parameters	Nomenclature	Values	Unity
Density	ρ	721	kg/m^3
Thermal conductivity	λ	0.159	W/(m.K)
Heat capacity at constant pressure	*Cp*	1260	J/(kg.K)
Dynamic viscosity	μ	1	Pa.s
Porosity	ε	0.3	1
Permeability	*K*	2.6e-12	m^2
Composition of biomass	*Cellulose*	57.9	%
	Hemicellulose	11.2	%
	Lignin	28.5	%

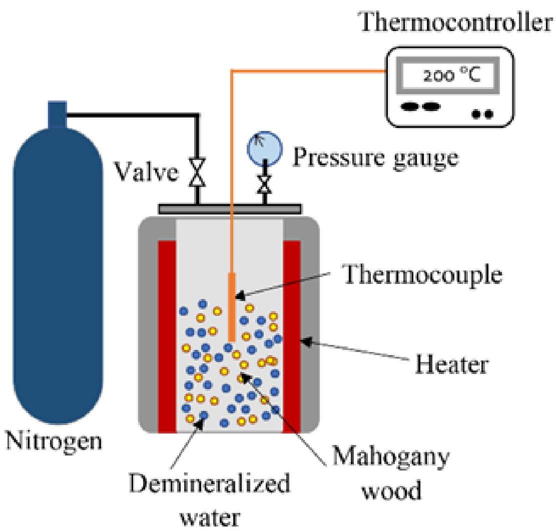

Fig. 1. The hydrothermal carbonization experimental device

In the hydrothermal process, the mahogany wood as a feedstock was weighed around 200 grams in each experiment and was made into needle-like particles with a diameter of around 1 mm. Initially, the wood was mixed with demineralized water with a 1:4 ratio, then it was inserted into the furnace. Then, the furnace was tightly closed with a bolt nut to ensure the furnace was airtight. The furnace was held in the closed system to keep a constant pressure of 5 atm. After it was tightly closed, the next step was to flow nitrogen gas for 5 minutes by opening the valve to forced out oxygen. Nitrogen gas was flowed beside to suppress oxygen, it also acted to increase the furnace pressure to 5 atm. After pressure gauge has shown 5 atm, the furnace was closed and nitrogen gas was stopped.

Then, the hydrothermal process was started by setting the temperature using a thermocontroller to reach a specific temperature of 200 °C. Furthermore, the hydrothermal process took place at a heating rate of 200 °C/hour. The thermocouples were attached to measure the temperature inside the furnace and the change of heat was recorded during the process. When the temperature reached 200 °C, the heater was turned off and the furnace was held according to various times. In this study, the holding time was varied at 30, 60, 90, and 120 minutes after reaching 200 °C around an hour. After accomplishing the process, the furnace was opened, and then the produced char was taken from the furnace and weighed using a scale.

The next investigation after accomplishing the hydrothermal process was measuring the char yields by observing their physical and chemical properties. The investigations of the properties were carried out by identifying moisture level, volatile matter, fixed carbon, and ash yields. The measurement was conducted similar to the proximate analysis finding the percentage of each compound [23]. The measurement also involved heating the char under various holding times to determine the yields by showing the temperature distributions during the process. Besides, the heating value was also measured by using a bomb calorimeter measurement device with the ASTM D 250 method to calculate the energy yields. Then, the snapshot of char yields also were taken to describe the color of char showing carbon quality and other properties. Then, all of the hydrothermally-produced char's properties were compared to the produced pyrolysis char and raw biomass (without undergoing thermochemical process).

3. Results

3.1 Produced Char of Hydrothermal Carbonization

After accomplishing the process, every experiment obtained char yields as shown in Figure 2. Physically, it describes the produced char in the hydrothermal process compared to raw biomass and the char yields of pyrolysis. The figure explains that the hydrothermal only produced the product in the form of solid yields. In this study, the worked hydrothermal temperature was on 200 °C, meaning only cellulose and a portion of hemicellulose decompose in that temperature range into gas and liquid yields, leaving many char yields. This is because cellulose and hemicellulose decompose at around 180 °C– 220 °C [24]. The remained char yields were left inside the furnace, which was then measured to analyse their physical and chemical properties until the energy yield that can be used as solid fuels was found.

Generally, the colour of mahogany wood's char changed from brown to dark brown, starting from a holding time of 30 minutes to 120 minutes. It shows that there was a significant change in the carbon content of the char [13]. If this process is compared to the pyrolysis process, the water content in the hydrothermal leaves the furnace in saturated vapor because, with high pressure, the water changes directly into the gas phase, so the char left in the furnace has a fixed minimum carbon composition [25,26]. The advantage of the hydrothermal process is that the biomass does not need to be initially dried like in the pyrolysis process—a simpler process. However, when compared with raw biomass, it is very clear that the color difference between the raw biomass and the hydrothermal char is significant and it seems that the carbon content of the hydrothermal char is higher than the raw biomass.

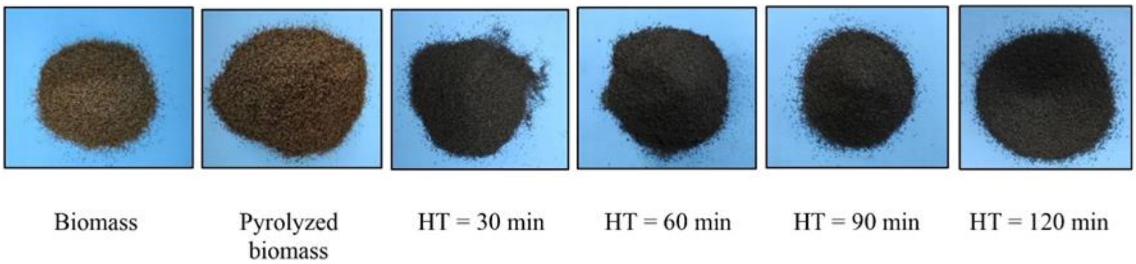

Fig. 2. Comparison of the char yields obtained

3.2 Temperature Distribution During the Hydrothermal Process

Figure 3(a) shows the temperature profiles during the hydrothermal process. After the temperature reached 200 °C at approximately an hour, the process was kept at a holding time of 30, 60, 90, and 120 minutes. From this figure, it can be seen that 10 minutes after the process, temperature distribution fluctuations occur in all variations of the holding time. Exactly at this time, the temperature shows 100 °C in which the peak temperature saturation occurs,which indicates the evaporation of water. A very fast change from the liquid to vapor phase occurs in all variations of the holding time. Heat absorption occurs very quickly where a release latent heat is seen. The phase change occurs for about 10 minutes, then the temperature increases at 60 minutes, showing 200 °C that is kept in holding time. The increase in temperature indicates that the biomass conditions are drier due to water evaporation and volatile matter leaving the furnace.

After that, about 60 minutes after the processing or during the holding time, the temperature fluctuated in all variations of the holding time. This occurs due to the presence of endothermic and exothermic reactions in biomass decomposition. Prior to holding, the biomass undergoes mostly endothermic processes of heat absorption. But after being held at a constant temperature of 200 °C, the temperature fluctuations were seen due to the occurrence of both heat reactions. Because there are repeated heat absorption and heat release during the holding time, this occasion is indicated by the presence of a temperature wave at the time as shown in Figure 3(b). This will give an effect on the release of carbon-hydrogen-oxygen bonds in the biomass constituent so that it will affect the carbon content left in the char yields.

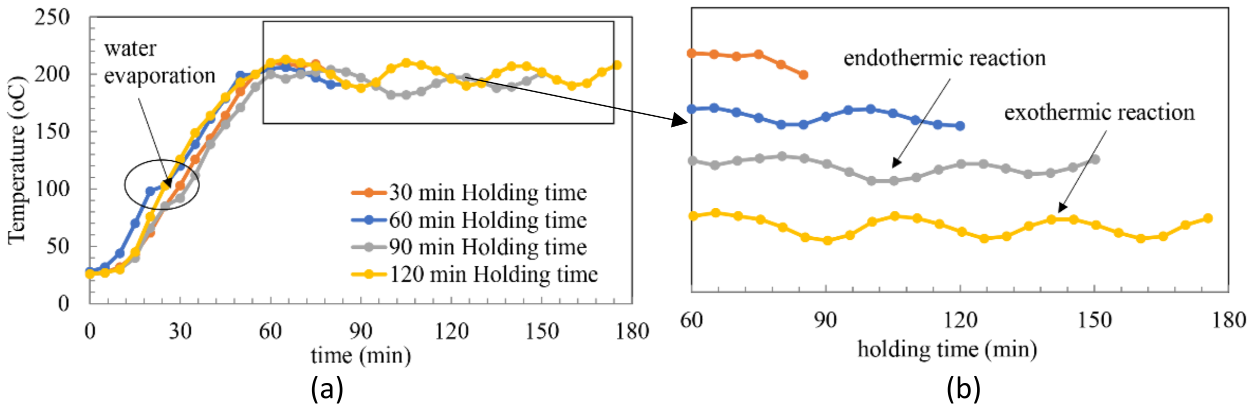

Fig. 3. (a) The hydrothermal temperatures in elapsed time, (b) Zoom in hydrothermal temperatures of the holding time

3.3 Effect of Holding Time on Char Mass Yields

Table 2 displays the initial and final mass of char yields between pyrolysis and the various holding times of hydrothermal experiments.

Table 2
The mass yield of pyrolysis and hydrothermal product

Holding Time (min)	Initial mass (g)	Final mass (g)
Pyrolysis	200	149,71
30	200	120
60	200	130,21
90	200	137,32
120	200	140,2

After identifying the final mass in the process, the percentage of mass yields is determined through Eq. (1). The percentage of mass yields governs the ratio of final mass (m_f) to initial mass (m_i).

$$\%\, mass\ yield = \frac{m_f}{m_i}\ x\ 100\% \tag{1}$$

Then, the percentage of mass yields was found as shown in Figure 4. The percentage of mass yields, with holding time of 30, 60, 90, and 120 min increased to 60.0%, 65.105%, 68.66%, and 70.1%, respectively. It signifies that the longer the holding time, the higher the mass yield. This is because the longer the holding time, the greater the time available for biomass to undergo the hydrolysis process intervened by the water, so that it will affect the final mass of the char products.

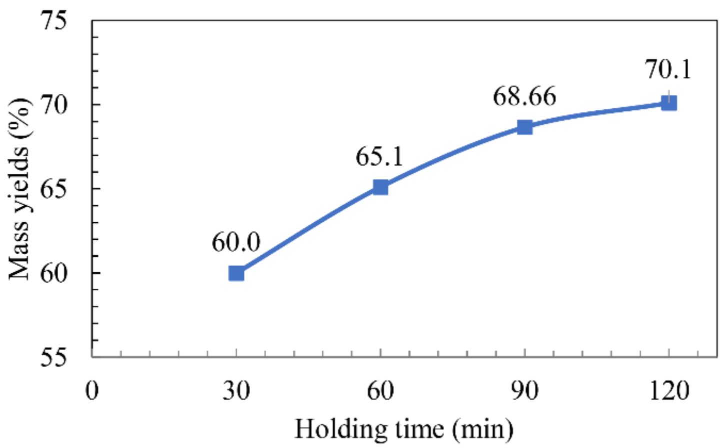

Fig. 4. Percentage of mas yields in the hydrothermal process

Hydrolysis process of cellulose [27]

$$(C_6H_{10}O_5)_n + {}_nH_2O \longrightarrow {}_nC_6H_{12}O_6 \tag{2}$$

Hydrolysis process of hemicellulose [27]

$$(C_5H_8O_4)_n + {}_nH_2O \longrightarrow {}_nC_5H_{10}O_5 \tag{3}$$

From Eq. (2) and Eq. (3), it can be seen that the results of the hydrolysis process of cellulose (Eq. (2)) having an initial relative mass of 162 form a relative mass of glucose of 180. Meanwhile, hemicellulose (Eq. (3)) having a mass of 132 will form a relative mass of glucose of 150. It seems that the empirical formula of relative mass of the hydrothermal products are greater than relative mass (*Mr*) of cellulose and hemicellulose. Therefore, with the increasing amount of cellulose and hemicellulose undergoing the hydrolysis process, more amount of glucose was formed. Then, as the holding time in the hydrothermal process gets longer, the higher the energy bonding of glucose molecule bonds. This, of course, strengthens the carbon molecule bonds, which will affect a higher final mass of the char product.

Figure 5 illustrates a comparison between the mass yield of pyrolysis and hydrothermal on mahogany wood, both at a temperature of 200 °C and holding time 60 minutes. If this is compared to the pyrolysis process, the mass yield of pyrolysis is 74.855% while the mass yield of hydrothermal yield is 65.105%. It can be seen that the mass yield of the pyrolysis is greater than the mass yield of the hydrothermal process. This is due to the important role of water in the hydrothermal process. Water functions as a substance that influence the breaking down of H and O bonds from the biomass compounds to gas yields. When this is associated with the latent heat, water forces the two elements to release into gas yields. This was confirmed by Figure 3, in which the latent heat occurs rapidly only during around 10 minutes.

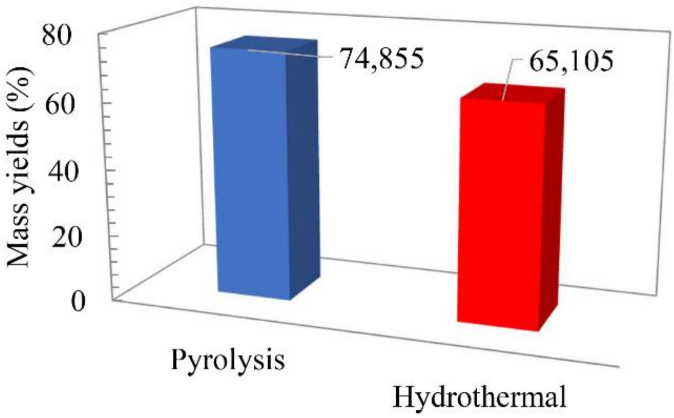

Fig. 5. Comparison of mass yields between pyrolysis and hydrothermal

Water or H_2O is a chemical compound that has hydrogen bonds. The bondsofits chemical elements are polar. The polar bonds of water make the bonds among the H_2O atoms very strong and difficult to break, causing the boiling point of water to be high. When the water is in the subcritical area, there will be a dielectric constant decrease as seen in Table 3, resulting in a reduction in the water polarity—causing the hydrogen bonds in water to become weak. Under conditions of high pressure and temperature, water molecules will move quickly, so they will crash into biomass molecules, then they decompose the components in the biomass (hemicellulose and cellulose) and will cause a hydrolysis process in biomass. In contrast, the pyrolysis method does not have a component that accelerates the decomposition of biomass, so at a temperature of 200°C, the hemicellulose and cellulose have not been decomposed.

Table 3
Physical properties of water [28]

Parameters	Normal water	Sub-critical water	Super-critical water
Temperature (°C)	25	250	400
Pressure (MPa)	0.1	5	25
Density (g/cm^3)	0.997	0.80	0.17
Viscosity (m Pa s)	0.89	0.11	0.03
Dielectric constant	78.5	27.1	5.9
Heat capacity (KJ/kg.K)	4.22	4.86	13
Thermal conductivity (mW/mK)	608	620	160

3.4 Effect of Holding Time on Chemical Properties of Char

To determine the chemical properties of char yields, it was obtained from a similar measurement to proximate analysis for solid fuels. The results obtained are moisture, ash, volatile matter, and fixed carbon. Figure 6 shows the comparison of the percentage measurement of the chemical properties by the proximate analysis carried out on raw biomass, the pyrolyzed char, and the hydrothermal char with a holding time of 30, 60, 90, and 120 minutes. If the proximate analysis is related to the heating value determined in Figure 7, the lowest percentage of fixed carbon belongs to raw biomass with 17.85% and a heating value of 1353.62295 kcal/kg. Meanwhile, the highest percentage of fixed carbon belongs to the hydrothermal process char with a holding time of 90 minutes at 24, 6% with a heating value of 4077.594 kcal/kg. Among these results, it can be seen that the thermochemical process can improve the chemical properties of char compared to that of without treatment (raw biomass).This study shows an increase in char performance for each treatment, as evidenced by the improvement in the percentage of fixed carbon and heating value from raw, to pyrolysis,and hydrothermal at holding times of 30 minutes, 60 minutes, 90 minutes, and 120 minutes.

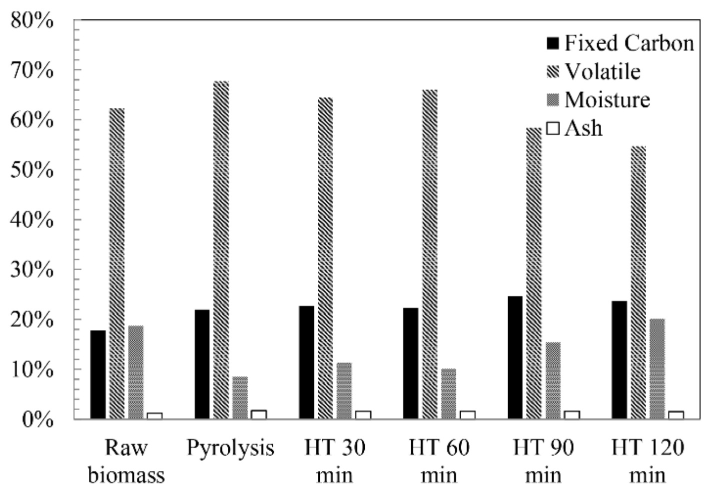

Fig. 6. Proximate analysis among biomass, pyrolysis, and hydrothermal char

Afterwards, one of the advantages of the hydrothermal process is that it works at a lower temperature, though at a higher pressure than the pyrolysis process, and does it not require treatment to reduce the moisture content which is usually less than 2%. The improvement of results of this treatment is proven by this study where the percentage of fixed carbon is higher for all holding times compared to the percentage of fixed carbon resulting from pyrolysis.

3.5 Effect of Holding Time on Char Heating Value

Heating value is an important parameter in measuring the potential energy of fuel. Therefore, the measurement of heating value of hydrothermal char was measured solely to find out how much the energy of fuel will be produced by considering the effect of its holding time as the basic benchmark for this subsequent treatment process. Figure 7 is a graph showing the effect of holding time on the heating value of hydrothermal products. Specifically, the heating value here is a value that describes the amount of energy produced by the combustion process in a certain amount between fuel and air/oxygen in the char yields.

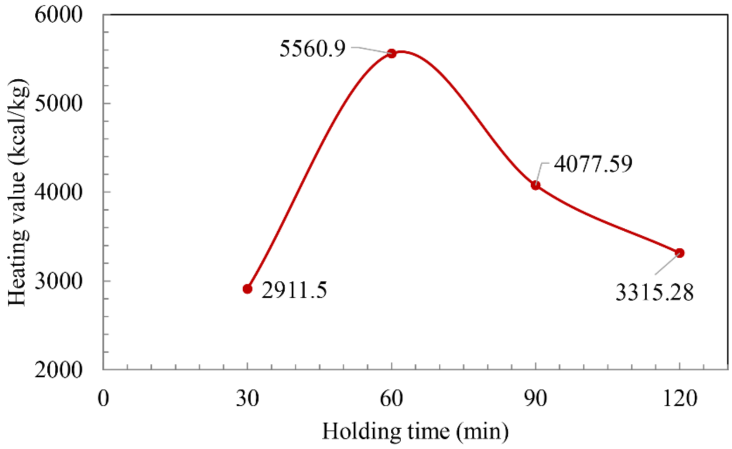

Fig. 7. Effect of Holding time on heating values of char

The heating value is influenced by many factors where, in this study, the factors that can cause changes in heating value are the carbon content (fixed carbon), ash content (ash), and water content (moisture content). Thus, the heating value cannot be separated from the measurement results of the proximate analysis. This can be associated with the previous section in Figure 6, showing the results of the proximate analysis. It was explained that the higher the fixed carbon, the higher the heating value. However, the more ash there is, the lower the heating value will be. Meanwhile, more water content will lead to a lower heating value. It showed that there are several parameters that affect the change in the heating values.

The heating values for each holding time of 30, 60, 90, and 120 minutes are 2911.501 kcal/kg, 5560.9088 kcal kg, 4077.5945 kcal/kg, and 3315.277 kcal/kg, respectively. There is an increase in heating value from a holding time of 30 minutes to a holding time of 60 minutes. This was due to insufficient H and O release at a decomposition time of 30 minutes. In other words, 60 minutes is the optimal time for biomass decomposition. After that, the heating value continues to decline until the holding time of 120 minutes. In general, after 60 minutes of holding time, there is a decrease in the heating values. This is because of longer of time for biomass (hemicellulose and cellulose) to decompose, resulting in more biomass being decomposed into char, as shown in Figure 4. However, after that, when the biomass was fully decomposed, the increase in holding time will only cause an increase in the water content of the biomass, leading to the re-binding of compounds containing H and O, which results in the decrease in heating value. It can be referred this to Figure 6, in which it can be seen that there is an increase in water content from 60 minutes holding time to 120 minutes holding time, indicating that there is a decrease in heating value in this hydrothermal process.

Another effect that affects heating value here is the volatile matter value. In the previous graph, it can be seen that the change in volatile matter value is proportional to the change in heating value. This is because volatile matter comprises flammable gases, such as H_2, CO, CH_4, and condensed liquid fuel, where the presence of these substances will reduce the heating value of a char. They reduce the heating value because their heating value increase proportionally to the increase of gas products [29]. The greater the volatile matter value, the lower the heating value of char.

Furthermore, when it is compared to other char process, Figure 8 shows the comparison of the heating value of chars among raw biomass, pyrolysis, and hydrothermal process. The heating value of pyrolysis and hydrothermal products have higher values than the heating value of raw biomass. So, this is evident that these two thermochemical processes both increase the carbon content of the biomass, therefore also increasing the heating value. However, the hydrothermal process is much more powerful in producing significantheating value of char. The calorific value of the hydrothermal method is much higher than the pyrolysis method, which is 5560.90kcal/kg compared to 3340.30 kcal/kg. This is because water in the hydrothermal process acts as a catalyst, where hemicellulose and cellulose can already be decomposed at temperatures between 180°C – 220°C. Meanwhile, in the pyrolysis process, the hemicelullose is decomposed at 200°C -300°C and cellulose is decomposed at 300°C – 400°C [24]. This may also be due to the effect of a higher pressure present in hydrothermal, in contrary to pyrolysis. This means that the pressure can exert force onto the molecule bonds, making the biomass decomposition easier.

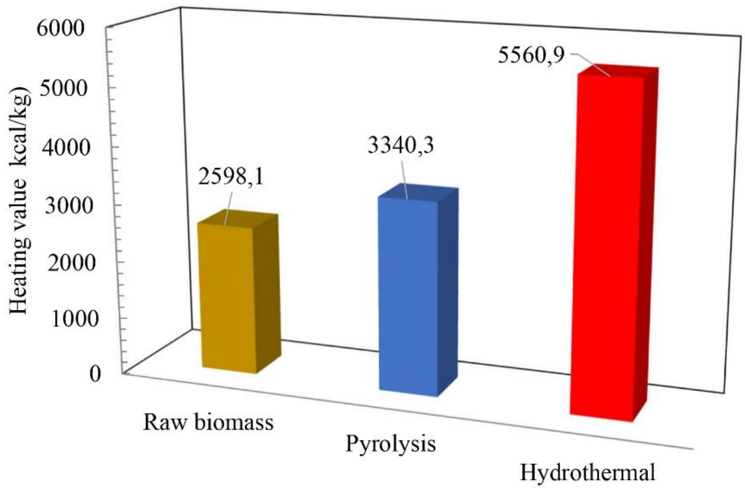

Fig. 8. Comparison of heating values among biomass chars

3.6 Effect of Holding Time on Energy Yields

Finally, the energy yields found by the hydrothermal carbonization process can be reported. Figure 9 describes the effect of holding time on the energy yields of char. The energy yields determine the increased values of the fuel quality—where the fuel is char—produced from the hydrothermal process involving the mass and heating value of char that is expressed by the following equation:

$$\% \ Energy\ yield = \frac{HV\ of\ char\ x\ mass\ of\ char}{HV\ of\ raw\ biomass\ x\ mass\ of\ raw\ biomass}\ x\ 100\% \quad (4)$$

The energy yield determines the comparison between the energy produced by the hydrothermal process and the potential biomass energy before being exposed to thermochemical treatment process.

Figure 9 shows that the energy yield values for each holding time of 30, 60, 90, and 120 minutes were 67.238%, 139.349%, 107.758%, and 97.183%, respectively. There is a line that initially increases from the 30-minute holding time to the-60 minute holding time, decreasing afterward. It shows that the longer the holding time, the higher the energy yield value, and until a certain holding time, it then decreases. It can be seen here that the energy yield trend is described as proportional to the heating value. This is because the heating value shows the amount of char energy, so the energy yield will be directly proportional to the heating value. Even though they were divided by the heating values of raw biomass, the energy yield will follow changes in the heating value which, on the previous chart, it also increased and then decreased. However, it was found that the optimum energy yield in the hydrothermal process is at the 60-minute holding time, i.e., occurring during the two hours of hydrothermal process.

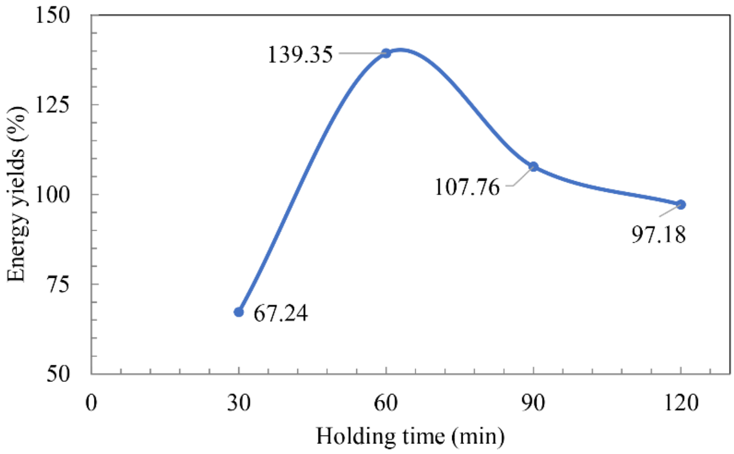

Fig. 9. Effect of holding time on the energy yields of char

4. Conclusions

The research highlights the impact of holding duration on energy output and char quality in hydrothermal carbonization, revealing that despite reduced mass production due to water presence, it enhances char quality. The hydrothermal process presents an advantage by eliminating the need for initial biomass drying, simplifying the process compared to pyrolysis. Notably, the hydrothermal char exhibited a significant color difference compared to raw biomass, indicating a higher carbon content

i. The hydrothermal process simplifies biomass drying, eliminating initial drying requirements, and resulting in higher carbon content char with a significant color difference compared to raw biomass.
ii. Temperature profiles stabilize around 200°C after an hour of hydrothermal processing, indicating water evaporation. Temperature fluctuations occur during biomass decomposition, lasting up to 60 minutes.
iii. The percentage of mass yields increased with holding time—30 mins (60.0%), 60 mins (65.105%), 90 mins (68.66%), and 120 mins (70.1%). The study found that longer holding times resulted in higher biomass hydrolysis, leading to higher char mass production. The hydrothermal process yielded higher mass yields with longer holding times, but the char mass yield was lower than pyrolysis due to water content and pressure differences.
iv. Despite lower mass yields, char quality improved due to increased fixed carbon and heating values, influenced by volatile matter from furnace gas yields. The hydrothermal process yields higher energy than pyrolysis, with a higher heating value (5560.90 kcal/kg) due to water's role as a catalyst. The energy yields for different holding times were 67.238%, 139.349%, 107.758%, and 97.183%, respectively.

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