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Gasification of Organic Waste in an Updraft Gasifier

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ABSTRACT

The majority of waste in Indonesia is constituted by organic materials, which can potentially be converted into energy. Among the various conversion methods, gasification with an updraft gasifier has proven to be the most effective way of converting waste into energy. Therefore, this study aimed to investigate the organic waste collected from TPST Piyungan, Yogyakarta, with a moisture content ranging from 16.95% to 53.74%. The impact of different moisture content categories, namely low, medium, and high, was also investigated to determine the operation time, fuel conversion rate (FCR), and heating rate. The results showed that the ideal value for the organic waste moisture content for a successful gasification operation was 15.68%. Furthermore, the operational time ranged from 61.57 to 193.69 minutes, with an optimum value of 66.68 minutes, resulting in an optimal FCR value of 38.28 gram/minute and heating rate values of 37.10oC/minute for IH (initial heating rate) and 19.96oC/minute for MH (maximum heating rate). The desired product quantity in ideal conditions was 86%, 8%, and 6%, for gas, liquid, and solids, respectively. Based on the complete testing process, the quantity of gas products ranged from 55.31 to 88.65%, followed by liquid at 1.64 to 4.57% and solids at 9.71 to 40.12%.

I INTRODUCTION

The current increase in global population and energy demand is significantly contributing to the study and adoption of cleaner energy forms due to the negative impact of the existing energy recovery systems on the environment. For both wealthy and developing countries, biofuels, specifically biomass, constitute a sustainable energy source [1]. Additionally, there is a significant potential for applying the use of MSW (Municipal Solid Waste) in urban areas in nations with high rates of population increase [2].

As a developing country and the 4th most populous nation in the world with 280,821,574 people and a population density of up to 151 per km2 in 2022, Indonesia must have a plan that emphasizes the value of diversity, environmental responsibility, and a rise in the use of domestic energy sources. By 2025, NRE (New and Renewable Energy) is required to account for 23% of the energy supply in the country. Additionally, Indonesia has committed to coordinating its energy supply with environmental sustainability on a global scale [3].

Indonesia recorded a significant increase in its MSW production due to population growth. MSW is a non-

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hazardous substance generated from routine activities of human life [4]. A previous study established that the characteristics and quantity of solid waste generated in a region were a function of the standard of living in the city or country [5]. As a developing country, Indonesia generates more organic waste than inorganic waste. However, developed countries frequently have a higher proportion of inorganic waste than organic [6]. In 2021, the amount of MSW produced was around 28 million tons, where approximately 15 million tons were an organic waste, according to information from the National Waste Processing Information System (SIPSN) collected from 215 regencies and cities [7],[8].

The amount of waste produced is calculated using a sample of 42% of 514 existing regencies and cities in Indonesia. Each person produces 251.3 kg of waste each year, amounting to 0.68 kg of waste per day. Therefore, in a household of four persons, there will be a daily production of 2.72 kg of waste. With this large amount, there is an opportunity to use waste in other forms, particularly in converting WtE, which has the highest potential. Organic waste is categorized as a type of biomass that can be used as an energy source. Moreover, the Indonesian government anticipates using 22.7 million tons of biomass as an energy source by 2050, with national energy security being the main objective of the energy development agenda. The use of WtE technology is one approach to making a national energy security program [9].

There are two main categories of WtE technologies, namely biochemical and thermochemical. Biochemical treatment involves processes such as digestion and fermentation, specifically anaerobic digestion to produce biogas, also known as biomethanation and fermentation to produce biofuels [10]. Although biological treatment is less expensive for comparable waste, it takes longer and is more difficult to manage the growth of the bacteria. This leads to the introduction of thermochemical treatment as a substitute for the enormous amount of waste [5].

In biochemical conversion, microorganisms or enzymes break down biomass molecules into smaller compounds, making it relatively slower compared to thermochemical conversion. Biochemical processes encompass digestion, fermentation, and enzymatic or hydrolysis, with digestion involving anaerobic and aerobic processes [10]. Meanwhile, in thermochemical conversion, the entire biomass is transformed into gases that can be used directly or to create the necessary chemicals. This process includes combustion, pyrolysis, and liquefaction, with gasification being the best approach due to its ability to generate the most gas [11].

Gasification involves the conversion of carbon into a gas product with a heating value, along with minor amounts of liquid and solid products. The process requires a medium for the reaction, such as air, oxygen, subcritical steam, or a combination of these gases [5]. The use of gas from gasification in higher efficiency electricity-production systems, such as gas turbines and reciprocating engines, provides excellent prospects for gasification-based WtE technologies to increase total plant efficiencies [12].

The most prominent kind of gasification reactor is the fixed bed, which can be further classified into updraft, downdraft, and crossdraft based on the positioning of the gasifying agent inlet and the gas product output. Each of the three reactors with fixed beds has its advantages and drawbacks in theory. However, the most prevalent and widely used types are updraft and downdraft models. The provision of a gasifying agent in the form of air for the initial combustion stage on the quality of the gas produced can be used to compare the differences between these prevalent gasifiers [13]. Based on this comparison, the updraft type is better in terms of producing an average LHV or higher calorific value, and the product gas composition has a greater percentage of CO gas [14].

As a raw material, MSW can be reduced by more than 75% through the gasification process, providing a more affordable and effective energy source compared to other methods. [15]. Among the components of MSW, organic waste has the potential to become a source of raw materials for renewable energy due to its larger amount. Organic waste is biomass that has a fairly high moisture content in the range of 15–40% [16]. The moisture content of biomass as fuel and volatile matter significantly affects the operation of the gasifier and the quality of the gas product [17]. Furthermore, there is a correlation between particle size distribution and bulk density for the best gasification process [18]. The temperature, fuel conversion rate (FCR), product quantity, and heating value of gas products are closely related to the moisture content of organic waste.

The moisture content of raw materials has a significant impact on the efficiency of the gasification process. Moreover, additional investigation is needed to better comprehend the impact of moisture content on the gasification process. The value of the heating rate, FCR, and the quantity of the gas produced, is used to evaluate the performance of the gasification process. To optimize the gasification process for organic waste and achieve ideal conditions, the use of an updraft gasifier is recommended. This approach will contribute to the efficient conversion of waste into energy, considering the effects of moisture content on heating rate, FCR, and product output.

II MATERIALS AND METHODS

2.1 Material

The raw material used in this study was organic waste collected from the Piyungan TPST, Yogyakarta, Indonesia. Subsequently, sampling was carried out 10 times at different points on the surface of the TPST area during the dry and rainy seasons. Initially, the collected MSW samples were sorted into inorganic and organic waste, which consisted of two types, namely natural and processed. Examples of natural organic waste included twigs, wood, leaves, coconut shells, coir, and straw. Processed organic waste consisted of household, restaurant, and small industry waste such as leftover food.

In this study, the type of waste used was natural organic waste. Due to the division of the Piyungan TPST area into sections, different collecting locations were employed. The division was influenced by the age of waste, with longer-standing MSW having lower moisture content. Moreover, the division of the area inadvertently occurred due to the movement of heavy vehicles that piled up waste in the landfill area. As presented in Figure 1, sampling at several points was essential to represent all landfill areas accurately.

The microalgae used in this experiment is Nannochloropsis sp which was purchased from Balai Budidaya Air Payau in Situbondo East Java Indonesia and delivered in green powder which was stored in a desiccator and used as received for further analysis.

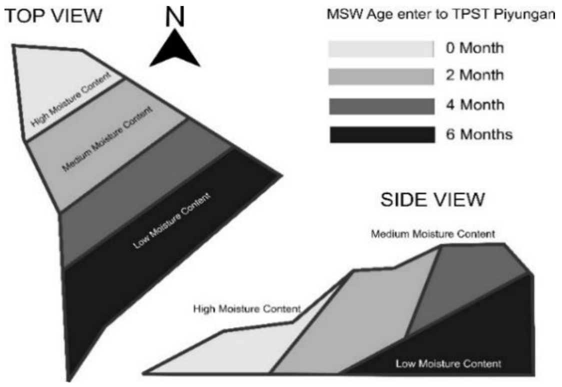


Figure 1. Top View Sampling Point at TPST Piyungan Area

2.2 Gasification Installation

This study was carried out using an experimental approach, employing an updraft gasifier, a fixed bed type, for the gasification procedure. The selection of an updraft gasifier was based on its ability to produce larger quantities and higher-quality goods [19], making it suitable for this experiment. Figure 2 shows the overall gasification installation.

The raw materials passed through a pre-treatment step before the main process, which involved drying the samples for about two weeks to achieve the desired moisture content levels, including low, medium, and high. Pre-treatment was carried out by drying the samples in a room with a temperature of 25^{o}C. The gasification process started with weighing the dried raw materials in a container, as shown in Figure 2. This process was carried out 10 times using air as a medium from a compressor with an airflow rate of 0.085 m$^{3/}$s. Combustion conditions in the gasification process were maintained with reference to air-fuel ratios of 0.2–0.3 [20].

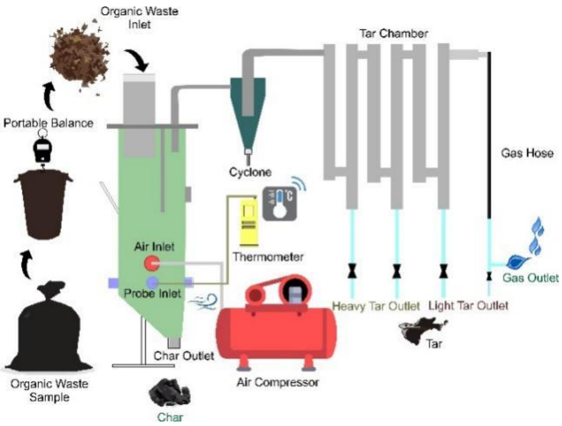


Figure 2. Overall Gasifier Installation

Time and temperature measurement instruments were used to determine the gasification process. Moreover, the actual gasification process began when the temperature increased to 600–650°C and continued until the raw materials were depleted, and the temperature dropped below 100°C.

III DATA ANALYSIS METHODOLOGY

3.1. The Extraction Energy Requirement

In a separate analysis, this study employed the moisture content (y) value as an independent variable, while the operational time, heating rate, and FCR were considered dependent variables. The impact of the heating rate on other significant factors was also taken into consideration. The heating rate (h_v) was obtained using Equation 1 and FCR was obtained using Equation 2, as expressed below.

$$h_v = \frac{T_i - T_e}{t} \qquad (1)$$

$$FCR = \frac{M_f}{\sum t} \qquad (2)$$

A correlation chart was used to show the link between the independent and dependent variables. The linear regression model was used as an approach to analyze the correlation between variables, as presented in Equation 3 [21].

$$y = ax + b \qquad (3)$$

Since the heating rate (Y) impacted multiple variables, namely the quantity of gas products (X1), liquid (X2), and solid (X3), it was necessary to use the approach with the multiple regression equation model in Equation 17.

Understanding the correlation between two quantitative variables is a frequent topic of interest in statistics. The value of the coefficient of determination (R^2) shows the strength of the relationship between these equations, with values ranging from -1 to 1. The total negative linear correlation between two variables is represented by -1.

A value of 0 denotes a lack of linear connection between two variables. The complete positive linear correlation between the two variables is represented by the number one [22],[23]. Meanwhile, calculations will be carried out to determine the coefficient value from the correlation chart, using Equations 4 to 6 [24].

$$(r = \frac{1}{n-1}\sum\left(\frac{x_i-\bar{x}}{s_x}\right)\left(\frac{y_i-\bar{y}}{s_y}\right) \qquad (4)$$

$$R^2 = 1 - \frac{RSS}{TSS} \qquad (5)$$

$$R^2 = (r^2) \qquad (6)$$

The value of 0 denotes a lack of linear connection between two variables. The complete positive linear correlation of two variables is represented by a number of one [23]. These coefficients are obtained to validate the line equation with a linear multiple regression model, following the steps with Equations 7 to 12.

$$A = \begin{bmatrix} n & \sum X_1 & \sum X_2 & \sum X_3 \\ \sum X_1 & \sum X_1^2 & \sum X_1X_2 & \sum X_1X_3 \\ \sum X_2 & \sum X_1X_2 & \sum X_2^2 & \sum X_2X_3 \\ \sum X_3 & \sum X_1X_3 & \sum X_2X_3 & \sum X_3^2 \end{bmatrix} \qquad (7)$$

$$H = \begin{bmatrix} \sum Y \\ \sum X_1Y \\ \sum X_2Y \\ \sum X_3Y \end{bmatrix} \qquad (8)$$

$$A1 = \begin{bmatrix} \sum Y & \sum X_1 & \sum X_2 & \sum X_3 \\ \sum X_1Y & \sum X_1^2 & \sum X_1X_2 & \sum X_1X_3 \\ \sum X_2Y & \sum X_1X_2 & \sum X_2^2 & \sum X_2X_3 \\ \sum X_3Y & \sum X_1X_3 & \sum X_2X_3 & \sum X_3^2 \end{bmatrix} \qquad (9)$$

$$A2 = \begin{bmatrix} n & \sum Y & \sum X_2 & \sum X_3 \\ \sum X_1 & \sum X_1Y & \sum X_1X_2 & \sum X_1X_3 \\ \sum X_2 & \sum X_2Y & \sum X_2^2 & \sum X_2X_3 \\ \sum X_3 & \sum X_3Y & \sum X_2X_3 & \sum X_3^2 \end{bmatrix} \qquad (10)$$

$$A3 = \begin{bmatrix} n & \sum X_1 & \sum Y & \sum X_3 \\ \sum X_1 & \sum X_1^2 & \sum X_1Y & \sum X_1X_3 \\ \sum X_2 & \sum X_1X_2 & \sum X_2Y & \sum X_2X_3 \\ \sum X_3 & \sum X_1X_3 & \sum X_3Y & \sum X_3^2 \end{bmatrix} \qquad (11)$$

$$A4 = \begin{bmatrix} n & \sum X_1 & \sum X_2 & \sum Y \\ \sum X_1 & \sum X_1^2 & \sum X_1X_2 & \sum X_1Y \\ \sum X_2 & \sum X_1X_2 & \sum X_2^2 & \sum X_2Y \\ \sum X_3 & \sum X_1X_3 & \sum X_2X_3 & \sum X_3Y \end{bmatrix} \qquad (12)$$

Before the final calculation, several matrices are solved to determine the coefficient values using Equations 13 to 16. In Microsoft Excel, the determinant function is used to solve the matrices ("=MDET(first column : end column)"). The determinant function is a quantity that can be solved with the square matrix elements in this study (4 x 4), causing 1 intercept (a) and 3 coefficients (b1, b2, and b3) [23].

$$a = \frac{DA1}{DA} \qquad (13)$$

$$b1 = \frac{DA2}{DA} \qquad (14)$$

$$b2 = \frac{DA3}{DA} \qquad (15)$$

$$b3 = \frac{DA4}{DA} \qquad (16)$$

The determinant results of each matrix (A1, A2, A3, & A4) are divided by matrix A to produce a coefficient value (a,b1,b2 and b3) to fill in Equation 17.

$$Y = a + b1X_1 + b2X_2 + b3X_3 \qquad (17)$$

By correlating the variables using simple linear regression created from correlation charts, this multiple regression method (Equation 17) is anticipated to be a valuable approach in determining the optimal value of variables that are influenced by moisture content. This model is validated with multiple linear regression values using IBM SPSS Software version 25.0. The graphical display is obtained by fulfilling the unstandardized predictive value of the three variables (X1, X2, and X3), which is deducted from the value of the dependent variable Y.

IV RESULT & DISCUSSION

The results showed that the moisture content of the organic waste raw material ranged from low (15-20%), medium (21-35%), to high (36-55%), as presented in Table 1. The moisture content was divided into ranges to map the source of organic waste according to Figure 1.

The mass of the fuel was obtained from the batch system in each testing process through a weighing procedure. The batch process for gasification was expected to make each test more measurable. This approach prevented the addition of fuel which can complicate the prediction of observed variable values during the process.

The next discussion continued with the operational time variable. In this study, the operational time (OT) was used as a reference parameter for observing gasification activities from the point where the fuel was full until everything had been consumed.

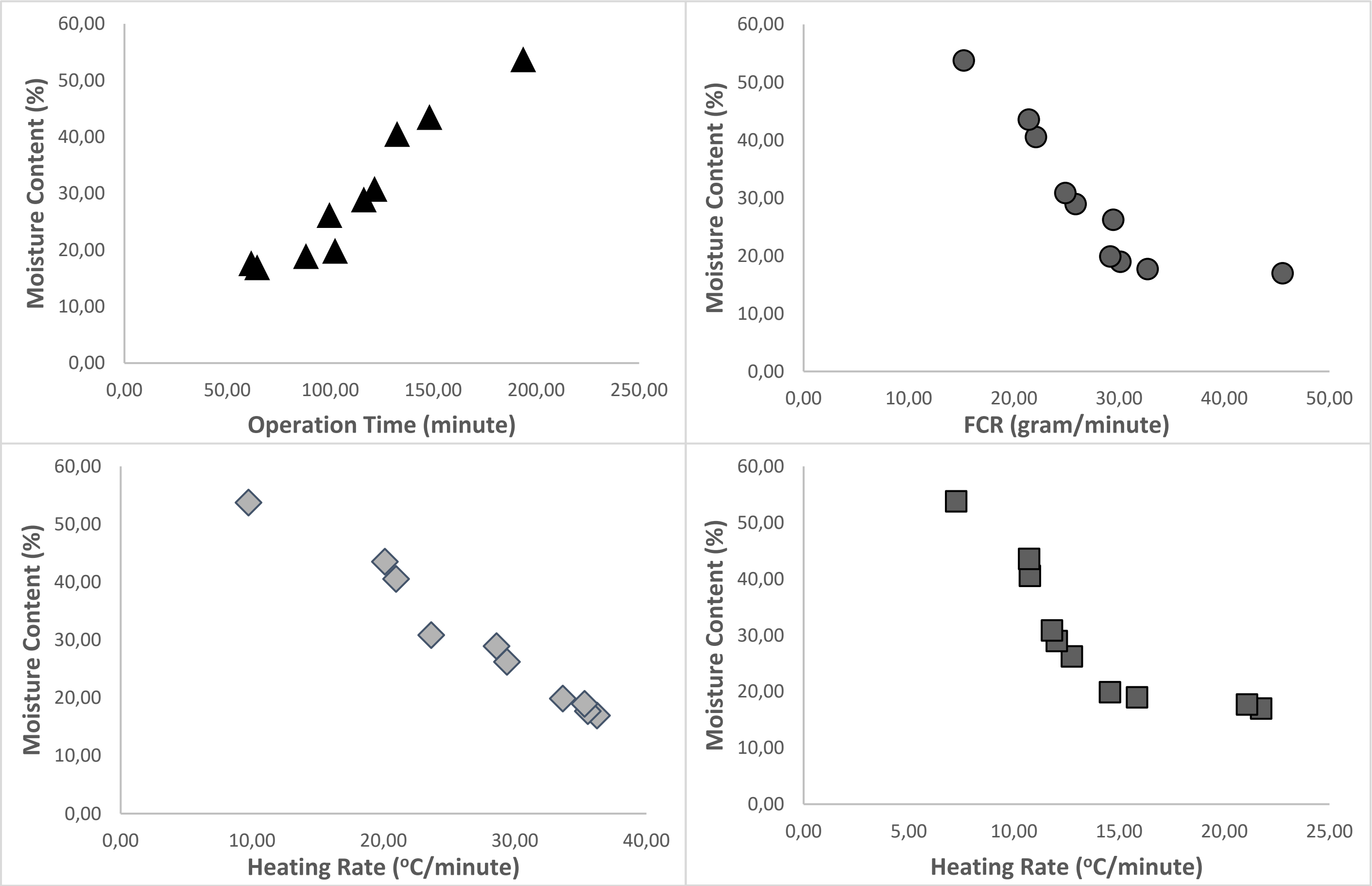
Table 1. Moisture Range, Moisture Content, and Fuel Mass

Moisture Range	Moisture Content (%)	Fuel Mass (gram)
Low	16.95	2935
	17.68	2015
	18.95	2657
	19.86	2985
Medium	26.21	2933
	28.94	3008
	30.83	3025
High	40.53	2928
	43.52	3175
	53.74	2954

Furthermore, it was influenced by the moisture content (MC) due to the longer completion of the drying process zone, as shown in Figure 3a. By using a regression model, the operational time was set as the dependent variable in the correlation graph, resulting in a coefficient of determination of 0.92. The chart in Figure 3 showed a precisely proportional relationship, indicating that the operational time increased with higher moisture content.

FCR is a parameter that measures how long it takes for the organic waste to run out in the entire existing gasification operational time. As shown on the correlation graph presented in Figure 3b, FCR is inversely correlated with moisture content. This indicated that as moisture content increased, FCR decreased, with a maximum coefficient of determination of 0.73.

The heating rate is the amount of temperature that rises at a time until it reaches a particular point. Figures 3c and d illustrated how the moisture content influenced the heating rate. Generally, there are two types of heating rates, namely the initial gasification temperature (IH) and the maximum temperature (MH). With a coefficient of determination for IH of 0.97 and MH of 0.74, the relationship between moisture content and heating rate was inversely proportional to the correlation chart, as shown in Figures 3c and d. Out of the four correlation relationships, the results of the linear line equation are as follows:



1. Figure 3. The Effect of Moisture Content on (a) Operation Time (OT), (b) Fuel Convertion Rate (FCR), (c) Heating Rate (IH) and (d) Heating Rate (MH)

$$MC = 0.3045OT - 4.6226$$
$$MC = -1.3228FCR - 66.3140$$
$$MC = -1.4343IH - 68.8920$$
$$MC = -2.3526MH - 62.3460$$

The primary objective of the gasification process is to generate gas-focused products, which are usually influenced by the heating rate [5]. Figure 4 shows the connection between the heating rate (MH) and the quantity of product (%) generated by each test procedure. The effect of moisture content on the heating rate showed a significant relationship. This was because the heating rate encompassed the entire process from room temperature (25°C) to the maximum gasification temperature.

In this experimental study, the mass of products was calculated by multiplying the fuel mass in Table 1 by each product percentage (gas, liquid, and solid) obtained from Figure 4, to determine the product quantity value with respective percentages. The results were presented in Table 2, with the value of the heating rate (MH).

Table 2. The Effect of Heating Rate on Quantity of Product

Heating Rate (°C/minute)	Gas (gram)	Liquid (gram)	Solid (gram)
21.76	1,727.83	42.18	245.00
21.09	2,349.87	54.13	529.00
15.86	2,200.75	61.25	395.00
14.57	2,601.93	48.07	285.00
12.76	2,204.00	116.00	855.00
12.04	1,634.00	135.00	1185.00
11.82	2,277.42	69.85	678.00
10.77	2,065.00	98.00	765.00
10.73	2,322.75	67.25	618.00
7.26	2,449.09	48.91	487.00

Based on the results in Table 3, the matrix was produced using Equations 7 to 12.

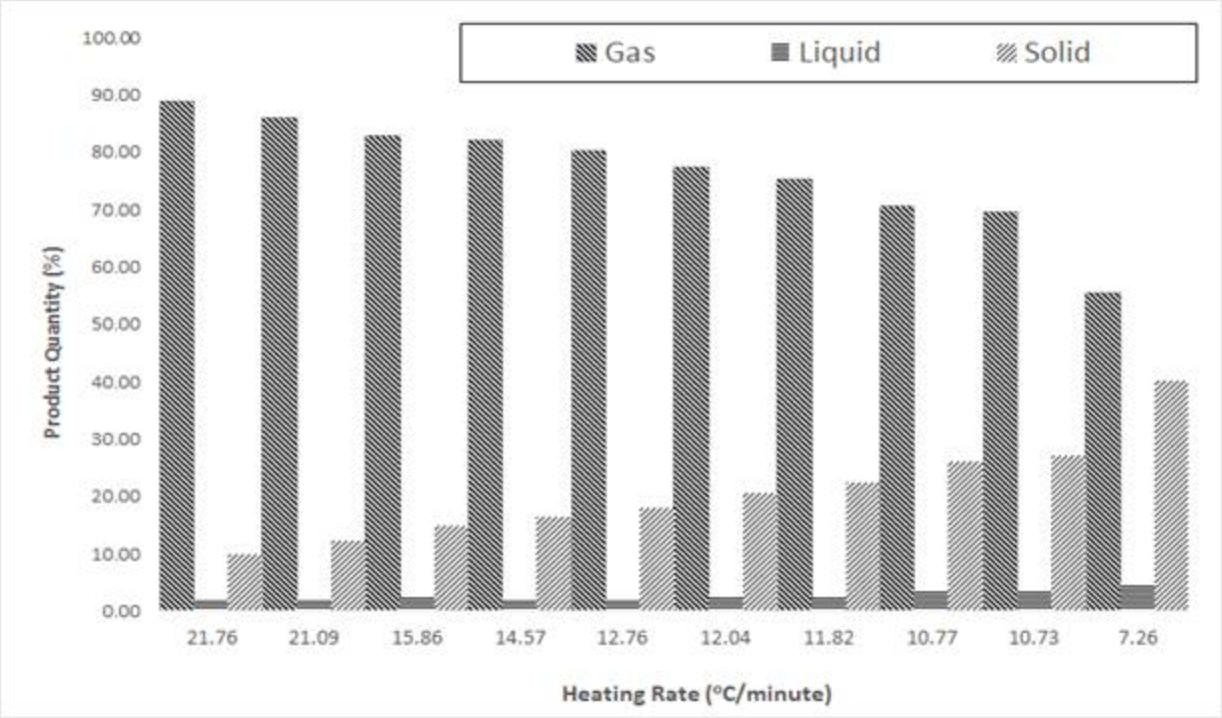


Figure 4. The Effect of Heating Rate (MH) on The Quantity of Gas, Liquid and Solid Products

Table 3. The Effect of Moisture Content on

∑ Variable	Value
Y	138.67
X_1	21,832.64
X_2	740.36
X_3	6,042.00
X_1Y	299,656.36
X_2Y	9,792.38
X_3Y	78,511.19
X_1X_2	1,573,009.94
X_2X_3	523,541.19
X_1X_3	12,849,936.81
X_1^2	48,492,271.10
X_2^2	63,812.02
X_3^2	4,376,368.00

$$A = \begin{bmatrix} 10.00 & 21{,}832.64 & 740.36 & 6042.00 \\ 21{,}832.64 & 48{,}492{,}271.10 & 1{,}573{,}009.94 & 12{,}849{,}936.81 \\ 740.36 & 1{,}573{,}009.94 & 63{,}812.02 & 523{,}541.19 \\ 6042.00 & 12{,}849{,}936.81 & 523{,}541.19 & 4{,}376{,}368.00 \end{bmatrix}$$

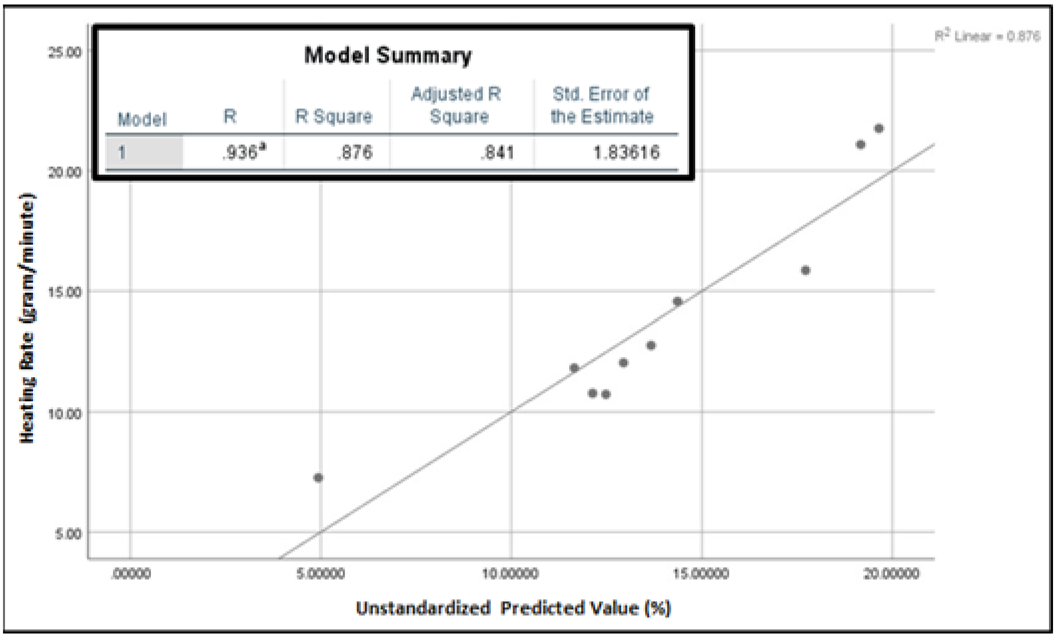
$$H = \begin{bmatrix} 138.67 \\ 299{,}656.36 \\ 9792.38 \\ 78{,}511.20 \end{bmatrix}$$

$$A1 = \begin{bmatrix} 138.67 & 21{,}832.64 & 740.36 & 6042.00 \\ 299{,}656.36 & 48{,}492{,}271.10 & 1{,}573{,}009.94 & 12{,}849{,}936.81 \\ 9792.38 & 1{,}573{,}009.94 & 63{,}812.02 & 523{,}541.19 \\ 78{,}511.20 & 12{,}849{,}936.81 & 523{,}541.19 & 4{,}376{,}368.00 \end{bmatrix}$$

$$A2 = \begin{bmatrix} 10.00 & 138.67 & 740.36 & 6042.00 \\ 21{,}832.64 & 299{,}656.36 & 1{,}573{,}009.94 & 12{,}849{,}936.81 \\ 740.36 & 9792.38 & 63{,}812.02 & 523{,}541.19 \\ 6042.00 & 78{,}511.20 & 523{,}541.19 & 4{,}376{,}368.00 \end{bmatrix}$$

$$A3 = \begin{bmatrix} 10.00 & 21{,}832.64 & 138.67 & 6042.00 \\ 21{,}832.64 & 48{,}492{,}271.10 & 299{,}656.36 & 12{,}849{,}936.81 \\ 740.36 & 1{,}573{,}009.94 & 9792.38 & 523{,}541.19 \\ 6042.00 & 12{,}849{,}936.81 & 78{,}511.20 & 4{,}376{,}368.00 \end{bmatrix}$$

$$A4 = \begin{bmatrix} 10.00 & 21{,}832.64 & 740.36 & 138.67 \\ 21{,}832.64 & 48{,}492{,}271.10 & 1{,}573{,}009.94 & 299{,}656.36 \\ 740.36 & 1{,}573{,}009.94 & 63{,}812.02 & 9792.38 \\ 6042.00 & 12{,}849{,}936.81 & 523{,}541.19 & 78{,}511.20 \end{bmatrix}$$



Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.936ª	.876	.841	1.83616

Figure.5. Multiple Linear Regression Models for Summary Model Validation.

The results of the matrix (A, A1, A2, A3, and A4) were processed using the Microsoft Excel function ("=MDET(first column: end column)", containing the coefficients (a, b1, b2, and b3) to create multiple regression equations with Equations 13 to 16. The multiple regression equation in Equation 17 was derived using the data from Table 2.

$$Y = 38.2744 - 0.0082\, X_1 + 0.0177\, X_2 - 0.0129\, X_3$$

The heating rate of a normal thermochemical process occurs at 30°C/minute [5]. Before applying the multiple regression model approach with the matrix method, the sum of each variable and their cross-multiplication were calculated, and the total results were shown in Table 3. The multiple regression yielded an R^2 value of 0.876 in Figure 5 for the validation model summary. Products from the gasification process typically contained 86% gas, 8% liquid, and 6% solid [19].

Based on the results, the product mass of gas, liquid, and solid was 2460.89 grams, 228.92 grams, and 171.69 grams, with an average fuel mass value of 2861.5 grams. According to the multiple regression equation, the optimum heating rate (MH) was at 19.96°C/minute, corresponding to the ideal moisture content of 15.68%. The optimal operational time value was 66.68 minutes, followed by the FCR value of 38.28 gram/minute and the heating rate (IH).

V CONCLUSION

In conclusion, this study showed that the optimal procedure for gasification involved the use of a fixed bed an updraft gasifier type. However, the organic waste raw material had a wide moisture content range of 16.95 to 53.74%. To ensure optimal gasification, a pre-treatment process was recommended before the main procedure for drying raw materials up to a value of 15.68%. Several factors, including operation time, FCR, heating rate, and product quantity, were used to assess the gasification process quality.

The results showed that the operational time was influenced by the moisture content, ranging from 61.57 to 193.69 minutes, with an optimum value of 66.68 minutes. During the entire testing process, the quantity of gas products ranged from 55.31 to 88.65%, followed by liquid at 1.64 - 4.57%, and solids at 9.71 - 40.12%. The ideal FCR value of 38.28 gram/minute was used as a guide to determine the capacity of the waste power plant. As a guide for creating standard operating procedures in waste power plants, the heating rate value with successive values for IH 37.10°C/minute and MH 19.96°C/minute was used to estimate the length of gasification operational time.

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