

Effective pyrolysis of LDPE plastic waste to fuel using titanium dioxide catalyst



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ABSTRACT

The widespread use of plastics has led to increased consumption of fossil fuels and worsened pollution, especially in oceans. Common waste management methods like landfills and incinerators often focus more on convenience than on environmental and economic sustainability. For example, incineration releases harmful gases such as carbon monoxide (CO), carbon dioxide (CO₂), ammonia (NH₃), nitrous oxide (N₂O), and nitrogen oxides (NO_x), significantly contributing to greenhouse gas emissions. Burning one ton of waste can produce at least 700 kg of CO₂. This study explores the use of Titanium Dioxide (TiO₂), derived from minerals like ilmenite, rutile, and anatase, to enhance the pyrolysis process of Low-Density Polyethylene (LDPE) plastic waste. TiO₂ helps stabilize heterogeneous catalysts and can improve the efficiency of plastic degradation, reduce the necessary temperatures, and shift the output from more liquid to more gas, with properties similar to commercial gasoline. The research tested different temperatures (300 °C, 350 °C, 400 °C, 450 °C) and catalyst amounts (12.5 g, 25 g, 37.5 g) to transform LDPE waste into liquid fuel. The best results were achieved at 350 °C with 37.5 g of catalyst, producing a fuel with a density of 0.7660 g/ml, viscosity of 1.04 mm²/s, calorific value of 36.1698 MJ/kg, and a flash point of 34 °C. Gas Chromatography-Mass Spectrometry (GC-MS) analysis showed that the fuel consisted of 49.41% gasoline, 10.56% kerosene-diesel, and 40.03% fatty acids. The findings indicate that using TiO₂ as a catalyst in pyrolysis not only serves as a practical alternative to traditional waste management methods but also supports a more sustainable and economically beneficial approach to recycling plastic waste into usable fuel similar to gasoline. This method could significantly reduce the environmental impact of plastic waste and support economic development through innovative recycling technologies.

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1. Introduction

Plastics play a significant role in modern life because of their varied mechanical and chemical properties. The growing economy and increasing population contribute to the rising demand for plastic products and the chemicals used to produce them (King and Locock, 2022). To accommodate this demand, the amount of plastic produced is increasing. In 2021, the global annual plastic production of plastics reached 390.7 million metric tons, an increase of 97 million tons compared to

2010 (Tiseo, 2022). If the current trend continues, our annual production rate could exceed one billion tons by 2050 (MacArthur, 2017). The widespread use of plastics not only increases fossil fuel consumption but also causes one of the biggest challenges related to plastics is its leakage into the environment and pollution of the marine environment (King and Locock, 2022). Plastic waste can be categorized into two main types: (1) pre-consumer or industrial plastic waste and (2) post-consumer or municipal plastic waste. Municipal plastic waste primarily consists of polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS), polyethylene terephthalate (PET), low-density polyethylene (LDPE), and high-density polyethylene (HDPE) (Maqsood et al., 2021). Depending on specific needs, different types of plastics are used across various sectors. Disposable plastics, which are typically made from LDPE, have an average service life of six months. LDPE is commonly used to

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produce packaging materials for items like food, water, milk, and other goods, which are often discarded after a single use (Muthukumar and Kasiraman, 2024). These short-lived plastics generate significant waste due to their low durability, limited usage, and low recycling value. However, they can be repurposed as fuel. Proper management of plastic waste is essential to protect the environment and preserve finite hydrocarbon resources (Xayachak et al., 2022).

Current approaches to plastic waste management are based more on convenience than sustainability and economic circulation. This is exemplified by the popularity of landfills and incinerators (Xayachak et al., 2022). However, incineration can pollute the environment by emitting harmful and deadly gases. Combustion causes chemicals that reflect the main criteria of GHGs and are relevant to climate. Incineration is associated with the release of CO, CO₂, ammonia (NH₃), nitrous oxide (N₂O), and nitrogen oxide (NOX). Dioxins and chemical additives are also released from this process. The burning of one ton of waste causes the release of (at least) 700 kg of CO₂ (Maqsood et al., 2021). Pyrolysis can be used to obtain fuel and reduce the volume of plastic fuel to the minimum possible black volume.

The use of pyrolysis oil increases the destruction of plastic waste, reduces pollution, and reduces environmental pollution caused by plastic waste (Muthukumar and Kasiraman, 2024). In the research of LDPE waste pyrolysis process, using magnesium bentonite catalyst at 340 °C temperature is maintained, with an average processing time of 200 minutes, 1% catalyst produces 77.97% cSt, and calorific value of 43.24 kJ/kg, no cetane 51.4, viscosity 2.86 cSt, physiochemical properties very similar to commercial diesel (Thangavel et al., 2023). The pyrolysis of plastics is mostly carried out with solid acid catalysts: zeolites (Hy, HZSM-5, HMordenite) and mesoporous MCM-41 (Jaroszewska et al., 2019; Chen et al., 2013; Zheng et al., 2018), Composite-MCM41/ZSM-5 (Ochoa et al., 2020; Yu et al., 2020), earthen pillared materials see, silica aluminate, oxides (CaO, ZnO, ZrO₂) and activated carbon (Yu et al., 2020). A class of catalysts that increase their catalytic activity due to their remarkable properties such as a) easy synthesis, b) simple structure, and c) abundant availability are transition metals, e.g., ZrO₂, NiO₂, and TiO₂ (García et al., 2005). Titanium dioxide consists of natural minerals such as ilmenite, rutile, and anatase (Yu et al., 2020). Titanium dioxide is commonly used to stabilize heterogeneous catalysts (Brindhadevi et al., 2022).

Titanium dioxide (TiO₂) catalytic pyrolysis enhances the degradation efficiency of plastics, reduces the pyrolysis temperature, and tends to yield less liquid and more gas. The resulting products have physiochemical properties comparable to commercial gasoline. Studies on catalyst activity showed that TiO₂/AISBA-15 (10%) was less active than AISBA-15 (27%) but more effective than SiSBA-15 and TiO₂ alone. Using the

TiO₂/AISBA-15 catalyst significantly increased the gasoline fraction from 45.6% to 85.4%, with a liquid fuel yield of 89.1% and a conversion rate of 98.4%. The liquid fuel produced with this catalyst exhibited a heating value of 47.8 MJ/kg, surpassing that of commercial fuel oil (Brindhadevi et al., 2022).

In another study, five types of plastics (HDPE, LDPE, PP, PS, and PET) were mixed and pyrolyzed in a fixed-bed reactor at temperatures up to 400°C for 90 minutes (Eldahshory et al., 2023). Specifically, the pyrolysis of LDPE plastic waste using a TiO₂ catalyst at 350 °C yielded optimal results. This process demonstrated high economic potential due to the significant product volume and relatively low temperature required for pyrolysis.

2. Methods

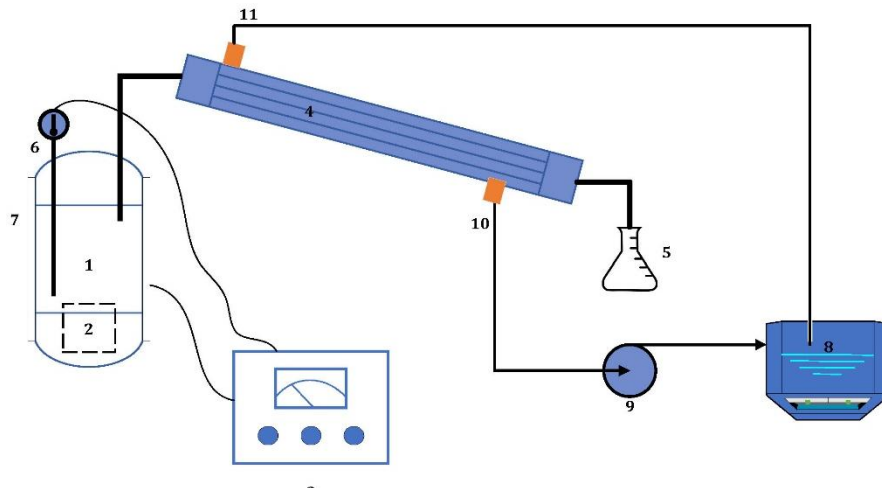
This research employs a descriptive, experimental approach to explore the potential of converting LDPE plastic waste into liquid fuel. The study focuses on the influence of varying titanium dioxide catalyst mass and reactor temperature on the process.

The materials used include titanium dioxide, LDPE plastic, a pyrolysis reactor, a bomb calorimeter, a flash point tester, a viscometer, a pycnometer, an analytical balance, a spatula, a stirring rod, a watch glass, a beaker, a thermocouple, and a glass funnel.

The LDPE waste, sourced from a 12 kg shredding bin, was processed into granules through grinding before use. Catalytic cracking was conducted in a pyrolysis reactor under varying temperatures of 300 °C, 350 °C, 400 °C, and 450 °C, with reactor pressure set at 70 psia for 60 minutes. Catalyst amounts of 12.5 g, 25 g, and 37.5 g were used to study their effects.

Product analysis involved qualitative and quantitative evaluations. The qualitative analysis examined the physical properties of the liquid fuel, such as density, kinematic viscosity, flash point, and calorific value, and compared these to the properties of conventional petroleum-derived fuels. Quantitative analysis determined the product yield as a percentage of the raw material used. Additionally, the chemical composition of the products was analyzed using gas chromatography-mass spectrometry (GC-MS).

The experimental procedure began with a size reduction of the LDPE using a crusher to produce fine granules, making the material ready for use. In the catalytic cracking process, 1000 gr of LDPE plastic was loaded into the reactor along with 12.5 gr of TiO₂ catalyst. The reactor was sealed, and the temperature was set to 300 °C. After the process, the reaction time and product volume were recorded. Once cooled, the reactor was cleaned of residues such as wax and carbon ash. The experiment was repeated at higher temperatures of 350 °C, 400 °C, and 450 °C, with catalyst amounts of 25 g and 37.5 g. The setup of the pyrolysis apparatus used in the experiments is illustrated in Fig. 1.



1: Pyrolysis reactor; 2: Sample container; 3: Miniature circuit breaker control panel; 4: Condenser tube; 5: Erlenmeyer product container; 6: Thermocouple; 7: Jacket electric heater; 8: Cooling water; 9: Cooling water pump; 10: Cooling water flow into the condenser; 11: Cooling water flow out of the condenser

Fig. 1: Pyrolysis apparatus set

3. Result and discussion

The decomposition of plastics begins at high temperatures, typically ranging from 300 to 900 °C (Jiang et al., 2022). The pyrolysis process produces three main end products: carbonized charcoal, non-condensable gas containing short-chain hydrocarbons with a high heating value, and condensable gas or vapor, which forms the liquid fraction. This liquid fraction may include heavy oil (diesel), light oil (gasoline), crude oil (naphtha), and wax (Sharuddin et al., 2016).

LDPE plastic, commonly used in food packaging, is highly suitable for pyrolysis within mechanical and chemical recycling technologies. The characteristics of the solid raw materials and the resulting gas and liquid products influence the pyrolysis temperature. High temperatures primarily enhance gas production, while low to medium temperatures favor the production of viscous liquids and wax (Buekens, 2006).

In this study, liquid fuel was produced from LDPE plastic waste through catalytic cracking. The research focused on evaluating the impact of catalysts on product density, viscosity, flash point, yield percentage, and overall quality. The product

with the highest yield underwent GC-MS analysis to identify its chemical composition (Fig. 2).

3.1. Relationship between the effect of temperature and catalyst mass on percent yield

The effect of temperature and mass of titanium dioxide catalyst is very influential on increasing pyrolysis yield. The effect of the temperature of each titanium dioxide catalyst has a curve comparison where the more mass of catalyst used, the % yield produced will increase, as can be seen in Table 1 and Fig. 3.

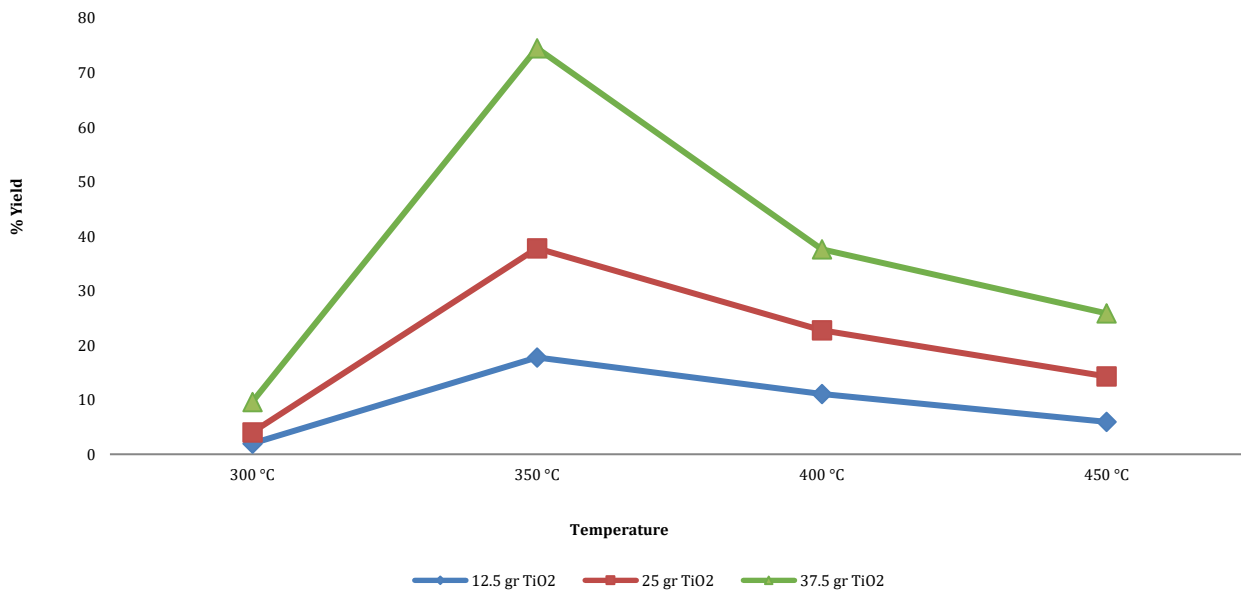
Based on Fig. 2, the highest % yield occurred at a temperature variation of 350 °C with a catalyst mass of 37.5 g of 36.71%, and the lowest % yield occurred at a temperature variation of 300 °C with a catalyst mass of 12.5 g. There was a decrease in % yield at temperatures of 400-450 °C. This is because the catalyst used (TiO_2) accelerates the rate of cracking reactions in the reactor, which occurs at temperatures of 350-400 °C so that the % yield of the product produced is less at 1 hour of operation above 350 °C. Where at temperatures above 350 °C, the % yield of gas will be more than the % yield of liquid.



Fig. 2: Liquid fuel product yield

Table 1: Data on the effect of temperature and catalyst mass on percent yield

Raw materials (gr)	Temperature (°C)	Catalyst (gr)	Product weight (gr)	% yield
1000	300	12.5	19.8	1.98
		25	20.5	2.05
		37.5	55.8	5.58
	350	12.5	177.6	17.76
		25	200.2	20.02
		37.5	367.1	36.71
	400	12.5	110.7	11.07
		25	116.7	11.67
		37.5	148.5	14.85
	450	12.5	59.3	5.93
		25	83.3	8.33
		37.5	115.9	11.59

**Fig. 3:** Graph of the effect of temperature and mass of TiO₂ catalyst on % yield of pyrolysis

This is because the catalyst used (TiO₂) accelerates the rate of cracking reactions in the reactor, which occurs at temperatures of 350-400 °C so that the % yield of products produced is less at 1 hour operating time above 350 °C. There is an increase in the production of non-condensable gas fractions and a decrease in liquid fuel production (Toktarova et al., 2022). Where at temperatures above 350°C, the % yield of gas will be more than the % yield of liquid. At high temperatures, kinetic energy increases, where carbon-carbon bonds, allowing an increase in polymer chain cleavage, form small gaseous hydrocarbons (C1-C4). Conversely, at low temperatures, kinetic energy is formed by polymer splitting into medium chains (C5-C40) (Xayachak et al., 2022). Jaafar et al. (2022) observed during the pyrolysis process of LDPE and HDP plastics an increase in gas as the temperature increased from 450 °C to 600 °C.

3.2. Relationship between the effect of temperature and catalyst mass on density

The use of catalysts in the catalytic pyrolysis process improves the efficiency of plastic degradation and lowers the pyrolysis temperature. However, this often results in a reduced liquid yield and an increased gas yield (Gopinath et al., 2020).

Catalysts possess specific physical, textural, and chemical properties, and each catalyst requires an optimal dosage to achieve maximum production.

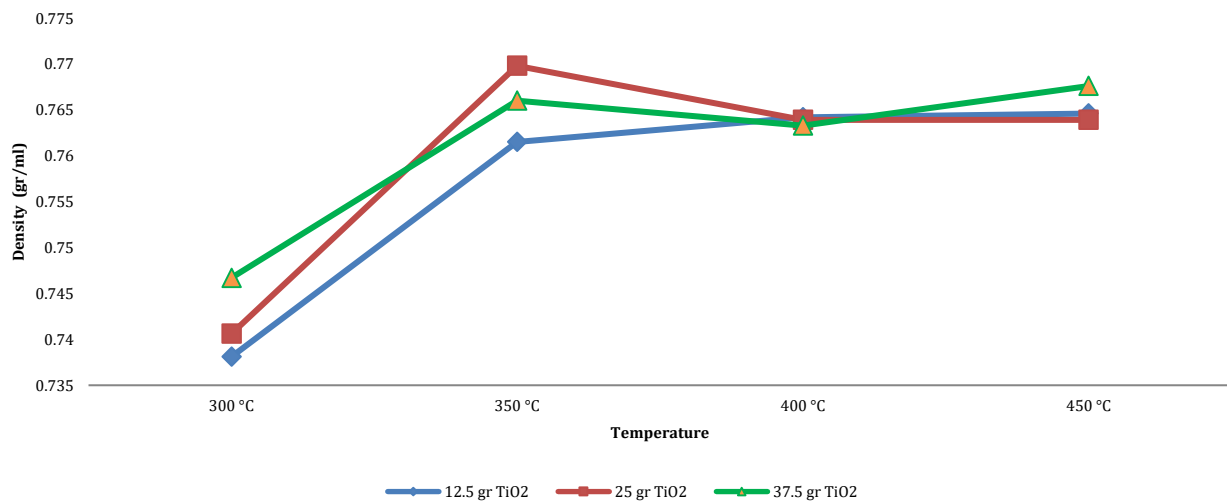
Catalyst dosage is usually measured using the catalyst/plastic ratio. The optimal catalyst/plastic ratio can differ greatly between studies, even within the same catalyst category. For example, Dement'ev et al. (2023) noted that the optimal catalyst/plastic ratio for ASA was 0.05. The relationship between the effect of temperature and catalyst mass on the density of LDPE plastic pyrolysis products is not too far different. Higher pyrolysis temperatures lead to higher reaction temperatures, which increase the density and viscosity of the products and result in the formation of longer molecular chains (Prurapark et al., 2020).

The relationship between temperature and catalyst quantity shows minimal variation in the density of LDPE plastic pyrolysis products. The density values observed in the study ranged from 0.7381 to 0.7698 g/ml. The highest density was recorded at a temperature of 350 °C with a catalyst mass of 25 g, while the lowest density was observed at 300 °C with a catalyst mass of 12.5 g. This indicates that LDPE plastic pyrolysis produces relatively consistent products, as shown in Table 2 and Fig. 4.

Table 2: Effect of temperature and catalyst mass on density

Temperature (°C)	Catalyst (gr)	Pycnometer + base weight (gr)	Density (gr/ml)
300	12.5	52.7198	0.7381
	25	52.7837	0.7406
	37.5	52.9418	0.7467
350	12.5	53.3216	0.7615
	25	53.5353	0.7698
	37.5	53.4382	0.7660
400	12.5	53.3919	0.7642
	25	53.3830	0.7639
	37.5	53.3676	0.7633
450	12.5	53.4014	0.7646
	25	53.3826	0.7639
	37.5	53.4784	0.7676

Fig. 4, which shows the graph of the effect of temperature and catalyst on density, indicates a significant increase in density between 300 °C and 350 °C. However, the density remains relatively stable at temperatures between 400 °C and 450 °C, particularly with a catalyst mass of 12.5 gr. The use

**Fig. 4:** Graph of the effect of temperature and mass of TiO₂ catalyst on density

3.3. Relationship between temperature and catalyst mass on viscosity

Another goal is to use catalysts to reduce kinematic viscosity (Papuga et al., 2022). Table 3 and Fig. 5 show that the kinematic viscosity of liquid fuel at temperature variations of 300 °C (12.5 gr TiO₂), 300 °C (25 gr TiO₂) and 450 °C (37.5 gr TiO₂) is the highest at 1.12 mm²/s and the lowest viscosity is at temperature variations of 350 °C (25 gr TiO₂), 350 °C (37.5 gr TiO₂) at 1.04 mm²/s. In Table 3 and Fig. 3, there is a decrease in viscosity with increasing temperature, but there is an increase in viscosity value at temperatures from 400°C to 450°C. This is attributed to changes in the product's structure, leading to increased viscosity. Higher pyrolysis temperatures result in higher reaction temperatures, which cause an increase in both density and

of catalysts in the catalytic pyrolysis process increases the efficiency of plastic degradation and lowers the pyrolysis temperature but tends to produce a lower liquid yield and a higher gas yield (Gopinath et al., 2020). Catalysts possess specific physical, textural, and chemical properties, and each requires a unique dosage to achieve maximum production. Catalyst dosage is usually measured as the catalyst-to-plastic ratio. The optimal catalyst-to-plastic ratio can vary significantly between studies, even within the same category of catalysts. For example, Dement'ev et al. (2023) reported that the optimal ratio for ASA was 0.05. The relationship between temperature and catalyst mass on the density of LDPE plastic pyrolysis products shows minimal variation. Higher pyrolysis temperatures lead to higher reaction temperatures, resulting in increased density and viscosity, and produce products with longer molecular chains (Prurapark et al., 2020).

viscosity and lead to the formation of products with longer molecular chains (Prurapark et al., 2020).

Table 3: Effect of temperature and catalyst mass on viscosity

Temperature (°C)	Catalyst (gr)	Time (s)	Dynamic viscosity (mPa.s)	Kinematic viscosity (mm ² /s)
300	12.5	80.79	0.83	1.12
	25	80.82	0.83	1.12
	37.5	80.72	0.82	1.10
350	12.5	80.44	0.81	1.06
	25	80.02	0.80	1.04
	37.5	79.72	0.80	1.04
400	12.5	79.90	0.80	1.09
	25	81.06	0.81	1.06
	37.5	82.61	0.83	1.09
450	12.5	82.23	0.83	1.09
	25	83.25	0.84	1.10
	37.5	85.76	0.86	1.12

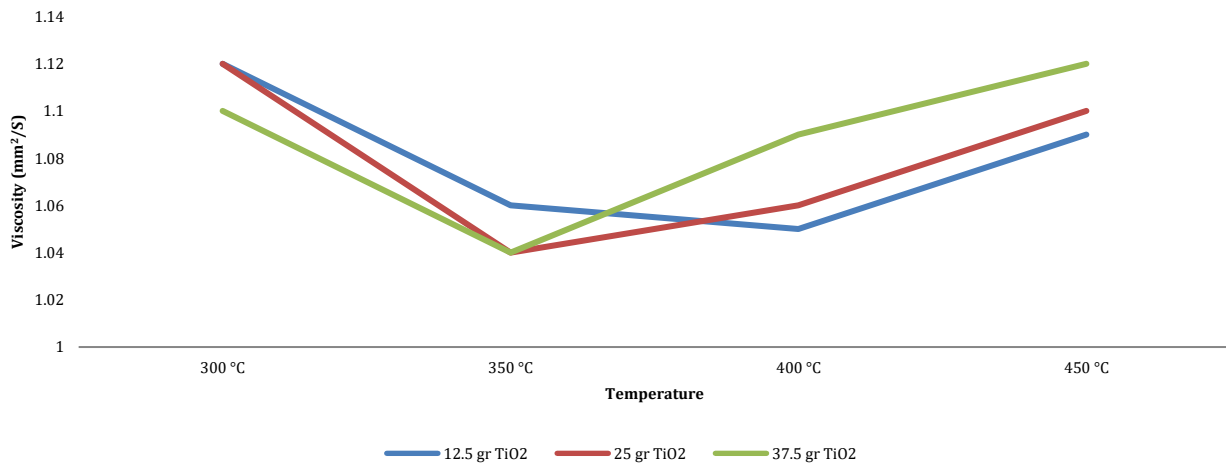


Fig. 5: Graph of the effect of temperature and mass of TiO₂ catalyst on viscosity

3.4. Relationship between the effect of temperature and catalyst mass on flash point

According to the Alternative Data Fuel Center (ADFC), the standard flash point of gasoline is -42.7778 °C. Where the flash point value of the product produced from the catalytic cracking pyrolysis process does not meet ADFC standards, it can be seen in Table 4. that the highest flash point is at a temperature variation of 350 °C with a catalyst mass of 37.5 gr of 34.0 °C and the lowest flash point is at a temperature variation of 450 °C with a catalyst mass of 37.5 gr of 30.1 °C.

Table 4: Effect of temperature and catalyst mass on flash point

Temperature (°C)	Catalyst (gr)	Flash point (°C)
300	37.5	31.9
		32.0
350	25	34.0
400	37.5	33.5
450	37.5	30.1

Flash points that do not meet ADFC standards are caused by the composition of compounds in liquid fuels, which remain a mixture of gasoline, kerosene, diesel, and fatty acid fractions. One factor influencing

Table 5: Fractions and chemical composition of liquid fuels

Fraction	Component	Compound composition (%)
C7-C11	Gasoline	49.41
C12-C20	Kerosene-Diesel	10.56
CxHxOx	Fatty acids and other compounds	40.03
	Total	100.00

3.6. Comparison of physical properties of products with standards

The yield of pyrolysis products is determined not only by quantity but also by the quality characteristics of the products, including carbon number, aromatic/aliphatic content, physicochemical properties, and calorific value. In plastic pyrolysis, gas products typically contain compounds with low carbon numbers (C1 to C4), such as short-chain alkanes and alkenes (Xayachak et al., 2022). Under optimal conditions, at a

the flash point value is the amount of catalyst used. Higher catalyst amounts result in liquid fuels that are more flammable and have faster fire propagation due to the lower flash point value.

3.5. Fraction and composition of liquid fuel chemical compounds

Gas Chromatography-Mass Spectrometry (GC-MS) analysis of catalytic cracking products from LDPE plastic was carried out with the aim of knowing the composition of chemical compounds contained in the product. GC-MS analysis was conducted on the product with the highest % yield, namely at a temperature variation of 350 °C and a catalyst mass of 37.5 g with a % yield of 36.71%. The fraction and composition of compounds can be seen in Table 5 and Fig. 6.

GC-MS analysis revealed that the product consists of 49.41% gasoline fraction (C7-C11), 10.56% kerosene-diesel fraction (C12-C20), and 40.03% other compounds (CxHxOx). The results of the catalytic cracking pyrolysis process in this study indicate that a significant proportion of other compounds remains in the product.

temperature of 350 °C and a catalyst mass of 37.5 gr, the calorific value was measured at 8644.7914 cal/gr, equivalent to 36.1698 MJ/kg. In comparison, the calorific value of Premium fuel from PT Pertamina (Persero), as tested by the Bandung Geological Agency, was 10,509 cal/gr or 43.9697 MJ/kg. The lower calorific value of the pyrolysis product may be attributed to a lower concentration of gasoline compounds and a higher presence of fatty acids or other compounds that negatively impact the calorific value of liquid fuels. Detailed comparisons of physical properties are provided in Table 6.

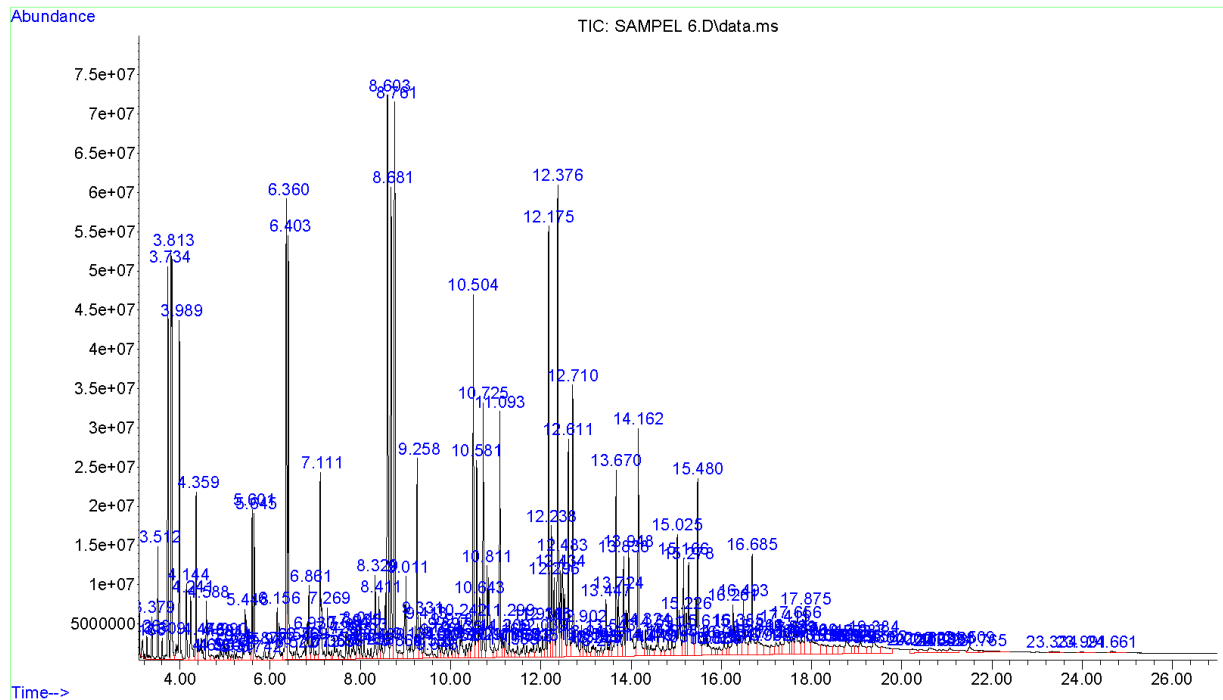


Fig. 6: Chromatogram of cracked liquid fuel

Table 6: Comparison of physical properties of products with standards

No	Characteristics	Standards			
		Premium Pertamina	Pertalite Pertamina	ADFC	Product
1.	Density (kg/m ³)	715-770	715-770	718-778	738.1-769.8
2.	Viscosity (mm ² /s)	-	-	-	1.04-1.12
3.	Flash point (°C)	-	-	-42.7778	30.1-34.0
4.	Calorific value	-	-	-	-
5.	Calorific value (MJ/kg)	43.9697	-	-	36.1698

4. Conclusion

Variations in the mass of titanium dioxide (TiO₂) catalyst greatly affect the % yield, with the highest value being at a temperature variation of 350 °C and a catalyst mass of 37.5 gr. The resulting liquid fuel product has a density value of 0.7381- 0.7698 gr/ml, a viscosity value of 1.04-1.12 mm²/s, a flash point of 30.1- 34.0 °C and a calorific value at a temperature variation of 350 °C and 37.5 gr of catalyst of 8,644.7914 cal/gr. Based on the characteristics obtained from the results of GC-MS analysis, the product of pyrolysis of LDPE plastic waste at a temperature variation of 350 °C and a catalyst of 37.5 g is a liquid fuel equivalent to gasoline.

Compliance with ethical standards

Conflict of interest

The author(s) declared no potential conflicts of interest concerning this article's research, authorship, and/or publication.

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