European Journal of Sustainable Development Research
2025, 9(1), em0278
e-ISSN: 2542-4742
https://www.ejosdr.com/

MODESTUM

Research Article

OPEN ACCESS

Comparative analysis of thermal and catalytic pyrolysis methods for converting waste plastic into fuel oil

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Citation: Ezeokolie, E. D., Maduoma, T. U., Nweke, B., Ekugbe, U. O., Ezekoka, O. A., Esonwune, J. N., Chukwuma, A. E., Onuoha, E. C., Success, O. D., & Chukwu, J. O. (2025). Comparative analysis of thermal and catalytic pyrolysis methods for converting waste plastic into fuel oil. *European Journal of Sustainable Development Research, 9*(1), em0278. https://doi.org/10.29333/ejosdr/15133

ARTICLE INFO

Received: 13 Sep. 2023
Accepted: 23 Jul. 2024

ABSTRACT

This study investigated the idea of using pyrolysis to convert plastic waste into an alternative fuel oil. The thermal and catalytic conversion of polypropylene waste plastic to fuel oil was investigated. The catalyst used was aluminum chloride on activated carbon. The experiment was conducted in two different phases. The first phase was done without a catalyst, and 83.10 cm^3 of oil was produced at a maximum temperature of 300 °C and a reaction time of 3 hours. The oil yield was 41.55%. The second phase was done using aluminum chloride on an activated carbon catalyst, and 108.46 cm^3 of oil was obtained at a maximum temperature of 300 °C and a reaction time of 2 hours. The oil yield was 54.23%. The amount of char product was also determined to be 0.3 g for the experiment done without a catalyst and 0.2 g for the experiment done with a catalyst. From the results, catalytic pyrolysis is more efficient than purely thermal pyrolysis. The fuel properties of the fuel oil were also investigated, and a comparison was made with the properties of diesel oil. The fuel oil showed similar characteristics to diesel oil. The study concluded that applying catalytic pyrolysis at a given temperature produced more oil products and that the degradation of plastics began at a lower temperature than with thermal pyrolysis alone. In light of this, the study suggested that pyrolysis be used as an alternative to combustion and incineration since it is known to create fewer hazardous byproducts and may also be used to recover fuel and other valuable raw materials.

Keywords: pyrolysis, plastic waste, fuel oil, thermal conversion, catalytic conversion, polypropylene

INTRODUCTION

The synthesis of fuel oil from waste plastic through pyrolysis is an innovative approach to address the pressing global challenges of plastic pollution and the increasing demand for fossil fuels. Plastic waste is a pervasive environmental issue, with detrimental effects on ecosystems, wildlife, and human health (Kumar et al., 2021; Oasmaa et al., 2020; Wang et al., 2021). On top of that, the production of plastics is inherently energy-intensive and contributes to greenhouse gas emissions and resource depletion (Nicholson et al., 2021). The world is very dependent on traditional fossil fuels. This reality contributes significantly to greenhouse gas emissions and exacerbates climate change (IEA, 2020). This experimental research aims to propose a solution that could help mitigate plastic waste and produce usable alternate fuel oil. The aim of the study is to understand and optimize the processes of plastic pyrolysis for maximizing oil products. The study will pursue the following objectives to achieve this aim: Use pyrolysis to obtain the crude oil component from the waste plastics. Collect data for density, viscosity, flash point, ash content, cloud point, pour point, color residence time, temperature, and amount of oil collected; analyze the product to determine the properties and individual components of the crude oil fraction; and conduct material balance to determine the yield of crude oil formed.

The synthesis of fuel oil from waste plastic through pyrolysis represents a transformative approach to both plastic waste management and energy production (Fahim et al., 2021; Sharma et al., 2022; Tulashie et al., 2019). Pyrolysis is a chemical decomposition process that involves the thermal degradation of organic materials in the absence of oxygen. This can lead to the formation of valuable products, such as crude oil. Pyrolysis of plastics yields a range of hydrocarbon products, including liquid fuels, which can be used to supplement or replace traditional fossil fuels (Oasmaa et al., 2020; Tulashie et al., 2019; Wang et al., 2021). There are two subtypes of pyrolysis: thermal and catalytic. The thermal process of pyrolysis is further subdivided into three according to the type of heat energy needed to break down plastic bonds: high-temperature, medium-temperature, and low-temperature. Low, medium, and high temperatures are defined as the range of temperatures utilized to degrade the polymeric structure, starting at 200 °C, 360 °C to 800 °C, and more than 800 °C for the categories, respectively (Qi et al., 2020). During catalytic means of chemical treatment or heat effects, crude oil derivative plastics are turned into monomers and other useful components, such as additives and plasters. These are categorized as the first derivatives of petroleum refining cuts and petrochemicals (Evode et al., 2021). The process of pyrolysis has gained increasing attention as a viable means of plastic recycling due to its potential to convert non-recyclable plastics into useful energy products. Pyrolysis capitalizes on the carbon-rich composition of plastics to convert them into a more manageable form while harnessing their energy content. Pyrolysis provides an alternative source of energy. While doing so, it could also be used to reduce the environmental burden associated with plastic waste disposal. This characteristic aligns with global climate goals and can help mitigate carbon emissions when substituted for conventional fossil fuels in the transport sector (Gebre et al., 2021; Tulashie et al., 2019).

Numerous studies have been done to address the problems with managing plastic waste and producing sustainable energy (Evode et al., 2021; Pandey et al., 2023; Vuppaladadiyam et al., 2024). The potential of pyrolysis as a promising technique for transforming plastic waste into raw materials has been the subject of numerous investigations (Huang et al., 2022; Kibria et al., 2023). Budsaereechai et al. (2019) conducted experiments on the pyrolysis of various plastic types and reported promising results in terms of fuel production (Budsaereechai et al., 2019). The use of catalytic pyrolysis to improve the production and quality of liquid fuels from plastic waste was also studied by Hussein et al. (2022). These studies demonstrate the potential of pyrolysis as a viable solution for managing waste.

However, this study advances the state of the art by providing a comprehensive comparative analysis of thermal and catalytic pyrolysis methods specifically for converting waste plastic into fuel oil. Unlike previous studies, which have often focused on either thermal or catalytic pyrolysis in isolation, this research simultaneously evaluates both methods under a unified framework, providing new insights into their relative efficiencies and product qualities. Furthermore, this study not only aims to optimize the pyrolysis process for higher oil yield but also conducts an in-depth analysis of the chemical composition of the resulting crude oil, which is critical for assessing its viability as an alternative fuel. The integration of material balance studies to evaluate process efficiency is another innovative aspect, addressing a significant gap in the current literature (Miao et al., 2021; Yang et al., 2022). While pyrolysis has been widely explored, there is a need for a comprehensive investigation into the specific components of crude oil obtained from waste plastics using this method. Understanding the composition of the resulting crude oil is key for evaluating its potential as a viable fuel source and for optimizing the pyrolysis process to yield a desirable product (Yang et al., 2022). Secondly, material balance studies are essential to assess the efficiency of the pyrolysis process in converting plastic waste into crude oil. These studies are often lacking in the current literature, hindering a complete understanding of the process's sustainability and economic viability (Miao et al., 2021). Addressing these issues will help create a more thorough evaluation of the pyrolysis method's sustainability and influence on the environment (Osung & Alabi, 2022).

METHODOLOGY

A small-scale semi-batch reactor design was used for the experiment. The steel cylindrical reactor with a volume of 7.25 liters was constructed using an LPG gas cylinder with an opening for feeding raw materials. The reactor was connected to a condenser using a hose pipe, the condenser was further connected to the collector material and then to the tube for collecting non-condensable gas. The waste plastic used for this experiment was shredded waste polypropylene plastic which was collected from the school polymer and textile laboratory. Furthermore, the plastics were washed, dried, and then kept for further processing. Without a catalyst, 200 g of dried, shredded waste polypropylene was charged into the reactor. After that, a gasket seal was used to seal the reactor aperture to prevent leaks. After that, the reactor was set on an LPG gas burner. Then, to allow the polymers to change gradually, a digital thermometer was mounted on the reactor, and temperature increments of 5 to 10 degrees Celsius were set. In the absence of oxygen, the reactor was heated. The water-cooled condenser was used to cool the gaseous end products. Eq. (1), for calculating the yield of pyrolysis fuel oil, was used to calculate the yield of the liquid products and the condensed products were measured.

$$Yield = \frac{Volume\ of\ fuel\ oil}{Weight\ of\ plastic\ waste} \times 100. \quad (1)$$

Catalytic Pyrolysis

Experiments using similar conditions above but with aluminum chloride on activated carbon catalyst were carried out and the yield was calculated.

Fuel Oil Product Characterization

The yield of fuel oil products was calculated using the volume of the collected liquid in relation to the initial volume of the pyrolytic plastic waste feed. The density, viscosity, flashpoint, cloud point, pour point, moisture content, and calorific value of the fuel oil were among its physical characteristics that were assessed. According to ASTM D1298 procedures, the fuel oil density was determined gravimetrically at 30 °C using volumetric glassware and a hydrometer (Yuliansyah et al., 2015). The crude oil was weighed using a digital mass balance after being placed in a 25 mL pycnometer. The fuel oil density was calculated using the Eq. (2).

$$\rho_L = \frac{(m_{BL} - m_B)}{V_L}, \quad (2)$$

Table 1. Table of oil yield

Material	Mass (g)	Time taken (hours)	Temperature (°C)	Produced oil (cm^3)	Oil yield (wt %)
Polypropylene without catalyst	200	3	300	83.10	41.55
Polypropylene with catalyst	200	2	300	108.46	54.23

where ρ_L is density of the liquid (g/cm^3), m_{BL} is mass of bottle and liquid (g), m_B is mass of bottle only, and V_L is volume of the liquid (cm^3). According to ASTM D445, the viscosity of the fuel oil was determined using a Cannon-Fenske type 200 viscometer. The Eq. (3) was used to determine the viscosity of fuel oil.

$$v = t.c_o(T), \tag{3}$$

where v is kinematic viscosity (centistokes, cSt [mm^2 /s]), t is flow time (seconds), and $c_o(T)$ is viscometer constant. Based on kinematic viscosity, v, Eq. (4) was used to calculate the calorific value of fuel oil as higher heating value (HHV) in MJ/kg.

$$HHV = +38.053. \tag{4}$$

Using the Fourier transform infrared spectroscopy (FT-IR) spectrum, the aromatic hydrocarbon group components in this plastic waste pyrolysis oil were examined. The process involved directing infrared light through the fuel sample, which interacted with the molecules present. Each chemical group within the sample absorbs specific frequencies of infrared light, resulting in a unique spectrum. The examination of aromatic hydrocarbon group components in the plastic waste pyrolysis oil involved scrutinizing the FT-IR spectrum for characteristic peaks associated with aromatic hydrocarbons. Aromatic hydrocarbons are compounds containing a ring-like arrangement of carbon atoms, and their presence can be identified by the distinctive peaks in the spectrum. These peaks are indicative of the specific chemical bonds and structural features associated with aromatic compounds.

To calculate the flash point, the fuel oil sample was placed in a container, and a flame was applied to the surface of the sample at regular intervals while the temperature was gradually increased. Then the lowest temperature at which a liquid produces a flammable vapor that can be ignited was recorded as the flash point. To determine moisture content, the fuel sample was typically heated to evaporate and remove any water present. The weight of the fuel sample before and after heating was used to calculate weight change. The cloud point was determined using the Pour and Cloud Point Tester PE-7200I. The fuel oil was cooled gradually, and observations were made for the point at which the liquid became cloudy. Using the same instrument, the fuel oil sample was cooled, and the temperature at which the fuel ceased to flow was recorded.

RESULTS AND DISCUSSION

During the experiment, we investigated how liquid fuel oil can be produced or synthesized from polypropylene plastic, with and without the use of a catalyst, at temperatures between 170 and 300 °C. The degradation of the plastic was observed to start at 119 °C, while the first vapor production took between 25-30 minutes in each experiment. It was further observed that, to provide the best yield margin, the maximum production temperature was increased to 300 °C. For the thermal pyrolysis, the process took about 3 hours; for the catalytic pyrolysis, it took about 2 hours to complete. The experiment ended after each sample was finished and was left to cool, after which characterization was done. The mass of oil with and without catalyst was determined to be 96.53 g and 70.22 g, while the mass of char with and without catalyst was determined to be 0.24 g and 0.33 g, respectively.

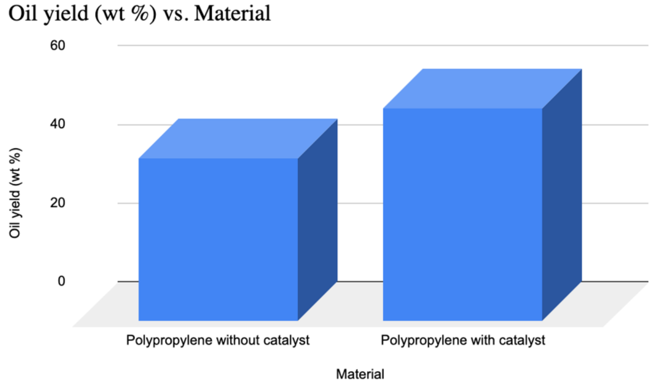

Figure 1. Graph of yield (%) of the fuel oil (Source: Authors' own elaboration)

The Yield of the Fuel Oil

Fuel oil was extracted from polypropylene alone, independently, and when a catalyst was added. The yield of the oil is collated and recorded in **Table 1**. **Figure 1** also represents the graphical view of the yield of the oil produced. The yield of the oil from polypropylene with a catalyst was 54.23%, while that without a catalyst was 41.55%, resulting in a difference of 12.68%. This shows that polypropylene waste plastic is a good feedstock for the production of fuel oil.

Comparing the yield of oil with and without a catalyst, it is evident that the introduction of a catalyst, aluminum chloride on activated carbon, increases the yield significantly. This result aligns with the research aim of investigating the impact of catalysts on the pyrolysis process. The catalyst promotes the degradation of polypropylene at a lower temperature (119 °C) and results in a higher yield of oil, indicating its effectiveness in enhancing the conversion process.

Effect of Catalyst on Reaction Temperature and Yield

The catalyst used for the reaction was homogenous (aluminum chloride on activated carbon). **Table 1** shows the temperature and yield attained after cracking the polypropylene plastic with and without a catalyst. It was found that the decomposition of plastic for simple thermal pyrolysis began at 132 °C and produced 83.10 cm^3 of oil. In contrast, the oil drop for catalytic pyrolysis began at a lower temperature of 119 °C and produced 108.40 cm^3 of oil. These data show that the degradation temperature for thermal pyrolysis is higher than for catalytic degradation. This is due to the catalyst's

Table 2. Fuel properties of oil

Properties	Polypropylene with catalyst	Polypropylene without catalyst
Density $\left(\frac{g}{cm^3}\right)$	0.890	0.845
Kinematic viscosity $\left(\frac{mm^2}{sec}\right)$	1.86	1.93
Flashpoint (°C)	24	20
Cloud point (°C)	-4.85	-4.94
Pour point (°C)	-23.0	-22.5
Moisture content (%)	0.31	0.28
Calorific value (kJ/kg)	49,163	49,163

Table 3. Fuel properties of crude oil (Speight, 2007, 2017)

Properties	Light	Medium	Heavy
Density $\left(\frac{g}{cm^3}\right)$	0.75-0.85	0.85-0.90	0.90-1.05
Kinematic viscosity $\left(\frac{mm^2}{sec}\right)$	1-5	5-20	20-500
Flashpoint (°C)	<38	38-65	>65
Cloud point (°C)	<-5	-5 to -10	>10
Pour point (°C)	<-10	-10 to 15	>15
Moisture content (%)	<0.1	0.1-0.5	>0.5
Calorific value (kJ/kg)	43,000-46,000	42,000-45,000	41,000-44,000

provision of alternate routes with lower activation energies. Additionally, it is evident from **Figure 1** that catalytic conversion results in a higher oil yield than pure thermal conversion. As a result, it can be said that catalytic degradation is an effective technique for pyrolyzing plastic waste into fuel.

Fuel Properties From Plastic

Density, kinematic viscosity, flash point, cloud point, pour point, ash content, calorific value, and moisture content were all test criteria used for the polypropylene oil. **Table 2** contains the values that were obtained. From **Table 2**, it was observed that the density of the fuel oil produced from polypropylene with a catalyst (0.89 g/cm^3) is higher than the one produced without a catalyst (0.845 g/cm^3). The kinematic viscosity of the fuel oil produced from polypropylene with a catalyst (1.86 mm^2/sec) is less than the one produced without a catalyst (1.89 mm^2/sec). Likewise, the flash point temperature of 24 ^{o}C for the fuel oil produced from polypropylene with a catalyst is greater than the one produced without a catalyst (20 ^{o}C). This implies that fuel oil produced in this work can easily catch fire when in contact with an ignition source.

The cloud point of -4.85 ^{o}C obtained in this work for the fuel oil produced from polypropylene with a catalyst is less than that of the fuel oil produced from polyethylene without a catalyst. Also, the pour point of -23 ^{o}C obtained in this work for the fuel oil produced from polyethylene with a catalyst is less than that of the fuel oil produced from polyethylene without a catalyst. The moisture content of 0.31% of fuel oil produced from polypropylene with a catalyst is greater than that of fuel oil produced from polyethylene without a catalyst. Finally, the calorific value of the oil from polypropylene with a catalyst is the same as that produced without a catalyst.

Comparison and Analysis of Fuel Oil Properties of Plastic and Crude Oil

Table 3 shows the fuel properties of crude oil according to Speight (2007, 2017). Comparing the data on fuel properties obtained from crude oil (**Table 1**) with the data on fuel oil produced from plastic (**Table 2**) provides insights into the potential of pyrolysis as a method for producing fuel oil and its characteristics with respect to traditional crude oil-based fuel.

The density of the fuel oil produced from polypropylene with a catalyst (0.89 g/cm^3) is higher than that without a catalyst (0.845 g/cm^3). This is consistent with the characteristics of crude oil-based fuels, which have varying densities depending on their grade (light, medium, or heavy). The higher density suggests that the catalytic process might result in a fuel oil closer to medium or heavy crude oil in terms of density. The kinematic viscosity of the fuel oil from polypropylene with a catalyst (1.86 mm^2/sec) which is slightly lower than that without a catalyst (1.93 mm^2/sec) falls within the range of the kinematic viscosity of light crude oil (1-5 mm^2/sec). The flash point of the fuel oil from polypropylene with a catalyst (24 °C) is higher than that without a catalyst (20 °C) but lower than that of crude oil (typically below 38 °C for light crude). Both the cloud points (-4.85 °C, -4.94 °C) and pour points (-23 °C, -22.5 °C) for the fuel oil from polypropylene with a catalyst and without a catalyst, respectively are higher than those of the fuel oil from crude oil. The moisture content of the plastic-derived fuel is relatively low (0.31%, 0.28%), and finally, the calorific value of the plastic-derived fuel (49,163 kJ/kg) is within the range of light crude oil (43,000-46,000 kJ/kg).

The analysis of fuel properties indicates that the fuel oil derived from plastic through pyrolysis with a catalyst exhibits properties consistent with light crude oil. The slightly higher density of plastic-derived fuel oil may be advantageous in certain applications. The lower viscosity makes it flow more easily and improves its usability in specific contexts. The higher flash point of plastic-derived fuel oil suggests it is less prone to ignition, which can be a safety benefit, especially during handling and storage. There is potential for better cold-weather performance due to the high pour point value. The result aligns to address plastic pollution and reduce the carbon footprint by converting plastic waste into a valuable resource. The properties of plastic-derived fuel oil, such as its low moisture content and comparable calorific value, make it a promising alternative to traditional fossil fuels.

CONCLUSION

This study looked into the practicality of recycling plastics in municipal plastic waste using the pyrolysis of plastic waste. Plastic wastes are easily transformed into hydrocarbon fuels using materials that are easily accessible nearby. There are hundreds of reactions and byproducts produced during the pyrolysis of hydrocarbon polymers, which is a very complicated process. The reactions and the products are significantly influenced by a number of factors. The project's investigations revealed that using catalytic pyrolysis at a particular temperature produced more oil products and that the degradation of plastics started at a lower temperature than when using thermal pyrolysis alone. Therefore, catalytic pyrolysis is a preferred method for turning plastic waste into fuel. Although liquid fuel from plastic pyrolysis may not be acceptable for the majority of engineering applications due to its high sulfur content, the study of fuel oil product revealed that the fuel oil has qualities similar to diesel oil. This can be avoided, though, by further processing and blending with fuel of a higher grade. Based on research objectives and findings presented in this study, several recommendations emerge that can guide future research and practical applications in the field of plastic waste pyrolysis and fuel oil synthesis.

The use of catalysts in plastic pyrolysis has shown promise in enhancing oil yield and lowering reaction temperatures. Further research is needed to optimize catalyst selection and design to improve both the efficiency and economic viability of the process. Investigating a broader range of catalyst materials and their effects on product yield, quality, and reaction kinetics can lead to more efficient plastic-to-fuel conversion methods. While some studies have touched upon the environmental benefits of plastic pyrolysis, there is a need for more extensive and in-depth assessments of its potential to reduce CO_2 emissions and minimize the volume of solid plastic waste in landfills. Future research should involve life cycle assessments to evaluate the overall environmental footprint of plastic waste-to-fuel processes, considering factors such as energy consumption, emissions, and resource use. Additionally, studies should explore the long-term environmental impacts and scalability of plastic waste pyrolysis on a larger, industrial scale.

The practical applications of the synthesized fuel oil should be explored in more detail. Researchers should investigate the feasibility of blending plastic-derived fuel oil with commercial-grade fuels to meet regulatory standards and improve its suitability for various applications, including transportation and heating. Compatibility testing and engine performance evaluations can help determine the potential for utilizing this fuel in existing systems.

Author contributions: EDE: conceptualization, resources, writing – original draft; **TUM:** conceptualization, data curation, formal analysis, visualization, writing – original draft, writing – review & editing; **BN:** formal analysis, project administration, resources, supervision; **UOE:** project administration, validation; **OAE:** formal analysis, methodology; **JNE:** data curation; **AEC:** data curation; **ECO:** investigation, methodology; **ODS:** investigation, writing – original draft; **JOC:** investigation, methodology. All co-authors have involved in all stages of this study while preparing the final version. They all agree with the results and conclusions.

Funding: No funding source is reported for this study.

Acknowledgements: The authors would like to thank the lab technicians at the chemical engineering laboratory at the Federal University of Technology, Owerri, for their assistance in the experiments.

Ethical statement: The authors stated that the study did not require approval from an ethics committee since it did not involve human participants nor the sacrifice of animals, and the data used were author-generated or collected from secondary sources in the public domain that do not collect or store identifiable data. The highest ethical principles of scientific publications were followed during the study.

Declaration of interest: No conflict of interest is declared by the authors.

Data sharing statement: Data supporting the findings and conclusions are available upon request from corresponding author.

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