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Effect of flow rate and condenser cooling water temperature on product yield of coconut trunk sawdust pyrolysis liquid smoke

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ABSTRACT

Liquid smoke is a product resulting from the pyrolysis of biomass waste that contains chemical compounds with various applications, such as food preservatives, natural pesticides, and raw materials for the chemical industry. Liquid smoke is a by-product of simultaneous pyrolysis. To maximize the yield of liquid smoke while minimizing mass loss that could potentially pollute the environment, the simultaneous pyrolysis reactor needs to operate under optimal condensation conditions. This study observed two condensation parameters: the flow rate and the cooling water temperature of the condenser, using the case study of pyrolysis of biomass waste from coconut trunk sawdust. Pyrolysis was conducted at a temperature of 400°C for 2.5 hours, varying the flow rate of the cooling water in the condenser (1, 2, 2.5, 3, and 3.5 liters/minute) and the temperature of the cooling water (10°C, 20°C, 25°C, and 30°C). A multivariable nonlinear mathematical model was obtained, relating the yield of liquid smoke (y; %) to the water temperature parameter (x_1) and the flow rate of the cooling water in the condenser (x_2), which is expressed as $y = 6.68 + 1.89x_1 - 0.04x_1^2 - 0.41x_1x_2 + 13.06x_2 - 0.89x_2^2$. It was concluded that the optimal condensation conditions consist of a flow rate and cooling water temperature of 2 liters/minute and 20°C, respectively, yielding a maximum of 36% liquid smoke, 33% charcoal, and a minimum mass loss of 31%. Based on the coefficient values in the obtained mathematical model, it can also be concluded that the more dominant parameter affecting the yield of liquid smoke is the flow rate of the cooling water in the condenser, with a coefficient value of 13.06. An effective condensation system can enhance the conversion efficiency of pyrolysis vapour into liquid smoke and minimize potential pollution, demonstrating significant potential in processing biomass waste into valuable products, such as liquid smoke and charcoal, while being more environmentally friendly and energy-efficient.

1. Introduction

Pyrolysis consists of the word's "pyro" and "lysis," meaning decomposition or breakdown. Pyrolysis is the decomposition of carbon-based polymer or macromolecule compounds by heating them at high temperatures (above 300°C) in the absence or minimal presence of oxygen, resulting in simpler compounds such as carbonized charcoal, which is a carbon-rich solid. Destructive distillation or carbonization is another term for pyrolysis [1].

Charcoal products can be made into briquettes to be used as alternative solid fuel, both for households and industries. Charcoal can also be used as a bio-adsorbent, for instance, in water purification or wastewater treatment processes [2,3]. Charcoal produced from the pyrolysis of coconut trunk sawdust can also be used as a bio-adsorbent that meets halal criteria in the clarification process of crude virgin coconut oil (VCO) [4].

Aladin et al. have observed the use of charcoal produced from the pyrolysis of coconut trunk sawdust as a bio-adsorbent for crude VCO clarification. With a bio-adsorbent particle fineness of 50/100 mesh and a bio-adsorbent-to-VCO volume ratio of 2 g/mL, a significant turbidity level of VCO was achieved, at 1.15 NTU [5].

The liquid smoke produced directly from pyrolysis is referred to as grade 3 liquid smoke, which can be used as a biopesticide, deodorizer, and anti-termite wood preservative [6]. Grade 3 liquid smoke can be further processed to produce grade 2 liquid smoke through redistillation. If redistilled a second time, grade 1 liquid smoke is obtained. Grade 1 liquid smoke can be utilized as a food preservative, bio-hand sanitizer, and raw material in the chemical industry [7].

An appropriate pyrolysis reactor design that prevents contact with external air can enhance charcoal production as the main product of pyrolysis. Aladin et al. [1,8] designed a simultaneous pyrolysis reactor equipped with a condensation system capable of condensing vapour products into liquid smoke as a valuable by-product. This simultaneous pyrolysis reactor is considered environmentally friendly, as most of the vapour/gas by-products can be liquefied (except non-condensable substances), preventing their release into the environment, which could potentially cause air pollution.

To maximize charcoal production as the main product, it is necessary to operate under the optimum conditions for pyrolysis, including temperature, time, and reactor volume. Depending on the raw material, such as sawdust from coconut

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trunks, the optimal conditions are 400°C, 2.5 hours, and ¾ of the reactor volume, respectively. From this research, a charcoal yield of about 32%, yield loss of 35%, and liquid smoke yield of 33% were obtained based on the dry weight of the raw material. The characteristics of this charcoal product, based on proximate analysis, are moisture content of 3.53%, ash content of 3.96%, volatile matter of 35.39%, fixed carbon of 57.12%, total sulfur of 0.03%, and gross calorific value of 7050 kcal/kg [1,4,6,9].

The simultaneous pyrolysis process has operated under optimal pyrolysis conditions [6,9], but has yet to operate under optimal condensation system conditions. Condensation conditions, such as the temperature of the condenser cooling water and the flow rate of the condenser cooling water, have not been controlled at constant and optimal levels. To maximize the by-product liquid smoke and minimize mass loss to the air, it is also necessary to operate under the optimum conditions of the condensation system in the simultaneous pyrolysis process.

The condensation system is a crucial component of the pyrolysis system, functioning to convert the pyrolysis vapour into a liquid phase (liquid smoke). The condensation system, including the temperature of the condenser cooling water and the flow rate of the condenser cooling water, affects the yield of liquid smoke. A lower temperature of the condenser cooling water can increase condensation efficiency, resulting in a higher liquid smoke yield. Conversely, higher condenser cooling water temperatures lead to lower liquid smoke yields [10].

The appropriate flow rate of the condenser cooling water ensures efficient heat transfer from the vapour to the cooling water. A flow rate that is too low cannot transport heat efficiently, resulting in incomplete vapour condensation. Conversely, a flow rate that is too high can lead to wasted energy and water without providing additional benefits to condensation efficiency [11]. Adjusting the optimal flow rate and temperature of the condenser cooling water can increase the liquid smoke yield.

Indonesia is known as one of the largest coconut producers in the world. According to data from the Central Statistics Agency (BPS), Indonesia's coconut production reaches over 2.89 million tons per year, making this commodity one of the most important in the national agricultural sector. One of the largest coconut-producing regions is Bone Regency in South Sulawesi, with a production of 11,100 tons per year and a coconut plantation area of 12,082 hectares [12]. Coconuts are not only consumed, but the trunks can also be used as building materials. However, the processing of coconut trunks into value-added products often results in waste, such as sawdust. This waste is typically generated from the cutting, sawing, and smoothing of coconut trunks to achieve the desired shape and size [13].

Coconut trunk sawdust consists of fine particles produced during the processing of coconut trunks. Coconut trunk sawdust contains 26.58% - 36.35% lignin; 69.51% - 80.07% hemicellulose; and 28.1% - 36.55% cellulose [13]. This waste is often considered useless and adds to environmental burdens if not properly managed. Given its composition, sawdust has significant potential to be processed into high-value products if treated with the appropriate methods, such as the simultaneous pyrolysis method, which produces two marketable products: charcoal and liquid smoke [14].

Based on the explanation above, this research aims to observe the optimal conditions of the condensation system in the simultaneous pyrolysis process, using the case study of coconut trunk sawdust biomass pyrolysis. The parameters examined are the flow rate and temperature of the condenser cooling water. The objective of this research is to develop a multivariable mathematical model that relates the liquid smoke yield to the flow rate and temperature parameters of the condenser cooling water. It also aims to determine the optimal conditions and dominant parameters between the two. The benefit of this research is to maximize the yield of liquid smoke, thereby increasing the economic value of coconut trunk sawdust while minimizing the environmental pollution potential from the vapour produced in pyrolysis.

2. Materials and Methods

2.1. Materials

The material for this research is coconut trunk sawdust waste obtained from coconut plantations in Nipa, Bone Regency, South Sulawesi. The main equipment used in this research is a set of simultaneous pyrolysis process apparatus (Figure 1).

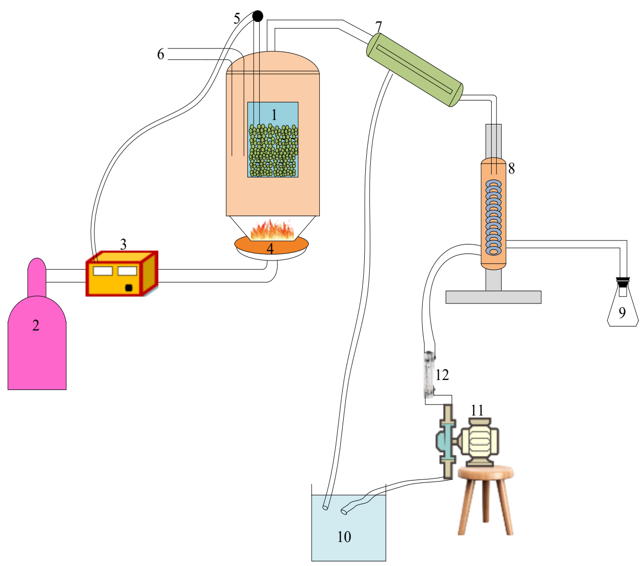

Fig. 1. Pyrolysis circuit [8]

Note:

1. Simultaneous Pyrolysis Reactor
2. LPG Gas Cylinder
3. Temperature Indicator Control
4. Stove
5. Thermocouple
6. Chimney
7. Condensor 1 (liebig)
8. Condensor 2 (spiral)
9. Liquid Smoke Container
10. Cooling Water Tub
11. Pump
12. Flowmeter

2.2. Research Methods

The coconut trunk sawdust feedstock was dried under direct sunlight for 3 days. A weight of 1000 grams of dry coconut trunk sawdust was placed into the simultaneous pyrolysis reactor. The pyrolysis process was carried out at a temperature of 400°C for 2.5 hours. Variations in the cooling water flow rate (1, 2, 2.5, 3, and 3.5 liters per minute) were observed using a calibrated flowmeter, with the cooling water temperature maintained at a constant 20°C. Based on the optimal flow rate obtained, variations in the cooling water temperature (10°C, 20°C, 25°C, and 30°C) were subsequently observed. Data from the observations of both parameters, flow rate and cooling water temperature, were processed to develop a multivariable mathematical model that connects the liquid smoke yield (y; %) as a function of the flow rate parameter (x_1) and the temperature parameter (x_2) of the pyrolysis cooling water. The model also aims to determine the dominant parameter between the two.

3. Results and Discussion

3.1. Effect of condenser cooling water flow rate variations on liquid smoke products

Data on the flow rate of the cooling water in the condenser in relation to the yield of liquid smoke has been obtained, as summarized in Table 1.

Tabel 1. Effect of cooling water flow rate in the condenser on pyrolysis products (T= 20ºC)

Cooling water flow rate in the condenser (litre/minute)	*Yield* charcoal %	*Yield* liquid smoke %	*Yield* loss %
1	33.0	33.33	33.67
2	32.8	35.65	31.55
2.5	33.0	35.86	31.15
3	33.1	35.96	30.94
3.5	33.0	35.95	31.05

From the data in Table 1, it can be seen that the yield of charcoal is relatively unaffected by changes in the flow rate of the cooling water in the condenser (Figure 2). This is because the condenser system is not connected to the process inside the pyrolysis reactor; it is only related to the output process of pyrolysis, which involves the condensation of vapor/gas outside the pyrolysis reactor (Figure 1). The results of this study are consistent with the research conducted by Aladin et al. (2023), which obtained a charcoal yield ranging from 30% to 35% in simultaneous pyrolysis processes [6].

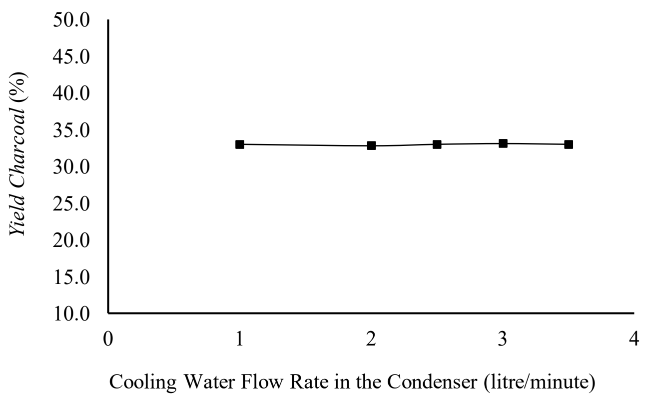

Fig. 2. Effect of flow rate on charcoal yield

Conversely, the data in Table 1 shows that the yield of liquid smoke increased from 33.33% to 35.65% as the flow rate of the cooling water in the condenser increased from 1 to 2 liters/minute. This is because a higher flow rate of cooling water enhances the convective heat transfer of the vapour/gas absorbed by the cooling water, leading to a greater amount of vapour being condensed. However, increasing the flow rate of the cooling water beyond 2 liters/minute does not significantly affect the yield of liquid smoke (Figure 3). An increase in flow rate above 2 liters/minute does not provide a corresponding benefit in product yield compared to the energy costs associated with increasing the cooling water flow rate.

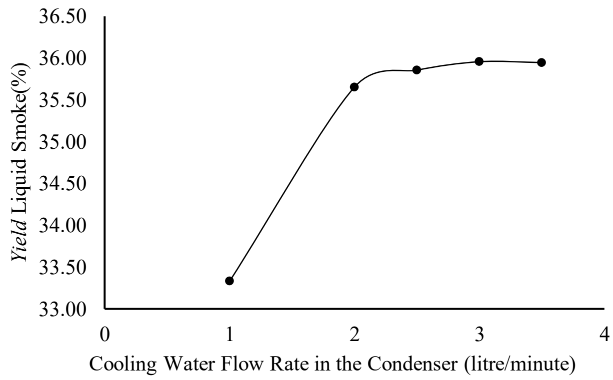

Fig. 3. Effect of Flow Rate on Liquid Smoke Yield

This is consistent with the research conducted by Ramadan (2020), which found that as the flow rate of the cooling water increases, the amount of liquid smoke produced also increases. It can be concluded that the optimal flow rate of the cooling water in the condenser is 2 liters/minute, which yields a maximum liquid smoke yield of 36% [15].

Based on the data in Table 1, it is evident that the increase in the flow rate of the cooling water in the condenser, which enhances the yield of liquid smoke, has a direct impact on the reduction of mass released into the environment. Figure 4 simultaneously illustrates the effect of the cooling water flow rate on the yield of charcoal, liquid smoke, and mass loss to the environment. At the lowest flow rate (1 litre/minute), the yield loss was recorded at 33.67% and continued to decrease, reaching 31.05% at the highest flow rate (3.5 liters/minute). This decrease in yield loss indicates that the increase in the flow rate of the cooling water in the condenser helps reduce the amount of material that is lost or not effectively condensed. Flow rates of cooling water higher than 2 liters/minute do not show a significant reduction in mass loss; this is due to the vapour/gas produced from pyrolysis containing non-condensable vapour [16].

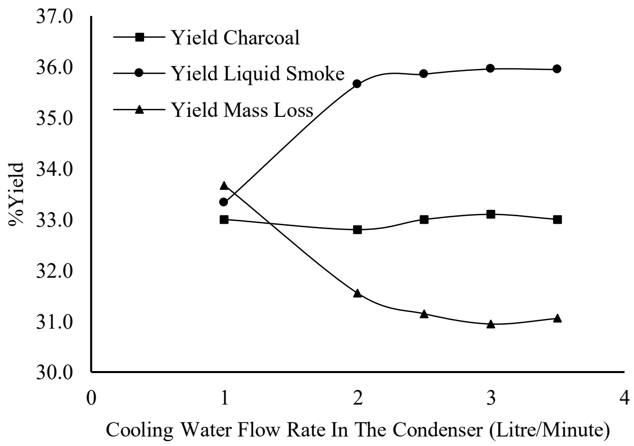

Fig. 4. Effect of flow rate on the yield of simultaneous pyrolysis products

Figure 4 shows that the flow rate of the cooling water in the condenser has a significant impact on the yield of liquid smoke and yield loss, while the yield of charcoal remains stable. A flow rate of 2 liters/minute is identified as the optimum point, where the yield of liquid smoke approaches its maximum and yield loss reaches a low value, indicating that the system operates efficiently. Increasing the flow rate beyond 2 liters/minute does not provide significant advantages in terms of enhancing the yield of liquid smoke or reducing yield loss, thus it can be concluded that this flow rate is the optimum flow rate for maximizing output and process efficiency in pyrolysis.

3.2. Effect of condenser cooling water temperature variation on liquid smoke products

Data on the cooling water temperature in the condenser within the observation range of 10 – 30°C in relation to the yield of liquid smoke has been obtained, as summarized in Table 2.

Table 2. Effect of cooling water temperature variation in the condenser on pyrolysis products (v = 2 liters/minute)

Cooling Water Temperature in the Condenser (°C)	*Yield* Charcoal %	*Yield* Liquid Smoke %	*Yield* Loss %
10	31.3	36.36	32.34
20	32.8	35.7	31.55
25	32.3	33.33	34.37
30	33.2	27.27	39.53

As with the effect of the cooling water flow rate (Table 1), the data in Table 2 shows that the yield of charcoal is relatively unaffected by changes in the temperature of the cooling water (Figure 5). This is because the condenser system is not connected to the process inside the pyrolysis reactor; it is only related to the output process of pyrolysis, which involves the condensation of vapor/gas outside the pyrolysis reactor. The results of this study are consistent with the research conducted by Aladin et al., which obtained a charcoal yield ranging from 30% to 35% in simultaneous pyrolysis processes [6].

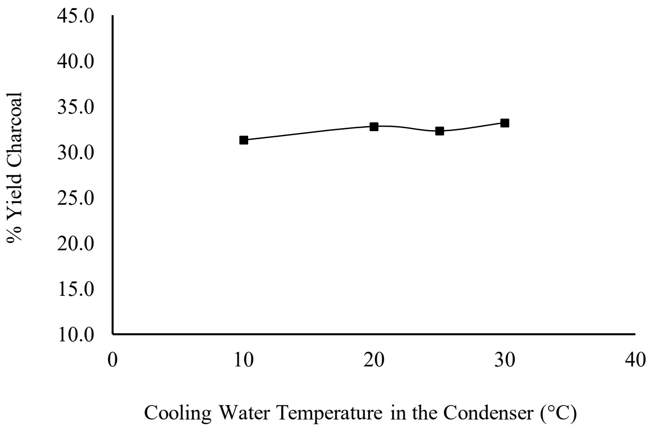

Figure 5. Influence of cooling water temperature variation on charcoal yield

Figure 6 illustrates the relationship between the temperature of the cooling water in the condenser and the yield of liquid smoke produced within the temperature range of 10-30°C. The yield of liquid smoke decreases as the temperature of the cooling water increases, with a significant decline in yield observed when the temperature rises above 20°C. In contrast, the increase in temperature from 10°C to 20°C does not lead to a significant reduction in the yield of liquid smoke. Therefore, it can be concluded that at the optimum flow rate of the cooling water in the condenser (2 liters/minute), the optimum temperature is 20°C, which yields a maximum of nearly 36%.

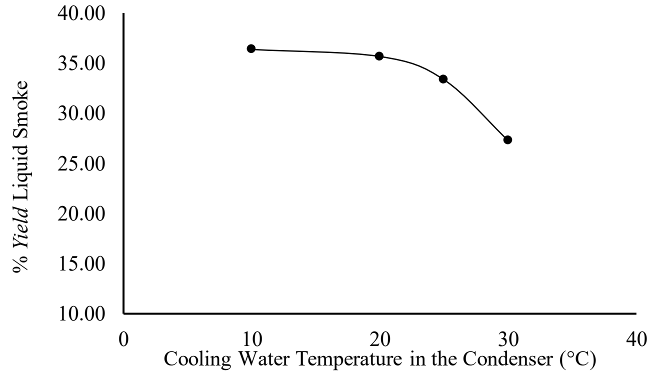

Figure 6. Effect of cooling water temperature variation in the condenser on liquid smoke yield

The decrease in liquid smoke yield at higher temperatures is due to the reduced capacity for condensing the vapor of liquid smoke at elevated cooling water temperatures. A condenser cooled at lower temperatures is more effective in cooling and condensing vapor into liquid, thereby increasing the amount of liquid smoke produced. Conversely, higher condenser temperatures result in less condensation, leading to lower liquid smoke yields. This is also supported by Ashoor et al. in their research, which states that variations in cooling affect the volume of liquid smoke produced from pyrolysis. The lower the cooling temperature, the more liquid smoke will be generated [17].

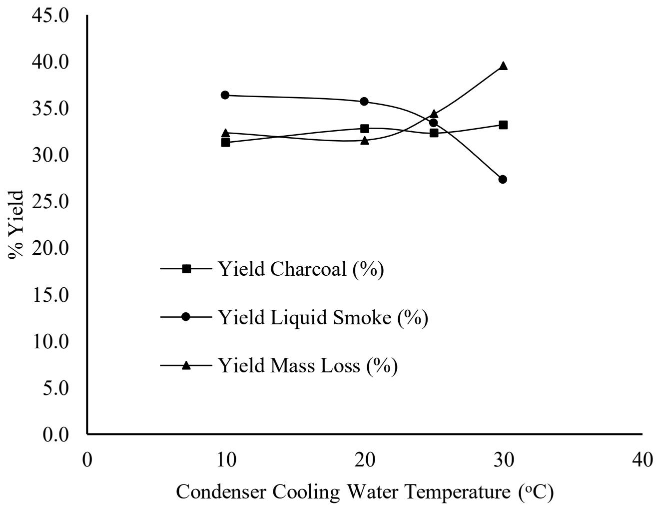

Figure 7. Effect of cooling water temperature variation on the yield of pyrolysis products

Based on the data in Table 2, it is evident that the increase in the temperature of the cooling water, which reduces the yield of liquid smoke, has a direct impact on the increase in mass released into the environment. Figure 7 simultaneously illustrates the effect of the cooling water temperature on the yield of charcoal, liquid smoke, and mass loss to the environment.

Simultaneous pyrolysis of coconut trunk sawdust under optimal pyrolysis conditions of temperature and time of 400°C and 2.5 hours, along with optimal condensation conditions of a flow rate of 2 liters/minute and a cooling water temperature of 20°C, produces nearly 33% charcoal and 67% vapour from pyrolysis. The vapour produced consists of 36% condensable vapour (liquid smoke) and 31% non-condensable vapour. Another conclusion is that the vapour from pyrolysis is composed of 54% condensable vapour and 46% non-condensable vapour.

Based on these optimal condensation conditions, the produced liquid smoke has a density of 1.10 g/ml, a reddish-brown colour, and a pungent odour. GC-MS analysis of the liquid smoke shows the presence of 38 compound spectra, which can be categorized into four major groups: carbonyl groups, acid groups, phenolic groups, and other categories (such as pyridine and carbohydrates), predicted to result from the decomposition of lignocellulose during pyrolysis. The highest percentage is in the phenolic group, reaching 65.39%, while the lowest content is in the acid group, which is only 7.8% [6].

3.3. A multivariable mathematical model that connects the yield of liquid smoke as a function of the cooling water flow rate and pyrolysis temperature

The dominant parameters of the condensation system in simultaneous pyrolysis that significantly affect the yield of liquid smoke can be determined through the modelling of a nonlinear multivariable mathematical equation. The nonlinear multivariable equation is used to describe the relationship between the temperature of the cooling water in the condenser and the flow rate of the cooling water in relation to the yield of liquid smoke. The nonlinear multivariable equation (two variables) can be generally written as:

$$y = a_0 + a_1x_1 + a_2x_1^2 + a_3x_1x_2 + a_4x_2 + a_5x_2^2 \quad (1)$$

Note:
y = *yield* liquid smoke (%)
x_1 = Condenser Cooling Water Temperature (°C)
x_2 = Cooling Water Flow Rate in the Condenser (liters/minute)

The values of each constant a_0, a_1, a_2, a_3, a_4, a_5 are obtained through the Hooke-Jeeves multivariable optimization process, which provides the smallest Sum of Squares of Error (SSE). The SSE is calculated using Equation (2):

$$\text{SSE} = \left(\sum_{i=1}^{n}(y\ data - y\ hitung)^2\right)/\text{n} \quad (2)$$

From the calculations, the values of each constant are presented in Table 3.

Table 3. Results of the calculation of coefficients for the nonlinear multivariable equation

a_0	a_1	a_2	a_3	a_4	a_5
6.68	1.89	-0.04	-0.41	13.06	-0.89

The mathematical model above is sufficiently valid, as indicated by the sum of squares error (SSE) being relatively small, approaching zero at 0.0954. From Table 4, it can be seen that the observed y values (lab data) and the y values calculated based on the model are quite similar, demonstrated by the small error between the actual values and the calculated results. At a temperature of 20°C and a flow rate of 2 L/min, the observed yield is 35.653%, while the calculated result using the equation is 35.70289%, with a relative error of only about 0.0025. However, at a temperature of 30°C, there is a significant decrease in yield to 27.27%, with the calculated result using the equation being 27.55%. This indicates that an increase in the cooling water temperature in the condenser above the optimum reduces condensation efficiency, leading to a decrease in liquid smoke yield.

Table 4. Results of the calculation of liquid smoke yield based on cooling water temperature and flow rate in the condenser

x_1	x_2	Y_{data}	y_{hitung}	SSE
20	1	33.33	33.4386	0.0118
20	2	35.653	35.7029	0.0025
20	2.5	35.855	36.1673	0.0975
20	3	35.956	36.1866	0.0532
20	3.5	35.9459	35.7607	0.0343
10	2	36.36	36.2657	0.0089
20	2	35.653	35.7029	0.0025
25	2	33.33	32.5761	0.5683
30	2	27.27	27.5524	0.0798
		Average		0.0954

In Table 3, it is shown that coefficient a_1 indicates a positive relationship between the cooling water temperature in the condenser and the yield of liquid smoke, while coefficient a_2 indicates the presence of an optimal point, where further increases in the cooling water temperature in the condenser actually reduce the yield of liquid smoke. Furthermore, the interaction between the cooling water temperature in the condenser and the cooling water flow rate, represented by coefficient a_3, also affects the yield of liquid smoke, although the largest contribution comes from the cooling water flow rate, as indicated by coefficient a4a_4a4, which has the highest value (13.06).

The cooling water flow rate in the condenser (x_2) proves to be the most influential factor on the yield of liquid smoke compared to the cooling water temperature in the condenser (x_1), with coefficient a_4 being significantly larger. An increase in the cooling water flow rate in the condenser significantly enhances the yield of liquid smoke, but if the flow rate becomes too high, it starts to reduce the yield of liquid smoke, as indicated by the squared flow rate coefficient ($a_5 = -0.89$). On the other hand, the cooling water temperature in the condenser also affects the yield of liquid smoke, but its impact is smaller compared to the cooling water flow rate, with the optimal point for the cooling water temperature at a certain value before increasing the temperature leads to a decrease in liquid smoke yield.

4. Conclusion

Research on the influence of cooling water flow rate and temperature parameters on the by-products of simultaneous pyrolysis in the form of liquid smoke: a case study of biomass waste from coconut sawdust pyrolysis. pyrolysis operating at a temperature of 400°C for 2.5 hours yielded a nonlinear multivariable mathematical model that connects the yield of liquid smoke (y;%) with the temperature of the cooling water (x_1, °C) and the flow rate of the cooling water in the condenser (x_2, liters/minute), expressed as: $y = 6.68 + 1.89x_1 - 0.04x_1^2 -$

$0.41x_1x_2 + 13.06x_2 - 0.89x_2^2$. The optimal condensation conditions consist of a flow rate and cooling water temperature of 2 liters/minute and 20°C, respectively, which provide a maximum yield of liquid smoke of 36%, charcoal of 33%, and a minimum mass loss of 31%. The parameter that has a more dominant effect on the yield of liquid smoke is the flow rate of the cooling water in the condenser, with a coefficient value of 13.06 for x_2.

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