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Recovery of Fuel Oil from Hazardous Sludge Maritime Oil via Pyrolysis: Characterization and Compliance with National Fuel Standards

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Abstract

Sludge oil is classified as hazardous and toxic (B3) waste, posing serious environmental risks if not properly managed, such as air pollution from direct incineration or soil contamination from untreated disposal. This study applies the pyrolysis method to recover oil from sludge oil and evaluate its potential as an alternative fuel. The objective of this research is to assess the yield, quality, and characteristics of pyrolysis oil at different temperatures (250°C, 300°C, and 350°C) and reaction times (5, 6, 7, and 8 hours). The results show that pyrolysis and condensation temperatures play a decisive role in determining the type of oil produced: Light Fuel Oil (LFO) is obtained at 250°C (condensation 215°C) and 300°C (condensation 270°C), while Heavy Fuel Oil (HFO) is produced at 350°C (condensation 310°C). Prolonged pyrolysis duration was also found to increase oil yield, reaching 60.86%, 65.75%, and 70.69% for each temperature range, respectively. Furthermore, quality analysis revealed that both LFO and HFO comply with the standards and specifications for low-sulfur Marine Fuel Oil (MFO) as stipulated in the Decree of the Director General of Oil and Gas No. 0179.K/10/DJM.S/2019. These findings demonstrate that optimizing pyrolysis temperature, condensation temperature, and reaction time is essential for controlling oil classification, yield, and compliance with national fuel standards.

Keywords
Sludge Oil Waste, Pyrolysis, Fuel Oil, Light Fuel Oil, Heavy Fuel Oil

1. Introduction

Sludge oil is a type of hazardous and toxic waste generated primarily from petroleum production facilities, storage tanks, refinery operations, and maritime activities such as oil tank cleaning and gas transport vessels. If not managed properly, sludge oil can cause severe environmental pollution, including soil contamination through improper land disposal and air pollution when incinerated directly without adequate treatment (Kurniasari, 2005). According to the Regulation of the Ministry of Environment and Forestry (PermenLHK) No. 6 of 2021, hazardous and toxic waste must be handled through specialized processes to prevent adverse environmental and health impacts.

Sludge oil typically consists of a complex mixture of hydrocarbons, water, sediments, heavy metals, and other contaminants. Common sources include used hydraulic lubricants, sludge from oil and gas production and storage facilities (primary and secondary refinery sludge), and tank-bottom residues. Due to its composition, sludge oil requires specific treatment technologies that not only ensure safe disposal but also enable potential resource recovery. Several technologies have been developed for the treatment of sludge oil, including solvent extraction (Zubaidy, 2010), centrifugation (Cambiella, 2006), surfactant-assisted separation (Yan, 2012), pyrolysis (Wang, 2007), electrokinetic remediation (Yang, 2005), incineration (Scala, 2004), and stabilization/solidification (Karamalidis, 2007). For instance, solvent extraction using a mixture of methyl ethyl ketone (MEK) and liquefied petroleum gas condensate (LPGC) in a 4:1 ratio has been reported to recover up to 39% oil, but it also generates sulfur- and carbon-rich residues and requires a large amount of solvent proportional to the sludge volume (Zubaidy, 2010). Meanwhile, incineration at 980–1200°C with a residence time of approximately 30 minutes can recover energy in the form of heat suitable for powering steam turbines or other industrial uses (Guangji, 2013). However, this method presents several challenges, such as the need to reduce the moisture content of the sludge, the generation of hazardous air pollutants, and high operational costs (Al-Futaisi, 2007).

Among these methods, pyrolysis has emerged as a promising approach for sludge oil treatment. It offers several advantages, including milder operating conditions, the recovery of energy in the form of pyrolysis oil, and lower pollutant emissions compared to incineration (Qin, 2015). Moreover, pyrolysis does not require the use of chemical additives, thereby minimizing the risk of chemical contamination in the recovered oil, which would otherwise increase post-treatment complexity and cost (Jati, 2019). Previous studies have demonstrated the potential of pyrolysis in sludge oil management. Wijayanti (2013) reported that the pyrolysis of municipal solid waste produced char with the highest calorific value at 300°C. Silalahi (2015) conducted pyrolysis of sludge oil at approximately 512°C under controlled pressure conditions (100–200 mbar and 200–300 mbar), yielding 31% oil, 31.4% paraffin oil, 8.8% activated carbon, 14.3% gas, and 14.5% water. Furthermore, Czernik (2004) highlighted that the liquid product from pyrolysis can be easily stored and transported, and its quality is comparable to that of low-grade petroleum distillates from commercial refineries, making it suitable for direct use in diesel engines.

Pyrolysis is a thermochemical process in which organic material is heated in an oxygen-deficient environment, causing the decomposition of chemical structures into gaseous, liquid, and solid fractions. The gaseous fraction is then condensed into pyrolysis oil, while the solid residue, primarily in the form of char, can be further utilized. The efficiency of this process depends on several factors, such as temperature, residence time, and the characteristics of the feedstock. Previous studies have shown that optimal pyrolysis typically occurs at temperatures between 300–500°C (Cahyono, 2018) for 4–7 hours (Ridhuan, 2019), although the exact parameters may vary depending on the material (Wijayanti, 2013).

1.1 Objectives

The pyrolysis method for sludge oil has already been implemented in Indonesia; however, it has not been widely applied to maritime sources such as ship sludge and offshore waste, as previous studies have primarily focused on onshore storage tanks. Therefore, this study aims to investigate the pyrolysis of various types of sludge oil, including used hydraulic lubricating oil, sludge from natural gas or petroleum production and storage facilities (primary and secondary refinery sludge), and tank bottom residues, at different temperatures of 250°C, 300°C, and 350°C with a residence time of 5–8 hours. The study specifically examines the effects of pyrolysis temperature, condensation temperature, and reaction time on the yield and physical properties of the resulting oil, which will be characterized in terms of density, kinematic viscosity, calorific value, flash point, and yield. Furthermore, the produced oil will be classified as Light Fuel Oil (LFO) or Heavy Fuel Oil (HFO) based on the standards and specifications for Marine Fuel Oil (MFO) stipulated in the Decree of the Director General of Oil and Gas No. 0179.K/DJM.S/2019. Ultimately, the findings are expected to provide insights into optimizing sludge oil pyrolysis to produce fuel oil that meets quality standards and has potential for industrial and marine applications.

2. Literature Review

Sludge oil is a complex, semi-solid waste product commonly described as a silt or black paste consisting of a mixture of soil, water, hydrocarbons, and various other materials (Pratiwi, 2012). This waste is predominantly generated from oil refining industry operations, especially from production processes, oil storage facilities, and tank cleaning activities. The composition of oil sludge typically includes emulsions of oil and water, heavy metal ions, and a substantial proportion of hydrocarbons—often classifying it as solid hazardous waste (B3 in Indonesian regulation) (Hui et al., 2020). The presence of these hazardous constituents, such as heavy metals and persistent hydrocarbons, underscores the need for stringent management due to their potential risks to environmental and human health. From a resource perspective, numerous studies have highlighted that the hydrocarbons present in sludge oil are valuable and have significant potential as renewable energy resources (Hui et al., 2020). Converting such waste into alternative fuels not only offers a route to waste minimization but also supports efforts to reduce reliance on non-renewable fossil sources (Hui et al., 2020). Pyrolysis has emerged as the most prominent technology in this context, capable of thermally decomposing sludge oil to yield reusable oil fractions that can serve as substitutes for conventional fuels (Wang et al., 2007). This process not only recovers valuable energy but also offers a managed disposal route for a challenging waste stream, with the liquid products from pyrolysis demonstrating properties comparable to diesel fuel.

The management of sludge oil, as with all hazardous waste, is tightly regulated. The Indonesian Ministry of Environment and Forestry's Regulation No. 6 of 2021 sets comprehensive guidelines for the management of hazardous (B3) waste, encompassing reduction, storage, collection, transportation, utilization, and final disposal (Kementerian Lingkungan Hidup dan Kehutanan Republik Indonesia, 2021). This regulatory structure aims to minimize the negative impacts of B3 waste by enforcing control at every stage of its lifecycle, echoing similar provisions found in international waste management frameworks. Sludge oil is emblematic of a broader category of industrial byproducts—materials or residues unwanted in the environment due to their lack of economic value, often causing pollution and necessitating proper management interventions (Yuliani, 2011; Berliana, 2023). In summary, the literature consistently emphasizes that effective and sustainable management strategies, including resource recovery via pyrolysis, are essential for addressing both the environmental burdens and the untapped resource potential of sludge oil waste.

The treatment of sludge oil waste can be carried out using several methods, including solvent extraction (Zubaidy, 2010), centrifugation (Cambiella, 2006), surfactant application (Yan, 2012), pyrolysis (Wang, 2007), electrokinetic treatment (Yang, 2005), incineration (Scala, 2004), and stabilization (Karamalidis, 2007). According to Zubaidy (2010), the solvent extraction method using a mixture of organic solvents—methyl ethyl ketone (MEK) and liquefied petroleum gas condensate (LPGC)—with a solvent-to-sludge ratio of 4:1 resulted in an oil yield of 39%, along with high amounts of sulfur and carbon residues. The advantage of this method lies in its simplicity and relatively short processing time, while its limitation is the dependency on the volume of waste treated and the need for an appropriate solvent proportion.

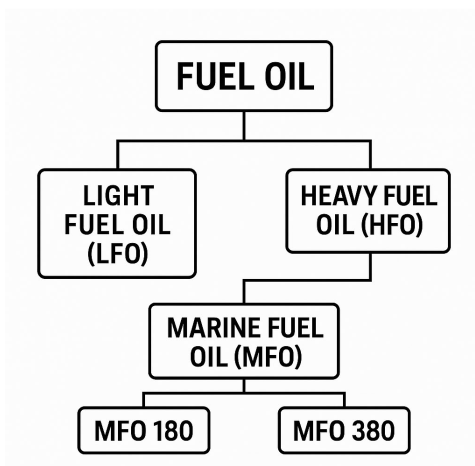

Figure 1. Classification of Marine Fuel Oils (MFO) Based on Viscosity Grades

Figure 1 illustrates the classification of marine fuel oils (MFO) based on their viscosity grades, specifically MFO 180 and MFO 380, which are derived from the ISO 8217 standard. MFO 180 is characterized as a lighter fuel oil with a viscosity of approximately 180 cSt at 50°C, making it easier to handle and suitable for medium-speed engines. In contrast, MFO 380 is a heavier fuel oil with a viscosity of around 380 cSt at 50°C, typically used in large, slow-speed marine engines and requiring preheating prior to combustion (Hossain et al., 2022; Li et al., 2021). These classifications are closely related to the broader distinction between light fuel oil (LFO) and heavy fuel oil (HFO), where MFO 180 tends to align more with lighter fractions and MFO 380 with heavier fractions due to differences in density, viscosity, and handling requirements.

3. Methods

The sludge oil samples were initially analyzed for their density, calorific value, viscosity, and flash point to establish a baseline characterization prior to undergoing the pyrolysis process. Subsequently, the pyrolysis oil products were subjected to preliminary analyses using parameters representative of fuel quality, in order to determine the characteristics that most closely align with established fuel classifications. These assessments, performed across pyrolysis oils obtained at various predetermined temperatures, encompassed measurements of density, calorific value, flash point, and viscosity.

The pyrolysis oil samples were obtained directly from the sludge oil pyrolysis process conducted within a reactor system. The B3 waste sludge oil, having been pre-treated to remove contaminants, was introduced into the reactor via an automatic feeder. Within the reactor, the sludge oil underwent pyrolysis at a maximum heating temperature of 500°C, while the reactor's material was rated to withstand temperatures up to 1000°C. During processing at 250°C, 300°C, and 350°C, the vaporized pyrolysis oil was collected using a condenser unit. The collected oil samples were then analyzed for viscosity, density, calorific value, and flash point to determine their classification, calculate oil yield, and enable more detailed quality assessments.

4. Data Collection

The data collected from each analysis were organized into a treatment matrix to evaluate the influence of pyrolysis temperature on oil characteristics. To assess the potential reuse of the pyrolysis oil as fuel, the results were compared against the quality standards outlined in the Decree of the Director General of Oil and Gas No. 0179.K/DJM.S/2019 on the Standards and Specifications for Low-Sulfur Marine Fuel Oil (MFO) Marketed Domestically.

5. Results and Discussion

5.1 Initial Characterization of Sludge Oil Waste

Sludge oil is a type of waste generated from petroleum processing and refinery operations (Silalahi, 2015). This waste typically contains between 20–95% water, 5–70% oil, and 5–10% solids (Kurniasari, 2005). Sludge oil is semi-solid in form, black in color, and exhibits extremely low solubility in water. According to Aliyev (2003), the composition of sludge oil and the scale of variation in its physical and chemical characteristics are quite broad. The density of sludge oil may range from 830 to 1700 kg/m³, while Monteiro (2014) reported density values in the range of 950–985 kg/m³, with viscosities reaching up to 1750 mPas.

The results of the initial characterization in this study are consistent with those previously reported, yielding a density of 986.7 kg/m³ and a kinematic viscosity of 571.4 cSt. The measured calorific value of the sludge oil was 44.8 MJ/kg. This result is consistent with previous studies showing that a higher oil content in sludge oil is associated with greater energy potential, highlighting its feasibility as an alternative energy source. Calorific values for sludge oil typically range from 4,776 to 9,553 kcal/kg (Chen, 2022). Furthermore, the determined flash point was 108°C (Table 1), which falls within the range of 35–120°C as reported in prior studies (Svet, 2015).

Table 1. Initial Characterization Results of Sludge Oil

Parameter	Analytical Result	Unit
Density at 15°C	986.7	kg/m³
Kinematic Viscosity at 50°C	571.4	cSt
Calorific Value	10,700	Kcal/kg
Flash Point	108	°C

5.2 Characteristics of Pyrolysis Oil

During the pyrolysis process, the reactor temperature was initially increased from 70°C during the first 1–4 hours to approximately 200°C to remove water vapor. Subsequently, the temperature was gradually raised to 250°C, 300°C, and 350°C to obtain different oil fractions. Condensation, which plays a crucial role in determining oil yield, occurred at corresponding condenser temperatures of 215°C, 270°C, and 310°C (Ridhuan, 2019). As reported by Gusnawati (2020), the amount of pyrolysis product tends to increase with higher reactor temperatures and longer residence times. In this study, the pyrolysis oils produced under these conditions were analyzed for density, viscosity, calorific value, and flash point to classify their fuel characteristics.

The density of pyrolysis oil increased with temperature (Figure 2). At 250°C, the density ranged from 931–932 kg/m³, while at 300°C it increased to 939–940 kg/m³, and at 350°C it reached 979 kg/m³. These values, obtained through hydrometer readings corrected to 15°C using ASTM D1250-80, indicate that higher pyrolysis temperatures promote secondary cracking and molecular recombination, leading to the formation of heavier fractions (Hidayat, 2022). This is consistent with previous findings, such as Larionov (2022), who reported a density of 884.2 kg/m³ for pyrolysis oil from sludge oil at 650°C for 45 minutes.

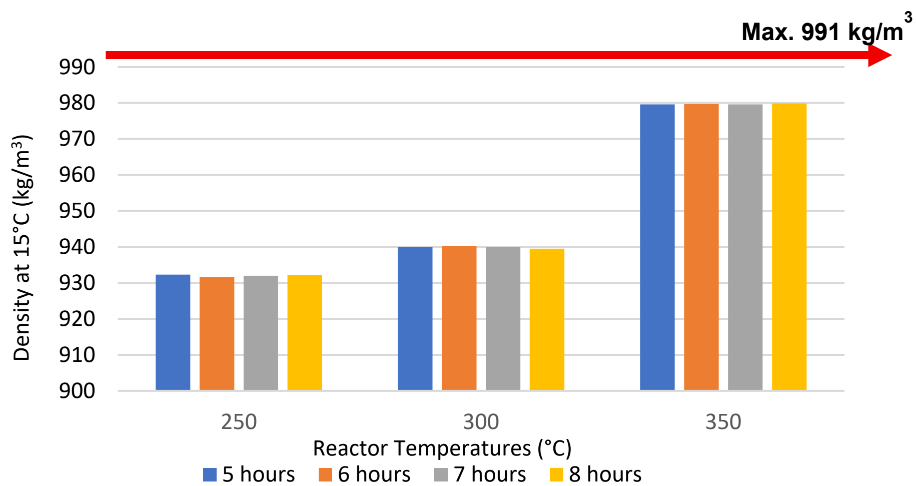

Figure 2. Correlation Between Temperature Increase and Density

A similar trend was observed in kinematic viscosity (Figure 3). At 250°C, viscosity ranged from 45.3–46.9 cSt, increasing moderately to 48.8–50.5 cSt at 300°C, suggesting partial recombination reactions that form heavier intermediates while maintaining a significant proportion of lighter hydrocarbons. In contrast, at 350°C, viscosity rose sharply to 186.1–188.5 cSt, indicating extensive polymerization and the formation of high-molecular-weight compounds. The proportional relationship between density and viscosity (Hidayat, 2022) further supports this observation.

These findings align with previous research (Adoe, 2020; Wahyudi, 2022) showing that higher pyrolysis temperatures yield heavier fractions with greater density and viscosity. However, while higher density can indicate improved combustion quality, excessive viscosity can hinder atomization and injection performance in engines (Wahyudi, 2023). Therefore, pyrolysis at 250–300°C is considered more favorable for producing oil with physical properties closer to those of conventional marine fuel oil, while pyrolysis at 350°C would require post-treatment such as distillation or blending to improve fuel quality.

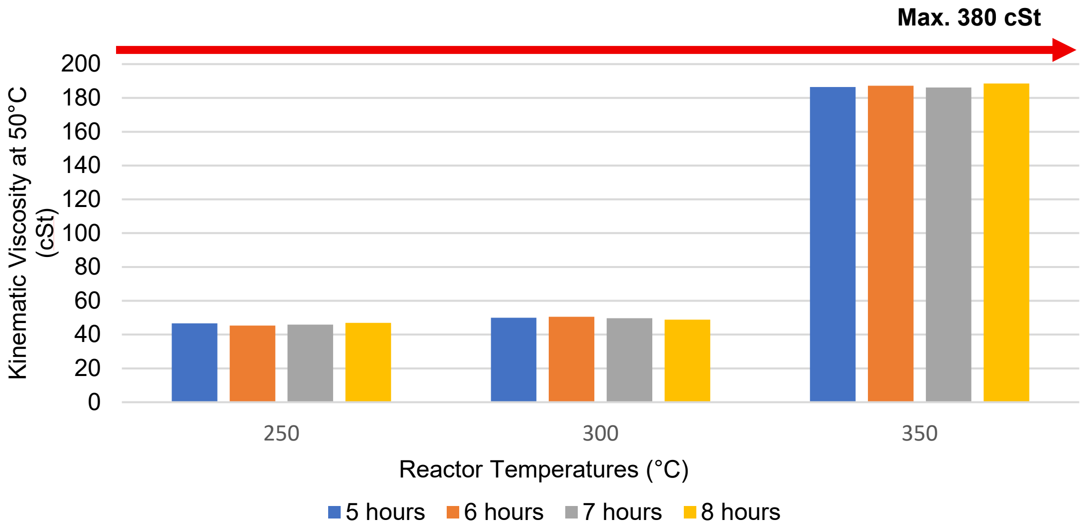

Figure 3. Correlation Between Temperature Increase and Kinematic Viscosity

Based on the analysis conducted in this study, the pyrolysis process applied to a mixture of sludge waste and plastic waste produced a calorific value of 10,748 Kcal/kg, as supported by findings from Janakova (2024). As illustrated in Figure 4, the calorific value at a pyrolysis temperature of 250°C ranged between 10,510 and 10,526 Kcal/kg. At 300°C, the range was slightly lower, between 10,501 and 10,506 Kcal/kg, while at 350°C, it further declined to a range of 9,758 to 9,986 Kcal/kg. These results indicate a downward trend in calorific value as the pyrolysis temperature increases. This pattern is consistent with the explanation provided by Hidayat (2022), who stated that fuel density and calorific value are inversely related. The higher the temperature, the greater the concentration of short-chain hydrocarbon fractions in the oil, which tend to yield lower energy compared to long-chain hydrocarbons. The findings of this study are comparable to previous research conducted by Gao (2020), who reported calorific values ranging from 10,509 to 10,986 Kcal/kg, and Larionov (2022), who documented a value of 10,174 Kcal/kg from the pyrolysis of sludge oil. These similarities suggest that the calorific outcomes in the present study fall within a reasonable and expected range. According to Putra (2023), a higher calorific value generally indicates better fuel performance during combustion, as it contributes to a more efficient thermal energy output.

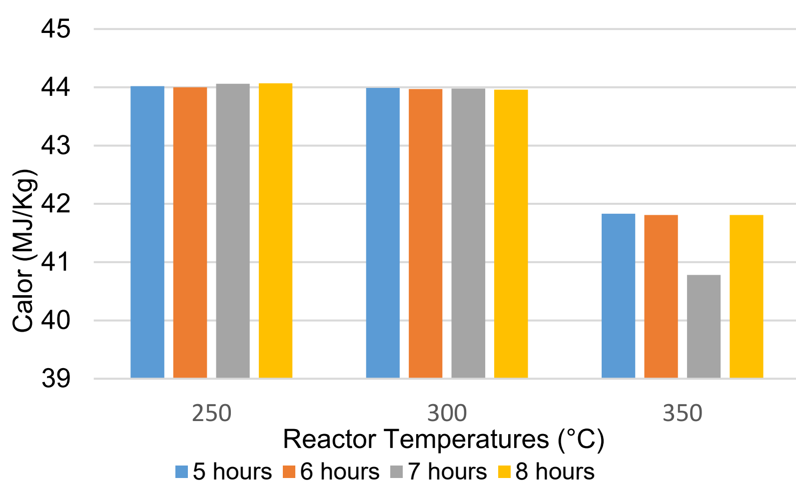

Figure 4. Correlation Between Temperature and Calorific Value

The calorific value of the pyrolysis oil, as shown in Figure 4, displayed a downward trend with increasing temperature. At 250°C, the calorific value ranged between 10,510–10,526 Kcal/kg (44.00–44.07 MJ/kg). At 300°C, it slightly decreased to 10,501–10,506 Kcal/kg (43.96–43.99 MJ/kg), while at 350°C, it declined further to 9,980–9,990 Kcal/kg (40.78–41.83 MJ/kg). This decrease is in line with Hidayat (2022), who noted an inverse relationship between density and calorific value. As temperature increases, a higher proportion of short-chain hydrocarbons is produced, which typically provides lower energy content compared to longer-chain hydrocarbons. These results are consistent with Janakova (2024), who reported a calorific value of 10,748 Kcal/kg for pyrolysis oil from a mixture of sludge waste and plastic waste, and Gao (2020), who documented a range of 10,509–10,986 Kcal/kg. Similarly, Larionov (2022) observed a value of 10,174 Kcal/kg for sludge oil pyrolysis. According to Putra (2023), higher calorific value is desirable for improving combustion performance and thermal efficiency. Therefore, pyrolysis at 250–300°C is preferable for producing oil with energy content comparable to commercial marine fuel oil, while oil produced at 350°C may require upgrading or blending.

From Figure 5 indicates the lowest temperature at which vapors ignite in the presence of an ignition source, also increased with temperature, as illustrated in Figure 4. At 250°C, the flash point ranged from 65.8–69.1°C (average 67.45°C), reflecting a higher concentration of volatile components. At 300°C, it increased to 72.4–77.8°C (average 75.25°C), while at 350°C it further rose to 81.6–85.7°C (average 83.5°C). These findings are comparable to Larionov (2022), who reported a flash point of 89°C for sludge-derived pyrolysis oil. The increasing flash point with higher temperatures indicates the formation of hydrocarbons with longer carbon chains and reduced volatility (Sunyoto, 2024). According to OSHA standards, all measured flash points in this study fall within the range of combustible liquids (37.8–93.3°C), indicating that the oils can be safely stored and transported. Flash point is also positively correlated with viscosity; as viscosity increases, the flash point rises due to the higher presence of heavy fractions (Azhari, 2014; Zurohaina, 2020).

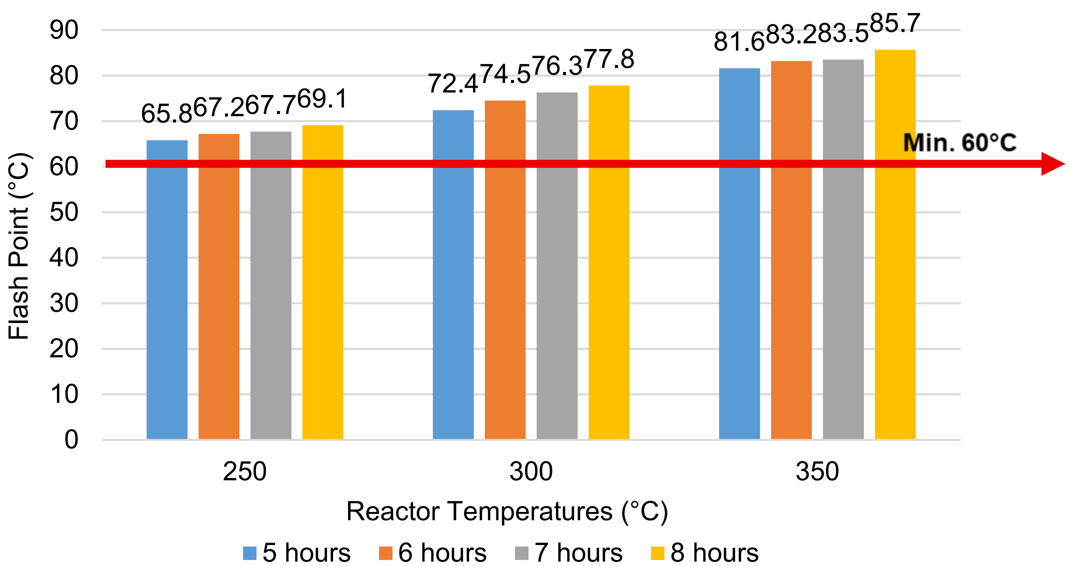

Figure 5. Correlation Between Temperature and Flash Point

The characterization results of the pyrolysis oil derived from sludge waste in this study were compared with several conventional fuel types show in Table 2, including gasoline, kerosene, diesel, light fuel oil (LFO), and heavy fuel oil (HFO). The condensation temperatures measured during the pyrolysis process at various set temperatures showed that at 250°C, the condensation temperature recorded in the condenser was 215°C; at 300°C, it increased to 270°C; and at 350°C, it reached 310°C. Condensation temperature serves as a key indicator for estimating the quantity of oil collected through the condenser. Based on the characterization results—particularly density, viscosity, calorific value, and flash point-the pyrolysis oil produced at condensation temperatures of 215°C and 270°C tends to resemble the characteristics of light fuel oil (LFO), while the oil condensed at 310°C aligns more closely with the properties of heavy fuel oil (HFO).

Table 2. Comparation Oil Pyrolisis with Several Fuel Types

Categories	Ref	Parameter Analysis					
		Density at 15°C	Kinematic Viscosity at 50°C	Kinematic Viscosity at 40°C	Higher Heating Value (HHV) / Gross Calorific Value (GCV)		Flash Point
		kg/m^3	mm^2/s (cSt)		MJ/kg	Kcal/kg	°C
Nafta, gasoline	ASTM D4814	680 – 710	-	0,69 – 0,72	46,4	11082,4496	-43
Kerosene	ASTM D3699	760 – 800	-	1,0 – 2,0	46,2	11034,6804	> 38 – 72
Diesel (solar)	ASTM D975 and EN 590	820 – 840	-	1,2 – 2,4	45,6	10891,3729	>52
Light Fuel Oil	ISO 8217:2017 (Spec. marine fuels)	920 – 960	43	1,2 – 3,6 2,5 – 15,7	44,0	10509,2195	>61
Heavy Fuel Oil		970 - 1000	> 180; 97,4 - 660	> 58 – 168	41,8	9983,75848	>61
Pyrolysis Oil 250°C		931 – 932	45,3 – 46,9	-	44,0 – 44,07	10.509 – 10.525	65,8 – 69,1
Pyrolysis Oil 300°C		940	48,8 – 50,5	-	43,96 – 43,99	10.499 – 10.506	72,3 – 77,8
Pyrolysis Oil 350°C		979	186,1 – 188,5	-	40,78 – 41,83	9.740 – 9.990	81,6 – 85,7

The yield analysis of pyrolysis oil from sludge oil waste demonstrates a clear relationship between pyrolysis temperature, reaction time, and oil production. As presented in Table 3, the oil yield at 250°C ranged from 13.98% at 5 hours to 16.31% at 8 hours, resulting in a total yield of 60.86%. At 300°C, the yield increased slightly, ranging from 15.04% at 5 hours to 17.71% at 8 hours, with a total yield of 65.75%. The highest yield was obtained at 350°C, where values ranged from 16.65% at 5 hours to 18.62% at 8 hours, culminating in a total yield of 70.69%.

These results indicate that both temperature and reaction time significantly influence the oil yield, which is consistent with the findings of Maulina (2017), who stated that higher temperatures lead to more complete thermal decomposition of the raw material, thus increasing the amount of oil produced. Similarly, Gusnawati (2020) emphasized the critical role of pyrolysis duration in achieving higher yields, as prolonged heating allows the feedstock to reach thermal equilibrium, enabling the decomposition of sludge oil into gaseous products that subsequently condense into oil.

The increasing trend in yield observed in this study also aligns with previous research. Wang (2007) reported an oil yield of 32.8% from sludge oil pyrolysis at 500°C, while Silalahi (2005) obtained 31% oil from 1 kg of sludge oil pyrolyzed at approximately 512°C for 60 minutes. Larionov (2022) reported a yield of 30.4% from 300 kg of sludge oil processed at 650°C for approximately 45 minutes. The differences between these studies and the current work can be attributed to variations in temperature, reaction time, and feedstock amount.

In this study, the yield obtained at 350°C was significantly higher than in previous studies. This increase is likely due to the combination of a longer reaction time (up to 8 hours) and the relatively lower pyrolysis temperature, which may have allowed for more controlled thermal cracking and better condensation of oil vapors. These results highlight the importance of optimizing both pyrolysis temperature and reaction time to maximize oil yield from sludge oil waste. The yield was calculated using Formula 1.

%Yield = (mass of liquid / mass of feedstock) x 100% (1)

Table 3. Pyrolysis Oil Yield Result

Time/ Temp.	%Yield		
	250°C	300°C	350°C
5 h	13,98%	15,04%	16,65%
6 h	14,95%	15,89%	17,39%
7 h	15,61%	17,11%	18,02%
8 h	16,31%	17,71%	18,62%
Total	**60,86%**	**65,75%**	**70,69%**

5.3 Quality Analysis of Pyrolysis Oil

Based on the characterization of pyrolysis oil, the condensation temperatures recorded during the process were 250°C (Condenser temp: 215°C), 300°C (Condenser temp: 270°C), and 350°C (Condenser temp: 310°C). At condensation temperatures of 215°C and 270°C, the pyrolysis oil exhibited characteristics of Light Fuel Oil (LFO), while at 310°C, it corresponded to Heavy Fuel Oil (HFO). This classification was determined based on density, kinematic viscosity, calorific value, and flash point measurements. Lower condensation temperatures favor the formation of lighter fractions with lower viscosity and density, whereas higher condensation temperatures promote the production of heavier fractions (Maulina, 2017; Hidayat, 2022). This classification is further supported by the quality analysis in Table 4, which compares the properties of pyrolysis oil to the standards for Marine Fuel Oil (MFO) established in the Decree of the Director General of Oil and Gas No. 0179.K/DJM.S/2019. Since specific standards for LFO and HFO have not been established, the MFO standard was used as a reference because both LFO and HFO share similar characteristics, particularly their heavy and viscous nature, and are therefore categorized as processed fuels.

Pyrolysis oil derived at condensation temperatures of 215°C and 270°C meets the specifications for MFO 180, with viscosity values below 180 cSt, making it suitable for low-speed diesel engines and industrial boilers. In contrast, oil obtained at a condensation temperature of 310°C aligns with the characteristics of MFO 380, which has a maximum viscosity of 380 cSt and is typically used in large marine diesel engines or high-capacity diesel power generators. However, due to its heavy and viscous nature, HFO requires preheating before use and is often blended with lighter fuels to improve flow properties and combustibility (Pertamina One Solution; Sugianto, 2023). These findings demonstrate that condensation temperature plays a key role in determining the final classification and potential applications of pyrolysis oil. By controlling condensation temperature during pyrolysis, it is possible to selectively produce LFO (MFO 180) for industrial and boiler applications or HFO (MFO 380) for marine and power generation sectors.

Table 4. Quality Analysis of Pyrolysis Oil

Paramaters	Unit	Quality Standard				Results	
		MFO 180		MFO 380		LFO	HFO
		Min.	Max.	Min.	Max.		
Density at 15°C	kg/m^3	-	991	-	991	938	980
Kinematic Viscosity at 50°C	mm^2/s (cSt)	-	180	-	380	50,51	187,35
Calorific Value	Kcal/kg	-	-	-	-	10,515	9979
Flash Point	°C	60	-	60	-	70	82
Pour Point	°C	-	30	-	39	11	18
Water Content	%v/v	-	0,5	-	0,5	0,2	0,4

6. Conclusion

Pyrolysis and condensation temperatures play a decisive role in determining the type and quality of oil produced through the pyrolysis process. At pyrolysis temperatures of 250°C (condensation 215°C) and 300°C (condensation 270°C), with reaction times of 5–8 hours, the resulting pyrolysis oil was classified as Light Fuel Oil (LFO), whereas at 350°C (condensation 310°C), the oil was categorized as Heavy Fuel Oil (HFO). Prolonged pyrolysis duration was also found to increase oil yield, with values of 60.86%, 65.75%, and 70.69% obtained at 250°C, 300°C, and 350°C, respectively. Furthermore, the quality of both LFO and HFO produced meets the standards and specifications for low-sulfur Marine Fuel Oil (MFO) marketed domestically, as stipulated in the Decree of the Director General of Oil and Gas No. 0179.K/DJM.S/2019 (Annex 19). Specifically, the LFO produced at 215°C and 270°C corresponds to MFO 180, while the HFO obtained at 310°C aligns with MFO 380. These findings emphasize that optimizing pyrolysis temperature, condensation temperature, and reaction time is essential to control oil yield, classification, and potential applications.

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Biographies

Linda Jati Kusumawardani is a lecturer in the Department of Chemistry at the Faculty of Mathematics and Natural Sciences, Universitas Pakuan. She holds a Master's degree in Chemistry from Universitas Indonesia and a Bachelor's degree from ST MIPA Bogor, with expertise in photocatalysis, advanced materials, energy, and adsorbents. Linda is known for her active research in wastewater treatment and renewable energy, publishing her work in national and international journals and earning a strong SINTA score that reflects her research impact. She has secured competitive research grants, including funding from the Ministry of Research, Technology, and Higher Education, and has received recognition from Universitas Pakuan for her contributions to laboratory accreditation and curriculum development. In addition to her academic achievements, Linda is committed to community service, leading training programs on food processing and environmental awareness, and is dedicated to integrating research with teaching to provide students with relevant and innovative scientific knowledge. Linda is also actively involved in enhancing laboratory quality and academic standards at Universitas Pakuan, having played a key role in the successful accreditation of the university's laboratory services according to ISO/IEC 17025:2017 standards. Her commitment to academic excellence extends to curriculum development, where she has contributed to the creation of practical chemistry modules and quality management courses. Linda's dedication to both research and education is evident in her ability to bridge theoretical knowledge with practical application, inspiring students to pursue innovative solutions in the field of chemistry.

Sutanto is a senior lecturer in the Department of Chemistry at the Faculty of Mathematics and Natural Sciences, Universitas Pakuan, Bogor. Born in Boyolali on December 6, 1959, he holds the position of Associate Professor and is highly regarded for his expertise in environmental chemistry, physical chemistry, analytical chemistry, and waste treatment. Dr. Sutanto has played a pivotal role in teaching core courses such as Basic Chemistry, Physical Chemistry, Analytical Chemistry, Environmental Chemistry, and Waste Treatment, and has supervised the academic progress of more than 200 undergraduate students as well as a doctoral graduate. He completed his undergraduate studies at Universitas Pakuan, earned his master's degree from Universitas Indonesia, and obtained his doctorate in Environmental Chemistry from Institut Pertanian Bogor (IPB). In addition to his teaching responsibilities, he has made significant contributions to research, particularly in environmental monitoring, photocatalysis, and the development of innovative materials for water and air purification. He has successfully led and completed multiple research projects funded by competitive grants, authored several practical chemistry manuals and textbooks, and holds registered intellectual property rights for scientific works such as biosorbents and chemistry textbooks. He has also been recognized for his role as an examiner in lecturer and student competitions, and is actively involved in community engagement through workshops, technical writing, and curriculum development, further enhancing chemistry education and environmental awareness at Universitas Pakuan.

Ivanny Dwi Krisanthy is a student in the Chemistry Study Program at the Faculty of Mathematics and Natural Sciences, Universitas Pakuan, Bogor. As an active undergraduate, Ivanny is known for her enthusiasm in both academic and organizational activities within the university environment. She has shown a keen interest in various branches of chemistry, participating in laboratory work, seminars, and student-led research projects. Throughout her studies, Ivanny has demonstrated a commitment to developing her scientific skills and contributing to the academic community. She is involved in collaborative projects with fellow students and faculty, aiming to deepen her understanding of chemical sciences and their applications. Ivanny's dedication to learning and active participation in campus life reflect her aspiration to excel as a future chemist and to make a positive impact in the field of science.