

Determining the Optimum Total Solid Yield of Hydrothermal Waste Processing Products Through Mechanical Drying

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Abstract. In the application of hydrothermal technology, it is necessary to optimize mechanical water drying to increase the calorific value of hydrothermal waste products. This study was conducted to find the total optimum solids, optimum drying time, and characteristics of hydrothermal waste processing products that occur after optimal mechanical drying. The mechanical drying design was carried out 4, 6, and 8 bars of pressure. At pressure bars 4, 6, and 8, the total optimum solid yields were 50.11%, 51.56%, and 54.56%, with 6.56, 6.82, and 5.11 minutes of drying time, respectively. Optimum mechanical drying yielded a calorific value of 5154 kcal/kg, which is the equivalent of sub-bituminous coal. An increase of the C/N (Carbon to Nitrogen) ratio to 32.185 resulted in hydrothermal waste processing products that did not comply with the Indonesia compost quality standard.

1 Introduction

Waste is an unavoidable consequence of human activity. In several urban communities, increased municipal waste has paralleled the growing population. Many developing countries are now facing serious challenges in terms of managing municipal solid waste. The poor collection, recycling, treatment, and unmanaged disposal of municipal waste can lead to both health and environmental issues [1].

The majority of municipal solid waste products are organic with a high moisture content and can easily be found in households, commercial centers, institutions, and urban services [2]. Municipal solid waste consists of organics, glass, paper, plastic, metal, and other materials such as styrofoam and bones. Figure 1 demonstrates that more than 50% of solid waste is composed of combustible matter. Reflecting on this statistic, effective waste management and the recycling of waste into something more valuable is considered important for developing more sustainable waste management. The economic benefits of reusing municipal solid waste include saving fuel, reducing the cost of waste management, reducing greenhouse gas emissions, and replacing some of the functions of fossil fuels [3,4]

One innovation of municipal waste management is the creation of hydrothermal carbonization technology (HTC) [5]. HTC processing is the thermal conversion process whereby organic compounds such as biomass and organic waste are transformed into value-added products in closed systems under certain pressures and temperatures (180-350°C) [6]. During hydrothermal treatment, coal is formed from organic matter in its liquid form through exposure to high temperatures and pressure. The biomass is then used as feedstock for hydrothermal treatment and processed in the reactor

batch with water and a suitable catalyst. The product of hydrothermal treatment is an aqueous black liquid comprised of normally dispersed particulate carbon particles called biochar. Biochar, a coal-like product, has a high carbon content and can be incinerated and used for industrial purposes after drying [7]. Hydrothermal treatment is advantageous as the product's water content can be easily separated. The calorific value of the hydrothermally treated product tends to be higher than other materials normally dried at higher costs [8,9].

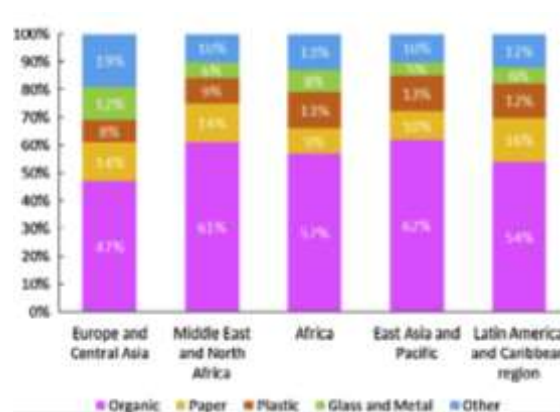


Fig. 1. Waste Composition in Several Areas of the World. Source: *The World Bank*, 2012, <http://data.worldbank.org/>.

In general, the hydrothermal drying process consists of two stages. The first drying stage is mechanical dewatering. The product is stacked and its water content is channeled gravimetrically through a drainage channel leading to a leachate pond [10]. This process creates hydrothermal products with a 40-50% moisture content. The second stage of the hydrothermal drying process is natural drying. Products are stacked in a greenhouse

environment and their moisture content is evaporated by the sun. This stage produces hydrothermal products with a water content of <10%. Once this process is complete, the hydrothermal waste processing product can be used as an alternative fuel with a high enough calorific value for the product to be reused during its processing [11].

The moisture distribution within a wet material shows a strong relationship between bound water content and process performance. Water found within a wet material is considered to be one of two types: bound water or free water [12]. Bound water is bonded both chemically and physically to a material, whereas free water is easily separated from a material through a mechanical method. The main purpose of water separation is to convert bound water to free water through conductive conditioning. According to Zhao et al. (2014), temperature and reaction time are two important parameters for influencing water separation [13].

Several previous studies have attempted to separate water from carbon materials in biochar [12-14]. In one study, water was drawn from biochar using a 30 ml piston filter press wherein the sample was loaded with a pressure of 4 kg/cm² within 16 minutes [13]. Zhao et al. (2004) conducted an experiment with a pressure of 6 kg/cm². The water content of the sample decreased from 85% to 60% in 15 minutes. From this study, it was concluded that when large amounts of pressure are added, moisture content is reduced greatly.

Ramke et al. (2009) compared water content outflow and stress duration [14]. The study was conducted using a press and cylinder container, and the sample was given a constant pressure of 15 kg/cm². The water extracted from the filter layer was weighed using an electronic scale. The comparison of water outflow and stress duration allows for an assessment of drying performance for materials that undergo hydrothermal processing. The hydrothermal waste processing product can be used as an alternative to fuel and has an equivalent calorific value to low-ranking sub-bituminous coal.

Between the years 1998-2005, Indonesian coal consumption grew by 13.29%. It is projected that by 2025, the domestic demand for coal will reach 191, 130 million tons. Due to limited coal reserves, solution strategies are needed in order to meet the energy demands of the future. When considering sustainable energy resources, the conversion of municipal waste to alternative fuel energy is an important development.

The use of hydrothermal products as a solution for waste processing is a relatively new concept in Indonesia. The large potential for generating renewable energy sources from processing urban waste highlights the need for this technology to be developed. Converting waste into an alternative fuel is needed to improve the efficiency of municipal waste processing. In many studies, the rate of mechanical dewatering is considered ineffective and an inhibitor of production rates. The use of mechanical dewatering during hydrothermal waste processing often takes longer to generate the desired water content levels.

This study aims to simulate the total optimum solid content yield of hydrothermal products during the

mechanical drying process. By determining the total optimum solid content yield of hydrothermal products, drying kinetics and drying time can be determined in order to obtain the optimum calorific value of the product.

2 Research Methodology

2.1. Sample

The samples were gathered from a hydrothermal system located in Summarecon Serpong, Tangerang. The hydrothermal waste produced from the reactor had an initial temperature range of 200-300°C. Thus, prior to treatment its temperature was reduced. This was done by placing the product in a temperature-decreasing basin until its temperature dropped to room temperature so the samples could be taken safely.

An initial characteristic test was conducted, and the total solid (TS), moisture content, volatile matter, ash content, C/N ratio, and calorific value were noted. The TS measurement was taken using the Indonesia standard method of SNI 03-1971-1990. The sample was inserted into an evaporating basin and dried in an oven at 105°C for 3 hours. The sample was then placed in a desiccator for 30 minutes and measured gravimetrically.

The volatile solid was measured using the Standard Method 2540 E. The dried sample was then reheated in a furnace at a temperature of 550°C for 1 hour. The weight difference before and after heating was defined as the volatile solid.

The ash content was measured by using the ASTM E 830-870. The sample was heated at a temperature of 575 ± 25°C, and was reheated in a furnace with a temperature of 950°C for 7 minutes. The sample was then placed into the desiccator at room temperature. The weight difference before and after heating was defined as the ash content.

The C/N ratio measurement was conducted using the Indonesia Standard of SNI 06-6989.28-2005. The C/N ratio was determined by calculating the carbon and nitrogen levels present in the sample. The reason for calculating the carbon was to decompose the sample with H₂SO₄. Thus, when the acid was concentrated, C reduced K₂Cr₂O₇ to Cr³⁺. The excess K₂Cr₂O₇ was reduced with FeSO₄. Excess FeSO₄ was titrated with KMnO₄ and the color of the endpoint was obtained. The nitrogen calculation was conducted using the DR 2000 spectrophotometer. The DR 2000 spectrophotometer then produced data using mg/l units.

2.2. Kinetics of the Total Solid

To obtain the kinetics of the total solid and the optimum stress duration, the quadratic graph function was obtained. The x and y vertex values of the quadratic equation represent the optimum total solid and the optimum stress duration. To obtain the quadratic function equation, the following formula was used:

$$y = ax^2 + bx + c$$

The above formula was used to determine quadratic equations where graphs were formed through three points. After determining the three points, a substitution was made in the function for each point. The X_{vertex} value was obtained by using use the following formula:

$$X_{\text{vertex}} = -\frac{b}{2a}$$

The Y_{vertex} value was obtained by using use the following formula:

$$Y_{\text{vertex}} = -\frac{D}{4a}$$

$$D = b^2 - 4ac$$

2.3. Pressure Tests

Pressure tests were performed to simulate the amount and duration of pressure required during the mechanical drying process. The amount and duration of pressure used in this experiment was based on the study conducted by Saveyn et al. (2009) [14], which used 4 kg/cm² of pressure in 16.67 minutes and 15 kg/cm² of pressure in 15 minutes [14]. This study used pressure variations of 2, 4, and 8 kg/cm² with a pressure duration of 16 minutes.

3. Result and Discussion

3.1. Optimum Total Solid Content Yield and Pressure Duration

The optimum total solid content yields at 4, 6, and 8 bars of pressure are shown in Figures 2, 3, and 4.

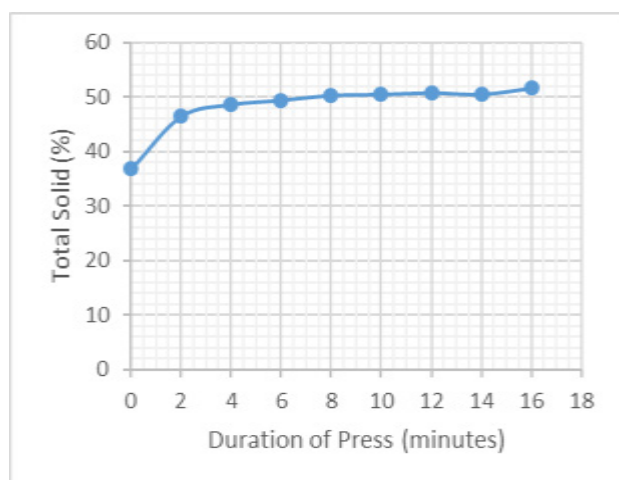


Fig. 2. Total Solid and Press Duration at 4 Bars of Pressure.

At 4 bars of pressure, the total solid content yield increased with an increased press duration. The highest total solid content was produced in minute 16, with a value of 51.64%.

Based on these values, the quadratic equation and resulting function obtained was as follows:

$$Y = -2.005x^2 + 8.82x + 36.9$$

At 4 bars of pressure, the value of the X_{vertex} was 2.199 minutes, or 2 minutes and 12 seconds. The X_{vertex} value indicates the duration of pressure required to obtain the total solid optimum value. In the mechanical dewatering design, optimum duration of the press was rounded to 3 minutes and the value of the Y_{vertex} was 46.59%. The Y_{vertex} value indicates the total optimum solid content value.

The graph in Figure 2 shows an ascending trend from the beginning to the end of mechanical dewatering process. Significant increases of total solid occurred between 0-4 minutes, while the graph began to slope after the fourth minute. This indicates that it took 0-4 minutes to achieve the total optimum solid in the mechanical dewatering design. The parabola calculation was obtained with a total optimum solid content value of 51.24% and an optimum water content of 48.76%, which took 3 minutes.

Below is a graph displaying the optimum value of the total solid and the press duration at 6 bars of pressure (Fig 3).

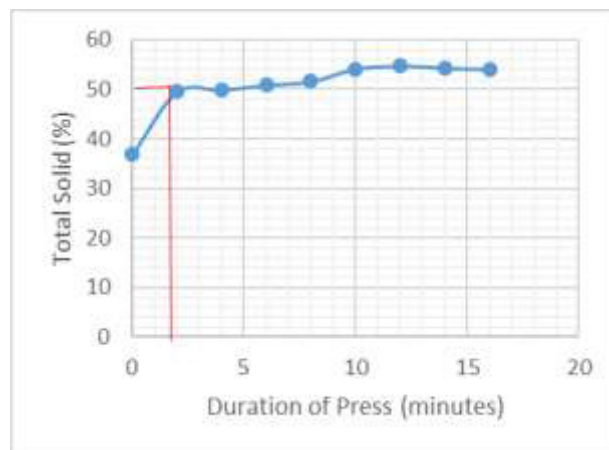


Fig. 3. Optimum Total Solid and Press Duration at 6 Bars of Pressure.

The function of the quadratic equation obtained from the total solid optimum at 6 bar is as follows.

$$Y = -1.5275x^2 + 9.36x + 36.9$$

At 6 bars of pressure, the value of the X_{vertex} was 3.0638 minutes, or 3 minutes and 2 seconds. The X_{vertex} value indicates the press duration required for obtaining the optimum total solid. In the mechanical dewatering design, optimum press duration was rounded to 3 minutes, and the value of the Y_{vertex} was 51.2387%. The Y_{vertex} value indicates the total optimum solid content value.

Previous studies have shown that at 6 bars of pressure, water content decreased from beginning to end [13]. Similar conditions occurred in the mechanical

dewatering process when water decreased significantly between minutes 0-4 and the optimum water content was in the range of 60-70%. This result is due to the difference in feedstock materials used. Paper sludge was used in previous studies as feedstock.

The function of the quadratic equation obtained for the total solid optimum at 8 bars of pressure is as follows:

$$Y = -1.7862x^2 + 11.0975x + 36.9$$

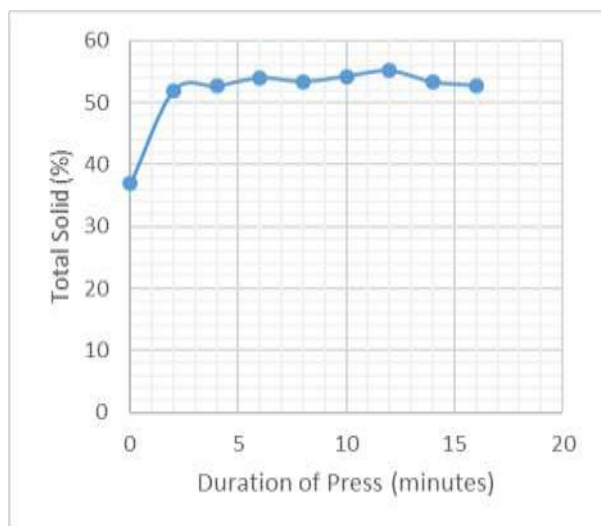


Fig. 4. Total Solid and Press Duration at 8 Bars of Pressure.

At 8 bars of pressure, the X_{vertex} value was 3.106 minutes, or 3 minutes and 6 seconds. The X_{vertex} value indicates the press duration required for obtaining the total solid optimum value. For the mechanical dewatering design, optimum press duration was rounded to 3 minutes and the value of the Y_{vertex} was 54.1365%. The Y_{vertex} value indicates the total optimum solid content value.

The graph shows a significant increase within 0-4 minutes of press duration (Fig 4). This indicates that it takes a period of 0-4 minutes to achieve the total optimum solid content when using the mechanical dewatering design at 8 bars of pressure. When calculating the parabola, a total optimum solid content value of 54.14% and optimum water content of 45.86% was obtained after 3.1 minutes.

In a previous study conducted by Ramke et al. (2009), the performance of hydrothermal waste drying was also studied. In that study, an increase in the volume of water released occurred within minutes 0-4 of the pressing process. A similar phenomenon was also noted in the same study at 8 bars of pressure. In the study by Ramke et al. (2009), the optimum values of various feedstocks were in the range of 40-65% [15]. This indicates that the feedstock material used in hydrothermal treatment affects the performance of water drainage in mechanical dewatering. The feedstock used in present study includes straw, organic waste, and mixed waste (biogas mud, straw, and dried horseradish). The use of organic waste as feedstock in the current study can be compared to the feedstock of previous studies as it is derived from municipal waste. In the

organic waste graph showed in fig 4, a significant increase of total solid was shown in minutes 0-3. A parabola calculation was used to reveal the optimum water content value of organic waste obtained in the previous study, which was 46.52% with a press duration of 2.54 minutes. These results are relatively similar to the optimum moisture content noted in the current study, which was 45.86% with a press duration of 3.1 minutes.

3.2. Comparison of Total Solid Content at 4, 6, and 8 Bars of Pressure

The highest optimum total solid content was produced at 8 bars of pressure (54.14%) with a press duration of 3.1 minutes. At 4 bars of pressure, the total optimum solid yield was 46.6% with a press duration of 2.2 minutes. This indicates that at 4 bars of pressure, it took less time to reach the optimum total solid content. In the drying system process of mechanical dewatering, energy and power requirements, cost, and economics are important considerations [13]. Within this study, the mechanical dewatering design with 8 bars of pressure provided the most optimal result, as the total solid content produced was higher than at other bars of pressure.

Table 1. Comparison of Optimum Press Duration and Total Solid.

Pressure (bar)	Optimum Press Duration (minutes)	Total Solid Optimum (%)
4	2.2	46.61
6	3.1	51.24
8	3.1	54.14

3.3. Volatile Matter, Ash, and Caloric Value

The hydrothermal product was compared before and after optimum mechanical dewatering. This comparison is shown in Table 2.

Table 2. Proximate Analysis Before and After Optimum Mechanical Dewatering

Proximate Analysis	Before OMD*	After OMD*
Moisture Content (% wt)	57.96	38.89
Volatile Matter (%)	82.71	85.31
Fixed Carbon (%)	3.12	2.26
Ash (%)	14.17	12.44
Heating Value (kkal/kg)	5154	5543.51

*OMD = *Optimum Mechanical Dewatering*.

After optimal mechanical dewatering, volatile matter increased from 82.71% to 85.31%. High levels of volatile matter in hydrothermally processed waste

products facilitate initial combustion when used as fuel [18]. The water content produced after optimum mechanical dewatering decreased significantly by 33% to equal 38.89%. A decrease in moisture content in solid fuels can lower transportation operation costs and save burning energy from evaporating moisture content in solid fuels. This will prevent slagging and fouling. However, optimal mechanical dewatering offers no calorific value increase. When compared with the ASTM D388-12, the heating value generated in this study falls within the *sub-bituminous* coal classification of the 19.3-26.7 MJ/kg range.

The results of this study were then compared with Yoshikawa's (2009) results [18]. Yoshikawa examined the composition of the hydrothermally treated material by varying treatments on the feedstock material. Samples A11 through B22 were hydrothermally processed products prior to dewatering. Samples B31d and C11d were hydrothermally processed waste products treated through mechanical dewatering by the centrifugal method.

Tables 3 and 4 demonstrate the hydrothermal treatment products used.

Table 3. Composition of Hydrothermal Waste Processing Product Analyzed in The Present Study

ID	Moisture Content (%)	Total Solid (%)	Combustible (%)	Ash (%)
Before Optimal Mechanical Dewatering				
V _{ash 1}	64.61	35.39	30.78	4.61
V _{ash 2}	61.60	38.40	32.52	5.88
After Optimal Mechanical Dewatering				
V _{ash 1}	43.11	56.89	50.18	6.71
V _{ash 2}	44.06	55.94	48.62	7.32

Annotation: (Combustible = Volatile Matter + Fixed Carbon).

Table 4. Composition of Hydrothermal Waste Processing Product from Hokkaido [18]

ID	Moisture Content (% weight)	Combustible (% weight)	Ash (% weight)	HHV db (kcal/kg)
A11	43.72	46.12	10.23	4260
A21	43.91	46.23	10.14	4490
B11	43.43	44.61	12.43	4260
B21	39.41	45.81	14.84	3850
B22	55.91	36.34	7.84	5790
B31d	48.37	43.91	7.42	6520
C11d	49.64	38.43	12.01	5670

Samples A11 to B22 were not dewatered, and can thus be compared with the characteristics of the present study sample before mechanical dewatering. The average water content of samples A11 to B22 was 45.26%. In this study, samples V_{ash1} and V_{ash2} had an average moisture content of 63.11%. The difference in moisture content was due to the waste composition used in hydrothermal treatment feedstock. In previous studies, the waste feedstock used came from municipal solid waste in Hokkaido, which is dominated primarily by plastic since the organic waste is used for compost. High moisture values in the V_{ash1} and V_{ash2} samples affected the combustible values (Volatile Matter + Fixed Carbon) and ash content.

Samples B31d and C11d are the product of mechanical dewatering and had an average water content of 48.985%, while the V_{ash1} and V_{ash2} samples had an average moisture content of 43.59%.

This study used a statistical approach to analyze the sample before and after the dewatering process and noted different results (SD +/- 0.87%). This variance can be attributed to differences in the waste composition used as feedstock for hydrothermal treatment.

Samples from Yoshikawa's (1990) study resulted in an average calorific value of 4997 kcal/kg, or 20.83 MJ/kg, and can be categorized under the *sub-bituminous* coal classification ASTM D388-12, which is similar to the sample obtained in this study.

3.4. C/N Ratio

Another option for hydrothermal waste processing product is to use it as compost. The C/N ratio is an important parameter in using this material as compost, as it has an effect on the discontinuation and release of nitrogen and other important nutrients into the soil [16]. According to the Indonesia standard of SNI 19-7030-2004, the C/N ratio for compost is between 10-20. The carbon and nitrogen contents, as well as the C/N ratio of the hydrothermal waste product before and after optimum mechanical dewatering, are presented in Table 5.

It is shown that before mechanical dewatering, the hydrothermal waste processing product has a C/N ratio value within the standard compost quality range. This means that the decomposition process operates optimally when carbon is used as a source of energy for the growth of microorganisms and nitrogen used in the formation of bacterial cells and remodel organic compounds in compost. Once optimal mechanical dewatering has been performed, the C/N value goes beyond the standard compost quality. Thus, the C/N ratio value increases when the moisture content in the sample decreases. This is because of the concentration of carbon content at the time of mechanical dewatering.

Table 5. Comparison of the C/N Ratio Before and After Optimal Dewatering

ID	Moisture Content (%)	Before Optimal Mechanical Dewatering				
		C (%)	N anorganic (%)	N organic (%)	C/N Ratio	
CN 1	53.63	37.6	0.74	2.25	12.59	
CN 2	63.06	44.5	1.37	2.21	12.48	
		C/N Ratio Average				12.54
		After Optimal Mechanical Dewatering				
		C (%)	N anorganic(%)	N organic (%)	C/N Ratio	
CN 1	43.16	54.9	0.93	0.65	34.87	
CN 2	44.05	64.2	1.46	0.72	29.51	
		C/N Ratio Average				32.19

Similar samples of hydrothermal waste processing products made from municipal solid waste have been analyzed and are presented in Table 6.

Table 6. Ultimate Analysis of Hydrothermal Waste Processing [18]

Ultimate Analysis	Hydrothermal Waste Processing Product
Carbon (%)	39.92
Hydrogen (%)	5.53
Nitrogen (%)	0.84
Oxygen (%)	26.68

Due to the similar use of the hydrothermal treatment method, the carbon content documented in Yoshikawa's study is relatively similar to sample CN1 from this study, which is 37.6. In Yoshikawa's (2009) study was used a pressure of 2 MPa at a temperature of 215°C while this present study, a pressure of 2 MPa at a temperature of 220°C was used.

The type of feedstock used can affect the resulting calorific value, and is closely related to the carbon content of the feedstock material [14]. The higher the carbon content is in hydrothermal processed products, the higher the produced calorific value will be. In previous studies, organic waste has been processed hydrothermally, resulting in products with a 35-40% carbon content.

In this study, the initial calorific value of the hydrothermal waste product was 23.21 MJ/kg, or 23204 MJ/kg. This is slightly higher than *sub-bituminous* coal, which is 21.58 MJ/kg.

4. Conclusion

This study used hydrothermal waste products as feedstock for a renewable energy source. The mechanical dewatering process with 4, 6, and 8 bars of pressure were used to obtain the total solid optimum with a press duration for each bar of pressure.

The total solid optimum was calculated using a parabolic formula based on the graph generated at each pressure variation. At each pressure variation, the time required to achieve the same total optimum solid content was within the 0-4 minute range. At 4 bars of pressure, the smallest total optimum solid yield was 46.60% with a press duration 2.2 minutes. At 6 bars of pressure, the total optimum solid yield was 51.24% with a press duration of 3.1 minutes. At 8 bars of pressure, the highest total optimum solid yield was 54.14% with a press duration of 3.1 minutes.

Optimum mechanical dewatering generated products with a calorific value of 23.21 MJ/kg. Processed products remained in the previous *sub-bituminous* coal classification with a measurement of 21.58 MJ/kg. Through the process of mechanical dewatering, there was an increase in both carbon and the C/N ratio of processed hydrothermal waste products.

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