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Experimental Study on The Characterization of Pyrolysis Products from Bagasse *(Saccharum Officinarum L.)*: Bio-oil, Biochar, and Gas Products

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A B S T R A C T

Sugarcane bagasse is one of the most abundant biomasses. This study aims to examine the characteristics of bagasse using a pyrolysis system to produce liquid, solid (Biochar), and gaseous. A fixed bed reactor was installed in pyrolysis with temperature variations from 300 to 600°C. The ultimate and proximate analysis was applied to evaluate the characteristic of bagasse. The experimental result found that the maximum bio-oil was obtained at a temperature of 550°C. Several characterizations were done, including gas chromatography and surface area analysis. The Levoglucosan compound of 78% area. The temperature effect on pyrolysis influenced the O/C ratio, H/C ratio, HHV value, and surface area of biochar. The High Heating Value was obtained from 16.698 to 18.496 kJ/kg. Biochar results indicated that the surface area, average pore size, and total pore volume are 180.3-198.0 m^2/g, 1.42-4.33 nm, and 0.11-0.12 nm, respectively. The study also analyzed its composition in biochar.

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1. INTRODUCTION

technology need to be developed. Many feedstocks from biomass have great potential for producing biofuels and chemicals (Treedet *et al*., 2022). Moreover, human activities produce large amounts of waste with a high carbon content as a component of biofuels and chemicals (Bhattabiocharjee & Biswas, 2019; Carrier *et al*., 2011; Demiral & Ayan, 2011).

The main components of biomass are lignocellulosic (cellulose, hemicellulose, and lignin), ash, and other compounds. (Chapel and Rotliwala, 2022; Miranda *et al*., 2021). The lignocellulosic compound from biomass consists of three compounds: cellulose, hemicellulose, and lignin, which can be produced from bagasse. These compounds are used as fuel in steam equipment and power supplies (Ordonez-Loza *et al*., 2021). However, this utilization is still not optimal, considering that the availability of this waste is extensive. Bagasse contains 54–86% polysaccharides, 31–54% cellulose, 13–39%, 11–27% lignin (dry basis), and acidic properties (Krishna *et al*., 2022; da Silva Veiga *et al*., 20121). The residual biomass is ash (1–6%) and extractive (2–25%), in small amounts contained in biochar. Excluding ash and extractives included other components, as much as 2-17% (Prasher *et al*., 2022; Varma *et al*., 2017).

The types of technology used for processing bagasse include thermochemical, biochemistry, chemistry, and physics. Thermochemical consist of liquefaction, pyrolysis, gasification, and combustion (Treedet *et al*., 2020). Biochemistry includes fermentation and enzymes. Chemistry includes hydrolysis, solvent extraction, and supercritical. Process physics consists of the mechanics of extraction, briquet, and distillation (Gautam & Chaurasia, 2020; Rodier *et al*., 2019; Savou *et al*., 2019). Pyrolysis produces different products (bio-oil, biochar, and gas); the benefits are more significant than other processes (Aini *et al*., 2022; Aboul-Enein *et al*., 2021; Varma and Mondal *et al*., 2017). Liquid product (bio-oil) as the main product can be applied as fuel for various kinds of industrial equipment by first carrying out an upgrading process to improve product quality (Garba *et al*., 2017; Ghorbannezhada *et al*., 2018; Montoya *et al*., 2017). Biochar is a solid fuel gasified to produce syngas, processed into activated charcoal and absorbent dyes, and used for mushroom cultivation, wastewater treatment, and soil fertility (David *et al*., 2017). In addition, gas can be used as fuel and heating in pyrolysis equipment (Miranda *et al*., 2021). According to (Bhattabiocharjee and Biswas (2019), the biochar result produced a ratio of H/C bio-oil of 1.33 MJ/kg and the HHV of 21.72 MJ/kg with the amount of C2-C18 having characteristics similar to petroleum. At the same time, the HHV biochar is 27.67 MJ/kg.

Varma and Mondal (2017) carried out bagasse pyrolysis in a semi-batch reactor at 350-650°C using samples with a biomass grain size of <0.25 to 1.7 mm and heating rates of 10 and 50°C/min and flow velocity. Nitrogen 50–200 cm^3/min. The process yields a maximum bio-oil of 45.23% by weight at 500°C. The H/C molar ratio and calorific value of bio-oil are 1.27 and 27.75 MJ/kg, respectively.

Paul *et al*. (2021) improved the process from batch to continuous at 350, 500, and 650°C with heating rates of 5°C/min. For constant process using 350, 500, and 650°C to produce bagasse biochar (batch and pilot scale). The continual process for biochar production results in higher carbon content and better aromatic structure than the batch process.

Pyrolysis of bagasse treated with acid and without acid can produce different amounts of Levoglucosan compounds (Guedesa *et al*., 2018). Levoglucosan is the main product formed from the pyrolysis of cellulose, which is then converted into ethanol and can also serve as chemical precursors, surfactants, and food and pharmaceutical additives.

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Biochar is known for its application in removing organic wastes such as naphthalene, phenol, and methylene blue (Zhang *et al*., 2013), inorganic waste in the form of heavy metals (Lu *et al*., 2014), H_2S gas or toxic volatile organic compounds and wastewater (Xu *et al*., 2014; Li *et al*., 2014). Based on various studies on the benefits of biochar in overcoming industrial waste, biochar from bagasse is very potential to be developed.

This study aims to examine the characteristics of bagasse using a pyrolysis system at 300-600°C. The fixed bed reactor was installed for the pyrolysis of bagasse and equipped with a cooler as a condenser. The pyrolysis product and its composition were analyzed.

2. METHODS

2.1. Experimental Materials

2.1.1. Preparation

Bagasse, the primary material in this experiment, was obtained from PT Madukismo Yogyakarta, Indonesia. The material was dried in the sun for three days to get a dry moisture content of less than 10%. The material was ground with a grinder and sieved to get a grain size of 10-40 mesh. The proximate and ultimate analysis of bagasse is shown in **Table 1**. These results were relevant to previous research.

2.1.2. Characterization

The proximate analysis includes moisture content, volatile matter, ash, and fixed carbon that are applied in this research using ASTM standards (E1535-93, D3172, E872-82, and NBR8112). This analysis was carried out at the Research and Development Center for Tekmira Bandung. Moisture content was calculated by weighing the mass lost during the oven at 105°C for 6 hours. Next, volatile content was determined by oven at 950°C for 7 minutes, and ash content was determined by oven at 550°C for 3 hours. The difference from the previous results determines the fixed carbon. Ultimate analysis used a CHN analyzer (Perkin Elmer 2400) based on ASTM D5291-96. The calorific value (HHV) can be calculated using the Dulong and Petit as shown in Eq. (1).

$$HHV = 33950\ C + 144200\left(C_2 - \frac{O_2}{8}\right) + 9400\ S \tag{1}$$

where *C* is carbon, *O* is oxygen, and *H* is hydrogen.

Table 1. Proximate and elemental analysis of bagasse.

Components	This study (wt.%)	Dhyani & Bhaskar, 2018 wt.%	Pradana *et al*., 2019 wt.%
Ultimate			
C	42.50	41.69	43.80
H	6.17	6.47	5.80
O*	51.00	47.66	47.10
N	0.23	0.29	0.40
S	0.10	0.04	-
Proximate			
Moisture	3.83	11.39	-
Fixed Carbon	21.95	13.51	-
Volatile matter	71.60	71.25	84.20
Ash	2.60	3.85	2.60
Cellulose	45.82	31.50	41.30
hemicellulose	20.20	5.40	22.60
Lignin	21.32	48.40	18.30

Note: *oxygen was calculated by difference.

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2.2. Experimental Method

2.2.1. Fixed bed reactor

The research was conducted in a pyrolysis unit with a fixed bed reactor equipped with a condenser. Fixed bed reactors are vertical cylinders with an inner diameter of 4.0 cm, an outer diameter of 4.4 cm, and a height of 60.0 cm. The sample holder is a cylindrical sleeve with an inner diameter of 2.9 cm, an outer diameter of 3.2 cm, and a height of 40.0 cm. Electric reactor heating through a nickel wire wound on the surface of the outer cylinder of the reactor, which has been coated with a phlogopite mica seal layer, which is resistant to temperatures up to 1000°C. Heat in the reactor is controlled by a K-type thermocouple connected to a PID controller, insulated with asbestos tape with a thickness of 9 mm, and then wrapped with fiberglass tape.

The condenser unit consists of 3 condensers; the first condenser with an inside diameter of 0.6 cm and a length of 15.0 cm, and the second and third condensers are Liebig condensers with a length of 40.0 cm. The pyrolysis unit is shown in **Figure 1**.

2.2.2. Procedure

Pyrolysis was carried out by inserting 15 g of bagasse into the reactor sleeve. The sleeve is inserted into the fixed bed reactor and then tightly closed. After that, warm up with a heating rate of 10-12°C/min; after the reactor, the desired temperature has reached. Temperature (300, 400, 500, 550, and 600°C), the heat is maintained isothermally for 60 minutes or until there are no more drips. After each pyrolysis, the equipment is cooled then the biochar product is taken from the reactor. The pyrolysis method in this study is presented in **Figure 2**. The work in this research was characterized in three-part; pyrolysis product, liquid product, and biochar surface.

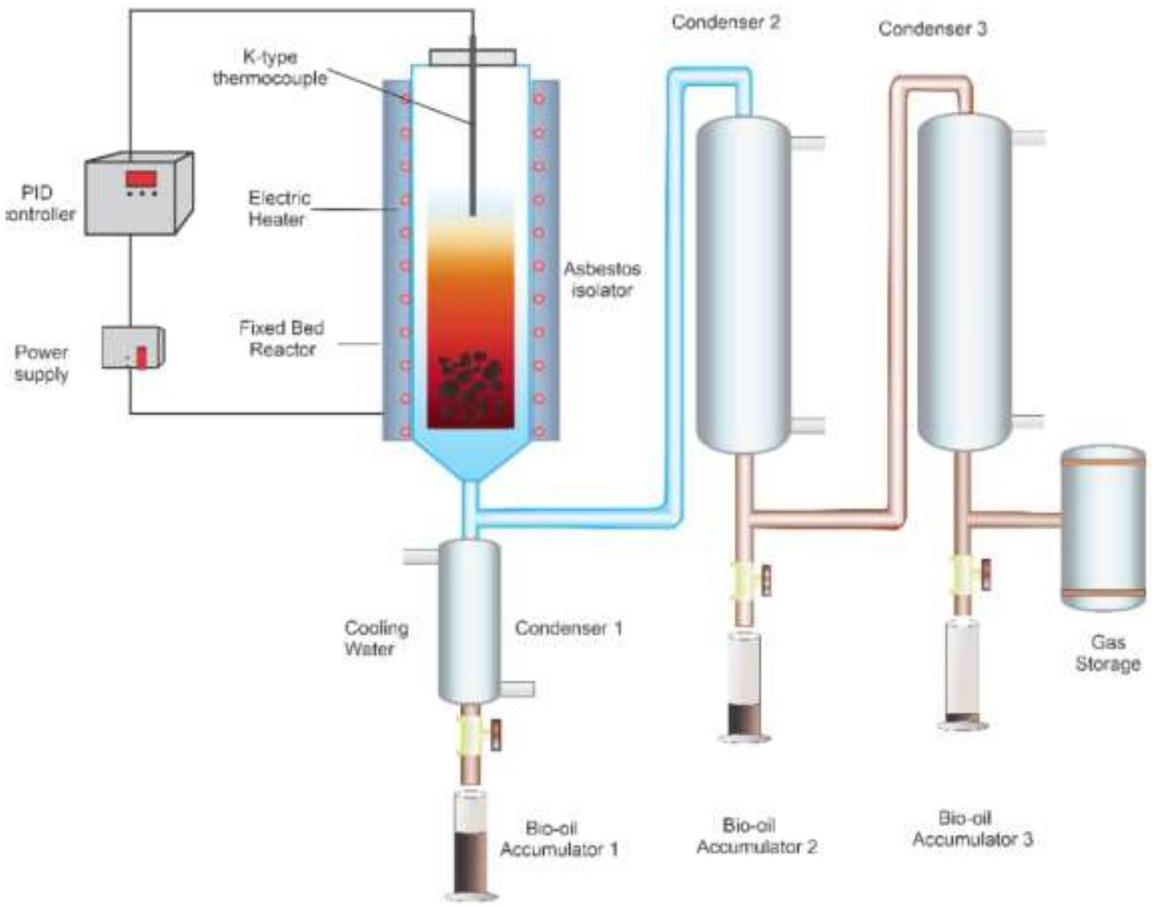

Figure 1. The schematic diagram of the pyrolysis process.

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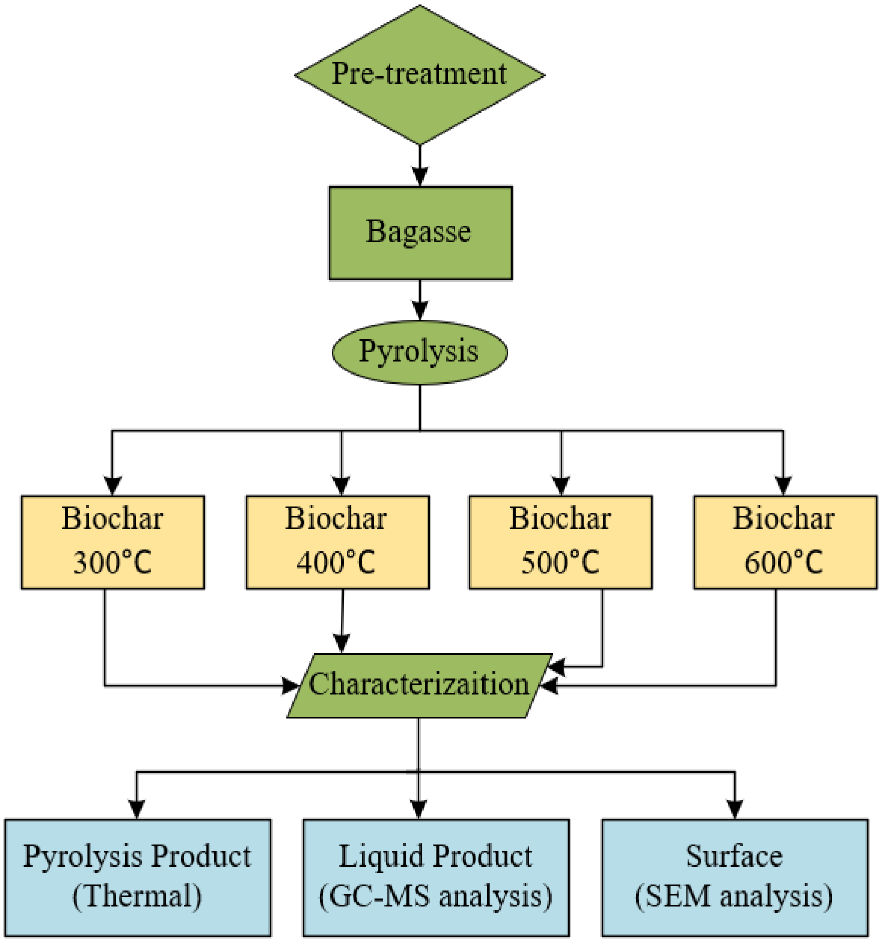

Figure 2. Schematic diagram of the pyrolysis methods.

2.2.3. Pyrolysis products

The pyrolysis product is weighed. The liquid consists of two phases: an aqueous phase and a weighed organic phase. The liquid was poured for 24 hours to separate the two layers, then weighed to determine the weight percent of the starting material. The results of biochar are taken to measure the weight. At the same time, gas yield is measured by calculating the difference between liquid and charcoal from their initial weight. The bio-oil, charcoal, and gas yield are calculated by Eq. (2) - (4).

$$Y_b = {}^{W_b}\!/_{W_m}\, x100\% \quad (2)$$

$$Y_c = {}^{W_c}\!/_{W_m}\, x100\% \quad (3)$$

$$Y_g = {}^{W_g}\!/_{W_m}\, x100\% \quad (4)$$

where Y_b, Y_c, and Y_g are yields of bio-oil (wt.%), biochar (wt.%), and gas (wt.%), respectively. W_m, W_b, and W_c, respectively, are the sample weight of bagasse (g), liquid product (g), and biochar (g).

2.2.4. Product analysis

2.2.4.1. Organic and water phase

The components that make up the organic and aqueous phases are tested with GC-MS (QP2010-SE, Shimadzu) with an RTx5MS capillary column with an inner diameter of 0.25 mm, a length of 30 m, and a film thickness of 0.25 m) and a quadrupole. The analyzer was operated in the electron collision mode (70 eV). The oven column temperature is programmed with an initial temperature of 100°C (5 minutes duration) with a heating rate of 20°C/min to 200°C (duration 6 minutes). Furthermore, the

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heating speed increased from 25°C/min to 300°C (10 minutes); the total time required is 29 minutes.

2.2.4.2. Gas analysis

The gas produced is stored in a plastic gas bag (gasbag), and its composition is analyzed with Shimadzu 8A. Gas Chromatography is equipped with four columns in the oven, two capillary columns, a split/splitless type injector, a flame ionization detector (FID), and a thermal conductivity detector (TCD).

2.2.4.3. Biochar analysis

Brunauer-Emmett-Teller (BET) calculated biochar's surface area and pore volume. Meanwhile, the distribution of pore size and average pore width was determined using the Barret–Joyner–Halenda (BJH) method.

3. RESULTS AND DISCUSSION

3.1. Effect of Temperature on the Pyrolysis Products

The effect of temperature on the pyrolysis product from bagasse as a raw material can be seen in **Figure 3**. In general, the pyrolysis product depends on the reactor temperature. The temperature ranging from 300°C to 600°C produces four products: organic phase, water phase, char, and gas. At 300°C, bagasse pyrolysis mainly decomposes to an organic phase of 3%, water phase of 34%, char of 35%, and gas of 25%. During the pyrolysis process, the pyrolysis product changes in line with the increased temperature. The highest organic phase yield occurred at 550°C with a weight of 6 %. An increase in temperature from 300°C to 550°C causes an increase in organic phase yield from 3 % to 6 %. According to (Varma & Mondal, 2017), The high organic phase is produced due to the increase in the pyrolysis temperature. In addition, (Lin *et al*., 2012; Melia *et al*., 2021) reported that the decomposition of biomass causes a rise in the organic phase. Decomposition of hemicellulose from biomass occurs at 250-350°C, decomposition of cellulose at 325-400°C, and lignin at 300-550°C (Yogalakshmi *et al*., 2022; Qin *et al*., 2022).

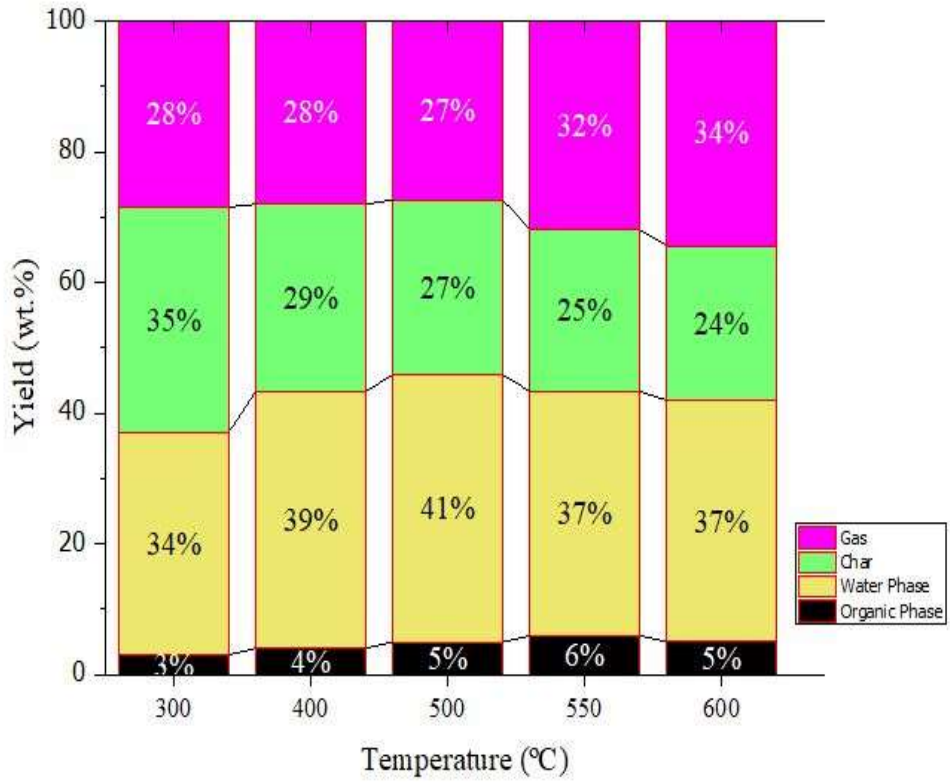

Figure 3. The effect of temperature on pyrolysis products (organic phase, water phase, biochar, and gas).

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The water phase has decreased with the temperature increase from 34% at 300°C to 41% at 500°C. The water phase in bio-oil is caused by pyrolysis dehydration (Tsai *et al*., 2007). The higher the temperature of the dehydration reaction, the more the water phase yield. A high amount of water cause phase separation in the resulting bio-oil product (Kan *et al*., 2016) and reduce calorific value and lower viscosity (Guedes *et al*., 2018; Omulo *et al*., 2019). The increase in temperature from 500 to 600°C causes a decrease in the water phase from 40.85% to 36.67%. An increase in temperature improves the occurrence of secondary cracking in the form of a water-gas shift reaction that produces CO_2 and H_2, as well as a reforming process that converts H_2O into H_2 gas (Davda *et al*., 2005; Han-u-domlarpyos *et al*., 2015). According to Cardosoa *et al*. (2019), The pyrolysis of bagasse of the type *Erianthus Arundinaceus* produced a liquid product of 27.50 wt.% with catalyst and 22.45 wt.% without catalyst.

The increase in temperature in the gas yield tends to be constant and even slightly decreases with increasing temperature. This occurs because the secondary reaction does not convert volatile components into non-condensable gases, resulting in low and high bio-oil yields. The increasing temperature causes lower biochar yield. The literature stated that pyrolysis at temperatures of less than 400°C produces more biochar yields (Melia *et al*., 2021). Pyrolysis at high temperatures produces less Biochar (Omulo *et al*., 2019), due to increasing temperature, the greater the decomposition of biomass, the higher the volatile components released (Jamilatun *et al*., 2019).

The char product in this study was compared with the experiment from (Santamaria *et al*., 2020; Tokmurzin *et al*., 2022), and the char product continuously increased with the temperature increase. Then char product slightly decreased at temperatures above 500°C.

The effect of temperature on the pyrolysis reactor also affects the conversion of pyrolysis products. The conversion product in this study is shown in **Figure 4**. The biomass conversion begins at a temperature of 300°C with 65.66% of biomass conversion. During the pyrolysis process, the temperature continuously increased with the increase of conversion. The high temperature increases the uniformity of the temperature of the biomass particles. Thus, it increases the decomposition of biomass into bio-oil, water, and gas phases. Thus, the higher the temperature, the higher the conversion of biomass. At 400°C, conversion was increased to 600°C. the highest conversion at 600°C was 76.50%.

3.2. Chemical Compound of Liquid Product

The liquid product as the pyrolysis product in this study is shown in **Table 2**. GC-MS analysis was applied in this study to identify the chemical composition of pyrolysis bagasse. The most abundant component is Levoglucosan. The area of Levoglucosan at 300, 400, 500, and 600°C were 48.06, 71.83, 70.52, and 75.28%, respectively. This percentage indicates that the levoglucosan content is very high at all temperatures. Levoglucosan is a material that can be processed into fuel, such as ethanol, and for other purposes. Another product is Hexadecanoic acid or palmitic acid, which helps to moisturize the skin to treat dry, scaly skin, psoriasis, and eczema for cosmetic purposes. Next is the food's flavoring and fragrance agent, heptyl formate (possibly 2-ethyl pentyl formate). According to (Soongprasita *et al*., 2021), aromatic furan (2,3-dihydro benzofuran) is obtained from the rapid pyrolysis of bagasse lignin at 400–600°C while alkyl phenol and phenol at 700°C.

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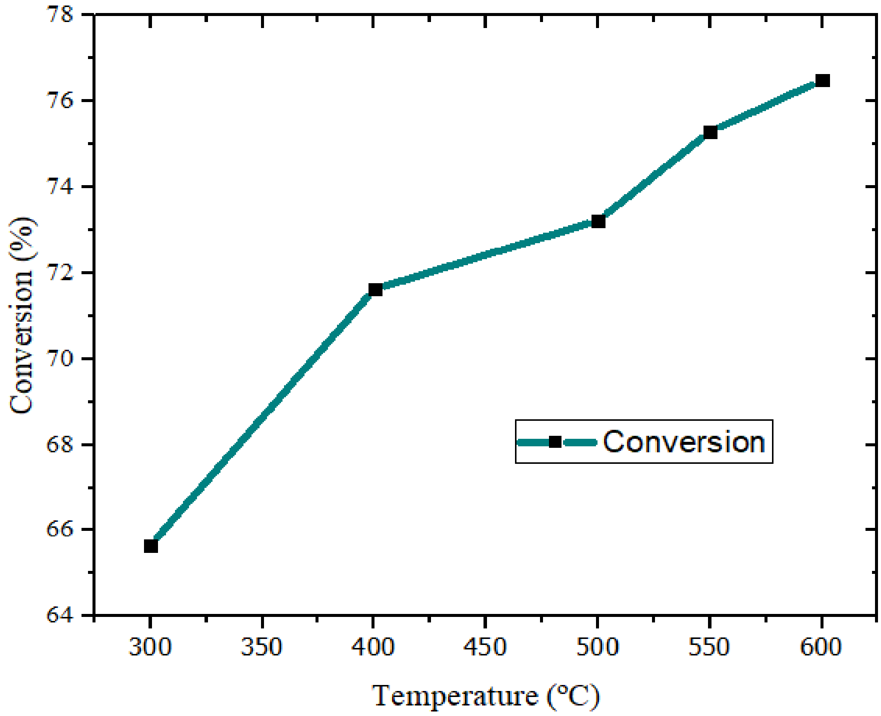

Figure 4. The relationship between temperature with bagasse pyrolysis conversion (%).

Table 2. Composition, percent area, and formula of the pyrolysis liquid product at various temperatures

Chemical Compound	Formula	Peak Area, %			
		300°C	400°C	500°C	600°C
1,2-Cyclopentanedione, 3-Methyl- (CAS)	$C_6H_8O_2$	5.72		1.33	1.37
Heptile Format (Probably 2-Ethylpentyl Format)	$C_8H_{16}O_2$	6.34	7.93	8.27	
Benzene, 1,2,3-Trimethoxy- (CAS)	$C_9H_{12}O_3$	1.54	2.46	4.04	
1,6-Anhydro-Beta-D-Glucopyranose (Levoglucosan)	$C_6H_{10}O_5$	48.06	71.83	70.52	75.28
Alpha. -Beta.-D-Ribopyranose, 1,3-Di-O-Acetyl	$C_9H_{14}O_7$	1.82		2.18	1.86
Hexadecanoic Acid (CAS)	$C_{16}H_{32}O_2$	5.99	2.01	2.02	2.36
9-Octadecenoic Acid -,2,3-Dihydroxypropyl Ester (CAS)	$C_{21}H_{40}O_4$			2.57	
Octadec-9-Enoic Acid	$C_{18}H_{34}O_2$				2.93
1,5-Dioxane, 2-Ethoxy-9-Methyl- (CAS)	$C_{10}H_{20}O_3$				7.26
4-Methoxy-3- (Methoxymethyl) Phenol	$C_9H_{12}O_3$				4.41
Benzeneethanamine, 3,4,5-Trimethoxy- (CAS)	$C_{11}H_{17}NO_3$				2.15
1,2-Cyclohexanedione (Cas)	$C_6H_8O_2$		2.58		
5-Isopropyl-3,3-Dimethyl-2-Methylene-2,3-Dihydrofuran	$C_{10}H_{16}O$		3.05		
Heptadecene-(8)-Carbon Acid-(1)	$C_{18}H_{34}O_2$	11.15	2.15		
1,2-Epoxy-3-Propyl Acetate	$C_5H_8O_3$	6.18			
3-Pentanol, 2-Chloro-4-Methyl	$C_6H_{13}ClO$	2.58			
Nonanal (CAS)	$C_9H_{18}O$	2.27			
2-Hydroxy-3-(Palmitoyloxy) Propyl (9e)-9-Octadecenoate	$C_{37}H_{70}O_5$	3.23			

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3.3. Elemental Analysis of Liquid Product

The pyrolysis process found chemical compounds, including carbon, hydrogen, nitrogen, oxygen, and sulfur. The elemental composition of bio-oil can be seen in **Figure 5**. Bagasse as raw material was pyrolyzed at temperatures ranging from 300 °C to 600 °C. Each temperature condition affects the bio-oil component obtained in this experiment. Sulfur and nitrogen content was obtained from 0% to 0.9%. This shows that the state of the bio-oil obtained is excellent. According to (60), the presence of nitrogen and sulfur in bio-oil can be detrimental because the combustion that occurs in bio-oil can release NOx and Sox, which can cause air pollution. The amount of nitrogen and sulfur depends on the amount of nitrogen and sulfur contained in the raw material. Differences in sulfur and nitrogen content in raw materials and bio-oil indicate that the pyrolysis process can cause degradation in chemical reactions. Oxygen content is obtained in the range of 7%-10%. The amount of oxygen in the bio-oil is used to determine the calorific value of the bio-oil. The carbon content obtained in bio-oil ranges from 32%-35%. In contrast, the hydrogen content ranges from 55%-59%. The percentage of hydrogen and carbon decreased in line with the decrease in pyrolysis temperature.

3.4. O/C, H/C, and HHV Ratio on Liquid Product

The experiment result indicated that H/C values decreased from 1.81 to 1.72 when the pyrolysis temperature significantly increased from 300°C to 600°C. These cases are affected by increasing the aromatic compound via transformation reaction. The quality of liquid fuel is affected by scores of O/C and H/C (Stegena & Kaparajua, 2010). In this study, the increase in the pyrolysis temperature affects the growth of O/C values. In contrast, increasing the pyrolysis temperature affects the decrease of H/C. This ratio is to determine the quality of liquid fuel. The parameter of good fuel has a low O/C value and a large H/C value. This result was compared to the previous experiment by Varma and Mondal (2017). Next, we experimented with bagasse pyrolysis with the result of 1.27 H/C and 0.3 O/C for a liquid product. The lower oxygen content is beneficial for the fuel and also increases the HHV of the fuel. The relationship between temperature and the ratio of O/C and H/C can be seen in **Figure 6.**

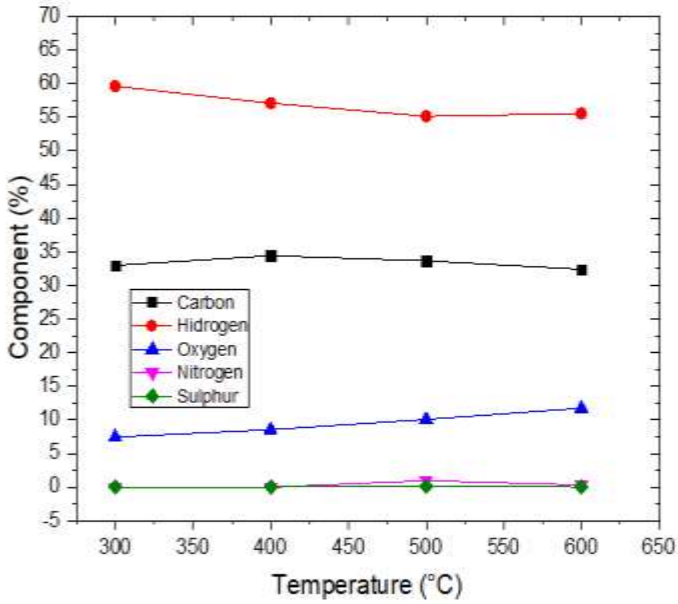

Figure 5. Component of bio-oil at different temperatures.

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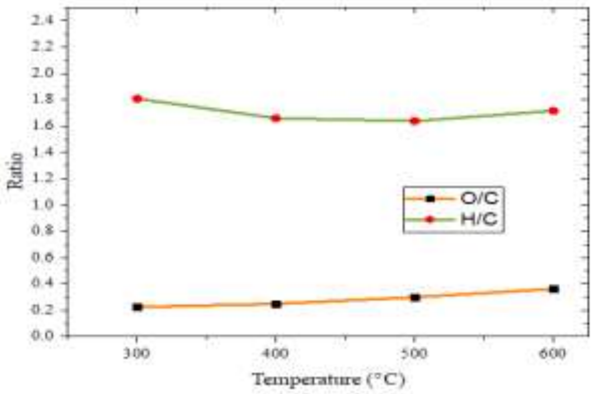

Figure 6. The relationship between temperature (°C) and the ratio of O/C and H/C.

Additionally, HHV in bio-oil is considered the most critical parameter to measure the quality of combustion energy. HHV is the total energy released from the fuel when it is burned with oxygen. Based on formula (1), the results of HHV in this study can be seen in **Figure 7**. O/C and H/C values influence the relationship between temperature and HHV. The increasing trend of O/C. The content of O reduces the calorific value (Varma& Mondal *et al.*, 2017). In this study, HHV has been compared with the results of previous studies, which can be seen in **Table 3**. HHV showed relatively the same results as previous studies. The calculation of HHV is influenced by the value of carbon, oxygen, and hydrogen obtained from bio-oil production.

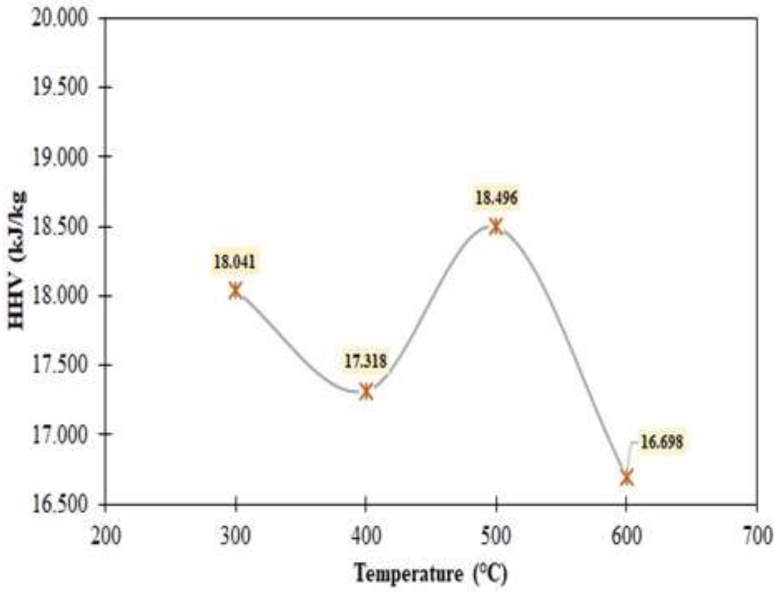

Figure 7. The relationship between temperature (°C) and HHV (kJ/kg).

Table 3. The comparison of HHV value.

Biomass types	Process	HHV Value (MJ/kg)	Author
Napier Grass	Pyrolysis	17.29	(Lee *et al*., 2010; Mufandi *et al*., 2020)
orange waste	pyrolysis	19.49	(Alvarez *et al*., 2018)
Spirulina S	pyrolysis	22.34	(Chaiwong *et al*., 2013)
This Study	**pyrolysis**	**18.49**	

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3.5. Biochar Products

The physical properties of biochar are essential for identifying the biochar applications such as soil remediation and wastewater treatment. This research applies specific surface area, total pore volume, and average pore size. The Biochar characteristic can be seen in **Figure 8.** Furthermore, biochar can be applied as an adsorbent on heavy metals such as Fe, Cu, Pb, Cd, etc.

The high carbon content in biochar can be used as an adsorbent by impregnation with metal to increase the potential to overcome liquid waste. In addition, the HHV height of biochar is 24.31 MJ/kg, which can be used for solid fuels. (Varma & Mondal, 2017). Biochar absorption is determined by surface area, pore volume, and size. The Surface area of biochar in this study was formed at a temperature ranging from 300 to 600°C.

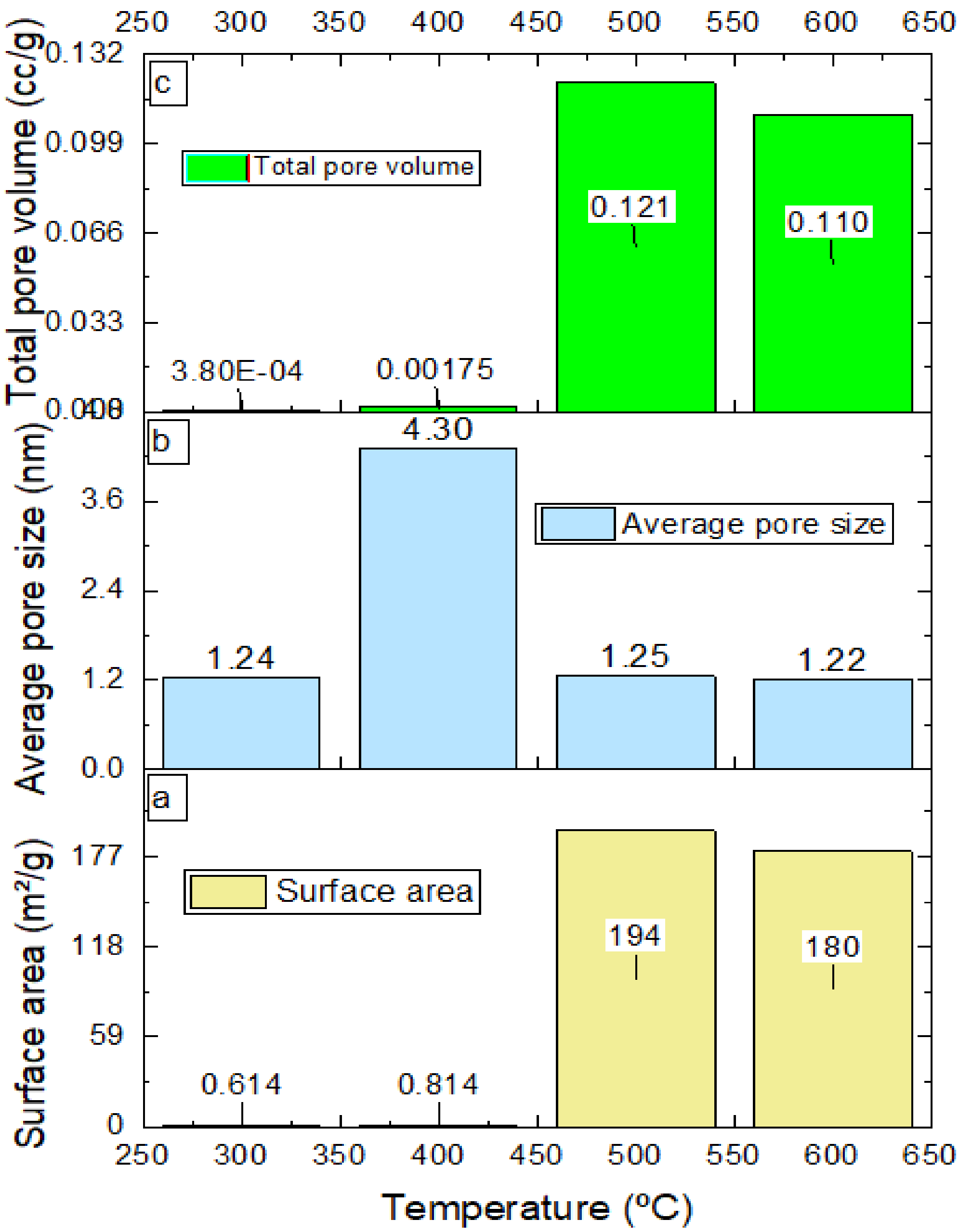

Figure 8. Biochar characteristics: a) surface area, b) pore size, and c) pore volume.

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The biochar formed at 300 and 400°C was 0.61 and 0.81 m^2/g, respectively. During the pyrolysis process, the pyrolysis temperature increases. The surface area of biochar increases when the pyrolysis temperature increases. This is due to the limited interaction of the secondary cracking of oil. According to (Chen *et al*., 2021), the lower biochar product and larger surface area are due to less coke deposition.

Surface areas at temperatures of 500 and 600°C were obtained at 180.3 and 198.0 m^2/g. Other parameters to determine biochar quality are mean pore size and volume. In this study, the maximum mean pore size of biochar was obtained at a temperature of 300, 400, 500, and 600°C with the result of 1.42, 4.30, 1,25, and 1.20 nm, respectively. While the total pore volume was obtained at the temperature of 300, 400, 500, and 600°C with the result of 0.0003, 0.001, 0.12, and 0.11 cc/g, respectively.

These indicate that higher temperatures can effectively increase biochar's specific surface area and pore volume. In addition, the difference between the surface area of the mesoporous biochar and the microporous biochar is not significant. Biochar can be developed into advanced materials (catalysts, adsorbents, and soil enhancers). From the BET test results, there is an excellent opportunity for biochar to be further processed into activated charcoal and used as an adsorbent impregnated with Fe.

The Fe/C material then treats industrial waste such as batik waste. Large pore volume provides quick access to oil filling to small clay particles, making it more efficient. The large pore volume accommodates much dirt to take certain impurities as waste. The larger the pore volume, the greater the ability to absorb dirt (Qin *et al*., 2022). According to the literature (Prasher *et al*., 2022), biochar produces activated carbon with an average pore size of 1-3.5 nm and a higher grain surface area than activated carbon on the market.

3.6. Morphology Analysis of Char Product by SEM

Biochar product was visualized by SEM method, and the result in this study can be seen in **Figure 9**. The pyrolysis temperature significantly affected the surface morphology of the biochar. SEM analysis in this study was applied at the temperature pyrolysis at 300, 400, 500, and 600°C. During the pyrolysis process, the surface morphology of the biochar becomes rough and has a relatively large hole.

This result is influenced by the organic components of the cracked biomass, and the resulting gas molecules expand the pore structure of the biochar. The morphology of biochar at 300°C showed a small hole enough, and a hole showed a non-significant difference. At the same time, the morphology of biochar at the temperature of 400°C began to show a hole with a size large enough.

The surface condition of the biochar at a temperature of 500°C experienced several broken holes, and the size was irregular. At 600°C, the morphological structure of biochar has a large and uneven porosity between layers. The results of this study are related to research (Leng *et al*., 2021; Liao *et al*., 2022). Biochar has several characteristics. All biochars have pores in the physical structure. The pore size of biochar changes in line with the increase in pyrolysis temperature.

3.7. Gas Product of Pyrolysis

Gas production from the pyrolysis of bagasse contains CH_4 and CO_2, shown in **Figure 10**. CO_2 gas at 300°C pyrolyzes has a concentration of 100 wt.%. and CH_4 has a concentration of 0 wt.%. With the increase of the pyrolysis temperature, CH_4 has decreased sharply from 4.96 wt.% to 1.90 wt.% at a temperature ranging from 400 to 600°C. In contrast, CH_4 gas has increased sharply from 95.04 to 98.10%. This condition indicated that the pyrolysis of bagasse could potentially produce gas for fuel.

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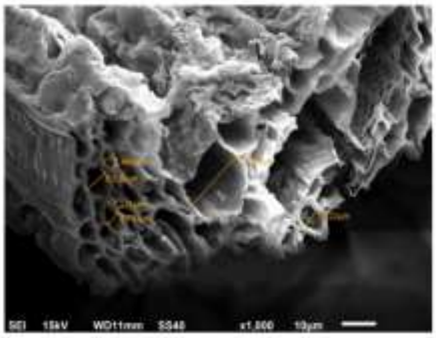
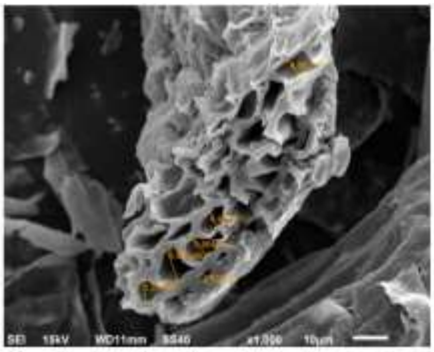
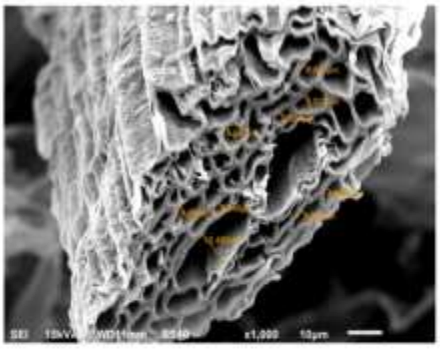
Gas products from bagasse pyrolysis can have almost 100% of the gas from burning bagasse containing CH_4. According to Varma and Mondal (2017), the pyrolysis of bagasse can produce more gaseous products at a temperature of 500°C consisting of 45.6 mol% of CO, 36.8 mol% of CO_2, 5.7 mol% of H_2, and 11.9 mol% of CH_4.



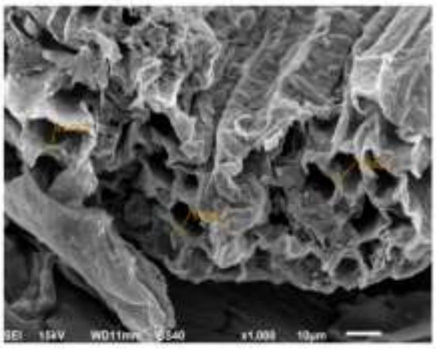
a) SEM images of pyrolysis bagasse at 300°C



b) SEM images of pyrolysis bagasse at 400°C



c) SEM images of pyrolysis bagasse at 500°C



d) SEM images of pyrolysis bagasse at 600°C

Figure 9. The SEM analysis for observation of biochar morphology at various temperatures: (a) 300, (b) 400, (c) 500, and (d) 600°C.

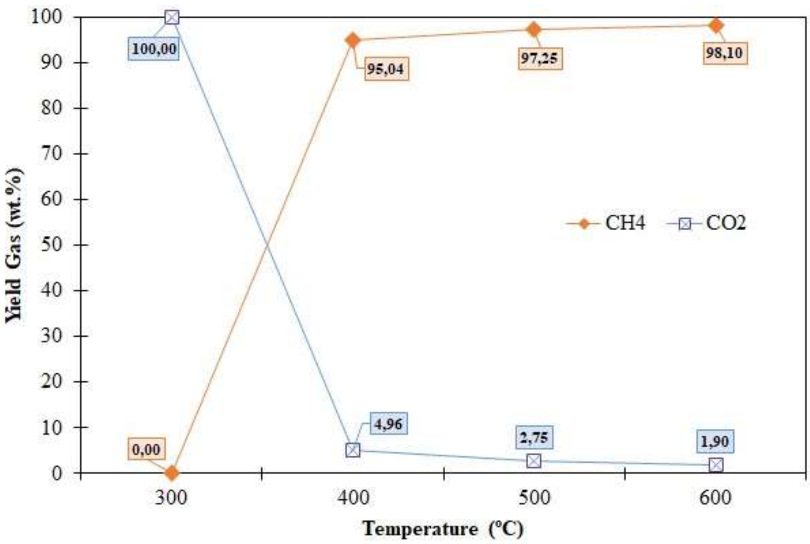


Figure 10. Relationship between temperature (°C) and gas yield (wt.%).

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4. CONCLUSION

Bagasse pyrolysis products have great potential to be developed into various valuable products. Three products from bagasse pyrolysis in this research include liquid, solid, and gas products. Liquid products for biofuels and very high levels of Levoglucosan can be used as materials for bioethanol production. The experiment found that the temperature characteristic affected the liquid, solid, and gas. The result of the liquid product was increased with the increase of the pyrolysis temperature. In addition, the surface area, total volume, and pore volume of biochar were affected by the temperature process. The O/C value in the water phase increased. However, the H/C value decreases—gas products for fuels with high CH4 content. Biochar products are used for industrial waste adsorbents, catalysts for chemical processes, and soil amendments. Biochar contains much carbon (C) and a large enough surface area to be further processed into liquid waste treatment materials. The increase in temperature causes the yield of liquid products to increase, while it causes the optimum temperature of 550°C to decrease. Biochar yield decreases with increasing pyrolysis temperature; the gas drops to a temperature of 500°C and rises to a temperature of 600°C.

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6. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. Authors confirmed that the paper was free of plagiarism.

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