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Feasibility Analysis of Industrial-Scale Pyrolysis of 200 kg Polyethylene and Polystyrene Plastic Waste

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ABSTRACT

This research investigates the potential for implementing industrial-scale pyrolysis of polyethylene (PE) and polystyrene (PS) plastic waste, using a feedstock capacity of 200 kilograms per day. The pyrolysis process was carried out at temperatures of 400°C, 450°C, and 500°C, continuing until full thermal decomposition was achieved, as indicated by the end of smoke production. The optimal conditions were then used for energy calculations in a 200 kg industrial process. Pyrolysis duration varied by plastic type and temperature, with PE at 450°C taking the longest time (98 minutes) and PS at 400°C the shortest (31 minutes). Higher temperatures resulted in lower heating rates for both plastics. Results show that increasing temperature enhances oil yield up to a point, after which it declines. PS yields higher oil than PE due to styrene monomers being in liquid phase. Oil yield from PS remains stable with temperature increases, while PE's yield rises before decreasing at the highest temperature. The decrease in PS oil density at higher temperatures suggests physical differences from PE. Energy consumption for PS pyrolysis (75.14–77.57 kJ/g) is higher than PE (18.7–33.94 kJ/g). Despite PS having a higher oil yield (79–80%), the energy produced is insufficient to sustain the pyrolysis process. Economically, converting PE and PS plastic waste to fuel is not entirely feasible. PE pyrolysis oil generates Rp 14,729,000/month, while PS yields Rp 30,927,000/month. However, the social benefit of reducing plastic waste adds significant value.

I. Introduction

Plastics are among the most widely used materials in daily life due to their lightweight, strength, durability, and affordability [1], [2], [3], [4]. However, their extensive use has led to serious environmental issues caused by the accumulation of plastic waste, which is difficult to decompose naturally [5], [6], [7], [8]. Among the most commonly found plastic wastes are polyethylene (PE) and polystyrene (PS), which are widely used in packaging, household products, and various industrial applications [6], [7]. Their resistance to natural degradation makes PE and PS waste a potential source of soil, water, and marine ecosystem pollution if not properly managed.

One potential method for processing plastic waste is pyrolysis, a process that decomposes plastic waste into liquid fuel through heating in the absence of oxygen. Pyrolysis can convert plastic waste into value-added products such as liquid fuel, gas, and solid carbon residue. These products can serve as alternative energy sources that are more environmentally friendly compared to conventional fossil fuels. Additionally, this method helps reduce the volume of plastic waste and mitigate its negative environmental impact.

At the laboratory scale, plastic pyrolysis has been extensively studied to determine optimal process parameters, such as operating temperature, catalyst type, and heating rate. However, the industrial-scale implementation of pyrolysis still faces various challenges, including energy efficiency, operational costs, and the stability and quality of the produced products. Therefore, a feasibility analysis is required to assess whether the pyrolysis of PE and PS plastic waste can be economically and technically viable on an industrial scale [9].

This study aims to analyze the feasibility of pyrolyzing PE and PS plastic waste with a capacity of 200 kg on an industrial scale. The analysis considers both technical and socio-economic aspects to determine the effectiveness of this technology's implementation. From a technical perspective, the study evaluates key parameters in the pyrolysis process, including operating temperature [10], [11], reaction time, and product yield. Meanwhile, the socio-economic analysis examines investment costs, operational expenses, and the revenue potential from pyrolysis products.

Several previous studies have demonstrated that pyrolysis can be an effective solution for processing plastic waste, particularly on a laboratory scale. However, there are still limitations in industrial-scale implementation, including high energy requirements and complex technology. Therefore, this feasibility study is expected to provide further insights into the opportunities and challenges of applying plastic pyrolysis technology on an industrial scale.

This study also examines the energy efficiency comparison between electricity and alternative fuels in the pyrolysis process. One of the main challenges in industrial-scale implementation is high energy consumption, necessitating optimization to enhance efficiency and cost-effectiveness. Additionally, the quality of the pyrolysis oil is evaluated to ensure its suitability as an alternative fuel for various industrial applications.

By considering these various aspects, this study aims to provide comprehensive recommendations for the industrial-scale implementation of plastic pyrolysis technology. The feasibility analysis results can serve as a basis for decision-making in the development of more sustainable and environmentally friendly plastic waste treatment technologies. Furthermore, this research can serve as a reference for industries and policymakers in designing more effective and efficient plastic waste management strategies.

Ultimately, industrial-scale plastic pyrolysis holds great potential as a solution to mitigate the environmental impact of increasing plastic waste. However, its widespread implementation requires a holistic approach in evaluating the feasibility of this technology. Therefore, this study serves as a crucial step in understanding how pyrolysis technology can be developed and optimally applied to address plastic waste issues in the future.

II. Method

A. Material of Research

This research employs polyethylene-based plastic waste (such as plastic bags) and polystyrene foam materials (commonly used in fruit and vegetable containers).

B. Stages of the research process

Operational Procedures of the Pyrolysis Method

In the initial stage, polyethylene plastic waste was cut into smaller pieces and weighed until it reached around 350 grams. The particle dimensions were adjusted to fit appropriately within the pyrolysis reactor. The prepared material was then placed into the reactor chamber, which was securely sealed to prevent air infiltration. Afterward, water was added to the condenser unit, followed by powering up the system and setting the reactor to operate at temperatures of 400°C, 450°C, and 500°C. A similar treatment was applied to polystyrene waste, using a sample mass of 50 grams. Following the thermal process and once the reactor had returned to room temperature, the pyrolysis oil product was collected.

In this research, a laboratory-scale pyrolysis reactor was employed, featuring dimensions of 36 cm in height and a base diameter of 9.5 cm. The accompanying heater measured 40 cm in height and 30 cm in diameter. Based on these specifications, the reactor was loaded with 350 grams of polyethylene (PE) plastic as the feedstock, resulting in an average material density of approximately 0.19 g/cm³ (0.19 g/ml) within the reactor tube. In comparison, 50 grams of polystyrene (PS) plastic were utilized, producing an average density of around 0.02 g/cm³ (0.02 g/ml) inside the same reactor.

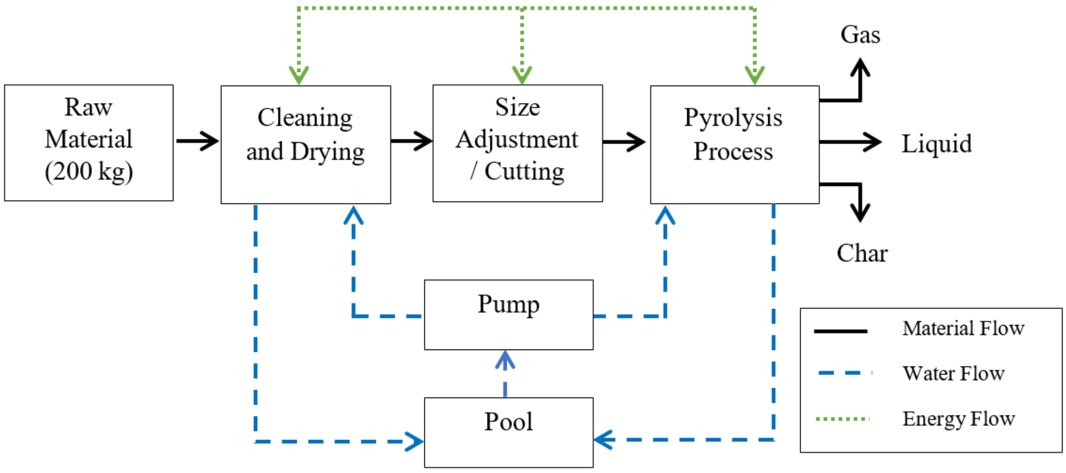

Figure 1. Procedure

III. Results and Discussion

A. Technical Feasibility

Polyethylene (PE) and polystyrene (PS) plastics were subjected to pyrolysis at temperatures of 400, 450, and 500°C for a certain period. Once the desired temperature was reached, it was kept constant until the feedstock was entirely decomposed. The completion of the feedstock was identified by the absence of smoke, indicating that the pyrolysis process had ceased inside the reactor. After the feedstock was fully consumed, the pyrolysis process was concluded. The duration of the pyrolysis reaction was recorded and is illustrated in Figure 2.

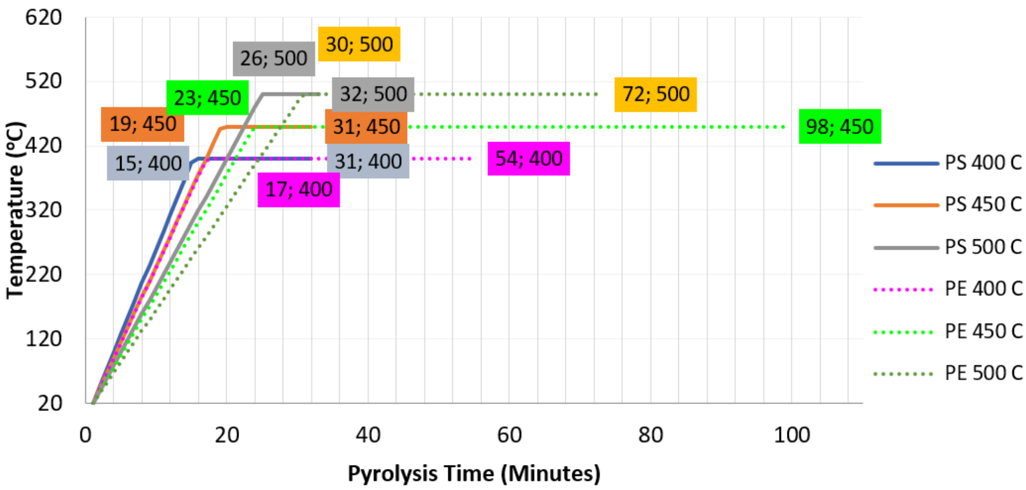

Figure 2. Pyrolysis Temperature Profile

Figure 2 illustrates the duration of the pyrolysis process for polyethylene (PE) and polystyrene (PS) plastics at temperatures of 400°C, 450°C, and 500°C. The recorded times were 54 minutes, 98 minutes, and 72 minutes for PE, and 31 minutes, 31 minutes, and 32 minutes for PS, respectively. The pyrolysis process for PE plastic took longer than for PS plastic due to its larger initial mass (350 grams) compared to PS plastic (50 grams). Consequently, the pyrolysis reaction in the reactor required more time as a greater quantity of feedstock was processed.

Besides the amount of feedstock, the pyrolysis duration is also influenced by the plastic's decomposition temperature. Caglar & Aydinli reported that PE plastic decomposes at approximately 495°C, whereas PS plastic decomposes at around 420°C [12]. This difference in decomposition temperatures further explains why the pyrolysis process for PE plastic takes longer than for PS plastic.

Higher temperatures lead to a reduction in the mass of plastic inside the pyrolysis reactor, as the plastic components break down more completely into liquid, gas, and a small amount of solid residue. Klass stated that temperature plays a crucial role in the pyrolysis process, with higher temperatures enhancing the decomposition efficiency [13]. Similarly, Ramadhan & Ali explained that during pyrolysis, long hydrocarbon chains are converted into shorter chains. The breakdown of plastic compounds contributes to the decrease in plastic mass within the reactor.

According to Figure 2, the heating rates for the pyrolysis of PE plastic at temperatures of 400, 450, and 500°C are calculated as 23.53°C/min, 19.56°C/min, and 16.67°C/min, respectively. Meanwhile, for PS plastic pyrolysis at the same temperatures, the heating rates are 26.67°C/min, 23.68°C/min, and 19.23°C/min, respectively.

An increase in temperature results in a lower heating rate for both PE and PS plastic pyrolysis. This is because, at the same pyrolysis speed, a higher temperature leads to a larger divisor, reducing the overall heating rate. Since heating rate depends on temperature, it can be concluded that temperature has a more significant impact on the yield.

Figures 3 and 4 respectively ilustrate the comparison of the average v/w_0 ratio and the average yield in the pyrolysis process of PE and PS plastics..

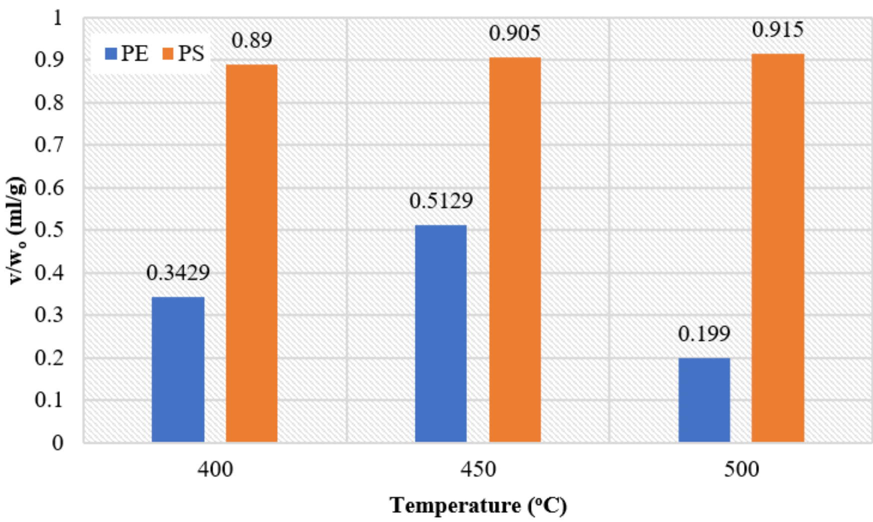

Figure 3. Comparison of the average v/w_0 ratio obtained from the pyrolysis of PE and PS plastics

Figure 3 illustrates that increasing the temperature initially causes the v/wo (ml/g) ratio to rise for polyethylene (PE) plastic, reaching a peak before it starts to decrease, suggesting the existence of an optimal temperature for maximizing this ratio. Conversely, the v/wo (ml/g) ratio for polystyrene (PS) plastic remains fairly constant across the temperature range. Notably, the pyrolysis oil yield per gram of PS plastic is substantially greater than that of PE plastic. This discrepancy can be attributed to the chemical nature of the materials: PS consists of styrene monomers, which are liquid at room temperature. As a result, depolymerization of polystyrene predominantly generates liquid products. In contrast, PE is made up of ethylene monomers that exist in gaseous form, leading to a comparatively lower production of liquid pyrolysis oil. This fundamental difference explains why the v/wo (ml/g) ratio for PS-derived pyrolysis oil is generally higher than that obtained from PE.

Figure 4 illustrates the yield from the pyrolysis of PE and PS plastics. In the case of PE plastic, the yield initially increases with temperature but then decreases, indicating that the yield is a temperature-dependent function, $f(T)$. Meanwhile, for PS plastic, the yield remains relatively stable despite increasing temperatures, with only a minor, insignificant rise that can be considered negligible. Although the v/w_o (ml/g) ratio and yield of pyrolysis oil from PS plastic appear consistent, their behavior differs. This distinction suggests a reduction in the mass of the produced oil, as at 500°C, the oil becomes lighter even though its volume increases. Similarly, at 500°C, the volume of pyrolysis oil from PS plastic is larger than at 400°C, but its mass is lower than the oil obtained at 400°C. This phenomenon is related to the density of the pyrolysis oil, where at 450°C and 500°C, the density is lower compared to the oil produced at 400°C.

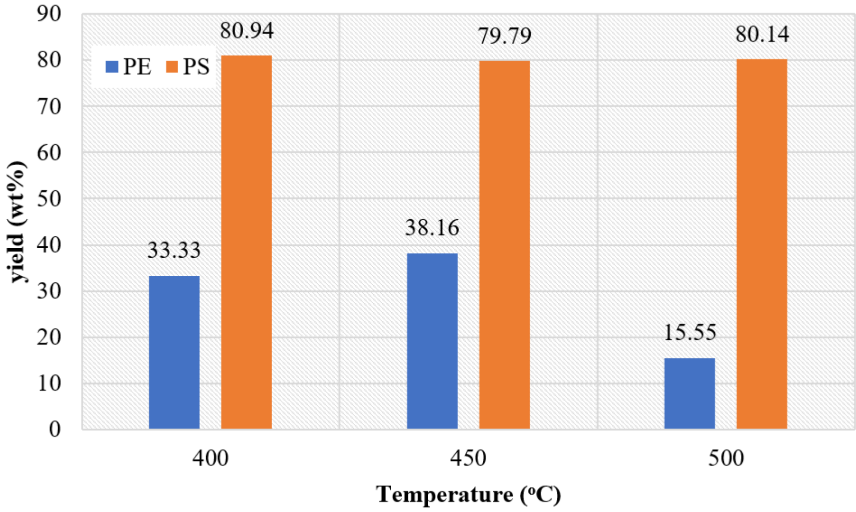

Figure 4. Comparison of the Average Yield in the Pyrolysis of PE and PS Plastics

In this study, the pyrolysis oil yield from PS plastic ranges between 79% and 80% of its initial weight. This result differs slightly from the study conducted by Efendi (2012), which reported a yield of 87.3 wt% for the pyrolysis of pure polystyrene at 450°C. This discrepancy can be attributed to several factors, including differences in the pyrolysis equipment used, such as reactor size, variations in the feedstock density within the reactor, and other influencing factors.

Table 1. Calculation of Electrical Energy Consumption for Pyrolysis of PE and PS Plastics at 400 °C, 450 °C, and 500 °C

Temperature (T), °C	**PE (m=350 g)**			**PS (m=50 g)**		
	400	450	500	400	450	500
Time (t), minutes	54	98	72	31	31	32
Energy (E), kJ	6.544,9	11.878	8.726	3.757	3.757	3.878
Energy/Mass, kJ/g	18,7	33,94	24,93	75,144	75,144	77,568

Table 1 presents the calculation of energy consumption per gram for the pyrolysis of PE and PS plastics at temperatures of 400, 450, and 500°C. The energy consumption is determined using the formula presented in Equation (1).

$$W = P \times t \quad (1)$$

Where: W : Energy (Joule)
P : Power (2.020 watt)
t : Time (seconds)

Figure 5 illustrates the relationship between energy consumption per gram and the resulting yield as the temperature increases. In the pyrolysis of PE plastic, energy consumption increases when the temperature rises from 400°C to 450°C but decreases at 500°C. This is because, at 400°C, the cracking process is not yet fully optimized due to insufficient heat, causing energy consumption to rise until it reaches the optimal temperature of 450°C. However, at 500°C, energy consumption decreases as the cracking process accelerates at higher temperatures, surpassing the optimal point. For PS plastic, energy consumption remains relatively stable, likely because it has already exceeded its decomposition temperature, meaning further temperature increases do not significantly impact energy usage. Comparing the energy consumption of PE and PS pyrolysis, it is evident that PS requires more energy than PE. This is likely due to PS having a higher melting point and lower thermal conductivity than PE. Although the energy consumption for PS pyrolysis is greater, the yield it produces is also higher compared to PE.

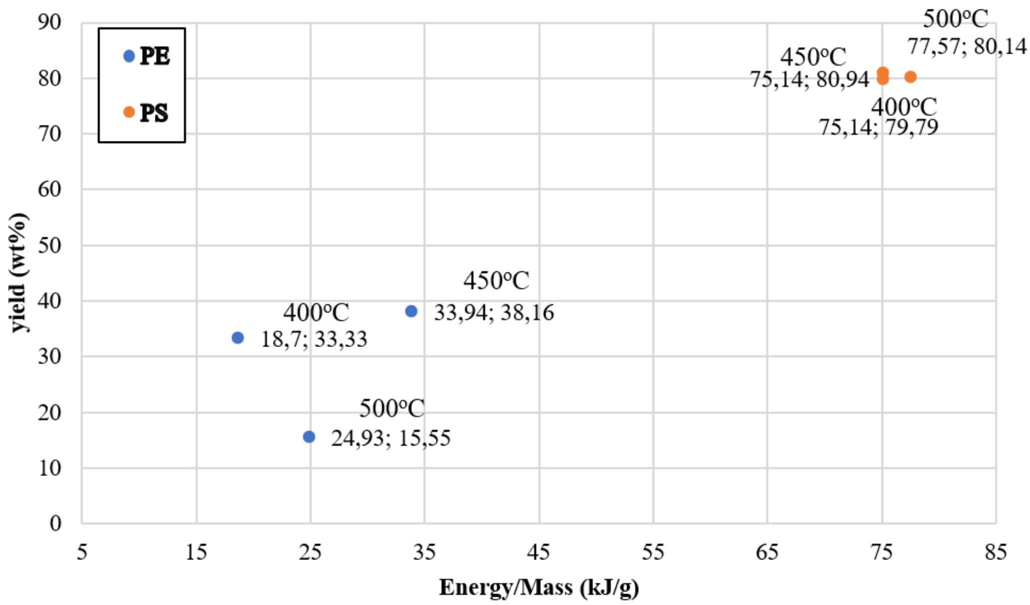

Figure 5. Energy Consumption and Yield in the Pyrolysis of PE and PS Plastics at 400 °C, 450 °C, and 500 °C.

When using LPG gas as an alternative fuel to electricity, it is known that 1 kg of LPG provides 55,000 kJ of energy. The pyrolysis of PE at 450°C requires 33.94 kJ/g or 33,940 kJ/kg. This indicates that to process 1 kg of PE plastic through pyrolysis, an energy input of 33,940 kJ is needed, resulting in the following calculation:

$$1 \text{ kg gas LPG/kg PE} = 55.000 \text{ kJ}/33.940 \text{ kJ} = 1,6$$

This indicates that 1 kg of LPG can be utilized to pyrolyze approximately 1.6 kg of PE plastic. In contrast, the pyrolysis of PS at 500°C requires 77.57 kJ/g or 77,570 kJ/kg. Therefore, to pyrolyze 1 kg of PS plastic, an energy input of 77,570 kJ is necessary, resulting in the following calculation:

$$1 \text{ kg gas LPG/kg PS} = 55.000 \text{ kJ}/77.570 \text{ kJ} = 0,7$$

This means that 1 kg of LPG can be used to pyrolyze approximately 0.7 kg of PS plastic.

The energy consumption and energy output from the pyrolysis of 350 grams of PE plastic at 450°C and 50 grams of PS plastic at 500°C are shown in Figure 6 and Figure 7, respectively.

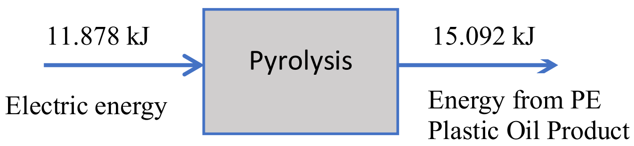

Figure 6. Energy Balance of PE Plastic Pyrolysis at 450°C

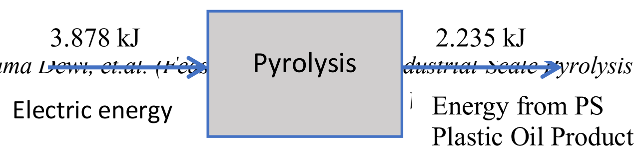

Figure 7. Energy Balance of PS Plastic Pyrolysis at 500°C

From the comparison between energy consumption and energy production, it can be seen that the energy generated during PE pyrolysis is 1.27 times higher than the energy required. On the other hand, for PS pyrolysis, the energy produced is 0.58 times lower than the energy consumed.

In addition to quantitative analysis, the pyrolysis oil derived from PE and PS plastics was also analyzed qualitatively based on its physical and chemical characteristics. The results of the physical characteristic tests for pyrolysis oil from PE and PS plastics at temperatures of 400 °C, 450 °C, and 500 °C are presented in Table 2.

Table 2. Analysis Results of Pyrolysis Oil from PE and PS Plastics at 400 °C, 450 °C, and 500 °C

Parameter	Unit	PE			PS			Inspection Method
		400 °C	450 °C	500 °C	400 °C	450 °C	500 °C	
***Specific Gravity at* 60/60 °F**	-	0.7687	0.7879	0.8087	0.9257	0.9217	0.9052	ASTM D 1298
***Viscosity Kinematic at* 40 °C**	mm^2/s	--	1.994	1.261	1.027	0.942	0.991	IKU/TK.5. 4/02
***Viscosity Kinematic at* 50 °C**	mm^2/s	4.706	--	--	--	--	--	IKU/TK.5. 4/02
Gross Heating Value	BTU/lb	20086	18540	18540	19079	19108	19222	*calculated*
Flash Point PM.C.C.	°C	46.5	30.5	24.5	34.5	32.5	28.5	IKU/5.4/TK-02
Pour Point	°C	36	27	15	*)	*)	-6	IKU/5.4/TK-04

Description:
*) Up to a temperature of -33°C, the sample remains in liquid form.

B. Social-Economic Feasibility

The socio-economic analysis is examined from both social and economic aspects of the materials and the resulting processed products. This analysis is carried out based on the potential use of pyrolysis oil from PE and PS plastics as a fuel alternative.

B1. *Pyrolysis Oil from Polyethylene (PE) Plastic Waste as a Fuel*

The energy required for the conversion of PE plastic into fuel, with a raw material capacity of 200 kg per day at a pyrolysis temperature of 450°C, is as follows:

a) Energy Requirement (Electricity) :
33,94 kJ/g x (200.000 g) = **6.788.000 kJ**

b) Energy generated from PE Pyrolysis Oil = 18.540 BTU/lb = 43.120 kJ/kg Thus, for 200 kg of PE plastic, the energy generated is:

43.120 kJ/kg x 76,32 kg = **3.290.918,4 kJ**

c) The required energy (electricity) can be sourced from the energy generated by the PE plastic pyrolysis oil itself, resulting in an energy requirement of:

-6.788.000 kJ + 3.290.918,4 kJ = **-3.497.081,6 kJ**.

Hence, it can be concluded that the energy generated from the pyrolysis oil of PE plastic is not sufficient to sustain the production process.

The production process of pyrolysis oil as a fuel is illustrated in Figure 8.

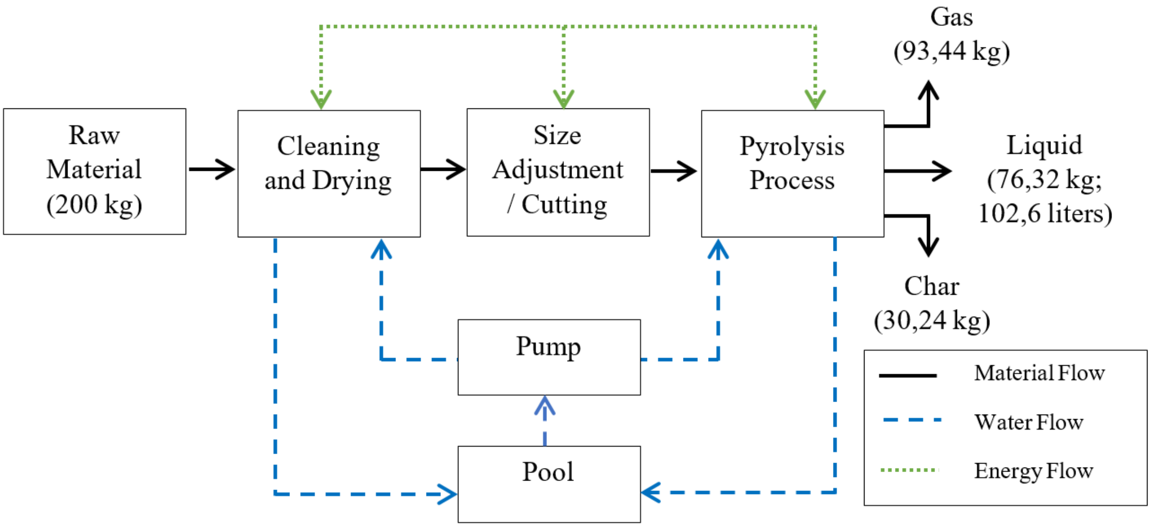

Figure 8. Process of Producing Pyrolysis Oil from PE Plastic as Fuel

Income is the monetary earnings obtained from selling business products (fuel).

The amount of raw material processed daily	: 200 kg
Efficiency	: 38.16 % (Research Results)
Oil Quantity	: 76.32 kg/day = 1,984 kg/month
Specific Gravity of Plastic Oil	: 0.7879
Oil Volume	: 103 liters/day= 2,678 liters/month
The selling price of the oil as fuel is assumed	= Rp 5.500/liters

Monthly revenue amounts to : Rp 5.500 * 2.678 = **Rp 14.729.000,-**

B2. Pyrolysis Oil from Polystyrene (PS) Plastic Waste as a Fuel

The required energy for converting PS plastic into fuel, with a raw material capacity of 200 kg per day at a pyrolysis temperature of 400°C, is as follows:

a) Energy Requirement (Electricity):
75,144 kJ/g x (200.000 g) = **15.028.800 kJ**

b) Energy from PS Pyrolysis Oil = 19.222 BTU/lb = 44.700 kJ/kg Thus, the energy produced from 200 kg of PS plastic is:
44.700 kJ/kg x 160,28 kg = **7.164.516 kJ**

c) The required energy (electricity) can be sourced from the energy produced by the PS plastic pyrolysis oil itself, resulting in an energy requirement of:
-15.028.800 kJ + 7.164.516 kJ = **-7.864.284 kJ**

Thus, it can be concluded that the energy from the pyrolysis product (PS plastic oil) is not sufficient for the production process.

The process of producing pyrolysis oil as fuel is shown in Figure 9.

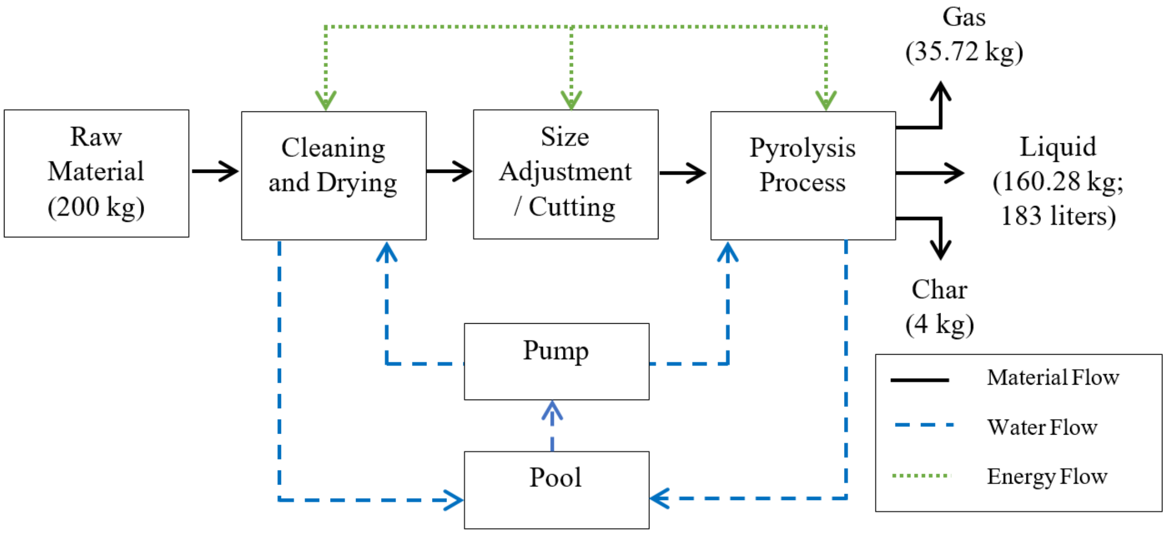

Figure 9. Process of Producing Pyrolysis Oil from PS Plastic as Fuel

Revenue refers to the income generated from the sale of business products (fuel).

The amount of raw material processed per day	: 200 kg
Efficiency	: 80.14 % (Research Results)
Oil Quantity	: 160.28 kg/day = 4,167 kg/month
Specific Gravity of Plastic Oil	: 0.9052
Oil Volume	: 183 liters/day = 4,758 liters/month

The assumed selling price of the oil as a fuel is = Rp 6.500/liters

The monthly revenue is : Rp 6.500 * 4.758 = **Rp 30.927.000,-**

While converting PE and PS plastic waste into fuel may not be economically feasible, the social benefits of plastic waste management offer significant advantages to the community that go beyond financial value.

IV. Conclusion

Based on economic analysis, the conversion of 200 kg of PE and PS plastic waste into fuel is considered not feasible. However, from a technical, social, and environmental perspective, managing 200 kg of PE and PS plastic waste through pyrolysis provides benefits to the community, making it viable. This can be achieved by implementing preventive measures to address the environmental drawbacks of the pyrolysis process.

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