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Research Article

The Effect of Temperature on the Pyrolysis PP and LDPE Plastic Waste: Implications for Pyrolysis Fuel Oil Characteristics

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Abstract

The accumulation of plastic waste continues to rise, necessitating effective solutions for its management. Pyrolysis is a promising method for converting plastic waste into liquid fuel by breaking down long hydrocarbon chains into shorter ones. This thermochemical process occurs at high temperatures in the absence of oxygen, producing fuel that can be utilized. This study focuses on the experimental extraction of fuel oil from two types of plastic waste: polypropylene (PP) and low-density polyethylene (LDPE). Through pyrolysis, the study also investigates the effect of temperature variations on the properties and characteristics of the resulting fuel oil. A total of 750 grams of PP and LDPE plastic waste were used, with pyrolysis temperatures ranging from 250°C to 350°C for a duration of 2 hours. The fuel oil was analysed using density tests, combustion rate analysis, and gas chromatography–mass spectrometry (GC-MS). The results showed that the highest yield of fuel oil, 280 ml, was obtained from LDPE waste at a pyrolysis temperature of 350°C. The density of the produced fuel varied between 0.730–0.750 g/ml. GC-MS analysis revealed that the fuel oil consisted of hydrocarbon chains ranging from C7 to C12.

Keywords: Polypropylene, low-density polyethylene, density, plastic waste.

INTRODUCTION

Addressing the issue of plastic waste requires specialized technical processes to enable proper utilization. According to the National Plastic Action Partnership (NPAP), plastic production in Indonesia is increasing by 5% annually. Data from the National Garbage Management Information System (SIPSN) show that waste generation in Indonesia reached 35.93 million tons in 2022, with 37.51% (13.48 million tons) being inadequately managed. Of this total, 17.9% is plastic waste, categorized by various types.

Plastic is widely used due to its lightweight, durability, corrosion resistance, and insulating properties. However, plastic waste poses serious environmental and health risks. Its resistance to decomposition by soil microbes negatively impacts soil fertility and ecosystems [1]. Moreover, burning plastic releases harmful toxins that are dangerous to human health. Pyrolysis has emerged as an alternative method to address plastic waste. In theory, pyrolysis is a thermochemical process that breaks down plastic waste into oil by decomposing carbon and hydrogen chains through heat [2].

Plastic waste, originating from naphtha and natural gas refining during the manufacturing process, can be converted into alternative fuels [3-9]. This conversion not only reduces waste but also addresses global issues such as the depletion of petroleum resources [10, 11]. Previous pyrolysis experiments on polypropylene (PP) plastic typically employed batch reactors with condensers at a temperature of around 330°C, using 8 kg of material. The resulting oil was analyzed for composition and calorific value, with gas chromatography–mass spectrometry (GC-MS) results revealing that PP-derived pyrolysis oil contains hydrocarbons ranging from C7 to C54, with the highest concentration in the C11 to C20 range. The calorific value of the oil exceeded premium fuel standards, reaching 46.199 MJ/kg, with a density of 0.726 g/ml.

Further research is needed to produce pyrolysis products with shorter carbon chains to meet the standards of premium liquid fuels required for commercial applications. This study builds on previous research and focuses on refining the pyrolysis process to yield hydrocarbons with shorter chains, aligning more closely with the criteria for commercially viable premium fuels [12-18].

EXPERIMENTAL METHODS

The target of this method and experiment is the process stage in the utilization of plastic waste, especially polypropylene (PP) plastic from mineral water bottle packaging with low-density polyethylene (LDPE) from plastic packaging. Both are combined for further processing. The initial stage is to select and sort the types of plastic. The waste that has been sorted and selected is then washed clean with water to remove various types of dirt that stick to the plastic as raw material for the experiment. After that, the plastic is cut into small pieces measuring approximately 3x3 cm using a cutting tool. The next stage is to dry the plastic in direct sunlight to remove the water content in the plastic. Then it is processed in the next process.

Process of Pyrolysis on Analysis

The pyrolysis process was conducted using a batch reactor with a capacity of approximately 750 grams. Initially, 750 grams of plastic waste was weighed and prepared for placement into the reactor. The reactor was securely sealed to ensure safety and prevent any gas leakage. Temperature control was monitored using a thermometer, with pyrolysis temperatures set at three varying levels: 250°C, 300°C, and 350°C. The process duration was maintained for 120 minutes.

A condenser was installed and carefully regulated to ensure cold conditions, facilitating the condensation of pyrolysis gases into liquid form. The condensed material was then collected in a beaker for subsequent analysis and further processing. The solid residue material remaining after pyrolysis is analysed to assess whether it has met the efficiency and completeness of the process. The results obtained in this research work have been focused on solids and oil, calculated through equation (1) by determining the ratio between the weight of the product produced and the weight content of the plastic that has been used as the main raw material:

$$d\ (\%) = \frac{Ratio\ Weight\ on\ product}{Raw\ Product\ Weight} \times 100 \qquad (1)$$

Density Analysis

To determine the mass weight of the test sample, a density test is carried out, using a pycnometer device, to ensure the measurement of material density in accordance with the needs. The stages of the procedure involve initial weighing as the initial setting for calibration. Then re-weighing after being filled with the appropriate sample. The density of the material is then calculated using the pycnometer equation (2) based on the standard, taking into account the difference in weight and volume of the known pycnometer. This method is applied to ensure accurate and precise results.

$$Density\ (g/ml) = \frac{mass\ (g)}{volume\ (ml)} \qquad (2)$$

Combustion Rate Analysis by GC-MS

To implement the suitability of the burning rate test, it is done by measuring the duration of the burning of an oil sample of approximately 5 ml. The equipment used is a Stopwatch as a combustion time recorder to obtain accurate results. The resulting data is analysed and calculated using a special formula designed to determine the capacity of the burning rate, see equation (3). This method is used to ensure accurate measurements and can be repeated, so that a scientific assessment of the characteristics of oil combustion can be applied.

$$Combustion\ rate\ (ml/s) = \frac{volume\ (ml)}{times\ (s)} \qquad (3)$$

The experiment was conducted using the Gas Chromatography-Mass Spectrometry (GC-MS) method, which is used for the qualitative and quantitative composition analysis of sample compounds present in the product. The GC-MS method based on the literature is a sophisticated analytical technique that combines two precise instruments: For gas chromatography, applied to separate complex mixtures into chemical component descriptions, and mass spectrometry, which identifies and measures these compounds based on the description of their fragmentation patterns.

The experiment was carried out by injecting the sample into a predetermined volume after the instrument was calibrated. When the sample decomposes, different peaks are produced in the chromatogram value, which corresponds to individual compounds. The peaks that have been recorded in the data are then compared with a widely known compound database, ensuring accurate identification and measurement of the chemical sample constituents.

The analysis was carried out comprehensively, to provide valuable basic science about the combustion rate, because the chemical composition of the fuel affects its flammability and energy output. The combination of gas chromatography and mass spectrometry was carried out to ensure a detailed and scientific evaluation of the fuel characteristics, so that it can be applied to its application. Table 1 provides detailed data on the yields of the pyrolysis process for various polymeric materials.

Table 1. Pyrolysis product yield data

Polymeric Materials	Raw Material Weight (g)	Temperatures (°C)	Yield (g)
Solid	Oil		
PP	750	250	60
LDPE	750	300	50
PP	750	350	45
LDPE	750	350	35

RESULTS AND DISCUSSIONS

The results of the impact of pyrolysis time on oil yield based on PP VS LDPE are shown in the Figure 1.

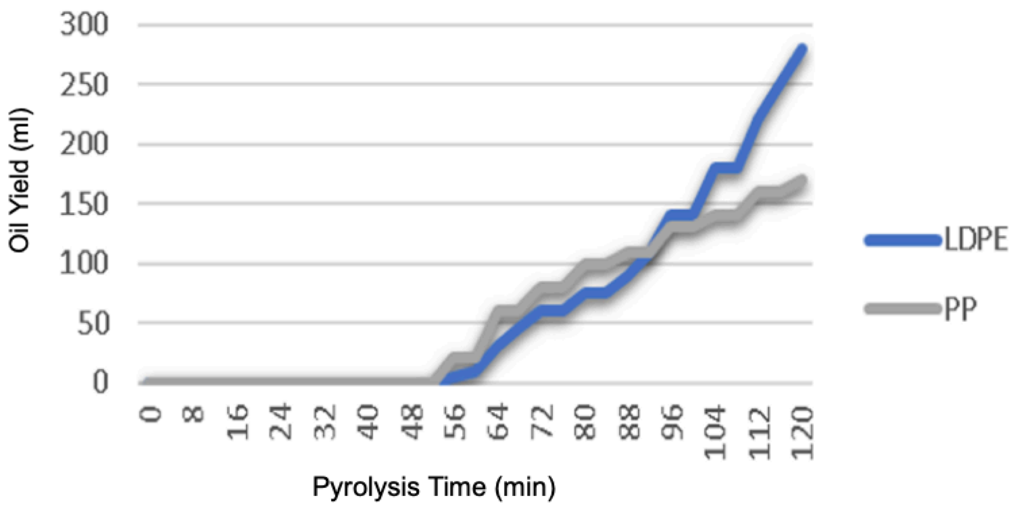


Figure 1. The impact of pyrolysis time on oil yield based on PP VS LDPE

The pyrolysis process involves varying the maximum temperature to utilize different types of plastic materials as the raw polymeric materials. The resulting oil yields are analyzed to assess the impact of temperature on the characteristics of the produced oil. This research work identifies the highest fuel oil yield from the pyrolysis of polypropylene (PP) and low-density polyethylene (LDPE) plastic waste, with the maximum yield occurring at a pyrolysis temperature of 350°C. This finding aligns with previous research [13], which demonstrated that reactor temperature significantly influences the physical properties of pyrolysis oil. Higher reactor temperatures not only increase fuel oil yield but also result in a more turbid appearance compared to lower temperature settings. This suggests that elevated temperatures enhance the breakdown of plastic into fuel oil, but also affect other physical characteristics.

Skodaar [9], has conducted similar experiments, where further studies showed that applying higher pyrolysis reactor temperatures usually resulted in less solid by-products, such as charcoal, especially in the pyrolysis of PP plastics at lower temperatures. This phenomenon can be attributed to the fact that, at a pyrolysis temperature of 350°C, the long carbon chains in PP and LDPE plastic waste decompose into shorter hydrocarbon chains, ranging from C6 to C18, facilitating the formation of liquid oil as can be seen in Figure 2.

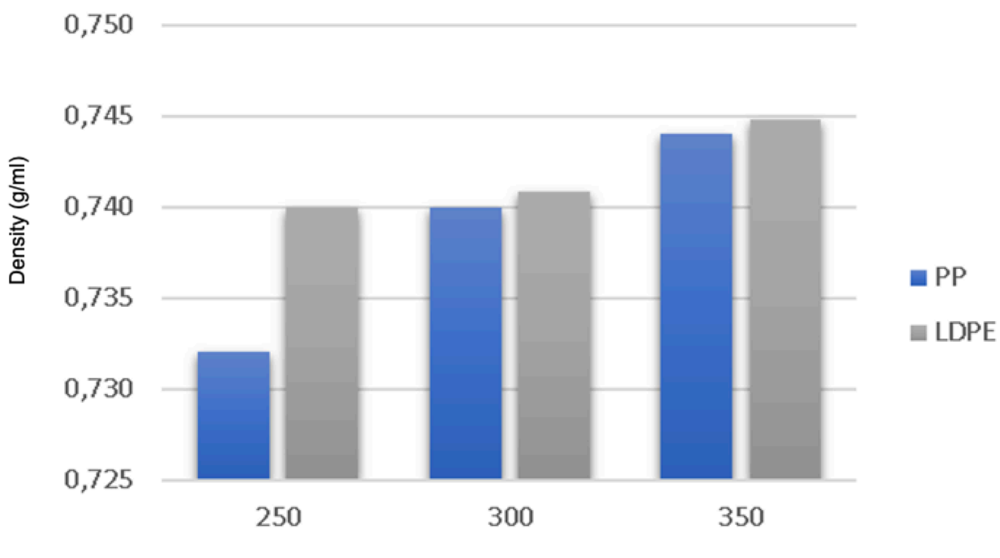


Figure 2. The effect of plastic type and pyrolysis temperature on the density for oil production

When comparing the pyrolysis of PP and LDPE plastic waste at 350°C, LDPE yielded the highest volume of fuel oil. The other hand, the findings resulting from Arif observations [13] show that PP plastic is more resistant to decomposition due to its regular bond structure, so that LDPE as a raw material is more efficient for oil production under these conditions. The solid residue produced during the pyrolysis process of PP and LDPE waste, it was observed that higher pyrolysis temperatures could cause a decrease in the amount of residual solids. This phenomenon indicates that more raw materials are converted into fuel oil when the operating temperature rises above 250 °C. Where the texture of the residual solids varies with temperature. At 350 °C, the solids are soft and fat-like, at a temperature of 300 °C, it becomes slightly harder. At 250 °C, the texture of the solids becomes harder. This phenomenon, based on the theory [10] indicates that the breakdown of raw materials into oil is less effective. Residual solids with high carbon, have the potential to be used as solid fuels. The characteristics of the charcoal produced during plastic pyrolysis make it suitable for solid fuel applications.

Time Effect on Pyrolysis Oil Revenue

Based on the general rule [14], fuel oil production starts around 50 minutes after the pyrolysis process. Initially, the yield of fuel oil from Polypropylene (PP) plastic waste exceeds that of Low-Density Polyethylene (LDPE) plastic waste, a trend that persists until around the 96th minute. However, by the end of the process at 120 minutes, the yield from LDPE surpasses that from PP. This difference may be attributed to the thermal properties of LDPE, which likely experiences uneven heating, leading to incomplete molecular breakdown and delayed oil production. In opposite, the initial yield of PP increases but slows down as the process progresses. The slowdown indicates that when PP is heated for a long time, the remaining structure becomes more resistant to further degradation. The result is fuel oil. This behaviour is the basis of the different pyrolysis kinetics of each material, according to [10], where LDPE will eventually achieve a higher total yield despite its slower initial conversion rate.

The Effect of Plastic Type & Pyrolysis Process

According to standard requirements [19], density values for gasoline typically range between 0.715 and 0.770 g/ml. The fuel oil produced in this study exhibits a density range of 0.730 to 0.750 g/ml, confirming its classification within the gasoline category. The results demonstrate that the pyrolysis temperature for Polypropylene (PP) and Low-Density Polyethylene (LDPE) plastic waste has a significant impact on the density of the resulting fuel oil. These findings align with previous studies, which suggest that higher pyrolysis temperatures lead to increased oil density. This effect occurs because elevated temperatures reduce the likelihood of secondary hydrocarbon vapors converting into gas, allowing heavier fractions to condense into the oil phase [5].

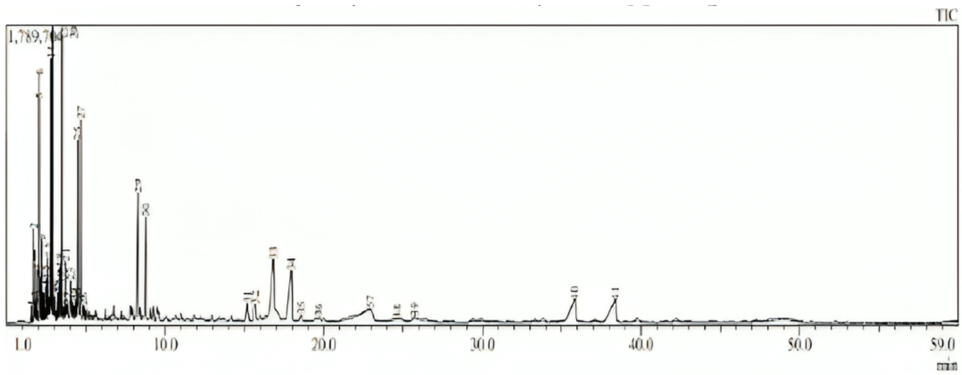
Combustion Rate of Oil Produced: Hydrocarbon Composition

GC-MS (Gas Chromatography-Mass Spectrometry) testing was applied to accurately determine the composition and distribution of hydrocarbons in pyrolysis oil. For Low Density Polyethylene (LDPE), the pyrolysis temperature has a significant impact on the hydrocarbon profile. At 250°C, most of the hydrocarbons are in the range of C7-C12, which classifies the oil as gasoline. When the temperature increases to 300°C, the composition shifts to C9-C12. In the extended traces reach C13-C14, indicating a mixture of gasoline fractions with the gasoline range (C6-C12). However, with varying chain lengths, indicating a finer polymer breakdown. For Polypropylene (PP), the composition of the oil varies: At 250°C, the main hydrocarbons are in the range of C8-C12, indicating a quality fuel that meets the criteria for gasoline. When the temperature rises to 300°C, the range remains within the range: C8-C12 but slightly expands to meet lighter fractions, in the categories (C7) and heavier (C11-C12), indicating a partial blend of gasoline and diesel. At 350°C, the hydrocarbons expand to C10-C14, indicating the formation of longer chains, which usually result from the breakdown of larger macromolecules at higher temperatures.

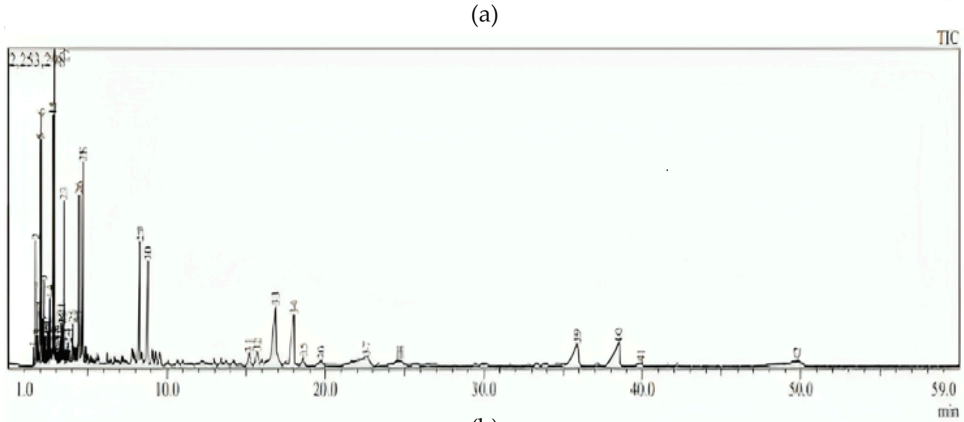
The combustion rate test assesses the practical usefulness of the fuels produced, in order to meet the highest combustion rates observed: observed at 250°C for PP (0.023 ml/s) and 350°C for LDPE (0.0198 ml/s), see Table 2 and Figure 3. These figures are lower when compared to commercial gasoline, which is due to the heavier hydrocarbon chains and impurities present in the pyrolysis oil. These factors hinder full combustion, thus reducing the overall efficiency. While the fuels produced are within the gasoline range, the presence of longer chains and impurities reduces the combustion performance. Efforts to control the refining process to improve fuel quality and usability in practical applications are needed for further experiments.

Table 2. Raw material variations: Plastic type, raw material weight, pyrolysis temperature, with burning rate (ml/s) for PP and LDPE at various temperatures.

Type of Plastic	Raw Material Weight (g)	Temperature (°C)	Combustion Rate (ml/s)
PP	750	250	0.023
PP	750	300	0.0185
PP	750	350	0.0183
LDPE	750	250	0.0187
LDPE	750	300	0.0181
LDPE	750	350	0.0198
LDPE	750	350	0.0327



(a)



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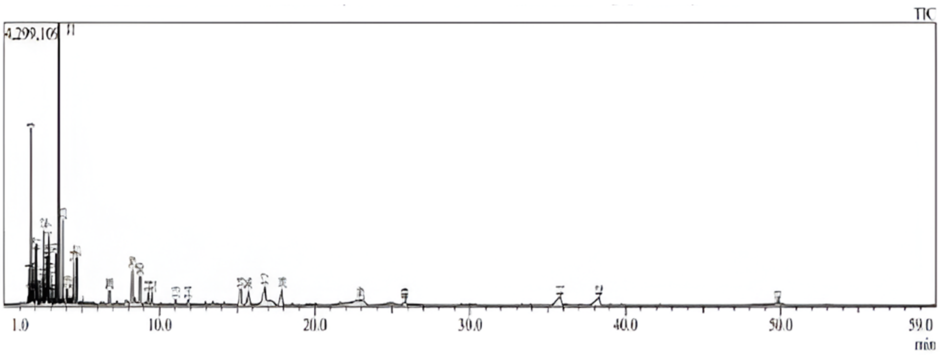

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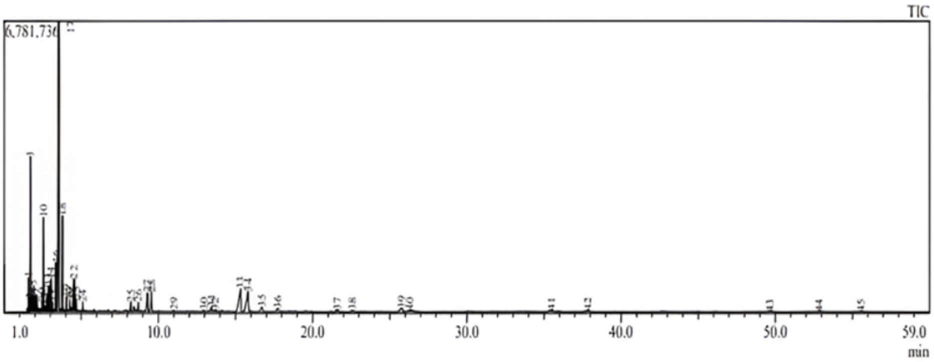

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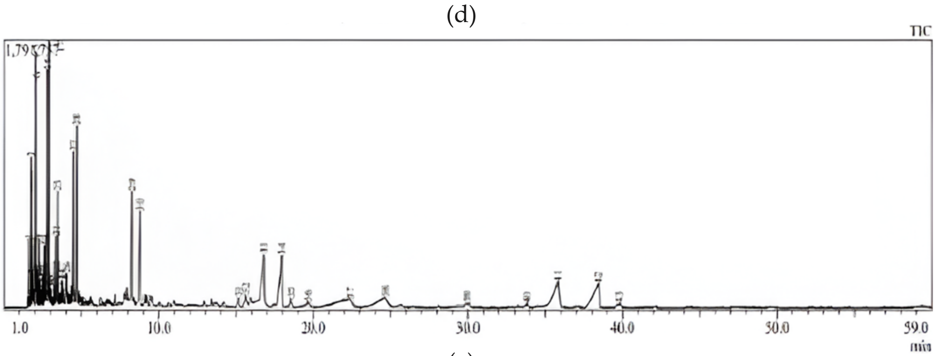

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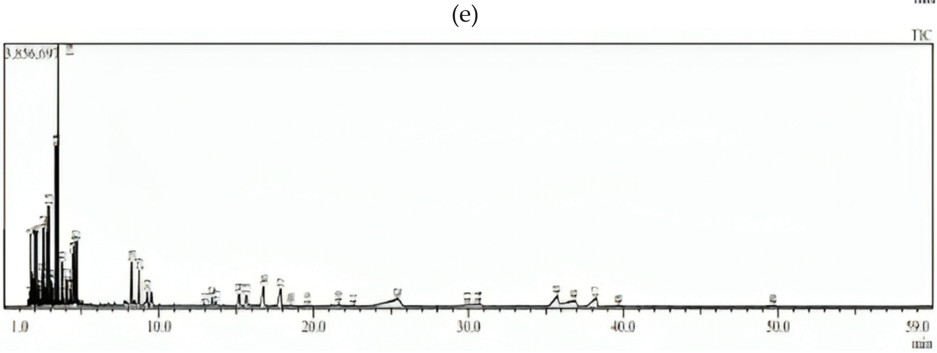

(f)

Figure 3. Chromatogram graphs of (a, c, e) PP and (b, d, f) LDPE samples at varying temperatures 250°C, 300°C and 350°C

CONCLUSION

The laboratory-based pyrolysis process applied to polypropylene (PP) and low-density polyethylene (LDPE) plastic waste has successfully produced fuel oil with a density comparable to gasoline. The variation in pyrolysis temperatures had a significant impact on both the yield and quality of the fuel oil. Higher pyrolysis temperatures improved the quality of the oil, particularly for LDPE, while PP demonstrated greater resistance to fuel decomposition. This research underscores the efficiency of pyrolysis as a method for converting plastic waste into valuable fuel products.

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CONFLICT OF INTERESTS

The authors declare that there is no conflict of interest associated with the publication of this study.

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