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Valorization of Banana Bunch Waste as a Feedstock via Hydrothermal Carbonization for Energy Purposes

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ABSTRACT

In this article, the potential use of banana bunch waste (BBW) as a source of bioenergy through hydrothermal carbonization (HTC) was investigated. BBW, a byproduct of banana production, is difficult to use as a fuel due to its low density and carbon ratio. However, its high lignocellulose content indicates its potential as a bioenergy source. To determine the optimal HTC conditions, an experiment was conducted using temperature, water to feedstock ratio, and processing time, with the RSM Box-Behnken method used to produce 15 trial formulations. Energy value and mass yield data were collected to determine the optimal values for both. The main parameter affecting energy yield was found to be the water to feedstock ratio, and the optimal conditions were determined to be a temperature of 180 °C, a water to feedstock ratio of 1.5:1, and a processing time of 15 minutes. The highest energy yield of 99.7% was observed under these conditions, while the lowest mass yield of 25.30% was observed at a temperature of 200°C with a water ratio of 2 and a time of 15 minutes. The heating value of the HTC solid product ranges from 17–27 MJ/kg, which is comparable to low-grade sub-bituminous coal, indicating potential for co-firing with coal and other hydrothermal products as a fuel.

Keywords: Response Surface Methodology, Hydrothermal carbonization, banana bunch waste.

INTRODUCTION

The environment can be done protected by utilizing the energy from several alternative energy sources, specifically renewable energy sources. One type of renewable energy that is abundantly available in Indonesia is renewable energy from biomass. Biomass is a fuel source that is carbon neutral or a fuel that has no carbon footprint. The abundant availability of biomass as waste and from bioenergy crops is the main factor that makes this renewable energy source very suitable for this country. Biomass includes, among others, firewood (wood, wood waste, charcoal), urban solid waste, industrial waste, and agriculture waste.

Bananas are one of Indonesia's leading commodity fruits. As a tropical fruit, bananas grow in almost all parts of Indonesia. Indonesia ranks 2nd in the world for banana production (after the Philippines), with a total production of 7.2 million tons (Scott, G.J., 2021). Once the fruit is harvested, the banana plant is left to rot and has no further use. Biomass waste, such as banana plant waste, can be helpful in various applications and sustainability.

In general, banana waste is widely used by the community. Banana waste can be recycled in a variety of ways. It can be used as compost and fertilizer for soil and gardens (Mago, M.et al., 2021, Leno, N. et al., 2021, Isibika, A. et al., 2021, Isibika, A. et al., 2019, Teshome. Z.T. et al., 2022), as feed for animals (Nannyoga, S. et al., 2018), or repurposed into other biomaterial products (Deb, S. et al., 2022, Motta, G.E. et al., 2022, Sawarkar, A.N. et al., 2022, Khan, A. et al., 2022, Phirom-on, K. et al., 2022). Additionally, it can be used as a source of energy through briquette, anaerobic digestion, or gasification [Sawarkar, A.N. et al., 2022, Djaenudin, 2021, Putra, H.E. 2018, Putra, H.E. et al., 2022, Serna-Jiménez, J.A. et al., 2021, Putra, A.E.E. et al., 2022, Pachaiyappan, S. et al., 2012, Fernandes, E.R.K., 2013, Singh, R.K., 2022, Jiang, F., 2023, Sena-jimenez, J.A., 2021, Mitan, N.M.M., 2019, Bot,B.V., 2022, Ku Ahmad, K., 2018, Krungkaew, S., 2022, Vimal, V., 2022). Most previous studies used banana stems and peel waste as raw materials. So far, there has not been much literature on studies using banana empty fruit bunches waste (BBW) [Putra, A.E.E. et al., 2022, Pachaiyappan, S. et al., 2012, Quintana, G., 2008, Lertchunhakiat, K. 2016, Adebisi, G.A., 2016, Prasad, R., 2009).

The lignocellulose composition of banana fruit bunch waste consists of cellulose, hemicellulose, and lignin. Cellulose is the main component, making up around 50–60% of the material. Hemicellulose makes up around 10–20% of the material, and lignin makes up around 10–20%. Cellulose is a polysaccharide with a high degree of polymerization that forms a linear chain-like structure. Hemicellulose is a polysaccharide that forms a branched structure, while lignin is a complex polyphenolic polymer that gives plants their rigidity and strength. According to (Abdullah, N., 2014), the lignocellulose content of banana fruit bunch waste was composed of cellulose (37.81%), hemicellulose (37.45%), and lignin (24.7%), which has high potential to be a bioenergy source. However, the energy content of BBW is assumed to be less than the banana stem, since BBW has a carbon ratio of 19 lower than the banana stem, which is 24 (Abdullah, N., 2014).

In addition, the low density of BBW causes difficulties in handling. Therefore, densification techniques aim to increase biomass density and its calorific content per unit of volume (Kusumaningrum W.B., 2014). In general, the production of charcoal has also been transformed into briquettes for handling convenience, dust reduction, and increased energy density (Sjølie, H.K, 2012). Briquette charcoal is a solid carbon-containing organic fuel with a high calorific value and can be lit for an extended period (Nuriana, W., 2014). Charcoal briquettes have numerous benefits, including cost, burn time, environmental sustainability, and the possibility of product standardization (Mwampamba et al., 2013).

The pyrolysis process or carbonization process involves heating wood or other organic material without oxygen, a common method for producing charcoal. One potential weakness of this process is that it can be challenging to control the temperature and oxygen levels during the pyrolysis process. If the temperature becomes too high, the wood can ignite and burn, rather than be converted into charcoal. On the other hand, if the temperature is not high enough, the wood may not fully pyrolyze, resulting in an incomplete conversion to charcoal. Another weakness of the pyrolysis process is that it can be time-consuming. Depending on the size of the batch and the type of wood being used, the pyrolysis process can take several hours or even days to complete (Manatura, K., 2013, Nguyen, C.T., 2022). It can be a disadvantage for large-scale production of charcoal, where time efficiency is essential.

Hydrothermal carbonization (HTC) is a process whereby organic materials such as biomass are converted into a carbon-rich solid through exposure to high temperature and pressure. HTC is mild pyrolysis, meaning it does not require oxygen. The process occurs in a water-based environment, with temperatures ranging from 180 to 250 °C and autogenous pressures (Putra, H.E. et al., 2022) During HTC, the biomass undergoes a series of complex chemical and physical transformations, producing a black, carbon-rich solid known as hydrochar. This hydrochar can be used for soil amendment, energy production, and carbon capture and storage (Ebrahimi, M., 2023, Mariuzza, D., 2021, Qiu, J., 2020, sethilkumaran, M., 2022, Drabold, E., 2020, Huang, F., 2021, Zhang, Y., 2022, Poomsawat, S., 2022, Paiboonudomkarn, S., 2022). Therefore, in-depth research on the BBW may be beneficial, particularly in upgrading via the hydrothermal carbonization process. This work aimed to characterize solid fuel using its physical, chemical, and calorific properties to assess how well it can be used as combustible biomass to produce added value and energy products.

MATERIAL AND METHOD

Banana bunch waste

The local government and the banana farmers manage BBW in Bandung. The government helps support banana farmers in terms of finance and other assistance. They also help promote sustainable practices among the farmers to reduce waste. In addition, local initiatives such as waste management programs and composting are being implemented to reduce the amount of banana bunch waste. The local government also works with NGOs to assist banana farmers in waste disposal. Unfortunately, with such high amount of banana production for sale and added to the characteristics of bananas that perish quickly, BBW is easy to find as market waste. This study obtained BBW from the temporary disposal at the central market in Gedebage, Bandung, West Java (Figure 1). The chemical composition of BPW is shown in Table 1.

Experimental set-up

HTC is a process used to convert wet organic materials such as biomass, food waste, and manure into carbon-rich solid materials. HTC involves treating these wet organic materials with high temperatures and pressures in the presence of water. The high temperatures and pressures break the organic material into its component organic molecules, and water catalyzes the breakdown of the organic molecules into solid carbon-rich materials.

In this study, a one-liter pressure reactor was used. The reactor has made of stainless-steel material 304 with a 10 mm thickness that can

Figure 1. Banana bunch waste in the central market of Gedebage, Bandung

Table 1. The physical and chemical composition of BBW

Parameter		Properties value	Standard method
Proximate analysis (moisture free, wt%)	Ash	17.3–22.7	ASTM D1102-84
	Volatile matter (VM)	70.5–75.2	ASTM E872
	Moisture content (MC)	6.5–11.4	ASTM E871-82
	Fixed carbon (FC)	0.3–5.7	By difference
Ultimate analysis (moisture free, wt%)	Carbon (C)	33.98–37.12	Elemental analyzer
	Hydrogen (H)	4.02–5.65	
	Nitrogen (N)	0.90–3.11	
	Oxygen (O)	57.26–57.96	By difference
Calorific value (MJ/kg)	Higher Heating Value (HHV)	14.5–15.7	Bomb Calorimeter
	Lower Heating Value (LHV)	10.9–12.8	

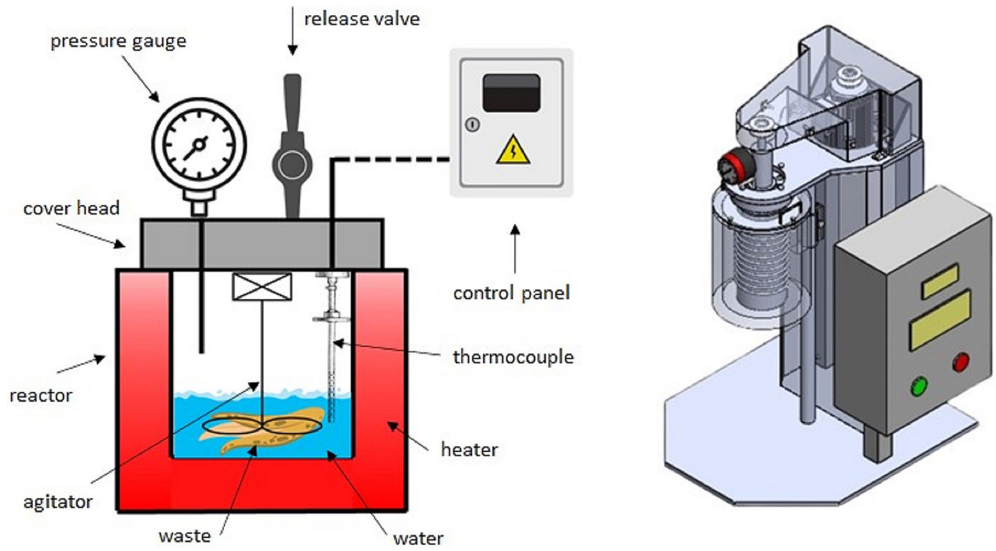

Figure 2. The scheme of the experimental apparatus of the HTC process

withstand the high temperatures and pressures required for the HTC process. An electric heating element is used as the heat source in order to generate the high temperatures required for the HTC process. The sketch of the experimental apparatus can be seen in Figure 2.

Experimental procedure

The HTC process has two initial inputs: water and BBW. At the beginning, water was supplied through a measuring cup. Then, 200 grams of BBW that had been chopped using a blender were placed into the reactor. Both feedstocks are treated hydrothermally based on predetermined operating conditions. Design Expert 10 software was used to determine operating conditions through the Respond surface method using Box Behnken Design. The operating conditions include temperature variables of 180–230 °C, a holding time of 20–60 minutes, and water to feed ratio of 1–2. After randomizing the combinations, the 15 treatments to be analyzed were discussed in the next section. At the same time, the experimental procedure is depicted in Figure 3. Experimental data were taken in three repetitions.

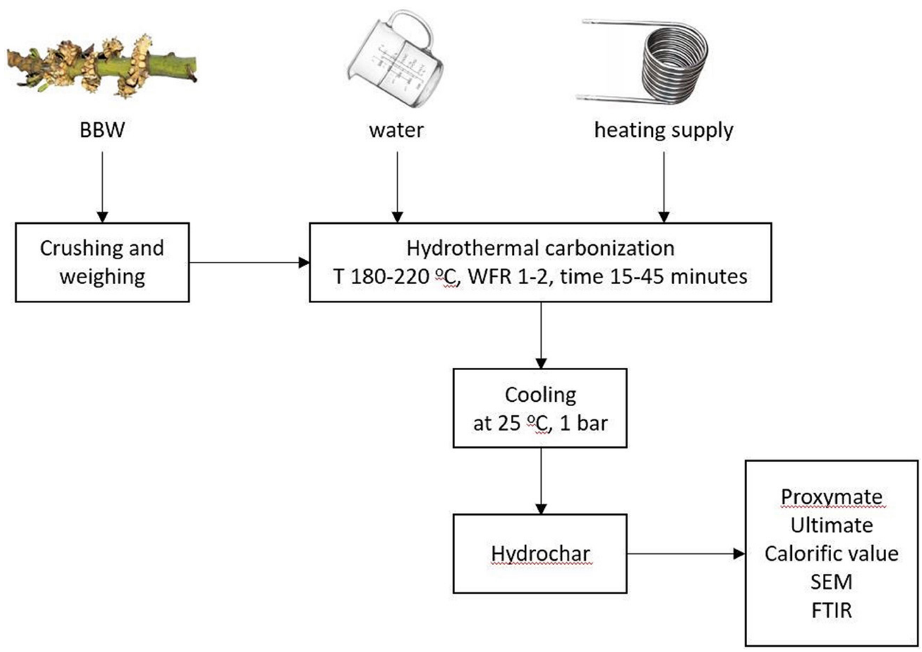

Figure 3. Process flow diagram

Analysis

In order to determine the structure, physical and chemical properties, and energy content, several analyses were conducted.

SEM analysis of hydrochar

A qualitative SEM (Scanning Electron Microscopy) analysis of hydrochar can reveal its surface features and allow for detailed observation of its microstructure. SEM analysis was used to determine the size, shape, and distribution of particles and to observe the surface characteristics of the hydrochar. It can also provide information about the composition and chemical properties of the hydrochar. SEM analysis can be used to evaluate the porosity of the hydrochar, as well as to identify any contaminants that may be present. In addition, SEM analysis can be used to assess the stability of the hydrochar and its ability to withstand environmental conditions. This study's measurement conditions/testing parameters comprised Au coating, 20 kV, secondary electron signal, and high vacuum condition. The type of SEM equipment is Hitachi SU-3500.

FTIR analysis of hydrochar

Fourier-transform infrared (FTIR) spectroscopy is a type of spectroscopy used to analyze the molecular bonds of a material such as hydrochar. It uses infrared light to measure the vibrational frequencies of material as well as determine the types and concentrations of molecules present. FTIR analyses various materials, including solids, liquids, and gases. FTIR is commonly used to identify unknown compounds, characterize polymers, quantify functional groups, and measure the purity of a material. It can also be used for quality control in manufacturing and tracking a reaction's progression. This analysis was performed by using Thermoscientific Nicolet iS-10.

Proximate and ultimate analysis of hydrochar

Proximate is a technique used to analyze the properties of hydrochar, a charcoal produced from the thermal degradation of biomass. It measures the concentration of total organic carbon, total inorganic carbon, and total nitrogen in the hydrochar sample. The ultimate analysis is a method used to determine the elemental composition of a sample. It is typically used to analyze the composition of coal and other hydrocarbons, but it can also be used to analyze hydrochar. Ultimate analysis of hydrochar measures the concentrations of carbon, hydrogen, oxygen, nitrogen, sulfur, and ash in the sample. The data obtained from the proximate and ultimate analysis of hydrochar can be used to calculate the energy content and carbon sequestration potential of the hydrochar. Using the following formula, the parameters mass yield (MY), energy densification ratio (ED), and energy yield (EY) were estimated

$$\text{Mass yield} = \\ = \frac{\text{Mass of dry hydrochar}}{\text{Mass of dry feedstock}} \times 100\% \quad (1)$$

$$\text{Energy densification ratio} = \\ = \frac{\text{HHV of hydrochar}}{\text{HHV of feedstock}} \times 100\% \quad (2)$$

$$\text{Energy yield} = \text{Mass yield} \times \\ \times \text{Energy densification ratio} \quad (3)$$

RESULT AND DISCUSSION

The optimum operating conditions for hydrothermal carbonization of banana bunch waste

This section presents the results of the measurements and formulations conducted as outlined in Section 2. The experiment was repeated three times to establish the optimal formulation, which was then analyzed in the laboratory. The optimum operating conditions for hydrothermal carbonization of banana bunch waste were determined using Design Expert v10 software. SPSS v26 was also used to determine the optimum operating conditions to verify the results. Table 2 displays the experimental design for the HTC of BBW.

The process parameters used in the experiment are three different factors: temperature, the ratio of water to feed, and processing time. In the analysis of response 1, the mass yield was obtained using the RSM (Response Surface Method), which resulted in a 3-dimensional graph, as shown in Figure 4a-c. It indicates the response surface at 15, 30, and 45 minutes, respectively, with the x-axis showing temperature, the y-axis showing the water ratio, and the z-axis showing the heat value. This results in a steep and then sloping surface on the low side. The highest mass yield reached 63.35% when observed at a temperature of 180 °C with a water ratio of 1.5 and a time of 15 minutes. At the same time, the lowest mass yield was 20.24% at a temperature of 220 °C with a water ratio of 2 and a time of 30 minutes. The organic matter's decomposition and volatilization rate increase along with temperature (Zhang et al. 2019; Wilk et al. 2021). This results in a lower mass yield of hydrochar because more organic matter is lost as gases and water vapor, especially for lignocellulosic biomass.

The highest energy yield reached 99.7% when observed at a temperature of 180 °C with a water ratio of 1.5 and a time of 15 minutes. At the same time, the lowest mass yield was 25.30% at a temperature of 200 °C with a water ratio of 2 and a time of 15 minutes. The response surface of energy yield during the HTC process at 15, 30, and 45 minutes can be shown in Figure 5a-c, respectively. The energy and mass yield of hydrochar depend on several factors, including the type and moisture content of the feedstock, the temperature and residence time of the HTC process, and the design and operation of the reactor. Additionally, they can be affected by the presence of impurities or other contaminants in the feedstock, the extent of the charring reaction, and the degree of carbonization. Typically, the mass yield of hydrochar ranges from 20–50% of the dry weight of the feedstock.

The highest energy yield reached 99.7% when observed at a temperature of 180 °C with a water ratio of 1.5 and a time of 15 minutes. At the same time, the lowest mass yield was 25.30% at a temperature of 200 °C with a water ratio of 2 and a time of 15 minutes. The response surface of energy yield during the HTC process at 15, 30, and 45 minutes can be shown in Figure 5a-c, respectively. The energy and mass yield of hydrochar depend on several factors, including the type and moisture content of the feedstock, the temperature and residence time of the HTC process, and the design

Table 2. The experimental design of HTC of BBW

Run	Temperature (°C)	Water to feed ratio (WFR)	Holding time	HHV average (MJ/kg)	Mass hydrochar (gr)
1	180	1.0	30	21.18	37.88
2	180	1.5	15	24.40	99.07
3	200	1.5	30	25.50	93.98
4	200	1.0	15	24.86	46.02
5	220	1.5	45	18.26	41.95
6	220	1.0	30	22.80	36.43
7	200	2.0	45	28.48	44.76
8	180	1.5	45	23.86	43.97
9	220	2.0	30	24.30	28.10
10	200	1.5	30	19.27	51.08
11	220	1.5	15	19.14	58.95
12	200	1.0	45	21.07	39.04
13	200	1.5	30	24.35	56.17
14	180	2.0	30	18.97	36.98
15	200	2.0	15	18.21	32.18

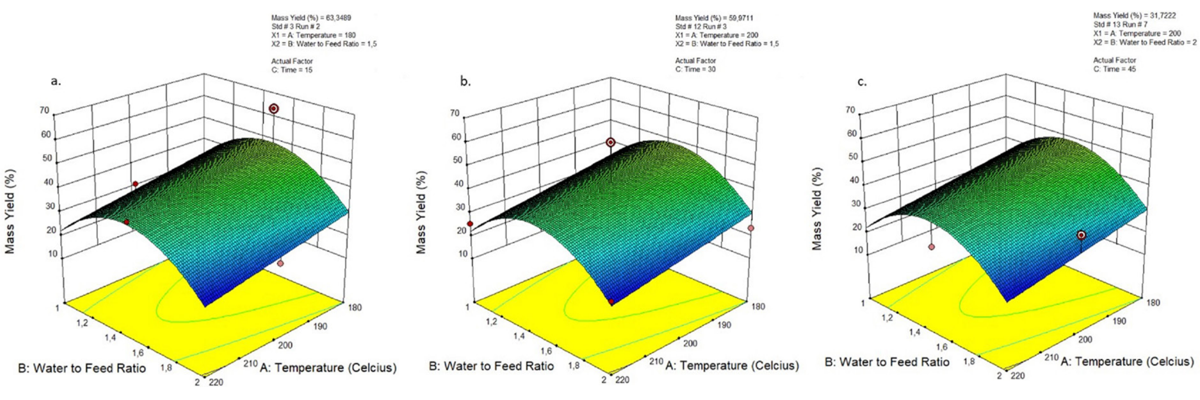

Figure 4. 3D Response surface of the mass yield at (a) 15, (b) 30, and (c) 45 minutes

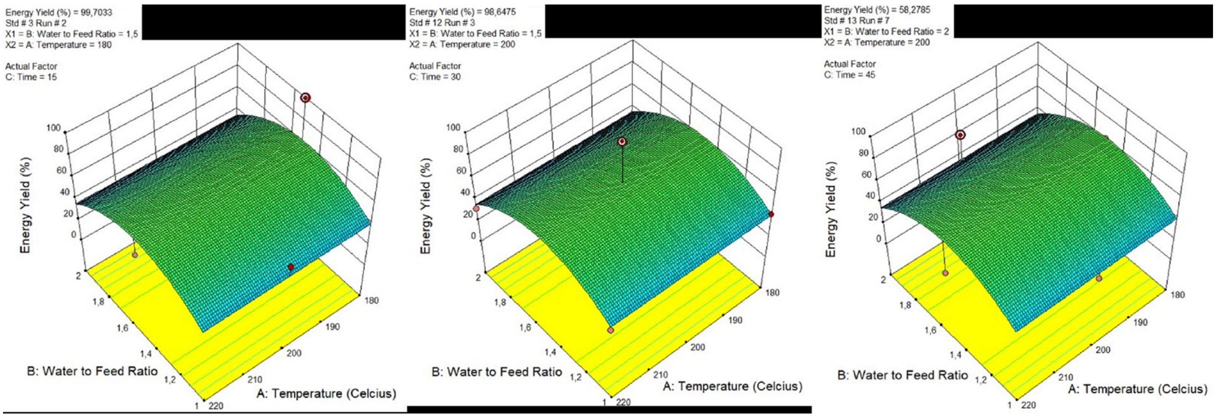

Figure 5. 3D Response surface of the energy yield at (a) 15, (b) 30, and (c) 45 minutes

and operation of the reactor. Additionally, they can be affected by the presence of impurities or other contaminants in the feedstock, the extent of the charring reaction, and the degree of carbonization.

The energy yield of hydrochar is not solely dependent on the high heating value but also the mass yield. The mass yield is the percentage of the original biomass that is converted into hydrochar, and the heating value measures the energy content of the hydrochar. A high mass yield of hydrochar means that more of the original biomass has been converted into hydrochar, which can result in a higher energy yield. However, the heating value of the hydrochar is also important, as it determines the amount of energy that can be obtained from a given mass of hydrochar. It is worth noting that, depending on the application and the specific use case, the energy yield of hydrochar can be calculated in different ways. For example, some studies may consider the energy yield as the amount of energy produced per unit of input biomass, while others may consider the energy yield as the amount of energy produced per unit of hydrochar mass (Ghavami, N. et al., 2022, Yang, H. et al., 2006).

The Duncan post-hoc was utilized to obtain the information about which combination of operating conditions will significantly differ. The Duncan post-hoc test is a multiple comparison procedure used in statistics to determine which means of a set of groups are significantly different from one another after a one-way ANOVA (analysis of variance) test has been conducted. Furthermore, a statistical analysis was performed to collect advanced information about what parameters give more influence to both energy and hydrochar yield. This analysis comprised of several step; passing the classical assumption test, linear regression with three predictors, significance test for multiple regression equation (F-test), and significance of multiple correlation coefficient (R-squared). The complete analysis data can be found in supplementary S-1. Table 3 and Table 4 showed the coefficient model summary of linear regression with three predictors in terms of the effect of operating conditions on the energy and mass yield, respectively.

As seen in the Coefficients model column in Table 3, it has a sig value of 0.02 at time. A sig value less than the probability value of <0.05 means H_1 is accepted and H_0 is rejected. The time variable has a probability value of 0.02, which is <0.05, so the H_1 hypothesis is accepted. The calculated value is 2.425 > t_{table} = 2.101; thus, it can

Table 3. The coefficient model summary of linear regression with three predictors: the effect of operating conditions on the heating value

Coefficients[b]								
Model		B	Coefficients std. error	Standardized coefficients beta	t	Sig.	Collinearity tolerance	Statistics VIF
1	Time	0.209	0.086	0.290	2.425	0.020	0.152	6.561
2	Temperature	0.101	0.065	0.187	1.562	0.126	0.152	6.561
3	Water ratio	7.541	2.057	0.505	3.665	0.001	0.115	8.700
a. Dependant variable: HHV								
b. Linear regression through the origin								

be concluded that the time variable contributes to HHV. Next, for the temperature variable, the probability value of 0.126 is greater than 0.05, so H_1 is rejected. Therefore, the temperature is not significant in increasing the caloric value. As for the water ratio, the probability value is below 0.05, which is 0.01. Therefore, the water ratio positively contributes to the increase in HHV, indicated by a calculated value of 3.665, which is higher than the $t_{table} = 2.101$. It can be concluded that only the time and the water ratio variables have a positive effect on HHV.

As seen in the coefficients model column in Table 4, there is a sig value of 0.746 for temperature. A sig value larger than the probability value of 0.05 means H_1 is rejected and H_0 is accepted. The time variable has a probability value of 0.304, which is >0.05, so the H_1 hypothesis is again rejected. However, for the water ratio, the probability value is below 0.05, which is 0.001. Therefore, the water ratio positively contributes to the increase in HHV, indicated by a calculated value of 3.592, which is higher than the t_{table} = 2.101. It can be concluded that only the water ratio variable positively affects hydrochar mass. In this case, there is no sufficient statistical evidence to state that there is a difference or significant effect in the phenomena being studied, specifically the relationship of temperature and time to the hydrochar mass produced in the hydrothermal carbonization process of banana empty bunch waste.

Due to the water to feedstock ratio being fully affected and the time having a partial effect on energy and mass yield, in order to make solid fuel, higher temperatures on the HTC process should be avoided for lignocellulosic biomass. Lignocellulosic slowly degrades at 160 °C (Yang, H. et al., 2006, Uslu, A., 2008). The higher temperatures may also cause changes in the chemical structure of the hydrochar, leading to variations in its physical and chemical properties. It is important to note that the optimal temperature for HTC of lignocellulosic biomass may vary depending on the specific feedstock and the desired properties of the resulting hydrochar. On the basis of the optimization process in Design Expert (Figure 6), the optimum operating conditions for HTC of banana empty bunch waste included a temperature of 180 °C, a water-to-feedstock ratio of 1.33, and a time of 15 minutes.

The effect of hydrothermal carbonization on the physical and chemical properties

Table 5 displays the ultimate and the proximate analysis findings. Dehydration, hydrolysis, and decarboxylation are a few chemical reactions

Table 4. The coefficient model summary of linear regression with three predictors: the effect of operating conditions on the hydrochar yield

Coefficients[b]								
Model		B	Coefficients std. error	Standardized coefficients beta	t	Sig.	Collinearity tolerance	Statistics VIF
1	Time	0.070	0.214	0.055	0.326	0.746	0.152	6.561
2	Temperature	0.297	0.285	0.174	1.042	0.304	0.152	6.561
3	Water ratio	24.416	6.797	0.693	3.592	0.001	0.115	8.700
a. Dependant Variable: HHV								
b. Linear Regression through the Origin								

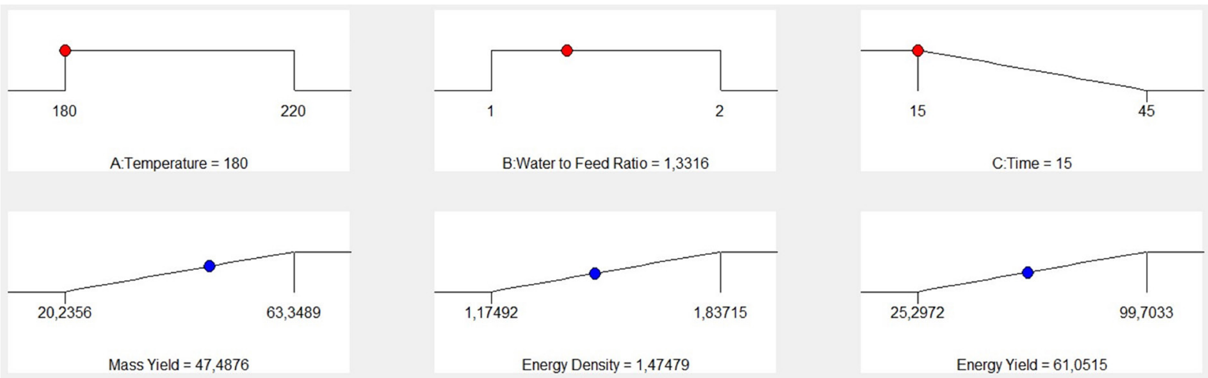

Figure 6. The optimum operating condition and the prediction of the results

during hydrothermal treatment that result in some carbon, hydrogen, and oxygen loss. As the reaction temperature rose, the HTC process increased the carbon content, which is consistent with the findings of the earlier (Djaenudin, 2022, Putra, H.E. et al., 2018, Ebrahimi, M., 2023, Mariuzza, D., 2021, Poomsawat, S., 2022, Paiboonudomkarn, S., 2022, Putra, H.E.). Compared to carbon, biomass loses considerably more oxygen and hydrogen during HTC. Consequently, as the HTC temperature rises, the calorific value of a product also rises. As mentioned, the heating value of HTC solid product ranges from 17–27 MJ/kg, virtually as much as low-grade sub-bituminous coal. It also suggests the potential for employing coal and products undergoing hydrothermal treatment as co-firing fuel. Except for HHV analysis, the five best samples with higher energy yield have been selected for further proximate and ultimate analysis.

Proximate and ultimate analyses are the most common methods used to determine the quality of coal and solid fuels. Content carbon from hydrochar produced ranges from 44–49%. The carbon content of the hydrochar produced from the carbonization of homogeneous components tends to be different but at low susceptibility, according to many works (Novianti, S., 2014, Hwang, L.H., 2012, Basso, D., 2015). Biomass raw materials usually have volatile matter and high oxygen content. With increasing reaction temperature hydrothermal, volatile materials and stable oxygen content increase; meanwhile, the fixed carbon number tends to increase because it is more affected by the reaction hydrolysis.

In Figure 7, SEM (a–e) compared the morphology of the characterized surfaces with 2500x magnification for each sample. Sample results from banana bunches before the HTC process

Table 5. The proximate and ultimate analysis of hydrochar

Sample Id.	Operating condition			Proximate (dry basis)			Ultimate (%, adb)				
	Temp. (°C)	WtF ratio	Time (min)	Ash	VC	FC	C	H	N	S	O
A	180	1.5	15	8.85	61.12	30.03	47.40	5.70	0.80	0.07	37.18
B	200	1.5	30	6.94	62.66	29.83	48.86	5.78	0.77	0.07	37.58
C	180	1.5	45	6.95	64.73	28.31	48.54	6.00	0.83	0.07	37.61
D	200	2	45	7.62	64.74	27.64	49.97	5.92	0.77	0.08	38.64
E	200	1	15	11.96	62.60	25.85	44.56	5.66	0.68	0.08	37.06

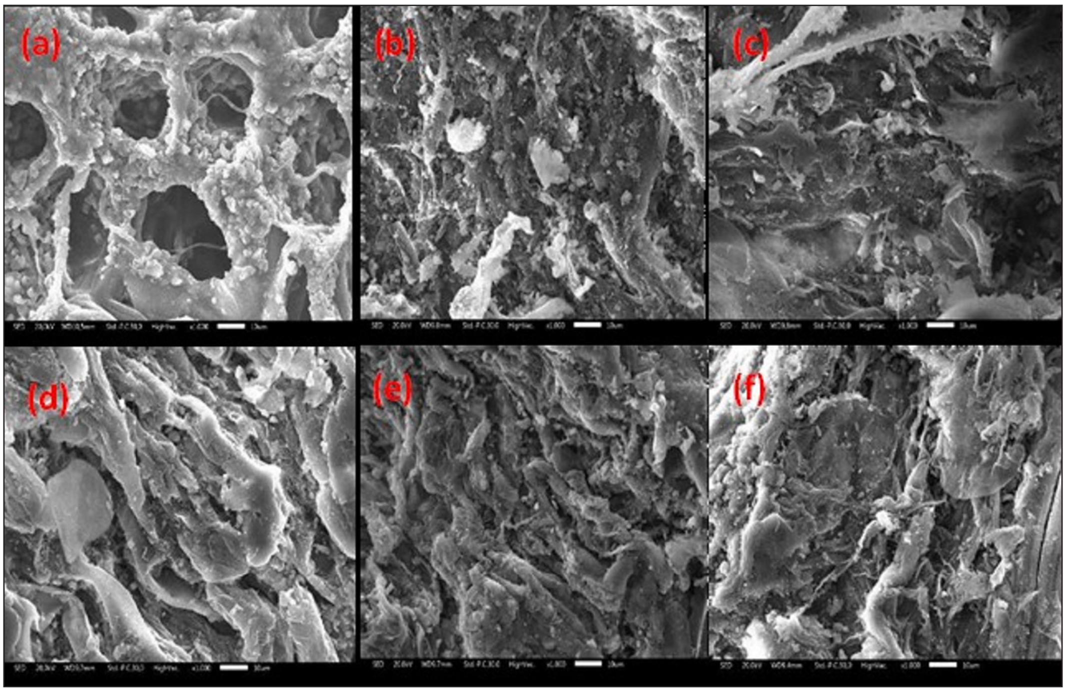

Figure 7. SEM of (a) banana empty bunch raw, (b) sample A, (c) sample B, (d) sample C, (e) sample D, and (f) sample E

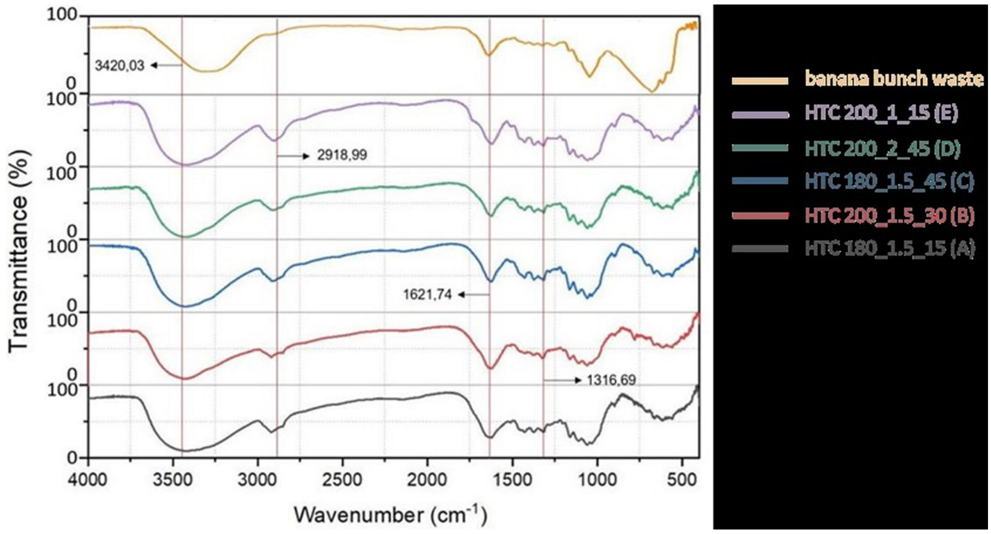

Figure 8. FTIR spectrum pre and post-hydrothermal carbonization process

were found to have a cavity with a rough surface which is large in structure with a small cavity diameter range of banana bunches after the HTC process, found to have no cavities, only shards elongated cavity unstructured and rough-surfaced. The elongated cavity fragments consist of the xylem, phloem, and sheath of vessels (Huang, F., 2021). This finding indicates a change in structure in the HTC process, but only breaking the cavity structure into long stem fragments, not much-becoming powder particles. In Figure 7b–e, it is not easy to compare them because of similar morphology. This morphological result can be one of the suspicions of the influence of formation structure and compaction in making banana stem bio briquettes.

The FTIR spectrum results in the range of 4000–450 cm^{-1} from 6 spectra of different colors can be observed to have several important peak areas (Figure 8). The broad band at the peak wavelength of 3420.03 cm^{-1} indicates the O-H functional group in accordance with hydroxide stretching vibrations. The C-H functional group at the peak wavelength of 2918.99 cm^{-1} is detected by vibrational stretching. The C=C functional group in the aromatic ring at the peak wavelength of 1621.74 cm^{-1} is in accordance with stretching vibrations. The fingerprint peak area at the wavelength > 1400 cm^{-1} cannot be specifically detected, but organic waste from banana bunch has unique functional groups that can be matched from 6 FTIR spectra. The pattern of the 6 FTIR spectra in this investigation studies the differences in the characterization of banana bunch waste before and after hydrothermal processing.

Results of the fire test

The fire test is carried out by burning bio-briquettes on a gas stove with a large flame and in a closed room. Then, the time required for the bio-briquette fire to blaze is recorded. The time is recorded in seconds. In Table 6, the fire test results of hydrochar banana trunk bio-briquettes show the highest time required is 145 seconds or equivalent to 2 minutes and 25 seconds. Meanwhile, the shortest time required for bio-briquettes to ignite is 75 seconds, equivalent to 1 minute and 15 seconds. From this table, it is consistent that as the particle density increases, the flame takes longer to spread.

The results of this testing indicate that the optimum condition for forming bio-briquettes made from hydrochar banana trunk charcoal is in the binder formulation of 15% and press pressure of 100 N/cm^2. This condition is categorized as good in the fire test. However, the obtained shatter index value is not optimal, but it can be considered sufficient, because bio-briquettes are not a product that prioritizes structural strength but instead their function as an alternative fuel.

Table 6. Results of the fire test for hydrochar banana bunch bio-briquettes

Additive (%)	Pressure of briquette press (N/cm^2)	Time required for biobriquettes to ignite (seconds)
10	100	75
	200	108
15	100	88
	200	122
20	100	93
	200	145

CONCLUSIONS

The introduction also describes the composition of banana fruit bunch waste, which includes cellulose, hemicellulose, and lignin, and discusses the potential for using this waste as a bioenergy source. However, the energy content of banana bunch waste is assumed to be less than that of banana stems, and its low density can make handling difficult. This study suggests that densification techniques, such as transforming banana bunch waste into briquettes or using hydrothermal carbonization (HTC) to produce hydrochar, can increase its energy density and calorific value.

The HTC experiment was conducted under optimum conditions using temperature, water to feedstock ratio, and processing time. The RSM Box-Behnken method was used to produce 15 random trial formulations. The data on energy value and mass yield were collected to obtain the optimal values for both. As the water-to-feedstock ratio was the main parameter which impacted the energy yield, the optimal conditions were determined to be a temperature of 180°C, a water-t-feedstock ratio of 1.5:1, and a processing time of 15 minutes. Several statistical approaches supported this claim. Analysis of hydrochar banana bunch waste using SEM revealed structural changes during the HTC process, with most of the structure appearing as long rods rather than powder grains. The bio-briquette formation experiment found that the optimal conditions for producing bio-briquettes from hydrochar were a binder formulation of 15% and a pressure of 100 N/cm^2. The primary focus of this material is its use as an alternative fuel source.

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