Plastic Waste Management through Pyrolysis in the Seribu Islands: Energy Efficiency and Fuel Oil Production Analysis

Bambang Raharjo[1*], **Aryan Winanda**[1], **Puguh Triwinanto**[1], **Taufan Firdhaus**[1], **Nursiwan**[1], **Prawoto**[1], **Eka Maulana**[1]

[1]*Program Studi Magister Teknik Mesin, Universitas Pancasila, Cikini, Jakarta Pusat 10320, Indonesia*

**Email Corresponding Author: raharjo5323005@univpancasila.ac.id*

ABSTRACT

Plastic waste in the Seribu Islands has become a significant issue threatening marine and coastal ecosystems. This study analyzes the conversion of plastic waste into diesel fuel through pyrolysis, employing three scenarios of plastic mixture ratios: LDPE and PP, PET, PS, and HDPE. With operating temperatures of 400 °C, 480 °C, and 550 °C, the research evaluates energy efficiency, diesel output, and return on investment (ROI). Results indicate that a mixture of 50% LDPE and PP, 15% PET, 10% PS, and 25% HDPE at 550 °C produces the highest diesel yield of 0.805 tons per 1,000 kg of plastic. The annual ROI is recorded at 0.26%, highlighting the project's potential to support environmental conservation while providing economic benefits.

Keywords: *Diesel fuel; Energy efficiency; ROI; Pyrolysis; Plastic waste*

INTRODUCTION

Plastic waste has become one of the most significant environmental challenges in archipelagic regions such as the Seribu Islands, including Pramuka Island, Panggang Island, and Air Island, where plastic dominates marine debris, particularly at depths of 3–5 meters within coral reef ecosystems [1]. The impact of this pollution disrupts ocean currents and wave patterns, harming the growth of coastal marine ecosystems [2]. Various types of plastic, including High-Density Polyethylene (HDPE), Low-Density Polyethylene (LDPE), Polypropylene (PP), Polystyrene (PS), and Polyethylene Terephthalate (PET), exert immense pressure on both marine and terrestrial ecosystems due to their non-biodegradable nature.

The amount of plastic waste in the Seribu Islands has increased in line with population growth and human activities in the region. In 2005, Pari Island recorded waste accumulation of 449.4 tons, with plastic as the most dominant component [3]. Data from Untung Jawa Island revealed daily land waste generation of 5.06 m³ on weekdays and 5.79 m³ on weekends, while marine debris averaged 7.67 m³/day [4]. Pyrolysis technology has emerged as a promising solution, utilizing a thermochemical process to break down plastic polymers at high temperatures in the absence of oxygen, producing valuable products such as liquid fuel (diesel).

This process not only reduces plastic waste accumulation but also offers economic benefits by converting waste into alternative energy sources. However, the success of pyrolysis depends heavily on process design, including plastic composition selection, optimal operating temperature, and energy efficiency [5]. This research aims to analyze the energy efficiency and diesel production yield from plastic waste in the Seribu Islands using three scenarios of plastic mixture ratios. Each scenario varies in plastic composition and pyrolysis temperature, specifically 450°C, 500°C, and 550°C. The analysis includes calculations for heating energy, cooling energy, and energy balance to evaluate the effectiveness of the pyrolysis process.

This research is expected to provide recommendations for optimizing the conversion of plastic waste into liquid fuel, offering both economic benefits and environmental preservation.

RESEARCH METHODS

The research involves analyzing the pyrolysis of plastic waste using five types of plastics: HDPE, LDPE, PP, PS, and PET. The specific heat capacity of plastic waste averages 2.0 kJ/kg°C. The research considers the types of plastic waste prevalent in the Seribu Islands. Data from the Seribu Islands Environmental Agency indicate that the region generates an average of 40 tons of waste per day, comprising transported waste, resident waste, and tourist waste, with 60% being transported waste, predominantly plastic [6].

The estimated composition of plastic waste in the Seribu Islands includes LDPE and PP (30%–50%), PET (10%–20%), PS (5%–10%), and HDPE (10%–20%). Based on these proportions, three plastic mixture ratios are proposed:

- Ratio 1: LDPE + PP (51.6%), PET (19.4%), PS (9.7%), HDPE (19.4%)
- Ratio 2: LDPE + PP (50%), PET (15%), PS (10%), HDPE (25%)
- Ratio 3: LDPE + PP (35%), PET (20%), PS (10%), HDPE (35%)

These ratios are designed based on the availability and thermal-chemical characteristics of each type of plastic. LDPE and PP are prioritized for their ease of degradation, PET for its contribution to aromatic compounds, PS for its high calorific value, and HDPE for stable pyrolysis oil production.

The pyrolysis process is conducted at 400°C, 480°C, and 550°C to determine the most efficient plastic mixture and temperature. Heating energy is calculated using the heating energy equation, while cooling energy is determined by reducing the temperature from pyrolysis levels to 100°C. A 15% process inefficiency is also factored into the energy balance. The results are analyzed by calculating diesel production based on the conversion efficiency of each plastic type: LDPE (0.85 tons/ton), PP (0.8 tons/ton), PET (0.5 tons/ton), HDPE (0.7 tons/ton), and PS (0.6 tons/ton).

This approach evaluates the impact of plastic mixtures and pyrolysis temperatures on process efficiency and diesel yield, aiming to identify the optimal conditions for plastic waste conversion into fuel.

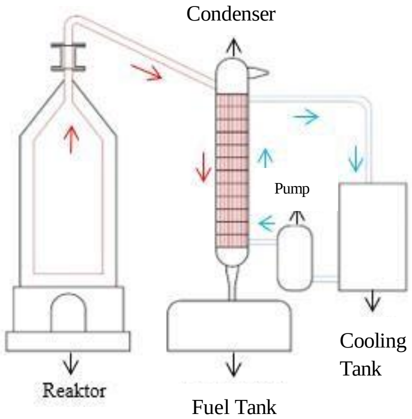

Figure 1. diesel fuel through pyrolysis

Figure 1 illustrates the pyrolysis process involving several key components. The process begins in the reactor, which functions to heat and break down the chemical chains of raw materials, such as plastic waste or biomass, into pyrolysis gas. The pyrolysis gas produced flows into the condenser, where it is cooled using cooling water, represented by blue arrows, causing it to change phase into a liquid, such as pyrolysis oil or diesel. The condensed liquid is then collected in a diesel tank for storage or further use. Meanwhile, the pump circulates the cooling water through the cooling system to maintain the condenser's temperature at an optimal level. After use, the cooling water flows to the cooling tank to be cooled again before being reused in the pyrolysis process.

The energy conversion efficiency into diesel products reaches 99% of the total plastic input. The optimal pyrolysis operating temperature varies between 450°C and 550°C, depending on the plastic mixture. In this study, the total plastic mass is 1000 kg per production cycle.

The mixture ratio is designed with varying plastic mixture ratios and pyrolysis temperatures to evaluate diesel production efficiency and the required energy. The heating energy is calculated using Equation 1 [7].

$$Q\ Heating = m \cdot c \cdot \Delta T \qquad (1)$$

Where Q Heating is the heat required for heating, m is the mass, c is the specific heat capacity, and ΔT is the temperature change. The higher the pyrolysis temperature, the greater the heating energy required to heat the plastic. Meanwhile, the cooling energy is calculated using Equation 2 [7].

$$Q\ Cooling = m \cdot c \cdot \Delta T \qquad (2)$$

Where Q Cooling is the heat required for cooling, m is the mass, c is the specific heat capacity, and ΔT is the temperature change. The value of ΔT for cooling is equal to the pyrolysis temperature minus 100 °C.

The energy balance in the pyrolysis process includes energy input and energy output. The energy input comprises the heating energy, while the energy output consists of the energy of the product, the cooling energy, and the energy lost due to a heating inefficiency of 15%. The energy balance is calculated using the following equation:

$$E\ in = Q\ heating\ \&\ E\ out = E\ product + Q\ Cooling + E\ Lost$$

RESULTS AND DISCUSSION

The results of the energy balance calculations are presented in Table 1.

Table 1 Energy Balance Diagram

Temp °C	Input Energy (MJ)	Product energy (MJ)	Cooling Energy (MJ)	Lost Energy (MJ)	Total output energy (MJ)
400	750	31.296,3	600	112,5	32.008,8
480	910	32.239,6	760	136,5	32.454,8
550	1050	33.332,9	900	157,5	32.753,8

Table 1 presents an energy analysis conducted for the pyrolysis process of plastic at three temperatures: 400 °C, 480 °C, and 550 °C. At 400 °C, the input energy for the heating process is 750 MJ, producing a product energy of 31,296.3 MJ as solar. The energy required for cooling is 650 MJ, while the energy lost due to process inefficiency is 112.5 MJ, resulting in a total output energy of 32,008.8 MJ. At 480 °C, the heating energy increases to 910 MJ, producing a product energy of 32,239.6 MJ. The energy required for cooling rises to 760 MJ, and the energy lost is 136.5 MJ, yielding a total output energy of 32,454.8 MJ. At the highest temperature, 550 °C, the required heating energy reaches 1,050 MJ, with the product energy increasing to 33,332.9 MJ. The cooling energy at this temperature is 900 MJ, while the energy lost is 157.5 MJ, resulting in a total output energy of 32,753.8 MJ. The solar energy produced is then calculated using Equation 3 [7].

$$F\ \text{Fuel} = \sum (x \cdot e) \quad (3)$$

Where F fuel is the amount of solar fuel produced (tons), x is the weight fraction of each type of plastic in the mixture, and e is the conversion efficiency of each type of plastic into fuel (tons/ton of plastic). The results of the fuel production calculations from the mixture ratios at pyrolysis temperatures of 400 °C, 480 °C, and 550 °C are displayed in Table 2.

Table 2 Results of Fuel Calculation

Ratio	T (°C)	Fuel (ton)
Ratio 1 LDPE dan PP: 51.6%, PET: 19.4%, PS: 9.7%, HDPE: 19.4%	400	0,747
	480	0,77
	550	0,796
Ratio 2 LDPE + PP: 50%, PET: 15%, PS: 10%, HDPE: 25%	400	0,758
	480	0,7805
	550	0,805
Ratio 3 LDPE + PP: 35%, PET: 20%, PS: 10%, HDPE: 35%	400	0,737
	480	0,762
	550	0,788

Table 2 compares the solar production from three plastic mixture ratios at pyrolysis temperatures of 400 °C, 480 °C, and 550 °C. Ratio 1 (LDPE and PP 51.6%, PET 19.4%, PS 9.7%, HDPE 19.4%) produces 0.747 tons of solar fuel at 400 °C, which increases to 0.77 tons at 480 °C, and 0.796 tons at 550 °C. Ratio 2 (LDPE and PP 50%, PET 15%, PS 10%, HDPE 25%) yields the highest result at 550 °C, producing 0.805 tons, while Ratio 3 (LDPE and PP 35%, PET 20%, PS 10%, HDPE 35%) produces the lowest amount, with 0.737 tons at 400 °C and 0.788 tons at 550 °C. Among the three ratios, Ratio 2 at 550 °C produces the highest amount of solar fuel, 0.805 tons.

The Return on Investment (ROI) calculation is conducted using the results from the plastic mixture ratios, with the maximum solar fuel production calculated in a table format. This table includes data on the amount of solar fuel produced, revenue from solar fuel, annual expenses, and ROI, using a pyrolysis machine with a capacity of 300 tons per year.

ROI is a financial metric used to assess investment efficiency by comparing the net profit obtained to the total investment made. In the ROI analysis, three main components are considered: (a) Initial Capital: The amount of money invested at the start of the project, including asset purchases, development costs, and other expenses necessary to begin operations; (b) Operational Costs: Routine expenses required to run the business, such as employee salaries, utility costs, raw materials, and maintenance expenses; and (c) Annual Revenue: The total revenue generated from business operations in one year, reflecting financial performance and the business's ability to generate profit.

The initial capital calculation for the ROI is presented in Table 3.

Table 3 Results of ROI Calculation for Initial Capital

Component	Cost (Rp)	Description
Pyrolysis Equipment (Reactor, Furnace, Heater)	550.000.000, 0	The cost of purchasing pyrolysis equipment, furnace, and heater.
Other Infrastructure	50.000.000,0	Costs for other infrastructure required in this project.

Installation and Testing Costs	200.000.000,0	Installation and Testing Costs for Equipment to Ensure System Functionality
Cooling system	120.000.000,0	Cooling System Costs Needed for the Pyrolysis Process
Product Processing System Costs	100.000.000,0	Costs for the Pyrolysis Product Processing System
Energy Management System	50.000.000,0	Costs for the Energy Management System in the Pyrolysis Process.
Total Initial Capital Investment	1.370.000.000,0	Total of All Costs Required to Start the Project

The calculation of operational costs in the ROI calculation is shown in Table 4.

Table 4 The result of the ROI calculation for operational costs.

Component	Cost (Rp)	Description
Cost of Plastic Procurement	8.000.000,0	Cost of purchasing plastics for processing.
Cost Energy	55.000.000,0	Energy costs required for the pyrolysis process and the operation of other systems.
Maintenance Cost	20.000.000,0	Routine maintenance costs for equipment and systems, such as reactor and cooling system maintenance.
Labor costs.	37.800.000,0	Salaries and benefits for workers in plant operations (Jakarta's minimum wage x 7 workers).
Cost of Fuel	20.000.000,0	The cost of fuel used in the pyrolysis process and equipment operation.
The total monthly operational costs.	1.689.600.000,0	The total cost required to run monthly operations.

The annual revenue calculation for the ROI is shown in Table 5.

Table 5 ROI Calculation Results for Annual Revenue

Component	Details	Description
Daily Solar Production	947.06 liter	Highest solar yield / 0.85 kg/L
Price of Solar/Liter	Rp 6,000,0	Minimum Cost
Revenue per Day	Rp 5.682.360,0	Daily production multiplied by the minimum price
Monthly Revenue	Rp 170.470.800,0	Monthly Revenue
Annual Revenue	Rp 2.045,649,600.00	Annual Revenue

Considering the three aspects, namely initial capital, operational costs, and annual revenue, ROI can be calculated using Equation 4 [8].

$$ROI = Total\ Investment / Net\ Profit \times 100 \quad (4)$$

$$ROI = \frac{2.045.649.600 - 1.689.600.000}{1.370.000.000} \times 100\%$$

ROI = 0,26%

With positive annual net revenue, the initial capital will start to be covered. The ROI becomes positive at the end of the first year, with an annual ROI of 0.26%.

CONCLUSION

This study concludes that pyrolysis is an effective method for processing plastic waste into fuel oil, with the highest energy efficiency achieved at a temperature of 550°C using a mixture of 50% LDPE and PP, 15% PET, 10% PS, and 25% HDPE. With a yield of 0.805 tons of solar fuel per 1,000 kg of plastic, this project offers a sustainable solution to the plastic waste problem in the Seribu Islands. Although the annual ROI is still low, at 0.26%, the results show potential for further development through optimization of operational costs and process efficiency improvements.

REFERENCE

[1] Ahmad Firza Fauzan and Agussalim Burhanuddin, “Potensi dan Tantangan Pariwisata Maritim Kepulauan Seribu,” *Student Scientific Creativity Journal*, vol. 1, no. 6, pp. 379–391, Nov. 2023, doi: 10.55606/sscj-amik.v1i6.2391.

[2] D. Dwiyanti Suryono, “Sampah Plastik di Perairan Pesisir dan Laut : Implikasi Kepada Ekosistem Pesisir DKI Jakarta,” *Jurnal Riset Jakarta*, vol. 12, no. 1, pp.

17–23, Sep. 2019, doi: 10.37439/jurnaldrd.v12i1.2.

[3] S. Rohana Nasution and A. Indra Tjahjani, "Analisis Laju Timbulan Sampah Di Pulau Pramuka DKI Jakarta," 2019.

[4] S. Darwati, "Pengelolaan Sampah Kawasan Pantai," *Puslitbang Perumahan dan Pemukiman, Kementerian PUPR*, 2019.

[5] M. Jamaluddin, E. Maulana, and dan Eddy Djatmiko, "Perancangan Burner untuk Reaktor Pirolisis Kapasitas 15 kg dengan Bahan Bakar Refuse Derived Fuel (RDF) dan Gas Design Burner for Pyrolisis Reactor Capacity 15 kg using Refuse Derived Fuel (RDF) and Gas Informasi artikel," vol. 4, pp. 1–12, 2022.

[6] Liputan6.com. (n.d.). *Sampah-sampah di bawah laut Kepulauan Seribu*. Diakses dari https://www.liputan6.com/regional/read/3 650161/sampah-sampah-di-bawah-laut- kepulauan-seribu

[7] Alexander, M. A. (2019). Neraca Masa dan Neraca Energi Pengelolaan Sampah Terpadu – Penujah Kabupaten Tegal**.** *Jurnal Teknik Lingkungan*, 20(3), 2103–2110.

[8] Fariantin, E. (2019). Analisis Pengaruh Return On Investment (ROI), Return On Equity (ROE), dan Debt to Equity Ratio (DER) Terhadap Harga Saham Pada Perusahaan Tekstil dan Garmen, Tbk yang Terdaftar di Bursa Efek Indonesia. *Jurnal Kompetitif: Media Informasi Ekonomi Pembangunan, Manajemen, dan Akuntansi*, 5(1), 1-13.