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Combustion characteristics of pyrolysis oil droplets from pyrolysis of polyethylene (PE) plastic waste

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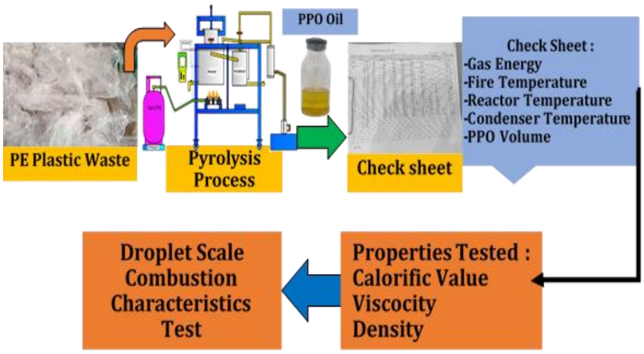

Highlights:

- Pyrolysis is an effective alternative way to process plastic waste.
- Polyethylene (PE) plastic wastes have the potential to be converted into liquid fuel.
- The combustion characteristics of PE Plastic oil are similar to diesel fuel oil.
- The caloric value of PE plastic oil is close to diesel fuel oil.

Abstract

Plastic waste is suspected to be a major contributor to environmental pollution, thus encouraging the need for innovative and effective management strategies to overcome it. Pyrolysis is considered an affordable way to process plastic waste, and even produce useful products in liquid form, which has the potential to be an alternative fuel in combustion engines. This study evaluated the combustion characteristics of pyrolysis oil derived from polyethylene (PE) plastic waste. The pyrolysis process was carried out under controlled conditions, at a furnace temperature of 250 °C, a reactor temperature of 400 °C, and a condenser temperature of 300 °C, processing 1 kg of PE plastic waste. Temperature data was monitored every 10 minutes by installing several thermocouples. The pyrolysis process was able to produce 671 ml of liquid, which was later identified as plastic pyrolysis oil (PPO PE-11) and the rest in the form of residue reached 45 g. The results indicated that PPO PE-11 has a viscosity of 5.93 mm^2/s which is higher than diesel 3.8173 mm^2/s. Meanwhile, its density is 0.779 kg/m^3, which is slightly lower than diesel. The calorific value of PPO PE-11 is slightly higher than diesel, reaching 11,046.4 cal/g. The droplet scale combustion tests give a shorter ignition delay of 0.6 seconds at 41.28 °C for PPO PE-11, compared to 1 second at 52.525 °C for diesel, indicating its flammability.

Keywords: Alternative fuel; PE waste; PE plastic waste; Plastic pyrolysis oil

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1. Introduction

Plastic has become a global issue that continues to receive significant attention due to its potential environmental impact [1],[2]. Plastics have been produced in large quantities since the 1950s. Since then, global plastic production has increased dramatically, rising from 1.5 million tonnes annually to 374.8 million tonnes in 2019. After a brief standstill in 2020 (375.5 million tonnes) attributable to the Covid-19 epidemic, it recovered in 2022 (390.7 million tonnes) [3]. If current production and waste management practices continue, it is estimated that by 2050, the amount of plastic waste disposed of in landfills or the environment will reach 12 billion tonnes [4].

Plastic is helpful to support human life in the current era [5],[6],[7],[8]. Among the commonly used polymers as primary raw materials are polyethylene (PE), polyethylene terephthalate (PET), high-density polyethylene (HDPE), low-density polyethylene (LDPE), polyvinyl chloride (PVC), and polypropylene (PP) [9],[10]. The commonly used types of plastic include polyethylene (PE) for plastic bags, polyethylene terephthalate (PET) for soft drink and mineral water bottles, high-density polyethylene (HDPE) for detergent bottles and packaging, low-density polyethylene (LDPE) for lightweight bags, and polypropylene (PP) for food grade packaging [11]. The rapid increase in global plastic production underscores the urgent need for effective plastic waste management. Improper disposal of plastic waste is a major contributor to environmental pollution. Traditional management methods, such as incineration, are widely employed but present significant drawbacks. For example, incineration emits harmful gases, such as hydrogen sulfide (H_2S), and, when plastic waste contains chlorine (Cl), produces dioxins and other carcinogenic compounds, particularly at low combustion temperatures [12],[13]. Recycling represents an alternative approach by converting plastic waste into new raw materials; however, it does not entirely eliminate plastic waste, as recycled products ultimately degrade and re-enter the waste stream [14],[15].

The increasing demand for fossil fuels, driven by technological advancements and economic growth, has exacerbated the global energy crisis [16],[17]. This challenge has prompted researchers to investigate alternative renewable energy sources. One promising approach is the conversion of plastic waste into alternative fuels, primarily through the pyrolysis process [16],[18]. Pyrolysis is a thermochemical decomposition method conducted in the absence of oxygen; wherein long-chain polymer molecules are broken down into smaller molecules. This process yields three primary products: liquid oil, gas, and char [11],[19].

Previous studies have demonstrated that pyrolysis is an effective method for mitigating plastic waste while generating high-calorific-value liquid oil comparable to commercial fuels. This process is particularly advantageous as it can handle mixed plastic waste types and additives that are typically challenging to decompose [20], [21]. At moderate temperatures of approximately 500 °C, pyrolysis has been shown to achieve a liquid oil yield of up to 80% [22],[23]. Furthermore, pyrolysis of Polyethylene (PE) plastic waste within a temperature range of 400–450 °C can yield approximately 68% oil [24]. In addition to its efficiency in waste reduction, pyrolysis has been acknowledged for its potential to lower greenhouse gas emissions when compared to conventional incineration methods. This dual benefit of environmental and economic value positions pyrolysis as a sustainable waste management strategy. By facilitating energy recovery from plastic waste, pyrolysis offers a promising alternative to traditional disposal practices, contributing to the advancement of resource efficiency and environmental sustainability [25],[26].

Therefore, this study aims to perform the pyrolysis process on polyethylene (PE) plastic waste using a pyrolysis reactor and condenser to produce pyrolysis oil. The produced oil is subsequently analyzed for its physical properties, including viscosity, density, and calorific value, to evaluate its characteristics and compare them with those of diesel [27]. These parameters are critical in determining whether the pyrolysis oil meets the standards required for fuel applications, particularly regarding energy density and flow properties. Furthermore, droplet combustion tests are conducted to assess combustion properties such as ignition delay, combustion duration, and flame morphology at the droplet scale [28]. These analyses are essential to validate whether the oil's characteristics align with the requirements for practical fuel performance, including efficient ignition and sustained combustion stability. This examining the relevance and validity of these parameters in defining fuel characteristics, this study contributes to understanding the feasibility of utilizing pyrolysis oil as a renewable energy source and its potential as an environmentally friendly and economically viable alternative to conventional fossil fuels.

2. Material and Methods

2.1. Material Preparation

The preparation of feedstock material is a critical step in ensuring consistent and efficient pyrolysis. In this study, polyethylene (PE) plastic waste was sourced from general waste streams, representing typical PE materials commonly found in post-consumer or industrial waste. The study focused on the pyrolysis process rather than distinguishing between specific types of PE, such as HDPE or LDPE [25],[29].

The process began with sorting and selecting PE plastic waste from the collected materials. The selected plastic was thoroughly washed to remove contaminants and then dried under direct sunlight for approximately 15 minutes. Once dried, the plastic was weighed to ensure a consistent feedstock weight of 1 kg, and the relevant data, including weight and preparation details, were recorded.

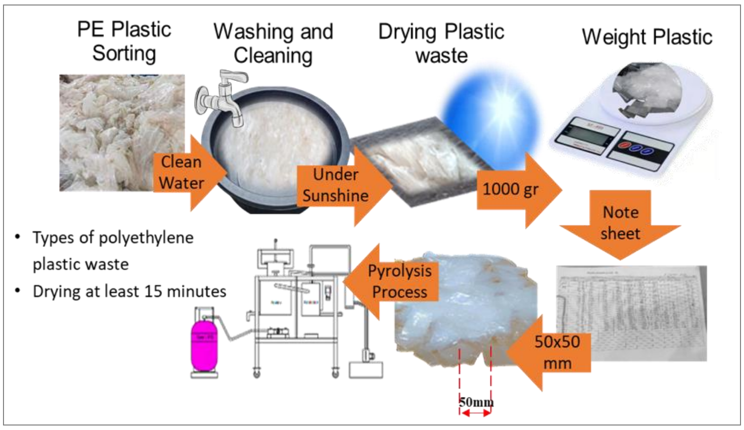

Figure 1. The schematic of material preparation

After weighing, the plastic was cut into smaller pieces measuring approximately 50x50 mm to enhance heat transfer during pyrolysis. The prepared plastic pieces were then loaded into a reactor tube to initiate the pyrolysis process. The schematic of material preparation is illustrated in **Figure 1**.

2.2. Pyrolysis Process and Experiments

The research method employed in this study consists of three primary stages. First, pyrolysis oil is produced from polyethylene plastic waste through a pyrolysis process. This process utilizes a stove with a heating rate set at 250 °C/min, a reactor maintained at 400 °C, and a condenser consistently conditioned to operate at 300 °C through the use of a temperature control system. A total of 1 kg of plastic waste is processed, with the temperature monitored at 10-minute intervals using a thermometer and thermocouple to ensure precise regulation and stability throughout the procedure. Second, the physical characteristics of the pyrolysis oil are analyzed to assess properties such as density, viscosity, and calorific value, enabling a comparison with conventional fossil fuels.

The third stage focuses on testing the combustion characteristics of polyethylene pyrolysis oil (PPO) and diesel fuel at the droplet scale. To ensure data accuracy and reliability, each experiment was repeated 13 times. This approach minimizes experimental variability, accounts for anomalies, and provides statistically significant results, ensuring robust and reliable findings that accurately represent the combustion behavior of the fuels tested. The combustion parameters examined include ignition delay, combustion duration, combustion temperature, and flame morphology. This comprehensive approach provides insights into the potential of pyrolysis oil as an alternative energy source. The sequence of research stages is illustrated in **Figure 2**.

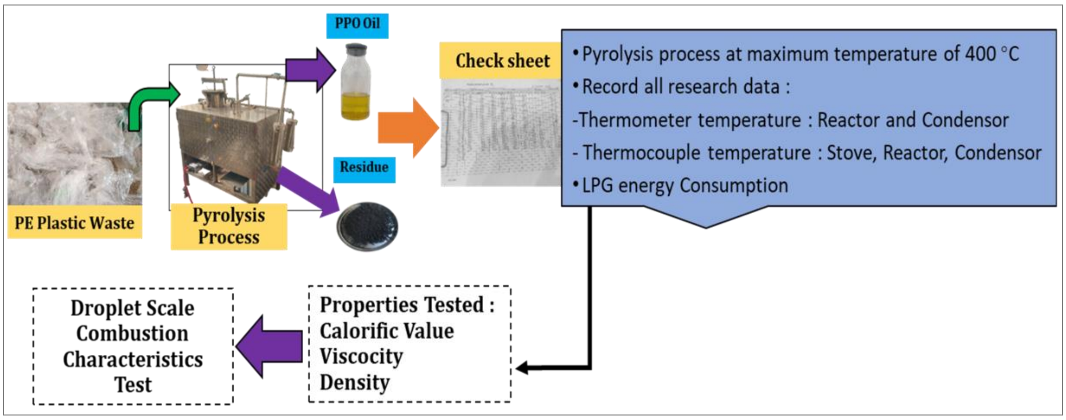

Figure 2. Research stages of PPO

3. Results and Discussion

3.1. Pyrolysis Oil and Diesel Fuel

The pyrolysis process, carried out under controlled heating and temperature conditions, lasted for 2 hours, with temperature and oil volume measurements recorded at 10-minute intervals. The process yielded 671 mL of oil and 45 grams of residue. The pyrolysis oil obtained was visually characterized by a bright yellow color and a distinctive plastic-like odor.

For comparison, the diesel fuel used in this study was obtained from public fuel stations (SPBU). Visually, diesel fuel exhibits a characteristic yellow-brown color. The pyrolysis oil is labeled as PPO (Plastic Pyrolysis Oil), while the diesel fuel is labeled as diesel. The visualization of the pyrolysis oil and diesel fuel products is presented in **Figure 3**. To further evaluate the characteristics

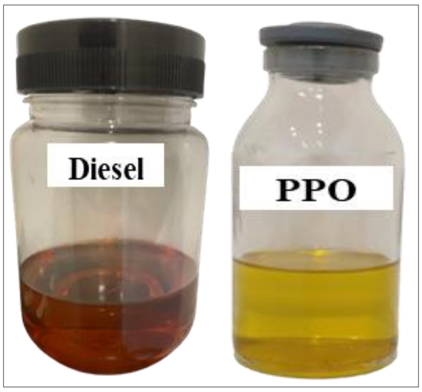

Figure 3. Plastic pyrolysis oil (PPO) and diesel fuel

of pyrolysis oil and diesel, physical properties such as density, viscosity, and calorific value were tested to assess the suitability of these fuels.

3.2. Properties of Plastic Pyrolysis Oil (PPO) and Diesel

The physical and chemical properties of pyrolysis oil and diesel fuel have been analyzed through laboratory testing and are summarized in **Table 1**, highlighting key similarities and differences to assess the potential of pyrolysis oil as an alternative energy source.

Table 1. Test results of PPO and Pertamina diesel fuel properties

Characteristics	Unit	Diesel Fuel Pertamina	Fuel PPO PE	Test Standart
Density	kg/m³	0.8375	0.7779	ASTM D-941
Viscosity at 40 °C	mm²/s	3.8173	5.9300	ASTM D-445
Calorific Value	cal/g	10,395	11,046.4	ASTM D-20

Based on **Table 1**, the results of the density test conducted using the ASTM D-941 standard indicate that the density of pyrolysis oil is 0.7779 kg/m³, which is lower than the density of diesel fuel at 0.8375 kg/m³. This difference is likely due to the operating temperature of the reactor, which affects the thermal decomposition of the plastic material during pyrolysis [30].

The viscosity of pyrolysis oil was measured using the ASTM D-445 standard, with a sample size of 25 ml at a reactor temperature of 400 °C. The measured viscosity of 5.930 mm²/s is higher than that of diesel fuel, which is 3.8173 mm²/s. This elevated viscosity reflects the unique chemical composition of pyrolysis oil [31]. Additionally, the viscosity of pyrolysis oil derived from polyethylene (PE) exceeds the standard range for diesel fuel (2.0–4.5 mm²/s), indicating that further refinement may be necessary to improve its compatibility for broader fuel applications.

The calorific value test, performed according to the ASTM D-240 standard, demonstrates that pyrolysis oil has a calorific value of 11,046.4 cal/g, which is higher than the calorific value of diesel fuel at 10,395 cal/g. This higher calorific value is attributed to the elevated polymer content in the pyrolysis oil [32]. To facilitate identification and classification, pyrolysis oil obtained from polyethylene (PE) plastic is labeled as PPO PE-11.

The reactor temperature of 400 °C was selected based on findings from previous studies, as this temperature has been shown to optimize the balance between oil yield and quality. At this temperature, polyethylene undergoes efficient thermal cracking, producing smaller hydrocarbon chains and resulting in oil with favorable calorific properties. It is recommended that future research incorporate Thermogravimetric Analysis (TGA) to further investigate the thermal behavior of the feedstock and refine process parameters to enhance pyrolysis efficiency and product quality.

3.3. Combustion Characteristic of Plastic Oil at Scala Droplet

Droplet scale combustion tests were conducted on PPO PE-11 pyrolysis oil and diesel, with 13 test repetitions. Several vital parameters were analyzed, including droplet diameter, ignition delay, fire start time, combustion duration, peak temperature, and fire-out time. The average droplet diameter for diesel fuel was 75.573 µm, while for PPO PE-11, it was 75.615 µm. This slight difference can be attributed to the variation in density between the two fuels [33].

The fire start time of PPO PE-11 oil is faster, taking 0.6 seconds, compared to diesel, which takes 1 second. This acceleration is influenced by the lower density of PPO PE-11 oil, making it more flammable [33]. Additionally, the burning duration of PPO PE-11 oil is longer, recorded at 2.8 seconds, compared to diesel, which burns for only 2.6 seconds. This difference is attributed to the higher viscosity of PPO PE-11 oil.

The peak temperature of PPO PE-11 oil reached 455.90 °C, which is higher than that of diesel, which reached only 440.71 °C. This temperature difference correlates with the higher calorific value of PPO PE-11. The fire-out time for PPO PE-11 oil was recorded at 3.8 seconds, with a temperature of 438.68 °C, while diesel took 4 seconds at a temperature of 424.69 °C. This difference is attributed to the calorific value and viscosity, which influence the combustion characteristics of both fuels [34]. The flame visualization is shown in **Figure 4** and **Figure 5**, while the droplet-scale combustion for both fuels is depicted in **Figure 6**.

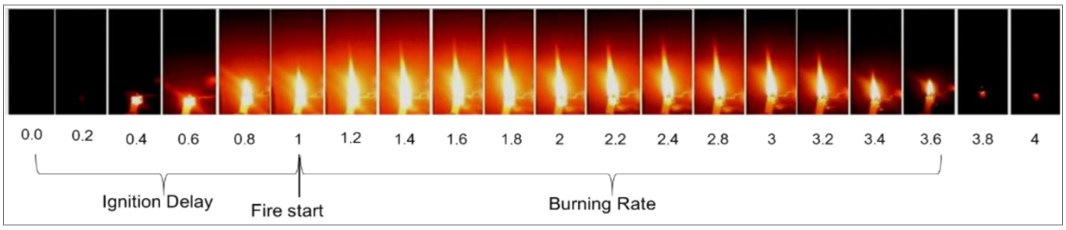

Figure 4. Visualization of diesel fuel flame

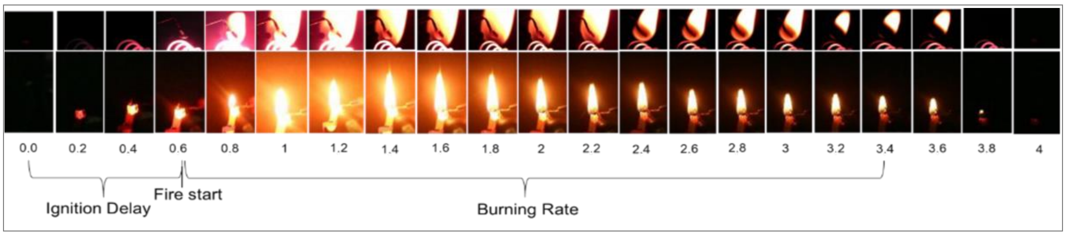

Figure 5. Visualization of PPO PE-11 fuel flame

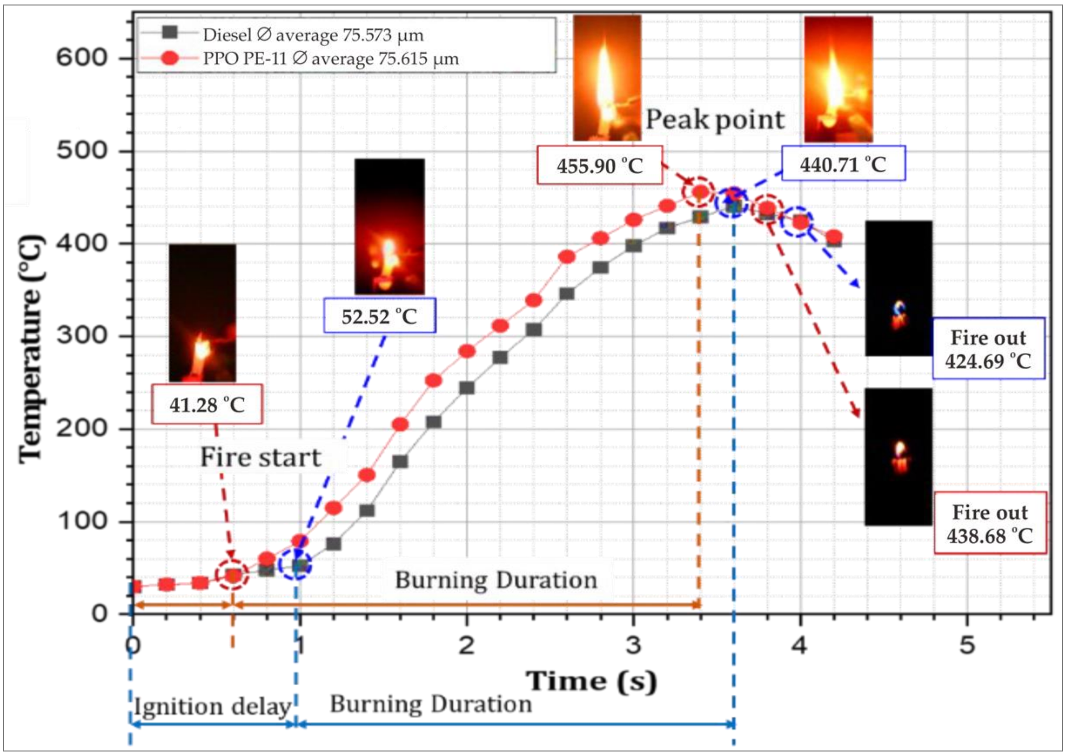

Figure 6. Droplet scale combustion of diesel fuel and PPO PE-11

4. Conclusion

The pyrolysis process has been successfully carried out to convert polyethylene (PE) plastic waste into PPO plastic oil. Based on observations of the pyrolysis process and the results of physical and combustion properties tests, it can be summarized that:

a. The pyrolysis process of 1 kg of PE plastic waste with a reactor heating rate of 400 °C/minute and a condenser temperature of 300 °C/minute for 2 hours produced 671 mL of PE-11 PPO oil and 45 grams of residue.

b. The characteristics of PPO PE-11 oil are very close to diesel fuel, especially in terms of density, viscosity, and calorific value. PPO PE-11 oil shows a higher calorific value than diesel, indicating its potential as an alternative fuel source.

c. In the droplet combustion test, PPO PE-11 oil shows prominent advantages, including a shorter ignition delay of 0.6 seconds compared to 0.7 seconds for diesel. In addition, the combustion duration of PPO PE-11 oil reaches 2.8 seconds, which is longer than the combustion time of diesel which is only 2.6 seconds. The maximum combustion temperature of PPO PE-11 oil reaches 455.90 °C, exceeding the 440.71 °C recorded for diesel.

d. This study examines pyrolysis oil derived from polyethylene plastic waste (PPO PE-11) as an environmentally friendly and energy-efficient alternative fuel. The findings highlight the practical potential of PPO PE-11 oil not only in reducing dependence on fossil fuels but also in addressing the global plastic waste challenges.

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Authors' Declaration

Authors' contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

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Availability of data and materials - All data is available from the authors.

Competing interests - The authors declare no competing interests.

Additional information – No additional information from the authors.

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