



ARTIKEL PENELITIAN

Physical properties and GC/MS analysis of pyrolysis oil from tire and plastic waste (HDPE/high-density polyethylene and PP/polypropylene)

Al Buchori Nur Fajar¹, Niken Safitri¹, Khoirina Dwi Nugrahaningtyas^{1,*}

¹Department of Chemistry, Faculty of Mathematics and Natural Science, Universitas Sebelas Maret, Jalan Ir. SUtami 36 Kentingan, Jebres, Surakarta Jawa Tengah, 57126, Indonesia

Received 28 March 2024; revised 05 June 2024; accepted 07 June 2024



OBJECTIVES The objective of this research is to determine the physical properties and chemical composition of the pyrolysis oil (PO) derived from waste tires and plastics (HDPE and PP), and to compare these characteristics with commercial fuels such as gasoline, kerosene, and diesel. **METHODS** Pyrolysis was carried out at 350°C for 4 hours. The produced PO is divided into two types, PO collected in a container (PO C) and PO collected in a tar trap (PO T). **RESULTS** The result shows that the physical properties of PO HDPE C are similar to gasoline with a density of 0.807 g/mL, dynamic viscosity of 0.623 cP, and kinematic viscosity of 0.771 cSt. However, its calorific value is still very low. PO PP C has a calorific value almost comparable to commercial fuel of 38.24 MJ/kg. Meanwhile, the physical properties of PO tires do not meet the required characteristics of fuel. GC/MS analysis reveals that Tire C1 (organic phase) has a high content of olefin and aromatic compounds, around 39.29% and 27.91% respectively. PO HDPE C and PO PP has relatively high content of paraffin and olefin groups but lacks aromatic compounds. However, PO PP has the highest paraffin content among other POs, about 66.55%. **CONCLUSIONS** The paraffin content in all commercial fuels tends to be the highest because paraffin provides the most energy during combustion. Therefore, PP derived Pyrolysis Oil is suggested to be more value added compared to other PO for use as fuel.

KEYWORDS plastic waste pyrolysis; pyrolysis; tires waste pyrolysis

1. INTRODUCTION

World energy reserves continue to change along with advances in technology, exploration, and global energy needs. The use of fossil fuels as the main energy source is increasingly rare and expensive. In addition, the use of fossil fuels is unfavorable for environmental, remembering the emissions produced are the main contributor of greenhouse gases emissions and these materials are non-renewable (Environmental Protection Agency (EPA) 2021; Karmaker et al. 2020). Meanwhile, increasing waste production makes a landfill became increasingly full (Subekti et al. 2023).

Pyrolysis is a thermal decomposition process that converts materials in high temperatures and vacuum condition or less of oxygen (Thahir et al. 2021), so that CO₂ emission levels are low and pollutants can be minimized (Dai et al. 2022). The result of this process is solid, liquid and gaseous. The solid product is a charcoal, the liquid product are tar and oil, and the gaseous product is synthesis gas (syngas) (Pappari et al. 2021). The yield of pyrolysis products also depends on the temperature applied. Research by Garcia-Perez et al. (2008) demonstrated that pyrolysis at temperatures of 450-475°C produces the highest amount of oil. Temperatures of 350-450°C yield more charcoal than oil, while pyrolysis at temperature above 500°C results in a higher production of gas. Additionally, variations in pyrolysis temperature result in oil with chemical components that do not differ significantly (Figueiredo et al. 2009).

Pyrolysis oil is one the most valuable pyrolysis product because it is potentially used as fuel. This oil can be a more sustainable alternative to fossil fuels, remembering materials obtained from renewable sources (Bharath et al. 2020). However, further studies are needed to ensure the quality and performance of pyrolysis oil. Characterizing the oil is a crucial initial step in assessing its efficiency and safety for use as fuel. Comprehensive analysis of physical properties such as density, viscosity, calorific value (Ra et al. 2008) and flammability (Rivera et al. 2012) is necessary, as these factors affect engine combustion (Ra et al. 2008). Additionally, identifying the chemical composition and presence of hazardous compounds or pollutants is essential to determine the potential risks associated with the use of pyrolysis oil (Mishra and

*Correspondence: khoirinadwi@staff.uns.ac.id

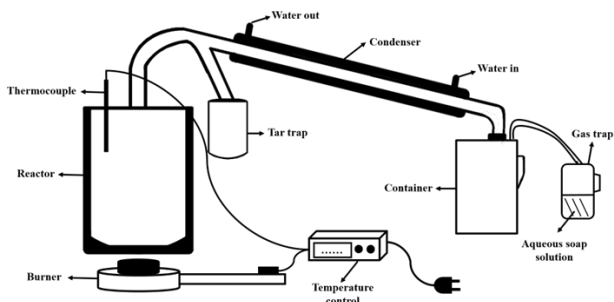


FIGURE 1. Schematic of the pyrolysis equipment.

Mohanty 2022).

The chemical compound content in pyrolysis oil depends on the type of raw material (Olalo 2021). Generally, the main content in this oil is a volatile hydrocarbon as a fuel component (Bharath et al. 2020). In research by Umeki et al. (2016) tire pyrolysis oil contains C7-C14 with the largest percentage of single ring alkyl-benzene and polycyclic aromatics. The calorific value obtained of 42 MJ/kg, the dynamic viscosity of 5.39 cP at 20°C, and the density of 0.930 g/cm³ that enable to be applied as fuel. HDPE plastic pyrolysis oil has a calorific value of 40.50 MJ/kg, the viscosity of 5.08 cSt at 40°C, and the density of 0.890 g/cm³ at 15°C. PP plastic pyrolysis oil has a calorific value of 40.80 MJ/kg, the viscosity of 4.09 cSt at 40°C, and the density of 0.860 g/cm³ at 15°C that similar to the properties of conventional diesel (Maqsood et al. 2021). To understand the extent to which pyrolysis oil can be used as fuel, it is necessary to compare its characteristics with those of commercial fuels such as gasoline, kerosene, and diesel. The results of this comparison will provide insight into the advantages and disadvantages of pyrolysis oil, allowing for its potential application as a fuel.

Pyrolysis technology offers attractive innovation by recycling various types of waste, including rubber, plastic, and biomass to be high-value products (Dai et al. 2022; Wang et al. 2020). Pyrolysis can be a good solution not only related to the requirements of sustainable energy needs, but also to solve waste problems (Sharma et al. 2021). In this research, some various raw materials as waste motorcycle tires and plastic High-Density polyethylene (HDPE) and polypropylene (PP) waste. The objective of this research is to characterize the pyrolysis oil produced from tires and plastic waste and to evaluate its suitability for use as commercial fuels such as gasoline, kerosene, or diesel.

2. RESEARCH METHODOLOGY

TABLE 1. Pyrolysis oil products obtained.

Raw material	Container	Tar trap
Tire	Tire C1 (organic phase)	Tire T
	Tire C2 (aqueous phase)	
HDPE	HDPE C	HDPE T
PP	PP C	PP T

2.1 Tools and materials

Various tools were employed in this research, including pyrolysis equipment system, pycnometer, viscometer Oswald, separating funnel, and an analytical balance. In addition, some instrument such as bomb calorimeter and Gas Chromatography/Mass Spectrometry were employed. Meanwhile, the materials used in this research are waste motorcycle tires, waste plastics of HDPE (High-Density Polyethylene) and PP (Polypropylene), and deionized water.

2.2 Pyrolysis process

The pyrolysis process is carried out on two types of raw materials, that is tires and plastic waste (HDPE and PE). The tire waste is from used motorcycles tires, while the HDPE plastic used comes from colored plastic bag waste, and the PP plastic from laundry plastic waste. The pyrolysis conditions are applied with the same treatment of all starting materials. Before initiate the pyrolysis process, both used tires and plastic waste are cut into small pieces with each raw material weighing about 4 kg. After cutting, the raw materials are washed and dried under sunlight for a day to remove impurities. Subsequently, the material is inserted into the reactor, and the reactor is sealed tightly. The system is made airtight to prevent the entry of oxygen. The pyrolysis process is conducted for 4 hours by controlling the reactor temperature using a thermocouple. Pyrolysis is conducted at a temperature of 350°C for energy efficiency.

The pyrolysis products are generated and collected in four vessels, that are container, tar trap, and gas trap, as well as producing charcoal that remains in the reactor (see Figure 1). Container are used to collect the pyrolysis oil products, while tar traps are used to collect the tar products formed. However, it is possible that some of the pyrolysis oil products may condense early and enter the tar trap. The gas trap is added with a soap solution to trap the gases formed so they do not escape and pollute the environment. This study focuses on characterizing the pyrolysis products, specifically the oil, found in the container and tar trap.

2.3 Physical properties analysis

2.3.1 Density analysis

Density (specific gravity) is a measure of the ratio of mass of an object per unit volume. The analysis is conducted to determine the molecular density of POT and POP. The density analysis utilizes a 5 mL-sides pycnometer. The analysis including the blank (deionized water) and all PO samples. The density calculation is performed using the following equation.

$$\rho = \frac{W1 - W0}{v} \tag{1}$$

Where:

1. ρ = density (g/mL)
2. W0 = weight of pycnometer (g)
3. W1 = weight of pycnometer + sample (g)
4. v = sample volume (mL)

2.3.2 Viscosity analysis

Viscosity analysis is carried out to determine the viscosity of POT and POP. The viscosity analysis is conducted using an

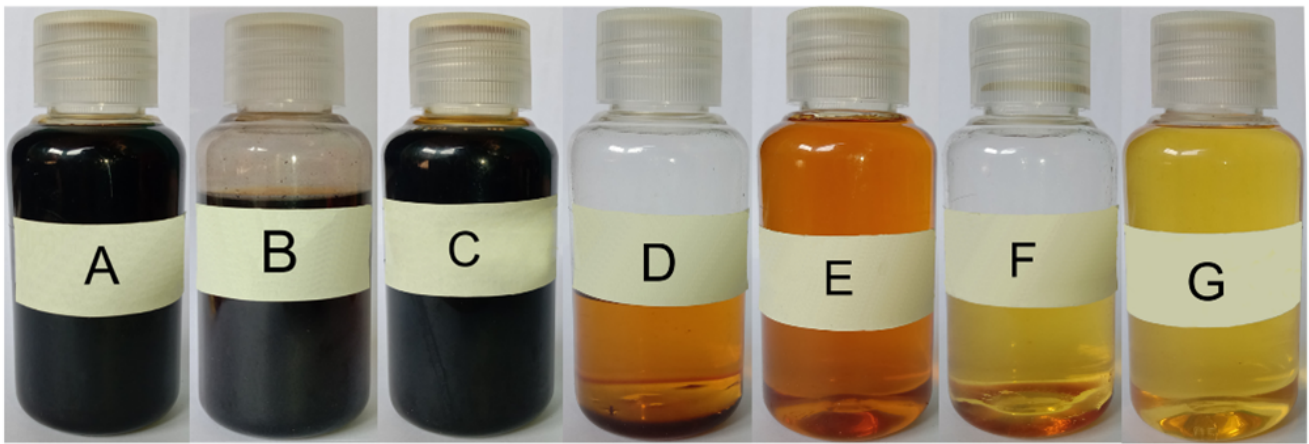


FIGURE 2. Pyrolysis products of Tire C1 (A), Tire C2 (B), Tire T (C), HDPE C (D), HDPE T (E), PP C (F), and PP T (G).

Ostwald viscometer with deionized water as the reference substance at a temperature of 30 °C. The viscosity analysis including dynamic and kinematic viscosity. Dynamic viscosity is calculated using the following equation.

$$\mu = \mu_0 \frac{t_1 - \rho_1}{t_0 - \rho_0} \tag{2}$$

Where:

1. μ = dynamic viscosity of sample (cP)
2. μ_0 = dynamic viscosity of the reference substance (cP)
3. t_1 = sample flow time (s)
4. ρ_1 = sample density (g/mL)
5. t_0 = flow time of the reference substance (s)
6. ρ_0 = density of the reference substance (g/mL)

Meanwhile, kinematic viscosity is calculated using the follow-

ing equation.

$$v = \frac{\mu}{\rho} \tag{3}$$

Where:

1. v = kinematic viscosity of the sample (cSt)
2. μ = dynamic viscosity of the sample (cP)
3. ρ = sample density (g/mL)

2.3.3 Calorific analysis

Analysis of the calorific value of pyrolysis products is conducted using bomb calorimeter. The purpose of this analysis is to determine the heat of fusion value of pyrolysis product. This information is crucial for determining the quality and efficiency properties of the fuel in the pyrolysis oil.

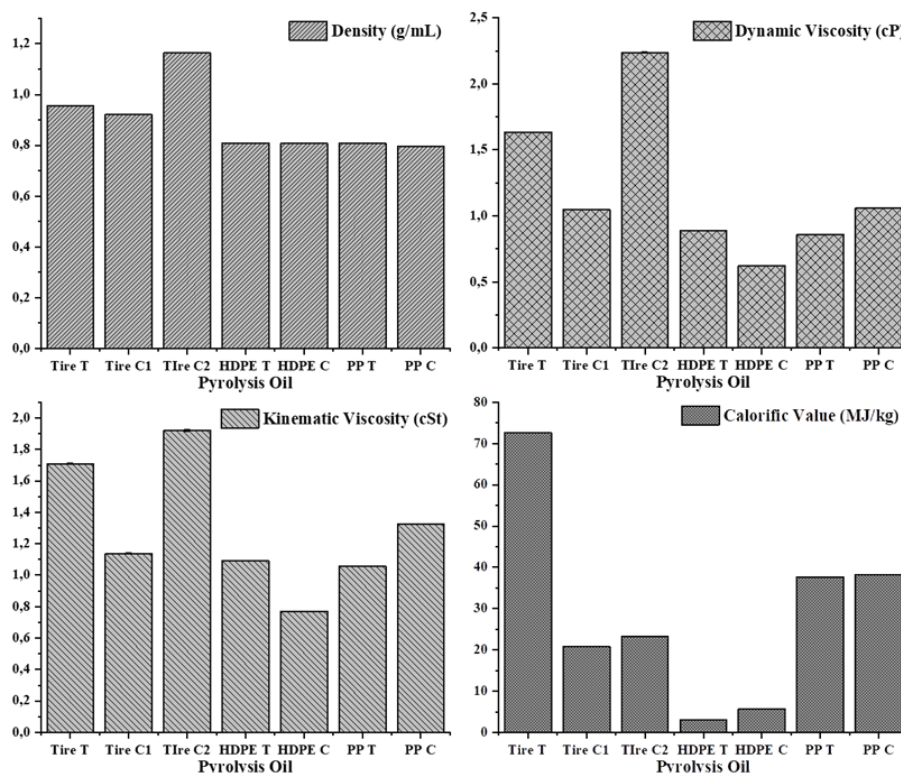


FIGURE 3. Experiment results for the physical properties analysis of pyrolysis oil.

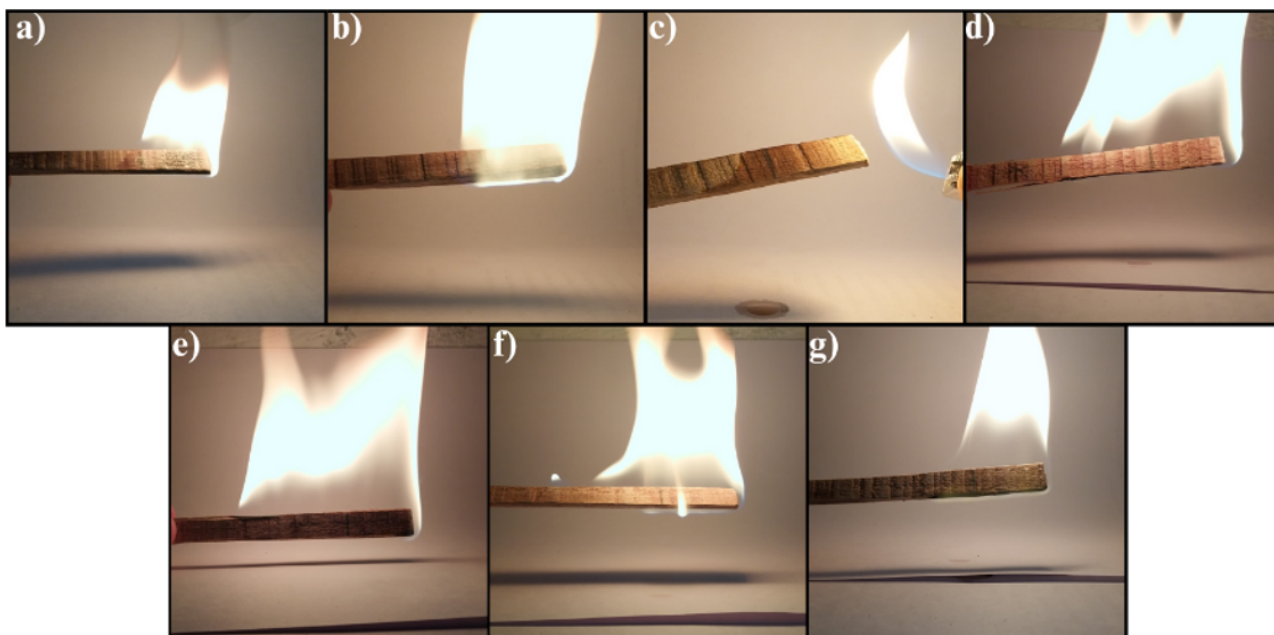


FIGURE 4. Experiment results for the flash point test of PO Tire T (a), Tire C1 (b), Tire C2 (c), HDPE T (d), HDPE C (e), PP T (f), and PP J (g).

2.3.4 Flammability test

The flammability test is conducted to determine how easily the pyrolysis oil can be ignited by flame. The flash point analysis is performed in a simple manner by igniting PO products using an open flame. A wooden stick is dipped into the pyrolysis oil with a depth of 2.50 cm, and then it is ignited using flame. The results of the flash point analysis on the pyrolysis oil are identified based on whether a flame occurs or not, serving as an indicator.

2.4 GC/MS analysis

Gas Chromatography-Mass Spectrometry (GC-MS) analysis is performed to identify the chemical compound present in the pyrolysis oil (PO). The GC-MS instrument used is the QP2010S Shimadzu. The capillary column employed is the Agilent DB-5MS with a length of 30 m, internal diameter (ID) of 0.250 mm, and a film thickness of 0.250 μm . The analysis process starts at an initial temperature of 40°C with a hold time of 4 minutes, followed by a column temperature increase until it reaches 300°C. Helium (He) is used as the carrier gas at a constant flow rate of 0.780 mL/min.

rier gas at a constant flow rate of 0.780 mL/min.

3. RESULTS AND DISCUSSION

The pyrolysis process in this research was influenced by the conditions during pyrolysis, particularly high temperatures for decomposing these materials. Higher temperatures can speed up the process, although they require a sufficiently high heat energy input. In this research, pyrolysis was carried out at temperature of 350°C, at which point the raw material can undergo decomposition. For the purpose of characterizing pyrolysis oil (PO), this temperature is chosen for energy efficiency, and variations in pyrolysis temperature do not significantly affect the chemical composition of the PO (Figueiredo et al. 2009). Prior to the pyrolysis process, tires and plastic waste are washed and dried first to remove the impurities. If not cleaned, impurities in the raw materials can evaporate and condense, contaminating the (PO). Contaminants can cause changes in the characteristic of the PO. Table 1 below shows the products obtained to facilitate understanding in naming the pyrolysis oil products.

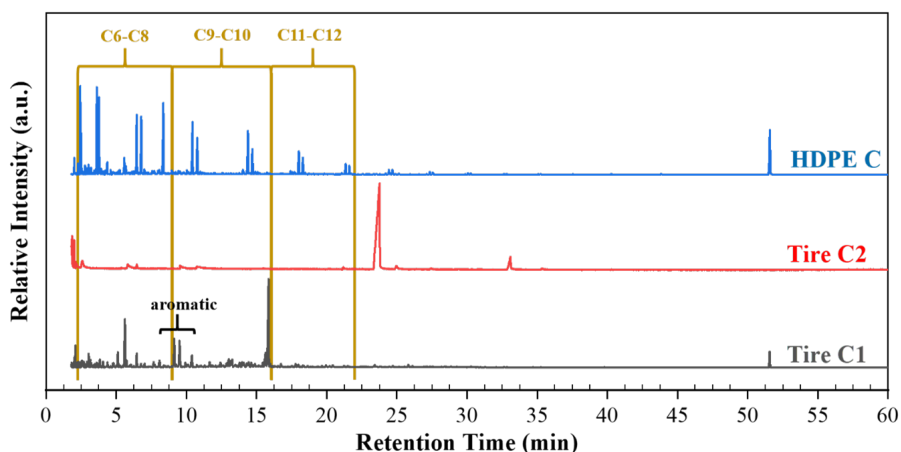


FIGURE 5. GC/MS chromatogram of Tire C1, Tire C2, and HDPE C.

TABLE 2. Pyrolysis oil products obtained.

Chemical compound	Chemical formula	% Area		
		Tire C1	Tire C2	HDPE C
1-hexane	C ₆ H ₁₄	0.46	-	2.07
1-heptane	C ₇ H ₁₆	0.42	-	6.25
1-octane	C ₈ H ₁₈	-	-	6.68
1-nonane	C ₉ H ₂₀	0.33	-	4.13
1-decane	C ₁₀ H ₂₂	0.31	-	-
Dodecane	C ₁₂ H ₂₆	-	-	6.33
4-methyl heptane	C ₈ H ₁₈	-	-	1.99
2,2,4-trimethyl pentane	C ₈ H ₁₈	1.28	-	-
2,4-dimethyl heptane	C ₉ H ₂₀	-	-	0.34
4-methyl decane	C ₁₁ H ₂₄	-	-	0.53
Methyl cyclopentane	C ₆ H ₁₂	0.43	-	1.02
1,2,3-trimethyl cyclopropane	C ₆ H ₁₂	0.46	-	-
Methyl cyclohexane	C ₇ H ₁₄	-	-	1.67
Ethyl cyclohexane	C ₈ H ₁₆	-	-	0.45
1,4-dimethyl cyclohexane	C ₈ H ₁₆	0.54	-	-
1,3,5-trimethyl cyclohexane	C ₉ H ₁₈	-	-	0.78
1-heptene	C ₇ H ₁₄	0.47	-	7.18
2-heptene	C ₇ H ₁₄	-	-	0.85
1-hexene	C ₆ H ₁₂	0.43	-	5.58
1-octene	C ₈ H ₁₆	-	-	8.2
1-nonene	C ₉ H ₁₈	-	-	7.51
1-decene	C ₁₀ H ₂₀	0.3	-	5.46
Dodecene	C ₁₂ H ₂₄	-	-	2.02
Undecene	C ₁₁ H ₂₂	-	-	2.77
2-methyl-2-butene	C ₅ H ₁₀	1.51	-	-
3-methyl-2-pentene	C ₆ H ₁₂	0.69	-	-
2,3-dimethyl-2-butene	C ₆ H ₁₂	0.51	-	-
2,4-dimethyl-1-pentene	C ₇ H ₁₄	-	-	0.66
2,3,4-trimethyl-2-pentene	C ₈ H ₁₆	0.63	-	-
Dimethyl heptene	C ₉ H ₁₈	-	-	8.97
4,6,8-trimethyl nonene	C ₁₂ H ₂₄	0.87	-	-
3-methyl cyclopentene	C ₆ H ₁₀	0.27	-	-
3-ethyl cyclopentene	C ₇ H ₁₂	0.36	-	-
3,5-dimethyl cyclopentene	C ₇ H ₁₂	2.27	-	1.18
Cyclohexene	C ₆ H ₁₀	0.36	-	0.28
1-methyl cyclohexene	C ₇ H ₁₂	0.58	-	0.74
1,3-dimethyl cyclohexene	C ₈ H ₁₄	2.49	-	-
Decadiene	C ₁₀ H ₁₈	-	-	0.56
Undecadiene	C ₁₁ H ₂₀	-	-	0.39
1,4-hexadiene	C ₆ H ₁₀	0.45	-	-
2,4-hexadiene	C ₆ H ₁₀	1.54	-	-
1,7-octadiene	C ₈ H ₁₄	-	-	0.27
2-methyl-1,3-butadiene	C ₅ H ₈	0.71	-	-
2-methyl-1,4-hexadiene	C ₇ H ₁₂	1.07	-	-
4,4-dimethyl-1,2-pentadiene	C ₇ H ₁₂	0.91	-	1.02
3-methyl-1,3,5-hexatriene	C ₇ H ₁₀	2.15	-	-
2,5,6-trimethyl-1,3,6-heptatriene	C ₁₀ H ₁₆	0.69	-	-
Benzene	C ₆ H ₆	1.16	-	-
Ethyl benzene	C ₈ H ₁₀	4.58	-	-
Dimethyl benzene	C ₈ H ₁₀	7.91	-	-
Trimethyl benzene	C ₉ H ₁₂	2.13	-	-
Propyl benzene	C ₉ H ₁₂	5.01	-	-
Toluene	C ₇ H ₈	7.12	-	-
Limonene	C ₁₀ H ₁₆	20.03	-	-
Others	-	28.57	100	14.12
Total				
Paraffins		2.8	-	28.32
Naphthenes		1.43	-	3.92
Olefins		39.29	-	53.64
Aromatics		27.91	-	-

A total of seven PO product were obtained that are collected from the tar trap (PO T) and container (PO C). In the container, these tire-derived POs were separated into two immiscible layers, Tire C1 and Tire C2. Tire pyrolysis generally

produces two separate layers. This is due to the complexity of the compounds that make up tires. These layers are the aqueous phase (bottom layer) and the organic phase (upper layer). The organic phase contains a lot of oil, while the aque-

TABLE 3. Pyrolysis oil products obtained.

Hydrocarbon groups	Chemical composition (%)						
	Tire C1	Tire C2	HDPE C	PP ^a	Kerosene ^b	Gasoline ^c	Diesel ^d
Paraffins	2.8	-	28.32	66.55	~55.20	29-48	~75
Naphthenes	1.43	-	3.92	7.58	~40.90	7-Mar	-
Olefins	39.29	-	53.64	25.87	-	5-Feb	-
Aromatics	27.91	-	-	-	~3.90	20-50	~25

Sources:

^a Ahmad et al. (2014)^b Energy Education^c Hussain (2022)^d Agency for Toxic Substances and Disease Registry (ATSDR) (1995)

ous phase generally contains a lot of aldehydes, ketones, and phenolic compounds (Shen et al. 2021).

The PO products exhibit distinct characteristics. PO T tends to have a darker color than PO C. PO T contains a mixture of tar and oil that condenses earlier, resulting in a higher content of heavy products. Figure 2 illustrates that the PO from tires, both Tire T and Tire C, has a darker color compared to PO from plastics. This can be explained by components in tires such as rubber, carbon black, and filler (Alsaleh and Sattler, 2014), which contribute to the black color of tire-derived PO. On the other hand, PO from plastics, both HDPE and PP, exhibits a clearer color. This is due to the fact that both types of plastic contain a higher proportion of unsaturated hydrocarbon and typically has fewer impurities. HDPE and PP plastics can produce PO with a clear color even at high pyrolysis temperatures (Fulgencio-Medrano et al. 2022). It is important to note that commercial fuels such as gasoline, diesel, and kerosene typically have a clear color, aligning with the characteristics of the PO produced from HDPE and PP plastics.

3.1 Physical properties analysis

Physical property analysis aims to evaluate various physical parameters of pyrolysis oil to determine the characteristics of the oil produced. The density, viscosity, calorific value, and flash point were analyzed. Figure 3 below illustrates the results of the physical property analysis of PO.

3.1.1 Density

From figure 3, it is evident that Tire C2 has the highest density, specifically 1.16 g/mL, while PP C has the lowest density, amounting to 0.796 g/mL. When compared to the density of commercial fuels, such as gasoline with a density in the range of 0.715-0.850 g/mL, diesel is around 0.820-0.850 g/mL, and kerosene is approximately 0.780-0.810 g/mL (Damayanti et al. 2023; Vempatapu et al. 2019). PO from plastics, both HDPE and PP, shows densities similar to gasoline and kerosene, around 0.807-0.809 g/mL and 0.796-0.809 g/mL respectively. In contrast, all PO tires have densities significantly different from the three commercial fuels. Tire-derived PO tends to contain heavy products such as high carbon deposits and tar, resulting in higher density. The presence of these heavy fractions is undesirable in combustion engines due to incomplete combustion, leading to the formation of carbon and tar deposits on the engine's internal surfaces (Wądrzyk et al. 2020). Therefore, understanding PO density is key in evaluating this potential as an alternative fuel.

3.1.2 Viscosity

The viscosity analysis indicates that both dynamic and kinematic viscosities of PO derived from tires tend to be higher than those PO from plastics. Dynamic viscosity is a measure of a fluid's resistance or friction to flow under externally applied forces. This parameter has a significant impact on the fuel's performance as it influences the fuel's ability to flow, atomize, and undergo combustion processes (Martyr and Rogers 2021). In this context, the dynamic viscosity of kerosene is approximately 1.54 cP (The Engineering Tool-Box 2008), gasoline is around 0.600 cP (The Engineering Tool-Box 2023), and diesel is about 3.35 cP (Hartman 2015), measured at room temperature. Tire-derived PO, especially Tire T, exhibits dynamic viscosity close to kerosene, about 1.63 cP, while HDPE C approaches the viscosity of gasoline, about 0.623 cP. For comparison, the dynamic viscosity of diesel remains significantly higher than all PO products.

Unlike dynamic viscosity, kinematic viscosity measures a fluid's internal resistance to flow under the influence of gravity (Troyer 2002). Commercial fuels contain specific chemical components with high purity, resulting in specific kinematic viscosities. The kinematic viscosity of gasoline is in the range of 0.710-0.880 cSt (The Engineering ToolBox 2003), kerosene is around 2 cSt (Dusling), and diesel is approximately 4.09 cSt (Hartman, 2015). HDPE C has kinematic viscosity similar to gasoline, around 0.771 cSt, while Tire C2 approaches the kinematic viscosity of kerosene, around 1.92 cSt. However, the kinematic viscosity of the other POs differs from the commercial fuels.

3.1.3 Calorific value

Calorific analysis is used to determine the amount of energy contained in PO and provides insights into energy efficiency and its potential as an alternative fuel. From figure 3, it can be observed that Tire T has the highest calorific value, about 72.54 MJ/kg, while HDPE T has the lowest calorific value, about 3.07 MJ/kg. Pyrolysis of tires can result in PO with a high calorific value due to the complexity of the tire composition that breaks down at high temperatures, forming heavy products. Tire C1 and C2 tend to have lower calorific values due to their relatively high-water content. This also applies to HDPE-derived PO, which has the lowest calorific value. The presence of water in the PO can be attributed to moisture in the raw materials, this water content in PO can reduce the calorific value as energy during combustion is used to vaporize water. In contrast, PP-derived PO has a relatively high calorific value. The calorific values of gasoline are 47.30 MJ/kg, diesel is 46.50 MJ/kg, and kerosene is

43 MJ/kg (Damayanti et al. 2023). Among the POs obtained, the calorific values of PP T and PP C approach the calorific value of kerosene, about 37.67 MJ/kg and 38.23 MJ/kg respectively, indicating their potential as alternative fuels with a sufficiently high calorific value.

3.1.4 Flammability test

The flammability test is a simple yet important analysis in understanding the characteristics of PO. This test provides information about the flammability of PO when exposed to an open flame. Fuels containing volatile compounds that are generally highly flammable. Figure 4 below shows the appearance of PO when burned by an open flame.

Based on Figure 4, it is evident that all pyrolysis oils can ignite when exposed to an open flame, except for Tire C2. This indicates that the overall PO products have potential uses as fuel. Tire C2 likely contains a significant amount of water, preventing it from burning. Factors such as higher density compared to other POs, the presence of non-combustible heavy components, and a lack of volatile compounds in Tire C2 may contribute to its inability to burn.

3.2 GC/MS analysis

Gas Chromatography/Mass Spectrometry (GC/MS) is a highly valuable analytical method for identifying the chemical components present in pyrolysis oil (PO). GC/MS is not only capable of identifying the chemical compounds in PO, but also measuring the concentrations of these compounds. Figure 5 below shows the GC/MS chromatogram of several PO products.

The GC/MS chromatogram shows several peaks indicating the presence of each chemical component in the pyrolysis oil. In Tire C1, 95 components were identified, Tire C2 had 14 components, and HDPE C had 61 components. These chemical components are categorized as paraffin (including iso-paraffins), naphthenes, olefin, aromatic (containing at least one aromatic ring), and other components besides these four groups. This categorization is based on the major components found in fuels. Gasoline typically consists of a mixture of C4-C12 hydrocarbons, kerosene consists of C6-C12, while diesel consists of C8-C21 or more (Malik et al., 2013). More specifically, gasoline has paraffin content up to 48%, naphthenes 3-7%, olefin 2-5 %, and aromatic 20-50 % (Hussain, 2022). Kerosene has paraffin content of 55.20 %, naphthenes 40.90 %, and aromatic 3.90 % (Energy Education). Meanwhile, diesel consists of paraffins 75% and aromatics 25% (ATSDR, 1995). Tables 2 below show the chemical components identified in Tire C1, Tire C2, and HDPE C.

Table 2 shows that the chemical composition of Tire C1 (organic phase) is predominantly composed of the olefin group, reaching 39.29%. Aromatics are also present in a significantly substantial amount, accounting for 27.91%, while the paraffin content are present in a relatively small amount, at 2.80%, and naphthenes at 1.43%. The high content of olefins in engine fuels can be problematic as olefin compounds tend to accumulate and form deposits in the fuel system (Ahadiat and Semar 2022). Therefore, olefin content in fuels is typically kept low to maintain engine cleanliness. On the other hand, paraffin content can enhance fuel ignition quality, while aromatics have a high-octane number, allow-

ing the fuel to be compressed more before ignition (Petrochemical Chemical & Energy 2019). Tire C1 has a high olefin, which may not be favorable for engine cleanliness. Tire C1 contains limonene (monoterpene olefin), with a content of approximately 20%. This compound is a major product generated from the pyrolysis of rubber, including tires (Pakdel et al. 2001). Although limonene is not found in commercial fuels, it has potential as a bio-additive due to its ability to increase the calorific value of fuels (Kumar et al. 2022).

The chemical composition of Tire C2 differs significantly from Tire C1 (see Table 2). None of the three functional groups were detected. This strongly supports the suspicion that there are no volatile compounds present in Tire C2 (aqueous phase). Hence, the flash point test for Tire C2 indicates that this PO cannot burn when exposed to an open flame. The highest compound detected in Tire C2 is caprolactam, with percentage of 78%. This compound is not commonly found in fuels. Additionally, other compounds such as acetic acid, propanone, and cyclopentanone were detected. This is consistent with the literature that the aqueous phase in tire pyrolysis contains a lot of ketones (Shen et al. 2021).

PO HDPE C, derived from plastic, has major compounds in the form of paraffins and olefins, with 53.64% belonging to the olefin group (Table 2). Similar to Tire C1, a high content of olefins in the fuel is not favorable for engine cleanliness. Meanwhile, the paraffin content in HDPE C is significantly higher than in Tire C1. However, there is no presence of aromatics in HDPE C. Other compounds, such as dioctyl phthalate and heptadienol, are present at 14.12%.

According to the research by Ahmad et al. (2014), PO PP contains 66.55% paraffin, 7.58% naphthenes, 25.87% olefin, and no aromatic compounds. This data was obtained from PP pyrolysis at temperature ranging from 250-400°C without the use of a catalyst. PO PP has a higher paraffin and naphthenes content, and a lower olefin content than PO HDPE C.

Table 3 shows the comparison of the chemical composition between PO and commercial fuels. Although commercial fuels contain varying compounds, paraffin compounds exhibit the highest concentration. The paraffin group provides higher energy compared to other groups during combustion (Ahmad et al. 2014). PO PP has the highest paraffin content compared to other POs, making PP-derived PO the most promising for use as fuel.

4. CONCLUSIONS

In this research, pyrolysis oil (PO) derived from tires and plastic waste demonstrates potential to be utilize as an alternative engine fuel. Physical property analysis reveals that PO HDPE C exhibits physical properties similar to gasoline, with a density of 0.807 g/mL, dynamic viscosity of 0.623 cP, and kinematic viscosity of 0.771 cSt. However, the calorific value of HDPE C is significantly lower compared to gasoline, at 5.71 MJ/kg. PO PP C approaches the calorific value of commercial fuels, reaching 38.24 MJ/kg. Unfortunately, all tire-derived POs exhibit physical properties and calorific value that do not meet fuel criteria. GC/MS analysis reveals that Tire C1 has a high content of olefin and aromatic compounds, around 39.29% and 27.91% respectively. Tire C2 contains very small amount of chemical compounds typical of fuel. PO HDPE C and PO PP has relatively high content of paraffin and olefin

groups but lacks aromatic compounds. However, PO PP has the highest paraffin content among other POs, about 66.55%. The paraffin content in all commercial fuels tends to be the highest because paraffin provides the most energy during combustion. Therefore, PP derived Pyrolysis Oil is suggested to be more value-added for use as fuel.

5. ACKNOWLEDGEMENTS

We are grateful for the financial support provided by UP-KKN UNS, the village head of Gentan, Baki, Sukoharjo for the opportunity, and Damacasta, Fadhia, Farhan, Muhammad David, Khoirunnisa, Galih, Nova, and Vicky for all assistance.

REFERENCES

- Agency for Toxic Substances and Disease Registry (ATSDR). 1995. Toxicological profile for fuel oils. Technical report.
- Ahadiat N, Semar D. 2022. The influence of olefin content in gasoline against deposit build up on intake valve of motor bike engine. *Scientific Contributions Oil and Gas*. 33(1):52–58. doi:10.29017/scog.33.1948. <http://dx.doi.org/10.29017/scog.33.1948>.
- Ahmad I, Khan MI, Khan H, Ishaq M, Tariq R, Gul K, Ahmad W. 2014. Pyrolysis study of polypropylene and polyethylene into premium oil products. *International Journal of Green Energy*. 12(7):663–671. doi:10.1080/15435075.2014.880146. <http://dx.doi.org/10.1080/15435075.2014.880146>.
- Bharath G, Hai A, Rambabu K, Banat F, Jayaraman R, Taher H, Bastidas-Oyanedel JR, Ashraf MT, Schmidt JE. 2020. Systematic production and characterization of pyrolysis-oil from date tree wastes for bio-fuel applications. *Biomass and Bioenergy*. 135:105523. doi:10.1016/j.biombioe.2020.105523. <http://dx.doi.org/10.1016/j.biombioe.2020.105523>.
- Dai L, Zhou N, Lv Y, Cheng Y, Wang Y, Liu Y, Cobb K, Chen P, Lei H, Ruan R. 2022. Pyrolysis technology for plastic waste recycling: A state-of-the-art review. *Progress in Energy and Combustion Science*. 93:101021. doi:10.1016/j.peccs.2022.101021. <http://dx.doi.org/10.1016/j.peccs.2022.101021>.
- Damayanti Z, Sudarti S, Yushardi Y. 2023. Analisis karakteristik fuel pirolisis sampah plastik berdasarkan jenis plastik yang digunakan: Review. *Jurnal Inovasi Teknik Kimia*. 8(1):26. doi:10.31942/inteka.v18i1.8092. <http://dx.doi.org/10.31942/inteka.v18i1.8092>.
- Dusling K. ????. Properties of common liquids at room temperature and pressure. <https://kdusling.github.io/teaching/Applied-Fluids/PropertiesOfCommonLiquids.html>.
- Energy Education. ????. Kerosene. <https://energyeducation.ca/encyclopedia/Kerosene>.
- Environmental Protection Agency (EPA). 2021. Sources of greenhouse gas emissions. Technical report.
- Figueiredo MK, Romeiro GA, Damasceno RN. 2009. Low temperature conversion (LTC) of castor seeds—A study of the oil fraction (pyrolysis oil). *Journal of Analytical and Applied Pyrolysis*. 86(1):53–57. doi:10.1016/j.jaap.2009.04.006. <http://dx.doi.org/10.1016/j.jaap.2009.04.006>.
- Fulgencio-Medrano L, García-Fernández S, Asueta A, Lopez-Urionabarrenechea A, Perez-Martinez BB, Arandes JM. 2022. Oil production by pyrolysis of real plastic waste. *Polymers*. 14(3):553. doi:10.3390/polym14030553. <https://pubmed.ncbi.nlm.nih.gov/35160542https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8838440/>.
- Garcia-Perez M, Wang XS, Shen J, Rhodes MJ, Tian F, Lee WJ, Wu H, Li CZ. 2008. Fast pyrolysis of oil mallee woody biomass: effect of temperature on the yield and quality of pyrolysis products. *Industrial & Engineering Chemistry Research*. 47(6):1846–1854. doi:10.1021/ie071497p. <http://dx.doi.org/10.1021/ie071497p>.
- Hartman J. 2015. Kinematic and dynamic viscosity of diesel, biodiesel, and JP-900 compared to other non-standard fluids with a demonstration of viscosity changes at varying temperatures. [Undergraduate report]: Pennsylvania State University, Philadelphia.
- Hussain N. 2022. Properties of gasoline fuel.
- Karmaker AK, Rahman MM, Hossain MA, Ahmed MR. 2020. Exploration and corrective measures of greenhouse gas emission from fossil fuel power stations for Bangladesh. *Journal of Cleaner Production*. 244:118645. doi:10.1016/j.jclepro.2019.118645. <http://dx.doi.org/10.1016/j.jclepro.2019.118645>.
- Kumar M, Tung Chong C, Karmakar S. 2022. Comparative assessment of combustion characteristics of limonene, Jet A-1 and blends in a swirl-stabilized combustor under the influence of pre-heated swirling air. *Fuel*. 316:123350. doi:10.1016/j.fuel.2022.123350. <http://dx.doi.org/10.1016/j.fuel.2022.123350>.
- Maqsood T, Dai J, Zhang Y, Guang M, Li B. 2021. Pyrolysis of plastic species: A review of resources and products. *Journal of Analytical and Applied Pyrolysis*. 159:105295. doi:10.1016/j.jaap.2021.105295. <http://dx.doi.org/10.1016/j.jaap.2021.105295>.
- Martyr AJ, Rogers DR. 2021. Engine exhaust emissions. doi:10.1016/b978-0-12-821226-4.00017-6. <http://dx.doi.org/10.1016/b978-0-12-821226-4.00017-6>.
- Mishra RK, Mohanty K. 2022. Pyrolysis of low-value waste sawdust over low-cost catalysts: physicochemical characterization of pyrolytic oil and value-added biochar. *Biofuel Research Journal*. 9(4):1736–1749. doi:10.18331/brj2022.9.4.4. <http://dx.doi.org/10.18331/brj2022.9.4.4>.
- Olalo JA. 2021. Pyrolytic oil yield from waste plastic in quezon city, philippines: optimization using response surface methodology. *International Journal of Renewable Energy Development*. 11(1):325–332. doi:10.14710/ijred.2022.41457. <http://dx.doi.org/10.14710/ijred.2022.41457>.
- Pakdel H, Pantea DM, Roy C. 2001. Production of dl-limonene by vacuum pyrolysis of used tires. *Journal of Analytical and Applied Pyrolysis*. 57(1):91–107. doi:10.1016/s0165-2370(00)00136-4. [http://dx.doi.org/10.1016/s0165-2370\(00\)00136-4](http://dx.doi.org/10.1016/s0165-2370(00)00136-4).
- Papari S, Bamdad H, Berruti F. 2021. Pyrolytic conversion of plastic waste to value-added products and fuels: A review. *Materials (Basel, Switzerland)*. 14(10):2586. doi:10.3390/ma14102586. <https://pubmed.ncbi.nlm.nih.gov/34065677https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8157045/>.
- Petrochemical Chemical & Energy. 2019. An introduction to olefins. <https://www.petro-online.com/news/fuel-for-tought/13/breaking-news/an-introduction-to-olefins/48730>.
- Ra Y, Reitz RD, McFarlane J, Daw CS. 2008. Effects of fuel physical properties on diesel engine combustion using diesel

- and bio-diesel fuels. *SAE International Journal of Fuels and Lubricants*. 1(1):703–718. doi:10.4271/2008-01-1379. <http://dx.doi.org/10.4271/2008-01-1379>.
- Rivera JdD, Davies GM, Jahn W. 2012. Flammability and the heat of combustion of natural fuels: A review. *Combustion Science and Technology*. 184(2):224–242. doi:10.1080/00102202.2011.630332. <http://dx.doi.org/10.1080/00102202.2011.630332>.
- Sharma A, Khatri D, Goyal R, Agrawal A, Mishra V, Hansdah D. 2021. Environmentally friendly fuel obtained from pyrolysis of waste tyres. doi:10.1007/978-981-16-1256-5_11. http://dx.doi.org/10.1007/978-981-16-1256-5_11.
- Shen XR, Geng CX, Lv BQ, Xu W, Xu Y, Zhao HZ. 2021. Tire pyrolysis wastewater treatment by a combined process of coagulation detoxification and biodegradation. *Environmental science and ecotechnology*. 8:100129. doi:10.1016/j.ese.2021.100129. <https://pubmed.ncbi.nlm.nih.gov/36156994><https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9488099/>.
- Subekti S, Sasmito A, Rahman B. 2023. Pemanfaatan sampah di tempat pemrosesan akhir (tpa) jatibarang sebagai sumber energi baru terbarukan. *Merdeka Indonesia Internasional (MIJI)*. 3:54–63. <https://merdekaindonesia.com/index.php/MerdekaIndonesiaJournalInternatiurnbn:de:00001MIJI.v3i1.69>.
- Thahir R, Irwan M, Alwathan A, Ramli R. 2021. Effect of temperature on the pyrolysis of plastic waste using zeolite ZSM-5 using a refinery distillation bubble cap plate column. *Results in Engineering*. 11:100231. doi:10.1016/j.rine.2021.100231. <http://dx.doi.org/10.1016/j.rine.2021.100231>.
- The Engineering ToolBox. 2003. Liquids – kinematic viscosities. https://www.engineeringtoolbox.com/absolute-viscosity-liquids-d_1259.html.
- The Engineering ToolBox. 2008. Liquids – dynamic viscosities. https://www.engineeringtoolbox.com/kinematic-viscosity-d_397.htm.
- The Engineering ToolBox. 2023. Gasoline - density, specific heat, viscosity and thermal conductivity vs. Temperature. https://www.engineeringtoolbox.com/gasoline-density-specific-heat-dynamic-kinematic-viscosity-thermal-conductivity-vs-temperature-d_2224.html.
- Troyer D. 2002. Kinematic viscosity explained. <https://www.machinerylubrication.com/Read/294/absolute-kinematic-viscosity>.
- Umeki ER, de Oliveira CF, Torres RB, dos Santos RG. 2016. Physico-chemistry properties of fuel blends composed of diesel and tire pyrolysis oil. *Fuel*. 185:236–242. doi:10.1016/j.fuel.2016.07.092. <http://dx.doi.org/10.1016/j.fuel.2016.07.092>.
- Vempatapu BP, Tripathi D, Kumar J, Kanaujia PK. 2019. Determination of kerosene as an adulterant in diesel through chromatography and high-resolution mass spectrometry. *SN Applied Sciences*. 1(6). doi:10.1007/s42452-019-0637-7. <http://dx.doi.org/10.1007/s42452-019-0637-7>.
- Wądrzyk M, Janus R, Rządźik B, Lewandowski M, Budzyń S. 2020. Pyrolysis oil from scrap tires as a source of fuel components: Manufacturing, fractionation, and characterization. *Energy & Fuels*. 34(5):5917–5928. doi:10.1021/acs.energyfuels.0c00265. <http://dx.doi.org/10.1021/acs.energyfuels.0c00265>.
- Wang G, Dai Y, Yang H, Xiong Q, Wang K, Zhou J, Li Y, Wang S. 2020. A review of recent advances in biomass pyrolysis. *Energy & Fuels*. 34(12):15557–15578. doi:10.1021/acs.energyfuels.0c03107. <http://dx.doi.org/10.1021/acs.energyfuels.0c03107>.