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Fuel Characteristics of Pyrolysis Oil from Plastic Waste: A Case Study of Banjarnegara Waste Bank

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Abstract: Oil derived from plastic waste pyrolysis has the potential to be a fuel replacement option. Plastic waste pyrolysis has been extensively studied. However, several challenges remain to be solved. These challenges include designing the pyrolysis machine to ensure continuous production, managing impurities that arise, controlling temperature, optimizing catalysts, and other elements that influence the quality of the pyrolysis oil. Banjarnegara Waste Bank (BWB), an environmental activist, has been continuously processing plastic waste into fuel but it has never been characterized. The study aims to examine the properties of pyrolysis oil produced from plastic waste by BWB as a potential alternative fuel. This research experimented with a homemade pyrolysis machine (Fastpol G-5) at 250–325 °C for 8 hours, followed by purification, esterification, and filtration. The raw material was mixed plastic waste, mainly polyethylene (PE) and polypropylene (PP). The resulting fuel (diesel equivalent) was tested to assess its characteristics in accordance with diesel oil standards outlined in the Decree of the Director General of Oil and Gas Number 146 of 2020. Additionally, gas chromatography analysis was conducted to examine the composition of the compounds. The results showed that the pyrolysis plastic produced by BWB generally met the quality standards of diesel oil 48, except for density and color parameters. The cetane number and sulfur content were 48.6 and 890% m/m, respectively. The fuel's chemical composition shows that it contains 54.46% aliphatic compounds, 22.85% aromatics, and 22.69% oxygenates. This substance's complex chemical composition, which consists of aromatic compounds, olefins, and primarily aliphatic hydrocarbons, makes it suitable for use as a fuel in a variety of applications. BWB's production of pyrolysis oil from plastic waste has proven to be a viable alternative fuel.

Keywords: pyrolysis oil; plastic waste; fuel characteristics; pyrolysis; alternative fuel

1. Introduction

The oil obtained from plastic waste pyrolysis has a variety of characteristics that indicate its potential as a viable substitute fuel. Firstly, waste plastic pyrolysis oil has a high energy content, which makes it an efficient fuel source. Pyrolysis oil density ranged from 670–790 kg m^{-3}, viscosity ranged from 1.611–2.401 cP, and the calorific value of pyrolysis oil ranged from 7394 – 8946 cal g^{-1} [1)]. The oil derived from the pyrolysis of polypropylene (PP)

plastic has a density of 811 kg m^{-3} at 250 °C and 782 kg m^{-3} at 350 °C. The viscosity at 250 °C and 350 °C is 2.02 cP and 0.86 cP, respectively. The PP plastic pyrolysis oil has a maximum calorific value of 10,870 kcal g^{-1} at 350 °C and the lowest calorific value of 10,386 kcal g^{-1} at 250 °C[2]. The study highlights the possibility of transforming mixed plastic waste into alternative fuels through pyrolysis[1,2]. Waste plastic pyrolysis oil has a lower sulfur content than fossil fuels, resulting in fewer sulfur compounds being released during combustion. The sulfur content of pyrolysis oil produced through a distillation pyrolysis process is reported to be in the range of 878 ppm to 1,314 ppm, indicating the production of lower sulfur products[3]. Furthermore, pyrolysis-derived plastic oil is a potential replacement for traditional petroleum-based fuels because it does not include sulfur[4]. Additionally, waste plastic pyrolysis oil can be considered a renewable fuel source due to its utilization of waste plastic. Improper management of waste plastic can lead to serious environmental problems.

Pyrolysis of waste plastics produces pyrolysis oil, which has favorable fuel characteristics. Research by Singh et al., (2020)[5] has revealed that oil resulting from the pyrolysis of plastic waste exhibits combustion qualities suitable for application in compression ignition (CI) engines. The fuel that comes from breaking down polyethylene (PE) in a low-density and linear way has enough potential to be used as a fuel source[6]. In addition, the drop-in liquid fuel characteristics fractionated from waste plastics have the potential for commercial-scale production of waste plastic pyrolysis oil[7]. The combustion and emission characteristics of pyrolysis oil derived from plastic bottle caps showed its suitability for use in diesel engines[8]. Plastic waste pyrolysis provides an opportunity to convert plastic waste into valuable liquid fuels, overcoming challenges in waste management and providing an alternative fuel source[9].

The characteristics of pyrolysis oil derived from waste plastic show similarities to diesel fuels, making it a suitable alternative source of fuel for diesel engines. Fourier Transform Infrared Spectroscopy (FTIR) analysis demonstrates that low-density polyethylene and high-density polyethylene oils have functional groups that are consistent with those of commercial diesel (96% similarity match)[10]. Pyrolysis PS produces the most liquid product (91.44 wt%), while pyrolysis PE produces a high percentage of the diesel range product (36.60 wt%). The study shows that the diesel properties of the PE pyrolysis oil, which are enhanced by the removal of naphtha, are similar to those of the commercial B7 diesel. In addition, the operating costs of the pyrolysis oil and diesel increase by 0.37 and 0.65 USD/L, respectively, which is lower than the current market price of the B7 diesel in Thailand[11]. Plastic fuels made from co-mingled municipal waste plastics have similar characteristics to diesel[12].

Studies have explored a combination of waste plastic oil and biodiesel as a potential alternative fuel for diesel engines. These studies emphasize the potential of this combination. Plastic waste pyrolysis oil (WPPO) is produced from high-density, low-density, polypropylene (PP), and polystyrene. It has comparable properties to diesel fuel but with a higher heating value of 40 to 43 MJ kg^{-1}. WPPO has a shorter ignition delay time than diesel because of its higher cetane number. Additionally, the use of WPPO results in a decrease in emissions from engine exhaust, including smoke, CO, and CO_2, as compared to diesel. WPPO can lead to higher NOx emissions, but there are ways to mitigate this issue. Methods like additive additions or exhaust gas recirculation can effectively reduce these emissions. WPPO has a bright future as a substitute fuel for diesel engines[13]. At a compression ratio of 17:114, the braking thermal efficiency of diesel fuel containing 20% plastic oil blended with 100 ppm graphene increases by 1.16% in comparison to diesel[14].

Producing pyrolysis oil from waste plastic can have a significant positive impact on the environment. Utilizing pyrolysis oil from plastic waste as a substitute fuel offers numerous benefits, including the reduction of carbon footprints and dependence on conventional fossil fuels, as well as the utilization of a renewable energy source[15]. Research by Mohan[16][17] shows that waste plastic pyrolysis oil has lower carbon emissions compared to conventional petroleum-based fuels. Furthermore, researchers have explored the use of exhaust gas recirculation in combustion with nano-coating chambers in diesel engines powered by used plastic oil. This research has shown promising results in improving engine efficiency and reducing emissions[18]. The above studies demonstrate the potential of WPPO as an alternative fuel, emphasizing its environmental and energy benefits.

The composition and amount of pyrolysis oil obtained from plastic waste can be influenced by various factors, including the type of plastic, pyrolysis parameters, and the inclusion of catalysts[19]. A study on the conversion of plastics into liquid fuels and chemical precursors highlighted that LDPE and HDPE have the highest production, emphasizing their significance in fuel production[20].

The catalyst and its quantity can influence pyrolysis oil's yield and properties. During oil shale pyrolysis, the addition of Fe_2O_3 and $CaCO_3$ catalysts has been shown to increase the yield of shale oil[21]. Similarly, the regeneration sequence of catalysts can impact the composition of upgraded pyrolysis oils[22]. Additionally, the pyrolysis technique and reactor type used have a significant impact on both the yield and characteristics of the resulting pyrolysis oil[23]. According to research conducted by Owusu et al. (2018)[24], plastic waste can be effectively transformed into valuable fuel derivatives, highlighting the potential of pyrolysis as a method of managing plastic waste and reclaiming resources.

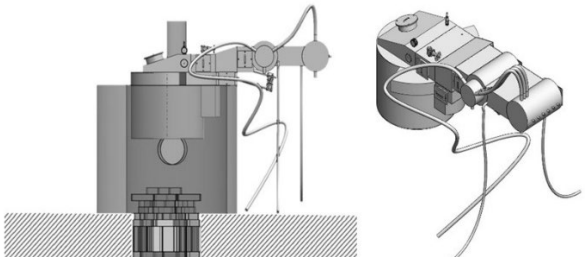
Studies on the pyrolysis of plastic waste have been conducted, but there are still many obstacles that need to be addressed. A significant obstacle is the design of

pyrolysis machines, which often lack continuous operation capabilities, leading to interruptions in fuel production[25]. The pyrolysis engine design, with its many elbow pipes, has the potential for a hard-to-clean crash and an explosion. The incident highlights the importance of improving pyrolysis machines' security features and operating protocols to reduce risks and ensure staff safety. Unoptimal pyrolysis engine design and operation can pose security risks[12]. The impurities in the bio-oil produced through pyrolysis have an impact on fuel quality. These impurities include water content, high viscosity due to tar content, and high ash content[26]. The overall efficiency and effectiveness of converting plastic waste into fuel must be improved by conducting a comprehensive examination of the impact of factors such as temperature, reactor design, and residence time on the pyrolysis process[27].

Banjarnegara Waste Bank (BWB), as one of the environmental activists in Central Java Province has begun processing plastic waste into diesel and petrol using pyrolysis technology. The process of processing plastic waste to energy at BWB is not only a pyrolysis process but also is continued with several subsequent treatments such as reducing acidity, purification, and filtering. This simultaneous process causes the quality of fuel, especially diesel produced by BWB, to be suitable for use and much needed by users. The produced fuel has also been used internally to power agricultural machinery and vehicles. Therefore, it is necessary to research the characteristics of fuel produced by BWB following applicable standards in Indonesia.

2. Materials and Methods

The research was conducted from May to August 2023 at the BWB in Banjarnegara Regency, Central Java Province, Indonesia. The process of thermally decomposing plastic waste was conducted using a homemade pyrolysis machine at 250–325 ºC. The pyrolysis machine (Fastpol Gen-5) was made of stainless steel and equipped with a thermometer, pressure gauge, safety valve, and others (Fig. 1). The pyrolysis machine



A B

Fig.1. Pyrolysis machine (Fastpol Gen-5) made by Banjarnegara Waste Bank, front view (A) and overall view (B)

was made of wood fuel, and coated with a clay insulator cover, while the heating furnace was designed to heat the fire source indirectly. The pyrolysis machine consisted of several main reactor chambers and re-heating reactors, as well as a 4-stage cooling condenser and a storage chamber for oil and methane gas fractions. Fastpol Gen-5 was designed to minimize elbow pipes to avoid blockages that could potentially lead to explosions. To minimize emissions, the methane gas produced was reused for reheating.

Plastic waste was processed into fuel in the form of mixed plastic waste from various kinds of plastic, mainly PE and PP. The fuel produced in the form of oil was mostly diesel (about 70–80%) and the rest was equivalent to gasoline. Therefore, this study primarily focused on the diesel fraction. The characterization test checked the quality of diesel fuel according to the Decree of the Director General of Oil and Gas Number 146 of 2020. It checked things like the cetane number (ASTM D613), cetane index (ASTM D4737), density at 15 ºC (ASTM D4052), viscosity at 40 ºC (ASTM D445), moisture content (ASTM D6304), acid number (ASTM D664), sulfur content (ASTM D4249), flash point (ASTM D93), cloud point (ASTM D2500), carbon residue (ASTM D189), copper strip corrosion (ASTM D130), ash content (ASTM D482), sediment content (ASTM D473), particulate contamination (ASTM D6217), color (ASTM D1500), and lubricity (ASTM D6079). In addition, the chemical composition of the diesel fuel produced was tested using Agilent Gas Chromatography-Mass Spectrometry (GC-MS) with column DB-1 (100% dimethylpolysiloxane). Analyses were carried out at the Fuel and Design Engineering Laboratory - BRIN and the Product Application Laboratory, Center for Oil and Gas Testing "Lemigas", Ministry of Energy and Mineral Resources., Republic of Indonesia.

2.1 The pyrolysis process of plastic waste into liquid fuel at BWB

The processing of plastic waste into fuel in Banjarnegara consisted of several stages, namely pyrolysis, esterification, purification, and filtration. The pyrolysis procedure was conducted at a specific temperature of 250–325 °C (Fig. 2).

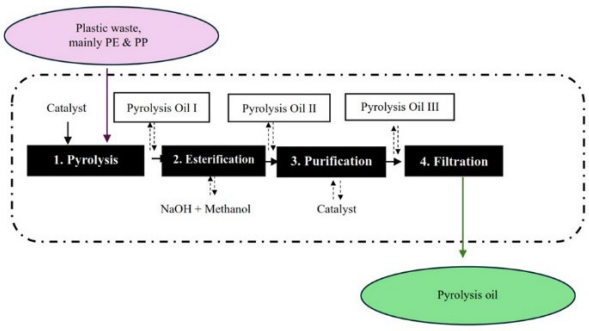


Fig.2. Processing plastic waste into fuel at Banjarnegara Waste Bank

The pyrolysis machine used wood fuel and gas produced from the pyrolysis process. The pyrolysis machine's capacity of 50 kg of plastic waste feedstock produced 40–45 liters of fuel oil (80–90%), depending on the cleanliness and dryness of the plastic waste feedstock. The plastic waste was inputted in stages, with a total of 50 kg being processed over 4 cycles at a temperature of 150 ºC each time. The first input was about 15–20 kg, followed by a subsequent input of 10–15 kg of plastic waste. During this process, a homemade clay catalyst was added (250 grams at the beginning of the input and 250 grams at the last input). This Gen-5 pyrolysis machine consisted of 2 core reactors. The initial reactor was responsible for incinerating the plastic waste and the second reactor was dedicated to the redistillation process, resulting in the production of cleaner fuel and separation of the fuel type. From the second reactor, the fuel was directed to the diesel processing room, where it reached a temperature range of 250–325 °C. The kerosene gas fraction rose to the next processing room, which had a temperature of 125–250 °C, the unprocessed gasoline fraction rose and was purified in the next processing room at a temperature of 40–90 °C. All these processes took place simultaneously. The methane gas produced was repurposed as fuel in the combustion chamber.

After obtaining pyrolysis oil I from plastic pyrolysis, the next process was to reduce acidity. In this stage, pyrolysis oil II (diesel) from the plastic fuel was mixed with up to 250 ml of a mixture of 30–50% NaOH and 95% methanol. The mixture was then exposed to air for 5-15 minutes, which made the fuel cleaner and less smelly. At this stage, there was a concentrated sediment that needed to be separated. After being separated, the fuel was processed for the next stage, namely the purification process. Crude oil from the previous process plus catalyst (the same as the catalyst when inputting raw materials into the engine) was stirred for 5 minutes and left for 3–12 hours. The final stage involves filtration with a special filter cloth that can be reused after washing.

2.2 Catalyst

The pyrolysis process of plastic waste utilized a homemade catalyst, namely "salt-activated bentonite". The catalyst synthesis was carried out by mixing raw materials such as bentonite clay and "krosok salt" in a certain ratio in a container filled with water. The mixture was allowed to stand for 24 hours to activate the absorption power. Afterward, the mixture was dried in the sun until the moisture content reached below 10%. Once the material was completely dried, the material was burned in an oxygen-less reactor at 300–400 ºC for 2 days. Subsequently, it was pulverized to a size of 200 mesh. Finally, the catalyst was prepared for use. The catalyst was kept in an airtight container until it was needed.

3. Results and Discussion

BWB is an environmental campaigner who began as a traditional waste bank that collected and sold rubbish. Due to the accumulation of waste, particularly plastic waste that could not be sold or processed, BWB attempted to find a solution so that BWB activities could continue to operate and be self-sufficiently funded. The pyrolysis technology was ultimately chosen to convert plastic waste into gasoline. Initially, trial and error were used until it was able to convert plastic waste into kerosene for family cooking stoves. After continued refinement, the current pyrolysis equipment may be utilized to convert plastic waste into fuel similar to diesel and gasoline.

In recent years, the resultant diesel fuel has seen limited use in agricultural machines and automobiles. Many people are pleased with the fuel performance. With the existing processing capacity of 400 kg day^{-1}, the waste problem in one sub-district, particularly plastic garbage, may be addressed. Although it has been used in a variety of machinery and automobiles, BWB's plastic waste-derived fuel has not been evaluated for quality in compliance with current requirements. As a result, it is necessary to characterize this plastic waste fuel to identify its quality and properties.

3.1 Yield of pyrolysis oil produced from the pyrolysis of plastic waste.

In this study, the raw material for plastic waste in BWB mostly came from household waste. Plastic waste was collected every month. In addition, plastic waste was sourced from market waste and collectors. At BWB, the plastic waste pyrolysis process produced 82% liquid fuel (with catalyst) and 68% (without catalyst). This finding is higher than Lamar et al. (2021)[20] which claims that LDPE has the highest liquid fraction yield at 390 ºC (72%), followed by HDPE and LDPE with 69% and 62% at 375°C, respectively. The mass-based liquid yield of HDPE, PP, and PS was found to be 80%, 82.6%, and 80%, respectively[24]. Utilizing a catalyst ensured the absence of any residue, whereas the absence of a catalyst resulted in the production of a char residue of 7% (Fig. 3). The use of a salt-activated bentonite catalyst can increase efficiency. The residue produced was repurposed as combustion material in conjunction with firewood, rather than being disposed of.

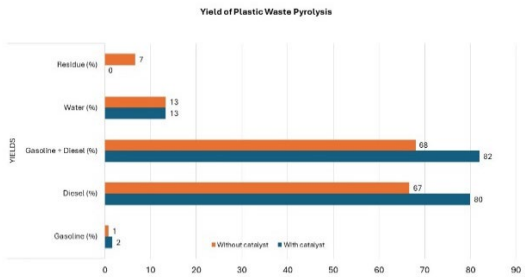


Fig.3. Yield of pyrolysis oil produced from the processing of plastic waste into fuel at the Bank Sampah Banjarnegara

The amount of yield produced depends on the type of plastic waste used, where plastic waste was a mixture of mostly PE and PP and the presence of a clay catalyst (homemade). Pyrolysis using catalysts on several types of plastics showed different yields of liquid oil, indicating the significant impact of catalysts on the process[28]. In addition, the type of plastic, such as high-density polyethylene (HDPE), PP, and polystyrene (PS) can significantly affect the composition of the pyrolysis oil[24]. The use of catalysts, such as graphene oxide-sulfonated zirconia (GO-Szr) and fluid catalytic cracking catalysts, has been shown to increase oil yields to as high as 92.76 wt.% [29] and 94 wt.%, respectively[30]. Certain catalysts can be used to break down different types of plastics, like polyethylene terephthalate (PET) and PS, and get high yields of liquid oil of up to 70% and 60%, respectively[28].

The production of liquid fuel from the pyrolysis of plastic waste was also influenced by the dryness and cleanliness of plastic waste. The drier and cleaner the plastic waste, the higher the yield. In addition, pyrolysis conditions, such as temperature and duration of stay, played an important role in determining the yield of pyrolysis oil. Higher pyrolysis oil yields of 37% were obtained at temperatures above 550 °C [31].

3.2 Characteristics of pyrolysis produce plastic waste oil as fuel.

Plastic waste fuel from pyrolysis possesses distinct qualities that render it appropriate for a variety of uses. The density, combustion properties, calorific value, and composition of this fuel were important factors to consider when selecting it for a particular application. Viscosity, waxy aspect, fluidity, amount of aromatic compounds, flash point, and heating value were important characteristics of plastic waste fuel from pyrolysis[8,32,33]. In addition, conducting experiments to test the performance and burning features of mixed plastic pyrolysis oil in an upgraded diesel engine can provide valuable insights into the adaptability of this fuel in various engine types[34]. Experimental and performance analyses of waste plastic pyrolysis systems for biofuel production shed light on the fuel's heating value, pour point, and kinematic viscosity, which were critical for its application in engines[35]. A study conducted by Owusu et al. (2018)[24] demonstrated the successful conversion of plastic waste into useful fuel products as well as the potential of pyrolysis as a means of plastic waste management and resource recovery. These studies collectively emphasized the importance of understanding the fuel characteristics of plastic waste fuel from pyrolysis to ensure its effective utilization in various applications.

The characterization of plastic waste fuel in this study was carried out for diesel equivalent fraction fuel derived from mixed plastic waste, mainly PE and PP types. The resulting fuel was subjected to laboratory tests in accordance with Directorate General of Oil and Gas Decree No. 146.K/10/DJM/2020 quality standards[36]. There were 17 parameters tested in this study and then aligned with the required standards (Table 1).

Table 1. Characteristics of pyrolysis plastic waste oil produced Banjarnegara Waste Bank

No	Test Parameter	Method	Unit	Value	Diesel Requirement 48*	Diesel Requirement 51*
1	Cetane Number	ASTM D613	-	48.6	min. 48	min. 51
2	Cetane Index	ASTM D4737	-	60.45	min. 45	min. 48
3	Density at 15 ºC	ASTM D4052	kg/m^3	814.6	815-870	810-850
4	Viscosity at 40 ºC	ASTM D445	mm^2/s	2.792	2.0 – 4.5	2.0 – 4.5
5	Moisture content	ASTM D6304	% m/m	108.46	max. 400	max. 280
6	Acid Number	ASTM D664	mg KOH/g	0.02	max. 0.6	max. 0.3
7	Sulphur content	ASTM D4294	% m/m	890	max. 2000	max. 500
8	Flash Point	ASTM D93	°C	52	min. 52	min. 55
9	Cloud Point	ASTM D2500	°C	n.d	max. 18	max. 18
	Pour Point	ASTM D97	°C	1.5	max. 18	max. 18
10	Carbon Residue	ASTM D189	% m/m	0.03	max. 0.1	max. 0.1
11	Copper Strip Corrosion	ASTM D130	class	1a	max. class 1	max. class 1
13	Ash Content	ASTM D482	% m/m	<0.005	max. 0.01	max. 0.01
14	Sediment Content	ASTM D473	% m/m	0	max. 0.01	max. 0.01
15	Particulate Contamination	ASTM D6217	mg/l	4.1		max. 10
16	Colour	ASTM D1500	No. ASTM	3.2	max. 3	max. 1
17	Lubricity	ASTM D6079	micron	353.5	max. 460	max. 460

3.2.1 Cetane Number (CN)

The cetane number serves as an indicator of the ignition characteristics of diesel fuel and indicates the flammability of the fuel. A higher cetane number represents better ignition quality, better combustion efficiency, and lower emissions [33]. The cetane number is particularly important for compression ignition (CI) engines, which are commonly used in diesel engines. The cetane number refers to the number of C16 in diesel (C14-C21). Increased C16 content in diesel fuel enhances

its combustion efficiency[25]. The study found that the pyrolysis oil derived from plastic waste at the BWB has a cetane value of 48.6, which satisfies the specifications for diesel 48. This showed that the diesel equivalent fuel from the pyrolysis of plastic waste at the BWB has good quality in terms of cetane number.

The cetane number was influenced by several things, such as the type of plastic waste that impacts the chemical composition, the pyrolysis process, the presence of catalysts, and so on. The chemical composition of the fuel, especially the presence of certain hydrocarbons, determined the cetane number. In particular, the concentration of straight-chain paraffin (alkanes) in the fuel plays an important role[37]. A higher concentration of these straight-chain hydrocarbons usually results in a higher cetane number, which signifies better ignition quality. On the other hand, the presence of branched-chain paraffin and aromatic compounds can reduce the fuel's cetane number. According to Sahar et al. (2018)[38], the cetane number of biodiesel from used cooking oil (WCO) depends on the fuel's carbon number and the concentration of Fatty Acid Methyl Ester (FAME). Ethers with longer alkyl chains can improve diesel fuel's cetane number, which is a measure of its ignition quality[28].

3.2.2. Density

The measure of fuel density is based on the mass of fuel contained within a specific volume. Density is expressed in kilograms per liter or pounds per gallon. Fuel density is an important factor in determining its energy content, as fuels with higher density generally have more energy per unit volume. The density of waste plastic oil obtained through pyrolysis varied depending on the specific plastic source material and the pyrolysis process conditions. For instance, the density of oil resulting from pyrolyzing low-density linear polyethylene was measured at 790 kg m^{-3} [29]. Fuel density differs based on the fuel type, with gasoline typically having a lower density compared to diesel fuel. This variance in density was attributed to the distinct chemical composition and molecular structure of gasoline and diesel fuels. Analysis of fuels generated through the pyrolysis of plastic films sourced from municipal waste revealed differing densities[39]

The density of diesel oil required by the Director General of Oil and Gas of the Government of Indonesia is 815-870 kg m^{-3} (diesel 48) and 810-850 kg m^{-3} (diesel 51) and the density of plastic waste fuels (PWF) in this study is 814.6 kg m^{-3}. This density met the diesel 51 standard, which was slightly lower than diesel 48.

According to Thahir et al. (2019)[40], the density, viscosity, octane-cetane number, ash content, and calorific value of fuel made from the liquid byproducts of pyrolysis of PP plastic waste were very similar to those of traditional fossil fuels. Plastic types like high-density polyethylene (HDPE) or low-density polyethylene (LDPE) can also change the density of plastic fuels. The density can also be changed by adding additives or catalysts during the conversion process[34,41]. Studies specifically focused on the properties of fuel oil obtained from low-density and linear polyethylene pyrolysis, describing potential density variations based on the type of plastic feedstock[6]. It is important to note that the density of plastic fuels can affect their performance when used in engines. Research has shown that the use of plastic-derived fuels in engines, such as CI engines, can impact combustion, emissions, and overall engine characteristics[42–44]. The study conducted by Alawa & Chakma, (2023)[45] on the impact of blending liquid fuels produced from waste plastics on engine brake thermal efficiency, showed the effect of fuel density on engine performance.

3.2.3. Viscosity

In various applications, the viscosity of fuel oil is an important factor that affects its flow and combustion properties. The viscosity of plastic fuel is influenced by a variety of factors, such as the pyrolysis process, the type of plastic used, and the properties of the resulting oil. Studies have shown that the properties of fuel oil obtained from plastic pyrolysis vary based on the type of plastic used and the pyrolysis process [6,32].

When using waste fuel as a fuel, it is important to pay attention to its viscosity to determine the flow characteristics and overall performance of a diesel engine. The viscosity of plastic waste fuel in this study was obtained at 2.792 mm^2 s^{-1} and met the requirements of the Director General of Oil and Gas of the Government of Indonesia, namely 2.0 - 4.5 (diesel 48 and 51).

The viscosity and clarity of a fuel have an impact on engine performance. Studying the mechanics of a variable compression ratio engine, its combustion process, and the pollutants produced when it utilized a combination of LDPE plastic pyrolysis oil and diesel fuel might provide insights into the impact of fuel viscosity on engine performance[43]. In addition, according to the research of Kaewbuddee et al. (2023)[46], blending biodiesel with 10% palm oil or castor oil in the fuel results in ideal lubricity and viscosity.

3.2.4. Sulphur content

The sulfur content of waste plastic fuel is an important parameter affecting environmental impact and regulatory compliance. Careful monitoring of the sulfur content is required to ensure that the plastic waste fuel meets the required standards and does not contribute to air pollution or harm the environment. The sulfur content of plastic waste fuel can vary depending on the plastic waste source and composition. It is important to properly manage production facilities and implement procedures that minimize sulfur contamination of plastic waste fuel. The sulfur content required by the Director General of Oil and Gas of the Government of Indonesia is a maximum of 2000% m/m (diesel 48) and a maximum of 500% m/m (diesel 51). This study showed that the sulfur content in

PP and PE plastic waste fuel complied with the requirement (diesel 48), measuring 890% m/m.

The degradation rate of plastics in the environment[15] and the properties of waste plastic fuel oil [29] are important factors to consider when evaluating the potential of waste plastic pyrolysis oil as an alternative fuel. Determining the effectiveness of waste plastic pyrolysis oil in blending diesel fuel[17] and producing other fuels through pyrolysis of waste plastic blends[32] is crucial in understanding the environmental impact of waste plastic fuels.

3.2.5. Color

The color of the fuel can be affected by its composition and additives. Plastic degradation can produce oils with different properties, affecting the color and quality of the resulting fuel[15]. When evaluating the overall quality of fuel, it was crucial to consider the correlation between color and fuel quality. Color can provide valuable information about the composition, stability, and combustion properties of the fuel. Darker colors in fuels can indicate higher concentrations of impurities or contaminants, which can negatively impact combustion efficiency and produce more pollutants. Furthermore, color can also serve as an indicator of the fuel's energy density. Fuels with darker colors tend to have a higher energy density, while lighter colors can indicate a lower energy density.

In this study, the color of liquid fuel from plastic waste is 3.2, slightly exceeding the maximum requirements of the Director General of Oil and Gas of the Government of Indonesia. For diesel 48, the maximum requirement is 3 while for diesel 51, the maximum is 1. This excess is likely due to the composition of plastic waste and the storage process. Pyrolysis of low-density, linear polyethylene plastics can reveal the properties of the extracted oil, which can affect the fuel's color and quality[6]. In addition, blending waste plastic oils with diesel fuel has been shown to impact engine performance and emission characteristics, indicating a potential influence of additives on fuel color and quality[3]. The addition of diethyl ether and nanographene additives to diesel fuel blended with waste plastic oil has been shown to improve engine characteristics, indicating a potential influence on fuel color and quality[14,47].

3.3. Chemical composition

The chemical composition of pyrolysis oil derived from waste plastics is very complex, influenced by various parameters such as the type of plastic, pyrolysis conditions, and the presence of catalysts. Analytical techniques such as GC-MS play an important role in identifying the specific compounds present in pyrolysis oil from waste plastics. According to Wiangkham et al., (2023)[47] waste plastic oil (WPO) consists mainly of middle distillate hydrocarbons (52.58% C13-C18 and 26.15% C19-C23). Although WPO has a lower specific gravity, density, and flash point, it meets diesel fuel specifications for kinematic viscosity and cetane index.

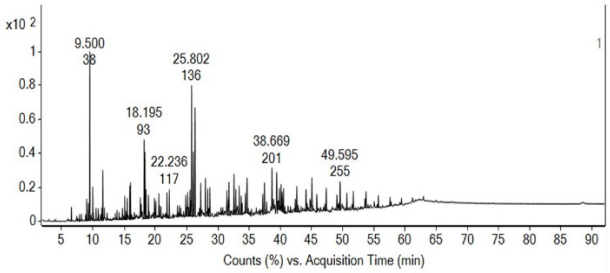


Fig. 4: GC-MS peak of pyrolysis oil sample at Banjarnegara Waste Bank

Gas Chromatography-Mass Spectrometry (GC-MS) analysis showed that the complex compounds range from aliphatic compounds of carbon chain C8-C13, like 2,4-dimethyl-1-heptene, to aromatic compounds of carbon chain C1-C7, like $C_3H_5N_3$ (4H-1,2,4-triazole, 4-methyl-), and oxygenate compounds, like $C_8H_{14}O_3$ (n-butyric acid tetrahydrofurfuryl ester). Table 2 provides further information. Based on the percentage of peak area visible, aliphatic compounds appear dominant with an amount of up to 54.46%, while aromatic and oxygenate compounds appear the same at 22% each. It has a lot of aliphatic compounds because the raw materials used are made of plastic waste, especially High-Density Polyethylene (HDPE), which is made up of a straight linear chain structure.

Table 2. Compound composition grouping of pyrolysis oil of plastic waste produced by Banjarnegara Waste Bank

Peak	RT	Height	Area	Area %	Name	Formula
1	9.5	8148012.11	31055745.78	9.38%	2,4-Dimethyl-1-heptene	C9H18
2	9.963	1644815.52	5934053.76	1.79%	2-Pyrazoline, 1-isopropyl-5-methyl-	C7H14N2
3	11.583	2421874.74	8481389.47	2.56%	2,3,3-Trimethyl-1-hexene	C9H18
4	15.88	1617330.06	5759390.1	1.74%	3-Ethyl-3-methylheptane	C10H22
5	16.024	1778632.61	6171327.05	1.86%	3-Ethyl-3-methylheptane	C10H22
6	18.195	3807871.15	13895618.8	4.20%	Cyclopentane, 1,1,3,3-tetramethyl-	C9H18
7	18.333	3211756.01	11693940.98	3.53%	n-Butyric acid tetrahydrofurfuryl ester	C8H14O3
8	18.495	1408610.21	5106011.51	1.54%	Cyclohexane, 1,2,3-trimethyl-	C9H18
9	22.236	1364023.11	5366534.51	1.62%	2,2-Dimethyl-3-heptanone	C9H18O
10	25.176	1138584.34	5944589.04	1.80%	2-Propenoic acid, 2-methyl-, ethenyl ester	C6H8O2

11	25.545	1270983.21	5386006.91	1.63%	1H-Tetrazol-5-amine	CH3N5
12	25.802	6281043.98	26642940.8	8.05%	Pentane, 3-ethyl-3-methyl-	C8H18
13	26.077	3093244.11	13389129.31	4.04%	1-Hexene, 2,5,5-trimethyl-	C9H18
14	26.358	5218074.32	22122094.77	6.68%	4H-1,2,4-Triazole, 4-methyl-	C3H5N3
15	27.272	1593629.31	7107181.31	2.15%	CH3NHCH2CN	C3H6N2
16	28.01	1819893.03	10045380.82	3.03%	1-Methyl-1H-1,2,4-triazole	C3H5N3
17	28.385	1319154.99	5469755.68	1.65%	1-Pentene, 3-methyl-	C6H12
18	28.729	1378546.38	6462576.82	1.95%	Octane, 2,7-dimethyl-	C10H22
19	31.456	1180490.01	6733599.15	2.03%	4-Hexen-3-one, 5-methyl-	C7H12O
20	31.788	1604967.5	7989496.43	2.41%	5H-Tetrazol-5-amine	CH3N5
21	32.601	1960100.4	8909380.57	2.69%	Cyclohexane, 1,1,3-trimethyl-	C9H18
22	32.889	1235224.55	5659438.33	1.71%	Methyl propargyl ether	C4H6O
23	33.421	1381718.2	7084729.49	2.14%	Hexane, 3,3-dimethyl-	C8H18
24	34.697	1701190.63	11269359.9	3.40%	Nonane, 5-methyl-5-propyl-	C13H28
25	37.199	995813.67	5380593.98	1.63%	3-Methylene-2,6-heptanedione	C8H12O2
26	37.48	1504757.43	8019778.65	2.42%	Ethanone, 1-oxiranyl-	C4H6O2
27	38.669	2033382.73	9660506.5	2.92%	2-Acetyl-1-pyrroline	C6H9NO
28	39.432	1733915.99	8833302.7	2.67%	Norflurane	C2H2F4
29	40.133	1265933.85	5630577.79	1.70%	1H-Tetrazol-5-amine	CH3N5
30	40.539	1158423.61	5524049.94	1.67%	Phosphonic acid, bis(1-methylethyl) ester	C6H15O3P
31	42.66	1236237.12	6188658.03	1.87%	5H-Tetrazol-5-amine	CH3N5
32	44.13	1036879.78	6065634.19	1.83%	2(5H)-Furanone, 5-(acetyloxy)-	C6H6O4
33	44.774	571873.71	5051347.26	1.53%	Carbamic acid, (trifluoromethyl)-, 1,1-dimethylethyl ester	C6H10F3NO2
34	45.074	1596489.17	9223334.87	2.79%	Norflurane	C2H2F4
35	45.851	872899.99	5139017.56	1.55%	1H-1,2,3-Triazole	C2H3N3
36	47.376	1093590.97	5407779.88	1.63%	Dodecane, 5-methyl-	C13H28
37	49.595	1367310.84	7212855.3	2.18%	1H-Tetrazol-5-amine	CH3N5

Description:

		Compound Type	% Peak Area
	:	Aliphatic	54.46
	:	Aromatic	22.85
	:	Oxsygenates	22.69

The study by Miandad et al. (2019)[28] investigated the catalytic pyrolysis of plastic waste made of polyethylene (PE) and polypropylene (PP). The study showed that the resulting liquid oil contains aromatic compounds, olefins, and naphthalene. These findings underscore the complex nature of the chemical composition of pyrolysis oils derived from waste plastics. These oils consisted of a wide array of hydrocarbons and aromatic compounds. Wiangkham et al. (2023)[47] showed that middle distillate hydrocarbons make up most of waste pyrolysis oil (WPO) (26.15% C19–C23 and 52.58% C13–19). With reduced specific gravity, density, and flash point, WPO nevertheless meets diesel fuel requirements for kinematic viscosity and cetane index. In another study on thermal catalytic cracking reactions, Nwankwor et al. (2021)[36] utilized zeolite and titanium (IV) oxide (TiO_2) in a fixed bed to produce gasoline-grade hydrocarbon fuels from waste plastics such as low-density polyethylene (LDPE), polyvinyl chloride (PVC), and polystyrene (PS). The pyrolysis oil contained C5 (1,2-dimethylcyclopropane), C6 (2-methylpentane), C7 (1,3-dimethylcyclopentane, 1-heptane), and C8 (2-octane, 4-octane, octane, 3-ethyl hexane). The study discovered that polystyrene cracking without any catalyst produced the lowest liquid yield, at 3.9%, while polystyrene cracking with a zeolite catalyst produced the highest liquid yield, reaching 89.3%. Moreover, Nisar and colleagues' investigation in 2019[37] delved into waste polystyrene (PS) sourced from landfills within a local market. They subjected this waste material to pyrolysis using a locally constructed furnace operating between 340 and 420 °C. The resulting pyrolysis oil displayed a diverse array of hydrocarbons ranging from C2 to C15, contingent upon the specific pyrolysis conditions. When the pyrolysis oil's composition was compared to the accepted ranges for diesel, gasoline, and kerosene, it became clear that the waste polystyrene-derived pyrolysis oil had a lot of potential as a fuel oil substitute.

4. Conclusions

Research conducted on pyrolysis oil derived from plastic waste produced by BWB shows that pyrolysis plastic generally met the quality standards of diesel oil 48,

except for density and color parameters. The cetane number and sulfur content were 48.6 and 890% m/m, respectively. The chemical composition showed that this fuel contained 54.46% aliphatic compounds, 22.85% aromatics, and 22.69% oxygenates. The complex chemical composition of this substance, which included aromatic compounds and a wide variety of mainly aliphatic hydrocarbons, made it suitable for use as a fuel in various applications. Pyrolysis oil, produced from plastic waste by BWB, has shown potential as an alternative fuel. These findings show the potential of plastic pyrolysis oil to be an alternative fuel, fulfilling diesel fuel specifications and promising as a substitute for fuel oil. The diverse composition of pyrolysis oil highlights its versatility and its potential to contribute to sustainable fuel production, reducing dependence on traditional fossil fuels. Overall, the findings indicate that pyrolysis oil derived from plastic waste has the potential to serve as a valuable resource for producing environmentally friendly and efficient alternative fuels. However, further research and development are required to optimize its production (especially degrading oxygenate compounds) and utilization.

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