Journal of Mechanical Engineering Science and Technology
Vol. 9, No. 2, November 2025, pp. 344-355

ISSN 2580-0817

Optimizing Zeolite Catalysts for Efficient LDPE Plastic Waste Pyrolysis

Hilda Porawati, Mazwan*, Sukadi

Mechanical Engineering, Jambi Polytechnic, Alam Barajo, Jambi, 36361, Indonesia
**mazwan@politeknikjambi.ac.id*

Article history:
Received: 20 June 2025 / Received in revised form: 5 July 2025 / Accepted: 10 July 2025

ABSTRACT

The problem of plastic waste, particularly from low-density polyethylene (LDPE) plastic bags, poses a significant challenge in environmental management due to its non-biodegradable nature and widespread use in daily life. This study evaluates the influence of catalyst types on the characteristics and energy efficiency of liquid fuel products produced from LDPE waste pyrolysis. The three treatments compared were no catalysts, natural zeolite catalyst, and synthetic zeolite catalysts, each subjected to three different temperature variations: 250°C, 300°C, and 350°C. The observed parameters in this study were volume, product mass, cetane index, density, sulfur content, viscosity, flash point, calorific value, and energy efficiency related to the energy consumed during the pyrolysis process. The experimental results showed that synthetic zeolite had a significant effect on increasing the yield and pyrolysis oil. In addition, the use of synthetic zeolite was also able to produce a higher volume of pyrolysis oil than natural zeolite, and without zeolite, with a value of 410 mL per 500 grams of LDPE, with the highest efficiency value of 89.97%. The use of synthetic zeolite also showed better physical characteristics with cetane index and flash point values approaching the national fuel standard (SNI). However, the calorific value and viscosity of all pyrolysis oil products still did not meet the standards and were still below the minimum value for diesel fuel.

Keywords: *Energy efficiency, LDPE, pyrolysis, synthetic catalyst, zeolite.*

I. Introduction

One of the main problems experienced by developing countries is plastic waste management. According to UN data, more than 430 million tons of plastic are produced annually worldwide, with single-use plastics contributing the highest value of more than 40%, such as plastic bags [1]. In Indonesia, it is estimated that more than 10 billion plastic bags are used annually, and most of this plastic waste ends up in water bodies, including rivers and oceans, causing environmental pollution. One of the most common types of plastic found in household waste is Low-Density Polyethylene (LDPE), which is widely used in the form of plastic bags [2]. This type of plastic bag is known to be flexible, lightweight, and inexpensive, but it is very difficult to decompose naturally [3]. LDPE has a serious impact on environmental ecosystems and also on human health [4],[5]. Common methods used are burning and landfilling waste, which can cause air and soil pollution [6].

To address those environmental issues, pyrolysis has emerged as a promising waste utilization method [7]. Pyrolysis is the thermal decomposition of organic matter in an oxygen-free environment at high temperatures. This process can produce liquid fuel (bio-oil), pyrolytic gas, and solid carbon (char) [8]. Pyrolysis liquid fuel has the potential to replace fossil fuels while reducing the burden of plastic pollution in the environment [9].

DOI: 10.17977/um016v9i22025p344

The pyrolysis process has been widely developed using various methods, including conventional pyrolysis, microwave-assisted pyrolysis, co-pyrolysis (which involves mixing plastic with biomass or other waste materials), and fluidized bed pyrolysis [10],[11]. Microwave pyrolysis offers faster heating rates and energy efficiency, while fluidized bed systems provide better temperature control and scalability. Co-pyrolysis enables synergistic interactions that can improve fuel quality. Each method has its own operational challenges and optimization parameters [12].

However, uncatalyzed pyrolysis produces low-quality oil, limited light fractions, and high levels of hazardous compounds. Therefore, the use of catalysts plays an important role in the pyrolysis process by increasing the efficiency of thermal cracking, increasing the yield of desired light hydrocarbons, and reducing the formation of unwanted residues and toxic substances [13]. Zeolite is a widely studied catalyst in plastic pyrolysis due to its porous structure, high surface area, and acidic properties that help break down long polymer chains into light hydrocarbon compounds [14],[15]. Recent studies highlight the superiority of synthetic zeolites, such as ZSM-5, in producing fuel with higher aromatic content and better combustion properties. However, their cost and availability remain limitations for large-scale or community-based applications [16],[17].

Natural zeolite, on the other hand, is abundant and low-cost, but typically exhibits lower surface area, non-uniform pore structure, and lower acidity, which affects its catalytic performance [18]. While many studies focus either on the application of synthetic zeolite alone or the optimization of pyrolysis parameters, comparative analyses that evaluate the performance trade-off between synthetic and natural zeolites, especially in the context of energy efficiency and conformity with fuel standards, are still limited [19],[20].

This study aims to directly compare the performance of natural and synthetic zeolite catalysts (specifically ZSM-5) in the pyrolysis of LDPE plastic waste. The main objective is to evaluate the effect of catalyst type on the physical characteristics of the resulting fuel and the overall energy efficiency of the pyrolysis process. By integrating analysis of fuel quality parameters—such as viscosity, density, and cetane index—with an assessment of energy return on energy invested (EROEI), this study seeks to provide comprehensive insights into the feasibility and sustainability of catalytic pyrolysis as a waste-to-energy conversion method. The main contribution of this study lies in the comparative approach used, which addresses the shortcomings of previous studies by highlighting the balance between catalyst performance and practical applications. This approach is particularly relevant for developing countries, where cost efficiency and material accessibility are crucial factors.

II. Materials and Methods

Material

LDPE plastic bag waste was collected from traditional markets in Pinang Merah sub-district, Jambi City. Natural zeolite was obtained from the Muaro Jambi area. Sodium hydroxide (NaOH), as a natural zeolite activator, and synthetic zeolite (ZSM-5) were provided by PT. Enviro Labora, Indonesia. ZSM-5 zeolite is an aluminosilicate-based synthetic zeolite composed of silica (SiO_2) and alumina (Al_2O_3), which forms a three-dimensional tetrahedral crystal framework through Si–O–Al bonds. The high Si/Al ratio makes it hydrophobic and thermally stable with a purity level of 99%. Natural zeolites have a relatively low specific surface area (~30–50 m^2/g), irregular pore distribution, and lower acidity due to the lower Si/Al ratio. Synthetic zeolite ZSM-5, in contrast, exhibited a higher specific surface area (300–400 m²/g), well-defined microporous structure (~5.5 Å pore size), high thermal stability, and strong Brønsted acid sites due to a higher Si/Al ratio (>30). These differences are critical, as they influence the cracking behavior of LDPE molecules during the pyrolysis process.

The tools used in this study are pyrolysis machines with specific specifications: the main component of this pyrolysis machine consists of a condenser tube made of an iron plate with dimensions of 30 cm × 35 cm, functioning as a cooling medium to convert pyrolysis vapor into liquid. Inside, a 5-meter-long copper condenser spiral pipe, which is designed to maximize the cooling surface area. The spiral connection uses a 3/8 inch copper elbow spiral to ensure smooth steam flow. For the inlet, a ¾ inch galvanized input pipe is used, which is resistant to high pressure and temperature, while a ½ inch galvanized output pipe functions to drain the condensate out of the system. In addition, the system is equipped with a ½ inch brass oil valve that allows precise and safe regulation of the condensate flow. Other tools used are a 50 ml measuring cup and a BENETECH GM320 infrared thermometer. Figure 1 shows the pyrolysis machine used in this study. This pyrolysis machine is the result of the final project of mechanical engineering students at Jambi Polytechnic.

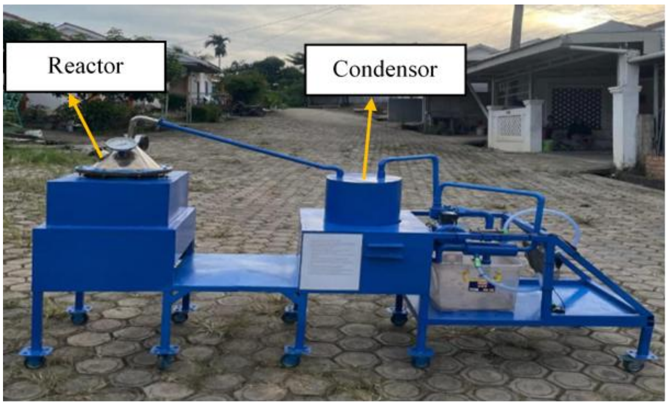

Fig. 1. Pyrolysis machine

Experiment Design

The research design used was experimental with two independent variables: catalyst type (without catalyst, natural zeolite, and synthetic zeolite) and pyrolysis temperature (250°C, 300°C, and 350°C) [21], [22]. Each combination of parameters will be replicated three times to address any potential interference factors that may occur during the pyrolysis process [23]. The observed parameters are volume, mass of pyrolysis oil, energy efficiency, and characteristics of the pyrolysis oil.

Experimental Procedure

Pyrolysis Process

The experimental procedure began with the preparation of LDPE plastic bag waste collected from traditional markets in Pinang Merah sub-district, Jambi city. The plastic was then washed, dried, and cut into small pieces measuring approximately 1–2 cm. For each experiment, 2.5 kg of LDPE plastic waste was weighed and inserted from the top of the reactor. If a catalyst is used, the catalyst is inserted together with the plastic waste at 1% of the plastic mass [24]. Then the gas regulator is operated and the desired temperature is set at variations of 250°C, 300°C, and 350°C. Then the condenser cooling water flow pump is operated. The equipment is operated for 6 hours, then the volume of condensed liquid fuel is measured and its physical properties are analyzed [13].

Product Analysis

Analysis was carried out on the pyrolysis oil, including cetane index, density, sulfur content, kinematic viscosity, flash point, and calorific value [25],[26].

Energy Efficiency Calculation

Based on the fuel product specification data, the energy requirement in the form of LPG heat input for the pyrolysis process was calculated. In addition, the energy contained in the pyrolysis fuel products was also determined to evaluate the thermal efficiency of the overall conversion process of LDPE plastic waste into liquid fuel. The energy produced from the liquid fuel product was calculated by multiplying the obtained fuel volume by the calorific value of kerosene, which is 10,475.95 kcal/kg. Meanwhile, the energy required during the pyrolysis process was calculated by multiplying the amount of LPG used as the heating fuel with the calorific value of LPG, which is 11,254.61 kcal/kg. The energy efficiency of the fuel product relative to fuel consumption was calculated by comparing the energy contained in the liquid fuel product with the total energy used during the production process. In addition, the energy efficiency is calculated by Eq. (1) – (4).

1. Product Mass (Kg)

$$m_{BBM} = V_{BBM} \times D_{kerosene} \quad \text{..........} \quad (1)$$

Description:
m_{BBM} : Product mass (Kg)
V_{BBM} : Product volume (m^3)
$D_{kerosin}$: Density kerosene (Kg/m^3)

2. Product Energy (Ep)

$$E_p = m_{BBM} \times HV_{kerosene} \quad \text{..........} \quad (2)$$

Description:
E_p : Product energy (kkal)
m_{BBM} : Product mass (kg)
$HV_{kerosin}$: Calorific value kerosene (10,475.95 kkal/kg)

3. LPG energy (ELPG)

$$E_{LPG} = m_{LPG} \times HV_{LPG} \quad \text{..........} \quad (3)$$

Description:
E_{LPG} : LPG energy (kkal)
m_{LPG} : LPG mass (kg)
HV_{LPG} : LPG calorific value (11,254.61 kkal/kg)

4. Efficiency (η)

$$\eta = \left(\frac{E_p}{E_{LPG}}\right) \times 100\% \quad \text{..........} \quad (4)$$

Data Analysis

To improve the validity of the results, statistical analysis was conducted. The mean values of fuel properties and energy output were reported with standard deviations. Oneway ANOVA was used to determine the significance of differences between treatments, and error bars representing standard deviation were included in all graphical representations of the data [27].

III. Results and Discussion

This study presents a comprehensive analysis of the influence of catalyst type and temperature variation on the pyrolysis results of LDPE plastic waste. The main focus is on the quantity of liquid fuel products, the energy efficiency of the process, as well as the physical characteristics of the fuel produced.

1. Effect of Temperature and Type of Catalyst on Product Quantity

The pyrolysis results show that the volume and mass of the product increase as the temperature increases. Without a catalyst, the number of products tends to be low because the polymer decomposition is not optimal. The use of natural zeolite improves yields, but synthetic zeolite has proven to be most effective in accelerating the breakdown of LDPE chains into lightweight fractions of hydrocarbons.

Based on Table 1, the amount of fuel product increased with the rise in pyrolysis temperature. At 350°C, all treatments showed maximum production. Synthetic zeolite produced the highest volume and mass at each temperature, indicating the active role of the catalyst's surface and pores in breaking down polymer chains. Without a catalyst, the decomposition process was slower, resulting in lower product yields.

Table 1. Volume and mass of LDPE pyrolysis products

Temperature (°C)	Treatment	Volume (mL)	Mass (kg)
250	No Catalyst	180	0.160
250	Natural Zeolite	210	0.180
250	Synthetic Zeolite	240	0.200
300	No Catalyst	240	0.200
300	Natural Zeolite	300	0.255
300	Synthetic Zeolite	360	0.310
350	No Catalyst	280	0.230
350	Natural Zeolite	340	0.289
350	Synthetic Zeolite	410	0.349

Based on Figure 2, it can be seen that the use of synthetic zeolite produces a higher volume and mass of liquid fuel compared to using natural zeolite without a catalyst. This indicates that the use of zeolite has a significant effect on the conversion of LDPE into liquid fuel fractions. The results of this study are in line with the results of studies conducted by Wong *et al.* [28], and Zhou *et al.* [29], where synthetic zeolite is able to increase the pyrolytic conversion of plastic into liquid products due to its high acidity and large surface area. The use of synthetic zeolites has proven to be more effective than natural zeolites and requires no catalysts for producing liquid fuels. This is because synthetic zeolites facilitate the breakdown of large molecules into lighter hydrocarbons and inhibit the formation of non-condensable compounds [30].

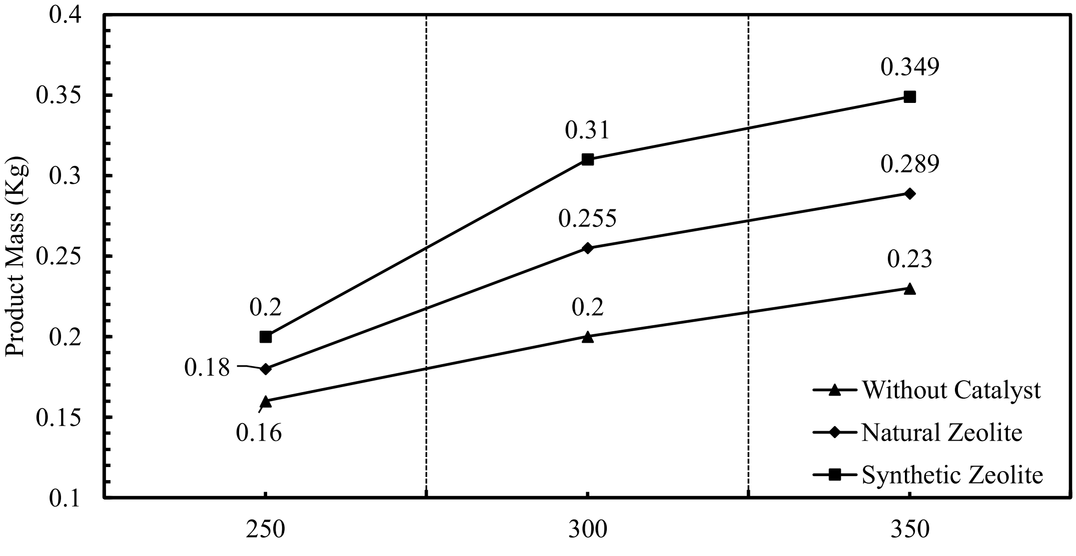

Fig. 2. Comparison of pyrolysis product results

2. *ANOVA Results*

The experimental data were subjected to ANOVA testing to determine the parameters that had a significant influence on the pyrolysis oil yield. The ANOVA test was carried out using experimental data. ANOVA was carried out on each response with a significance value (α) of 0.05. A process variable is significant to the response when it has a P-value less than 0.05 at the 95% confidence level. The percentage of contribution was used to determine the contribution of various process variables to the responses towards the total variance.

From Table 2, temperature accounts for the largest proportion of variation, contributing 57.38% of the total variability. The F-value of 20.06 and a p-value of 0.008 (which is less than 0.05) confirm that differences in pyrolysis temperature (250°C, 300°C, and 350°C) have a statistically significant influence on the pyrolysis outcomes. This suggests that temperature plays a crucial role in the thermal decomposition behavior of LDPE. Generally, increasing the pyrolysis temperature enhances the cracking rate of polymer chains, potentially improving the yield of lighter hydrocarbons and increasing the calorific value of the liquid fuel, up to an optimal point.

Table 2. ANOVA results

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-value	P-value
Temperature (°C)	2	0.018758	57.38%	0.018758	0.009379	20.06	0.008
Treatment	2	0.012060	36.89%	0.012060	0.006030	12.90	0.018
Error	4	0.001870	5.72%	0.001870	0.000468		
Total	8	0.032688	100.00%				

The analysis of variance (ANOVA) results indicates that both independent variables—pyrolysis temperature and treatment (type of catalyst)—have a statistically significant effect on the dependent variable (e.g., fuel yield, energy efficiency, or physical characteristics of the liquid fuel produced).

The treatment factor, referring to the type of catalyst used (no catalyst, natural zeolite, and synthetic zeolite ZSM-5), contributes 36.89% of the total variance, with an F-value of 12.90 and a p-value of 0.018. This result also indicates a significant effect of catalyst type on the pyrolysis performance. The catalytic role is critical in enhancing the breakdown of polymer chains and influencing the composition of the resulting fuel. The resulting error value of 5.72% across all variations demonstrated that the model captured most of the variability in the experimental data.

3. Energy Efficiency of Pyrolysis Process

One important parameter for assessing the feasibility of a pyrolysis process is energy efficiency. Figure 3 shows a comparison of energy efficiency between synthetic zeolite, natural zeolite, and uncatalyzed zeolite.

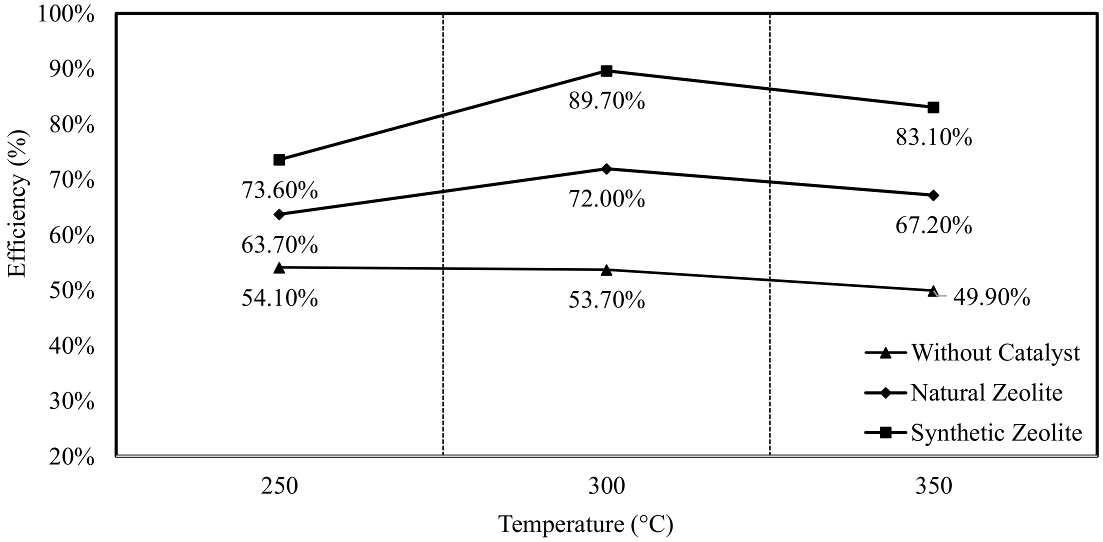

Fig. 3. Product energy efficiency to energy consumption (LPG)

One of the product energy efficiencies against energy consumption (LPG) in the pyrolysis of LDPE plastic waste is an important indicator to assess the extent to which the pyrolysis process is able to convert heat energy from LPG into energy in the form of liquid fuel. Efficiency is calculated by comparing the total energy contained in the pyrolysis oil product with the total energy used from LPG fuel during the process. The higher the efficiency value, the better the energy conversion that occurs in the system. From Figure 3, it can be seen that the highest energy efficiency was recorded at a temperature of 300°C with the use of a synthetic zeolite catalyst of 89.7%. This result shows that almost 90% of the energy used was successfully converted into energy in the form of pyrolysis oil, thus making the combination of temperature and catalyst the most optimal parameter configuration in the experiment [31].

These findings demonstrate not only technical viability but also highlight the strong industrial and economic relevance of energy efficiency. A high conversion ratio of input energy to useful fuel output can lower operational costs, reduce energy waste, and improve the scalability of plastic-to-fuel technologies for commercial applications. Experiments without a catalyst produced the lowest efficiency value of 49.9% at a temperature of 350°C. This proves the important role of catalysts in the pyrolysis process [32]. These results are supported by research conducted by Zang *et al.* [19], which stated that the use of zeolite can reduce reactions and increase mass conversion to oil. This is because the pyrolytic reaction is faster and more selective when using synthetic catalysts [33].

Table 3 shows that the highest efficiency occurs at a temperature of 300°C with synthetic zeolite. This indicates that at such temperatures, the reaction rate is optimal and not too much energy is wasted, and the resulting oil fraction is more easily condensed [19].

Table 3. Product energy efficiency to fuel consumption

Temperature (°C)	Treatment	Energy efficiency (%)
250	No catalyst	54.1
250	Natural zeolite	63.7
250	Synthetic zeolite	73.6
300	No catalyst	53.7
300	Natural zeolite	72.0
300	Synthetic zeolite	89.7
350	No catalyst	49.9
350	Natural zeolite	67.2
350	Synthetic zeolite	83.1

4. *Physical Characteristics of Pyrolysis Products*

The quality of pyrolysis oil is tested based on conventional fuel standards. The results show that the use of synthetic zeolite catalysts is able to produce products with quality that is closest to SNI standards.

Table 4. Physical characteristics of pyrolysis fuel products

Parameters	No catalyst	Natural zeolite	Synthetic zeolite	SNI
Cetane index	40.1	45.3	48.7	Min. 48
Density (g/mL)	0.925	0.870	0.850	0.820–0.870
Sulfur (ppm)	720.0	390.0	190.0	Max. 500
Viscosity (cSt)	1.9	0.53	1.0	2.0–5.0
Flash Point (°C)	42.0	55.0	66.0	Min. 52
Calorific value (MJ/kg)	34.7	37.21	38.10	Min. 40 min.

The cetane index is a key indicator of the combustion speed of fuel in diesel engines—higher values reflect better ignition quality. Table 4 indicates that the pyrolysis oil produced without a catalyst showed the lowest cetane index at 40.1, indicating poor combustion performance. The use of natural zeolite increased the cetane index to 45.3, while synthetic zeolite resulted in the highest value of 48.7, meeting the Indonesian National Standard (SNI) for diesel fuel. This improvement is attributed to the increased formation of saturated hydrocarbons (alkanes) and the reduction of complex aromatic compounds. The higher surface area and acidity of synthetic zeolite promote the breakdown of LDPE into shorter, thermally stable, and more combustible hydrocarbon chains [24].

In terms of density, which influences the energy volume per unit mass, the fuel from non-catalyzed pyrolysis exhibited a relatively high density of 0.925 g/mL, suggesting a dominance of heavier compounds. Synthetic zeolite yielded a fuel density of 0.850 g/mL, aligning more closely with diesel fuel standards due to a higher proportion of C10–C20 hydrocarbon fractions [33].

Sulfur content is a critical parameter, as high sulfur levels lead to SO_2 emissions and catalytic converter degradation. The sulfur concentration in the non-catalyzed sample was 720 ppm, which exceeds the SNI limit of 500 ppm. Natural zeolite reduced sulfur content to 390 ppm, while synthetic zeolite achieved a significant reduction to 190 ppm. This result suggests the ability of zeolites—particularly synthetic types—to absorb or degrade sulfur-containing compounds during pyrolysis [34].

Kinematic viscosity affects fuel flow and air–fuel mixing within the combustion chamber. SNI specifies a diesel viscosity range of 2.0–5.0 cSt at 40°C. However, all samples in this study fell below this threshold. The viscosities measured were 1.9 cSt (no catalyst), 0.53 cSt (natural zeolite), and 1.0 cSt (synthetic zeolite), indicating the presence of very light hydrocarbons (C5–C10 range) in the fuel. Such low viscosity can cause issues like leakage in injection systems, incomplete combustion, and reduced engine efficiency.

The limitations in viscosity and calorific value suggest that post-treatment, such as fuel blending (e.g., with conventional diesel) or distillation, may be necessary. These processes would enhance fuel stability, combustion quality, and energy output, making the product more suitable for engine applications. According to Fulgencio-Medrano *et al.* [35], low viscosity is a common limitation of plastic pyrolysis oils, particularly when not followed by post-processing or blending with conventional diesel.

Flash point is another important safety parameter, representing the minimum temperature at which vapor from the fuel can ignite. The use of zeolite, both natural and synthetic, can increase the flash point by 66°C. This value is above the minimum standard of 52°C. However, pyrolysis without a catalyst only produces a flash point of 42°C, indicating that using a catalyst is more effective in increasing the flash point of the liquid fuel produced by pyrolysis.

The minimum calorific value standard for diesel fuel according to the Indonesian National Standard (SNI) is 40 MJ/kg. The calorific value of the liquid fuel produced by pyrolysis in this study using a synthetic zeolite catalyst was 38.10 MJ/kg, using a natural zeolite catalyst was 37.21 MJ/kg, and without a catalyst was 34.7 MJ/kg. These results indicate that the values are below the SNI standard and do not meet diesel performance standards.

IV. Conclusion

This study confirms that catalytic pyrolysis, particularly using synthetic zeolite (ZSM-5), significantly improves the conversion of LDPE plastic waste into liquid fuel. Experimental results, supported by ANOVA analysis, show that both pyrolysis temperature ($p = 0.008$) and catalyst type ($p = 0.018$) have a statistically significant effect on fuel yield and energy efficiency. At the optimum condition of 300°C with synthetic zeolite, the process achieved the highest liquid fuel yield (360 mL, 0.31 kg) and energy efficiency (89.7%), indicating a highly effective conversion of input thermal energy into usable fuel. The resulting pyrolysis oil also demonstrated physical characteristics closest to diesel fuel standards, meeting key parameters such as cetane index (48.7), sulfur content (190 ppm), flash point (66°C), and density (0.850 g/mL). However, some limitations remain, notably in viscosity (1.0 cSt) and calorific value (38.10 MJ/kg), both of which fall below SNI minimum standards, suggesting a need for further upgrading processes such as distillation, blending with commercial diesel, or catalytic reformulation.

Beyond its technical outcomes, the study presents broader implications for waste-to-energy strategies in the context of sustainable development. High energy recovery efficiency and partial conformity to fuel standards demonstrate the potential of catalytic pyrolysis as a viable alternative energy pathway, particularly in regions facing plastic waste surpluses and limited fuel access. The findings support the feasibility of modular pyrolysis units for community-scale energy solutions and open opportunities for industrial-scale adaptation within a circular economy framework. Incorporating this technology into local energy policies could reduce dependence on fossil fuels, minimize environmental burdens from plastic pollution, and stimulate green innovation at the intersection of waste management and renewable energy. As such, catalytic pyrolysis represents a promising bridge between environmental responsibility and economic utility, particularly when aligned with national agendas for renewable energy and low-carbon industry.

Acknowledgement

This research was independently funded by the author, with the support of laboratory facilities from the institution where the author teaches. Thank you to the student team involved in the data collection process, as well as to all parties who have helped both technically and non-technically.

Reference

[1] Y. Chen, A. K. Awasthi, F. Wei, Q. Tan, and J. Li, “Single-use plastics: Production, usage, disposal, and adverse impacts,” *Sci. Total Environ.*, vol. 752, p. 141772, 2021, doi: 10.1016/j.scitotenv.2020.141772.

[2] P. Kasar, D.K. Sharma, and M. Ahmaruzzaman, “Thermal and catalytic decomposition of waste plastics and its co-processing with petroleum residue through pyrolysis process,” *J. Clean. Prod.*, vol. 265, p. 121639, 2020, doi: 10.1016/j.jclepro.2020.121639.

[3] O. Szlachetka, J. Witkowska-Dobrev, A. Baryła, and M. Dohojda, “Low-density polyethylene (LDPE) building films – Tensile properties and surface morphology,” *J. Build. Eng.*, vol. 44, no. June, 2021, doi: 10.1016/j.jobe.2021.103386.

[4] A.S. Lubis, Z.A. Muis, and N.A. Siregar, “The effects of low-density polyethylene (LDPE) addition to the characteristics of asphalt mixture,” *IOP Conf. Ser. Earth Environ. Sci.*, vol. 476, no. 1, 2020, doi: 10.1088/1755-1315/476/1/012063.

[5] I.N. Santhiarsa, “Effect of variations in pyrolysis reactor with glass wool equipped and without glass wool on the weight of the oil produced,” *J. Mech. Eng. Sci. Technol.*, vol. 5, no. 2, p. 89, 2021, doi: 10.17977/um016v5i22021p089.

[6] T.Y.A. Fahmy, Y. Fahmy, F. Mobarak, M. El-Sakhawy, and R.E. Abou-Zeid, “Biomass pyrolysis: past, present, and future,” *Environ. Dev. Sustain.*, vol. 22, no. 1, pp. 17–32, 2020, doi: 10.1007/s10668-018-0200-5.

[7] H. Porawati, A. Kurniawan, and E. Yuliwati, “Effect of temperature on gasification of biomass using zeolit,” *J. Phys. Conf. Ser.*, vol. 1845, no. 1, 2021, doi: 10.1088/1742-6596/1845/1/012040.

[8] M.M. Hasan, M.G. Rasul, M.M.K. Khan, N. Ashwath, and M.I. Jahirul, “Energy recovery from municipal solid waste using pyrolysis technology: A review on current status and developments,” *Renew. Sustain. Energy Rev.*, vol. 145, no. September 2020, p. 111073, 2021, doi: 10.1016/j.rser.2021.111073.

[9] I.M. Maafa, “Pyrolysis of polystyrene waste: A review,” *Polymers (Basel).*, vol. 13, no. 2, pp. 1–30, 2021, doi: 10.3390/polym13020225.

[10] B. Rimez, S. Breyer, O. Vekemans, and B. Haut, “Co-pyrolysis of low-density polyethylene and motor oil—investigation of the chemical interactions between the components,” *Recycling*, vol. 5, no. 4, pp. 1–13, 2020, doi: 10.3390/recycling5040033.

[11] A.Y. Aminullah, S. Sukarni, R. Wulandari, and M. Shahbaz, “Pyrolysis kinetics of spirulina platensis and non-condensable gas product distribution in a fixed-bed reactor,” *J. Mech. Eng. Sci. Technol.*, vol. 8, no. 1, p. 151, 2024, doi: 10.17977/um016v8i12024p151.

[12] M. Raza, S.R. Naqvi, A. Inayat, A. Ahmed, F. Jamil, C. Ghenai *et al.*, “Progress of the pyrolyzer reactors and advanced technologies for biomass pyrolysis processing,” *Sustain.*, vol. 13, no. 19, pp. 1–42, 2021, doi: 10.3390/su131911061.

[13] K. Murthy, R. J. Shetty, and K. Shiva, “Plastic waste conversion to fuel: a review on pyrolysis process and influence of operating parameters,” *Energy Sources, Part A Recover. Util. Environ. Eff.*, vol. 45, no. 4, pp. 11904–11924, 2023, doi: 10.1080/15567036.2020.1818892.

[14] N. Sobuś and I. Czekaj, “Comparison of synthetic and natural zeolite catalysts’ behavior in the production of lactic acid and ethyl lactate from biomass-derived dihydroxyacetone,” *Catalysts*, vol. 11, no. 8, 2021, doi: 10.3390/catal11081006.

[15] M. Król, “Natural vs. synthetic zeolites,” *Crystals*, vol. 10, no. 7, pp. 1–8, 2020, doi: 10.3390/cryst10070622.

[16] N. Kordala and M. Wyszkowski, “Zeolite properties, methods of synthesis, and selected applications,” *Molecules*, vol. 29, no. 5, 2024, doi: 10.3390/molecules29051069.

[17] R. Cai, X. Pei, H. Pan, K. wan, H. chen, Z. zhang, and Y. zhang, “Biomass catalytic pyrolysis over zeolite catalysts with an emphasis on porosity and acidity: A state-of-the-art review,” *Energy and Fuels*, vol. 34, no. 10, pp. 11771–11790, 2020, doi: 10.1021/acs.energyfuels.0c02147.

[18] J. Szerement, A. Szatanik-Kloc, R. Jarosz, T. Bajda, and M. Mierzwa-Hersztek, “Contemporary applications of natural and synthetic zeolites from fly ash in agriculture and environmental protection,” *J. Clean. Prod.*, vol. 311, no. May, p. 127461, 2021, doi: 10.1016/j.jclepro.2021.127461.

[19] Y. Zang, J. Wang, J. Gu, J. Qu, and F. Gao, “Mesoporogen-free synthesis of hierarchical HZSM-5 for LDPE catalytic cracking,” *CrystEngComm*, vol. 22, no. 21, pp. 3598–3607, 2020, doi: 10.1039/d0ce00255k.

[20] A. Santoso, A. Sholikhah, S. Sumari, M.R. Asrori, A.R. Wijaya, and I.B. Rachman, “Effect of active zeolite in the pyrolysis of polypropylene and low density polyethylene types of plastic waste,” *J. Renew. Mater.*, vol. 10, no. 11, pp. 2781–2789, 2022, doi: 10.32604/jrm.2022.021401.

[21] P. Sudalaimuthu, U. Ali, and R. Sathyamurthy, “Optimization of process parameters of catalytic pyrolysis using natural zeolite and synthetic zeolites on yield of plastic oil through response surface methodology,” *Sci. Rep.*, vol. 14, no. 1, pp. 1–14, 2024, doi: 10.1038/s41598-024-78180-1.

[22] A.A.P. Susastriawan, Purnomo, and A. Sandria, “Experimental study the influence of zeolite size on low-temperature pyrolysis of low-density polyethylene plastic waste,” *Therm. Sci. Eng. Prog.*, vol. 17, no. February, p. 100497, 2020, doi: 10.1016/j.tsep.2020.100497.

[23] Mazwan, S.D. Utama, and R.A. Fajardini, “Multi-objective optimization in EDM

process using backpropagation neural network-genetic algorithm (BPNN-GA)," *Int. J. Eng. Model.*, vol. 37, no. 2, pp. 81–97, 2024, doi: 10.31534/engmod.2024.2.ri.05d.

[24] N. Lee, J. Joo, K.Y.A. Lin, and J. Lee, "Waste-to-fuels: Pyrolysis of low-density polyethylene waste in the presence of H-ZSM-11," *Polymers (Basel).*, vol. 13, no. 8, pp. 1–9, 2021, doi: 10.3390/polym13081198.

[25] C.Y. Lin and X.E. Wu, "Determination of cetane number from fatty acid compositions and structures of biodiesel," *Processes*, vol. 10, no. 8, 2022, doi: 10.3390/pr10081502.

[26] J.B. Silva, J.S. Almeida, R.V. Barbosa, G.J.T. Fernandes, A.C.F. Coriolano, V.J. Fernandes Jr, and A.S. Araujo, "Pressurized differential scanning calorimetry and its calculated cetane index," *Process*, vol. 9, no. 174, pp. 2–11, 2021.

[27] M. Mazwan, M.K. Effendi, B.O.P. Soepangkat, S.D. Utama, and R.A. Fajardini, *Multi-objective Optimization of Turning Process Steel SKD 11 Using BPNN-Artificial Bee Colony (ABC) Method*. Atlantis Press International BV, 2022. doi: 10.2991/978-94-6463-134-0.

[28] S.L. Wong, S. Armenise, B.B. Nyakum, A. Bogush, S. Towers, C.H. Lee *et al.*, "Plastic pyrolysis over HZSM-5 zeolite and fluid catalytic cracking catalyst under ultra-fast heating," *J. Anal. Appl. Pyrolysis*, vol. 169, no. November 2022, 2023, doi: 10.1016/j.jaap.2022.105793.

[29] N. Zhou, L. Dai, Yuancai Lv, H. Li, W. Deng, F. Guo *et al.*, "Catalytic pyrolysis of plastic wastes in a continuous microwave assisted pyrolysis system for fuel production," *Chem. Eng. J.*, vol. 418, no. December 2020, p. 129412, 2021, doi: 10.1016/j.cej.2021.129412.

[30] M. Díaz, E. Epelde, J. Valecillos, S. Izaddoust, A.T. Aguayo, and J. Bilbao, "Coke deactivation and regeneration of HZSM-5 zeolite catalysts in the oligomerization of 1-butene," *Appl. Catal. B Environ.*, vol. 291, 2021, doi: 10.1016/j.apcatb.2021.120076.

[31] O.A. Kolenchukov, K.A. Bashmur, V.V. Bukhtoyarov, S.O. Kurashkin, V.S. Tynchenko, E.V. Tsygankova *et al.*, "Experimental study of oil non-condensable gas pyrolysis in a stirred-tank reactor for catalysis of hydrogen and hydrogen-containing mixtures production," *Energies*, vol. 15, no. 22, 2022, doi: 10.3390/en15228346.

[32] B. Csutoras and N. Miskolczi, "Thermo-catalytic pyrolysis of sewage sludge and techno-economic analysis: The effect of synthetic zeolites and natural sourced catalysts," *Bioresour. Technol.*, vol. 400, no. February, p. 130676, 2024, doi: 10.1016/j.biortech.2024.130676.

[33] S.R. Khan, M. Zeeshan, A. Ahmed, and S. Saeed, "Comparison of synthetic and low-cost natural zeolite for bio-oil focused pyrolysis of raw and pretreated biomass," *J. Clean. Prod.*, vol. 313, no. March, p. 127760, 2021, doi: 10.1016/j.jclepro.2021.127760.

[34] B.L. Murillo, M. Pala, A.L. Paioni, M. Baldus, F. Ronsse, W. Prins, P.C.A. Bruijnincx, and B.M. Weckhuysen, "Catalytic fast pyrolysis of biomass: catalyst characterization reveals the feed-dependent deactivation of a technical ZSM-5-based catalyst," *ACS Sustain. Chem. Eng.*, vol. 9, no. 1, pp. 291–304, 2021, doi: 10.1021/acssuschemeng.0c07153.

[35] L. Fulgencio-Medrano, S. García-Fernández, A. Asueta, A. Lopez-Urionabarrenechea, B.B. Perez-Martinez, and J.M. Arandes, "Oil production by pyrolysis of real plastic waste," *Polymers (Basel).*, vol. 14, no. 3, p. 553, 2022, doi: 10.3390/polym14030553.