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Research Paper

Distillation, Characterizations, and Testing of Distillation Products from Waste Lubricant Oil (WLO) using Compression-Ignition Engine

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Abstract

Waste lubricant oil (WLO) is always found in motor vehicle repair shops. Utilizing WLO by distilling it will provide benefits. For this reason, WLO was distilled in this research. Several characterizations were conducted to determine the viscosity, density, low heat value (LHV), and flash point of WLO and distillation products (DP). The DP is less viscous, denser, LHV, and flash point than WLO. The DP was mixed with Pertamina Dex (0, 5, 10, and 15 vol.%) and then filled into the fuel tank for the engine performance test. The present experiment utilized a compression-ignition (CI) engine to measure performance. CI engine speed variations were carried out at 1000, 1500, 2000, and 2500 rpm to see the influence of the mixed fuel on torque, power, specific fuel consumption (SFC), thermal efficiency, and smoke opacity. The increase in CI engine speed leads to an increase in torque, power, thermal efficiency, and smoke opacity, but at the same time, SFC decreases to 2500 rpm. Increasing the DP content in the mixed fuel decreases torque, power, SFC, thermal efficiency, and increased smoke opacity.

Keywords: Waste lubricant oil; Distillation product; CI Engine performance

1. Introduction

Fossil fuel is a non-renewable energy source, but it is still the main choice of fuel in the industrial and transportation sectors [1–4] which results in the depletion of petroleum reserves and presents significant problems. Various studies have been conducted to substitute fossil fuels with other alternative fuels, such as biodiesel from edible and non edible plant [5–9], chicken waste [10], waste cooking oil [11–13], syngas [14], and pyrolysis product [15–17].

Apart from those mentioned, recently, utilizing WLO (WLO) for fuel has also attracted the attention of many researchers due to its abundant availability [18,19]. WLO is an inorganic liquid containing various residual engine lubrication particles and is a hazardous liquid waste [20–22]. WLO can be converted into fuel because the main composition of used lubricant oil is hydrocarbon [23]. According to Zare et al. [24], fuel converted from WLO has the characteristics of low calorific value (LHV) of 43.07 MJ/kg, density of 0.89 g/cc, and flash point of 98 °C.

Distillation is commonly used to convert WLO into fuel [25]. Wang and Li [23] converted WLO using distillation, and the resulting fuel with density at 20 °C is 842 kg/m³, LHV is 42 MJ/kg, and a flash point is 60 °C. Effendy et al. [26] distilled a WLO using distillation apparatus, and the resulting fuel has a density of 0.8091 kg/m³, calorific value of 47.3 MJ/kg, and a flash point of

15 °C. Arpa et al. [27] distilled a WLO using distillation apparatus, and the resulting fuel with density of 15 °C is 818 kg/m³, LHV is 42500 kJ/kg, and flash point (open cup) is 57 °C. Li et al. [28] distilled a WLO using distillation equipment, and the resulting fuel had a calorific value of 45.752 MJ/kg.

The injection system, pumps, and injector must deliver diesel fuel precisely to reach proper combustion; therefore, fuel density is the crucial parameter affecting engine performance [29]. According to Özgür and Tosun [30], LHV is an important parameter affecting engine performance besides density. Effendy et al. [26] have found that higher LHV leads to lower fuel consumption levels. To reach suitable density and LHV, distillation products (DP) are commonly blended with commercial fuel. Generally, several solar products in Indonesia are known as Pertamina Dex, dexlite, and biosolar. According to Cappenberg's [31] study, Pertamina Dex typically has higher torsion, power, and thermal efficiency than others, and it also has a lower fuel consumption than others. Moreover, Rozak et al. [32] have found that Pertamina Dex has a medium smoke opacity when compared to both biosolar and dexlite.

Researchers blended diesel with other components and filled it into the fuel tank to investigate the effect on the engine performance. Seifi et al. [33] have investigated diesel engine performance using fuel from water-diesel fuel emulsion with composition 2:98, 5:95, 8:92, and 10:90. Those mixed fuels influence the diesel engine's power, torque, and noise emission. Zare et al. [24] tested a diesel vehicle (Euro IV) using fuel from blended diesel with WLO as a fuel additive (100:0, 99:1, and 95:5), resulting in a decrease in NOx with an increase in WLO content in mixed fuel. Effendy et al. [26] compared diesel, blended diesel-distillation product of waste oil (50:50), and distillation product of waste oil, then tested using compression-ignition (CI) engine to investigate brake torque, brake power, brake mean effective pressure, brake specific fuel consumption, brake thermal efficiency, and smoke opacity. Katekaew et al. [34] blended waste cooking oil biodiesel and diesel-like fuel with composition 6:94, 10:90, 20:80, 30:70, and 34:66, then fueled into a single-cylinder diesel engine tank to investigate engine speed and performance. Yadav et al. [35] mixture hydrocarbon fuel with diesel fuel from waste transformer oil (25:75, 50:50, and 75:25) and used in CI engines to investigate brake torque, brake power, and CO emission.

Furthermore, to examine the effect of mixed fuel on engine performance at various engine speeds, several researchers conducted experiments by filling blended fuel in diesel engine tanks and testing at different engine speeds. Hardiyanto and Prawoto [36] mixed biodiesel and diesel, then tested in heavy-duty diesel engines using engine speeds between 1300 – 2250 rpm. They found an increase in engine speed promoted to decrease in brake torque and brake thermal efficiency. Ooi et al. [37] blended palm oil and biodiesel-diesel and then tested them in single-cylinder diesel engines using 1500, 2000 and 2500 rpm engine speed, resulting in the highest brake-specific fuel consumption at 1500 rpm and brake thermal efficiency at 2000 rpm. Al-Bawwat et al. [38] conducted a diesel blend with biodiesel from muskmelon seeds, then fueled in a single-cylinder diesel engine and ran with various engine speeds (1200-2000 rpm). An increase in engine speed promoted increased brake-specific fuel consumption and decreased brake thermal efficiency.

According to various findings, using WLO for the distillation process resulted in the DP's varying densities, LHV, and flash points. Therefore, the present research was conducted on distilled WLO through a distillation process. The viscosity, density, LHV, and flash point of WLO and DP were determined by several characterizations. An engine performance test using a CI engine was also conducted, where the DP was mixed with Pertamina Dex (0, 5, 10, and 15 vol.%). CI engine speed variations were also carried out at 1000, 1500, 2000, and 2500 rpm to see the influence of the mixed fuel on torque, power, specific fuel consumption (SFC), thermal efficiency, and smoke opacity.

2. Methods

2.1. *Material and Distillation*

WLO was collected from several vehicle repair shops. Distilled WLO using distillation equipment, as seen in **Figure 1**. Firstly, seven liters of WLO were filled into the main tank of the customized distillation equipment. Afterward, the custom distillation equipment was run. The heater heated the WLO and transformed it into a vapor phase. The vapor phase moves to the condenser, converts to the liquid phase, and then fills the fuel storage tank. After reaching the 380-minute distillation process, the DP reached 500 ml of volume, and then the distillation was stopped. The DP was collected and stored for further characterization.

According to Figure 2, at the 140-minute time measurement, the temperature in the reactor reaches 150 °C and increases straight forward until it reaches 250 °C at the 380-minute measurement time. By increasing time, the molecular chain breaks down and decomposes the WLO [22]. Moreover, increasing the temperature also increases the distillation product volume [25].

2.2. *Characterization*

The WLO and DP, such as viscosity, density, LHV, and flash point, are being investigated according to ASTM D 445, ASTM D 4052, ASTM D 4809, and ASTM D 92/93 standards, respectively. Before the experiment for engine performance test using the CI engine, the DP was mixed with a commercial diesel product from Pertamina (Pertamina Dex). DP mixed properly with Pertamina Dex utilising a composition of 0, 5, 10, and 15 vol. % (0%DP, 5%DP, 10%DP, and 15%DP). This composition was selected because several researchers used to start from a small amount of addition to higher concentration.

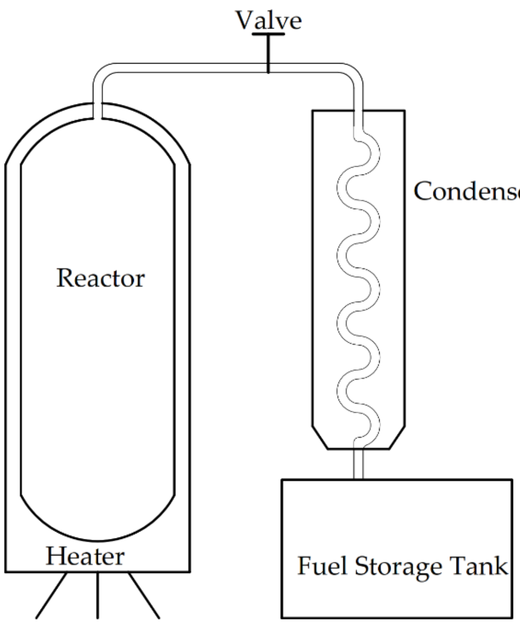


Figure 1. Schematic of distillation equipment

The mixed fuels results are presented in Figure 3. Fuel compositions were investigated to find density and LHV. According to Figure 3, it can be seen that more added DP in the diesel would change the mixed fuel color to darker. Furthermore, there are no visible lumps, which indicates that the fuel mixture can be mixed evenly.

2.3. *Experimental in Compression-Ignition (CI) Engine*

The CI engine tests were performed using single-cylinder, vertical, four-stroke, forced cooling, and direct injection type in the experiment. The specifications of the CI engine can be seen in Table 1.

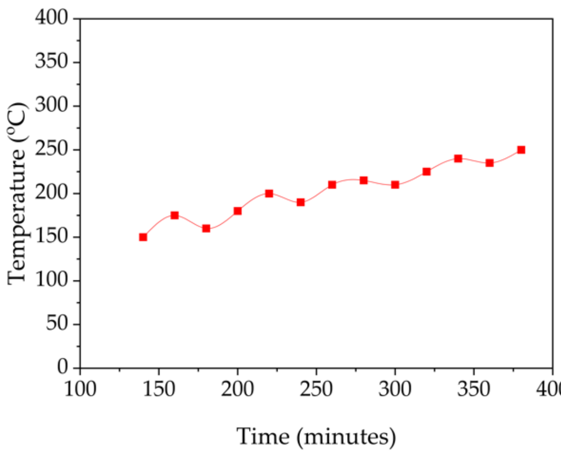


Figure 2. Temperature vs. time for distilled WLO in distillation equipment

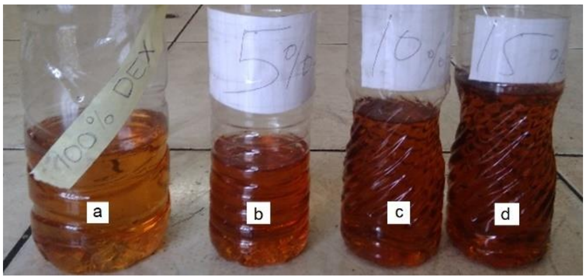


Figure 3. Fuels for an experiment on a CI engine: (a) 0%DP; (b) 5%DP; (c) 10%DP; (d) 15%DP

Table 1. Specifications of the CI engine

Parameter	Value
Displacement	441 cc
Bore	86 mm
Stroke	76 mm
Maximum power	6.8 kw/3600 rpm
Idle speed	1300+100 rpm
Maximum torque	22 N.m/2400 rpm
Compression ratio	21:1

Fuel was filled into the fuel tank, and the CI engine was started and ran at idle for around 15 minutes. After reaching 15 minutes of operation, various CI engine speeds were set at 1000, 1500, 2000, and 2500 rpm to see the influence of various fuel compositions on rotating speeds. Those speeds used (1000 to 2500 rpm) in the present experiment were chosen due to several researchers using 1200 to 2500 rpm [36–38]. While the engine was running, fuel would automatically pump into the diesel engine. In this stage, fuel consumption could be found. Furthermore, the hydro brake would measure the force and be presented in an indicator panel. Generally, the force and fuel consumption (mass flow rate) were found according to the apparatus used (**Figure 4**). Moreover, the smoke opacity was measured using Neomotec Opacity Smoke Meter CGO-600 equipment. The equipment is periodically calibrated before the test is conducted. The completed schematic CI engine performance test is presented in **Figure 4**.

For advanced investigation, torque, power, SFC, and thermal efficiency were calculated using the following equations [5,39,40].

$$T = F \times L \tag{1}$$

$$P = \frac{2 \times \pi \times n \times T}{60000} \tag{2}$$

$$SFC = \frac{\dot{m} \times 1000}{P} \tag{3}$$

$$\eta_{th} = \frac{P}{\dot{m}h} \tag{4}$$

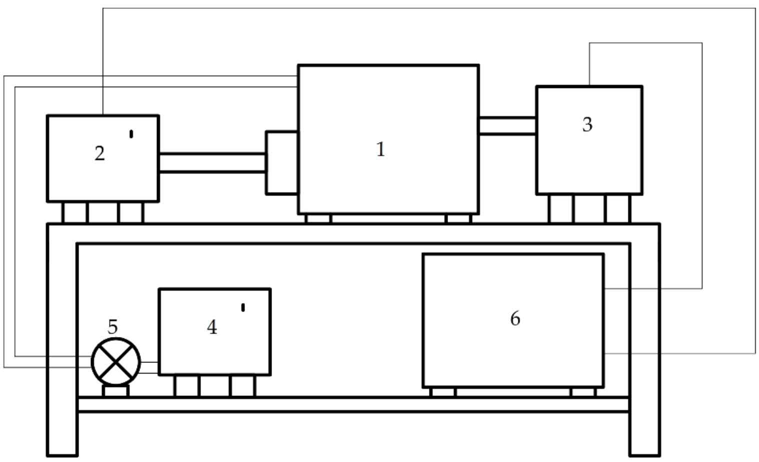
where T is torque (Nm), F is force (N), L is length (m), P is power (W), n is IC engine speed (rpm), SFC is specific fuel consumption (kg/kW h), $\dot{m}$ is mass flowrate (g/s), η_{th} is thermal efficiency (%), and h is LHV (kJ/kg).

All calculations according to Eq. (1) to Eq. (4) in the present research use Microsoft Excel to avoid any potential human error in calculating the torque, power, SFC, and thermal efficiency. Potential human errors are commonly found if the calculation is used manually, such as with a calculator.

3. Results and Discussion

3.1. *Material Characterization Result*

Several property characterizations for WLO and DP were conducted to examine kinematic viscosity, density, LHV, and flash point. Then, both were compared to verify that the distillation process was successful. The properties of the WLO and DP are presented in **Table 2**. The properties of those materials must be found according to several ASTM measurement standards.



No	Equipment
1	Diesel Engine
2	Hydro Brake
3	Emission Test
4	Fuel Tank
5	Fuel Pumps
6	Indicator Panel

Figure 4. Schematic engine performance test

Table 2. Properties of the WLO and DP

Property	Unit	Result		Measurement standard
		WLO	DP	
Kinematic viscosity at 40 °C	mm/s²	48.33	9.879	ASTM D 445
Density at 15 °C	g/cm³	0.8737	0.8553	ASTM D 4052
LHV	kJ/kg	45359.3	44160.4	ASTM D 4809
Flash point	°C	174	33	ASTM D 92/93

As shown in **Table 2**, the viscosity of DP is lower than that WLO. Lower viscosity is due to distillation processes such as evaporation, atomization, and fuel-air mixing [26]. Therefore, different research could result in different viscosities of DP. Effendy et al. [26] have found that the DP kinematic viscosity of the WLO is around 2.155 mm/s². Wang and Ni's [23] study found that the kinematic viscosity value of the DP is 4.3 mm/s² when conducting distillation using WLO.

Daopiset et al. [25] research shows that the kinematic viscosity of diesel at 40 °C is between 2 and 4.5 mm/s². As shown in **Table 2**, DP has a higher viscosity than diesel used in the Daopiset et al. study. The viscosity value of the DP is significantly influenced by the accumulation of raw materials in the oil lubricants. Fresh lubricant oil raw material contains various compounds [26]. Moreover, WLO could contain heavy metals. Hence, the DP viscosity of different research studies on oil lubricant waste could differ. Zare et al. [24] used WLO in their research with a viscosity of 30 mm/s². The present study employed a waste engine oil with a viscosity of 48.33 mm/s². Moreover, the type of distillation apparatus used in the various research studies is also different; this might have caused the product viscosity of each researcher's results to differ.

Generally, DP characteristics such as density, LHV, and flash point decrease after the distillation process. According to the Predojević [41] study, the formed density of the fuel depends on the raw material and the purification steps. Arpa et al. 's [27] resulting density of the DP from WLO is around 0.818 g/cm³. According to Li et al. [28], different stages of oil processing also influence the LHV. Wang and Ni's [23] study found that the LHV of the DP from WLO is around 42000 kJ/kg. The flash point of diesel fuel varies between 52 and 96 °C [25]. According to Effendy et al. [26], material with a higher flash point has a tendency difficulties to be more flammable than material with a lower flash point.

The mixed fuel density and LHV are presented in **Table 3**. The density of mixed fuel and LHV were found using the characterization test according to ASTM D 4052 and ASTM D 4809. Increasing the DP value affects an increase in density and a decrease in LHV. This phenomenon indicates the DP's density is higher than Pertamina Dex, and the LHV value of the DP is lower than Pertamina Dex [26]. Özgür and Tosun's [30] research has predicted density using an artificial neural network for a mixture of diesel and biodiesel. Biodiesel has a higher density than diesel, and when biodiesel content in the mixed fuel increases, it increases the mixed fuel's density.

Furthermore, increased density in the mixed fuel could decrease engine performance in areas such as torque and power [33]. A decrease in LHV value could affect reduced specific fuel consumption (SFC) and thermal efficiency of the tested engine [27,42]. Those influences will be discussed in another section.

3.2. Engine Performance Test Result

3.2.1. Torque

The torque vs CI engine speed rotation can be seen in **Figure 5**. The torque was calculated using Eq. (1). According to **Figure 5**, all fuels behave similarly; increasing the CI engine speed rotation from 1000 to 2500 rpm could enhance torque. This behavior is due to lesser friction and more complete combustion at higher engine speed rotation. The result is consistent with the engine specifications (**Table 1**). Generally, all mixed fuel torque values are lower than neat fuel. According to **Figure 5**, it can be seen that at constant engine speed, torque decreases when the content of the DP in the mixed fuel increases. This condition is probably due to the higher density of the mixed fuel than neat fuel. Seifi et al. [33] have found that increased density in the mixed fuel promotes decreased torque of the tested engine.

The fuel density has the most significant effect on the diesel engine injection timing. The higher density of the fuel requires an earlier injection time [43]. The fuel density also influences the spray tip penetration and spray characteristics. Higher fuel density resulting a larger spray angle [44]. Increasing fuel density lowers the spray tip/tail penetration rate [45]. Moreover, as fuel is injected into the combustion chamber, the chain changes from atomization→ breakup→mixture. This is strongly affected by the density of the fuel [46]. Therefore, it could be affecting combustion behavior. Lower combustion behavior promoted a decrease in the engine's torque [47].

Table 3. Mixed fuel density and LHV value

Property of Fuel	Density (g/cm³)	LHV (kJ/kg)
0%DP	0.8200	45130
5%DP	0.8215	45081.5
10%DP	0.8230	45033
15%DP	0.8245	44984.5

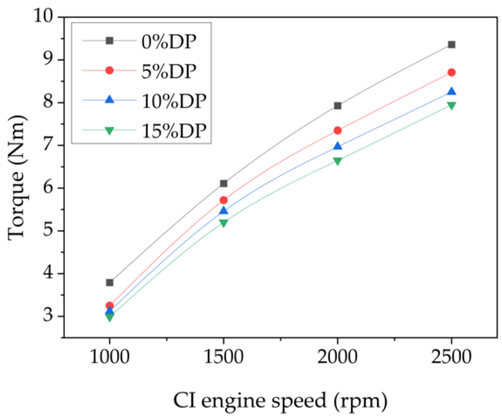


Figure 5. Torque vs CI engine speed rotating

3.2.2. *Power*

Power was calculated using Eq. (2). Power vs CI engine speed rotation can be seen in **Figure 6**. It seems all fuels have similar behavior; increasing CI engine speed rotation from 1000 to 2500 rpm would increase the power. This condition, probably due to a higher engine speed, led to increasing fuel flammability and more power. Compared to the engine specification (**Table 1**), the maximum power of the tested CI engine is 3600 rpm, which is consistent with the present result. According to **Figure 6**, the CI engine operated using mixed fuel and tended to lower power than neat fuel, which behaves similarly to torque (see **Figure 5**). Increasing the content of the DP in the mixed fuel influenced by a decrease in power. Seifi et al. [33] have found that the power decreases due to the increased density of the mixed fuel. As seen in **Table 3**, an increase in DP content in the mixed fuel led to an increase in density. The fuel density value could affect combustion duration. An increase in fuel density could be resulting a decrease in combustion duration [48]. According to Dzida et al. [49], an increase in fuel density would decrease engine power due to different mass flows of fuel injected. Moreover, increased fuel density could also decrease flammability, contributing to reduced engine power [26].

The decrease in engine power is also influenced by a reduction in heating value [33]. A decreased heating value contributed to a reduced net heat release rate [50]. Moreover, a reduction in LHV could decrease the energy level of the mixed fuel, therefore decreasing engine power [51]. According to **Table 3**, the fuel LHV decreases when the DP content in the mixed fuel increases, resulting in a decrease in engine power.

3.2.3. *Specific Fuel Consumption (SFC)*

SFC was calculated by using equation (3). The SFC vs CI engine speed rotation can be seen in **Figure 7**. Increased rotation speed of the CI engine from 1000 to 2500 rpm promoted to a decrease in SFC. This behavior is probably due to heat losses through the wall of the combustion chamber being higher proportionally and combustion efficiency being low at low speed. Therefore, this results in higher specific fuel consumption at lower speeds [52]. Moreover, comparing **Figure 6** and **Figure 7**, it can be seen that the power and SFC are inverse proportionally in various engine speeds. Prasanna Raj Yadav et al. [35,53] have found that the SFC depends on power; increasing power reduces SFC, which perfectly agrees with present research.

Increased DP content in various mixed fuels at constant IC engine speed resulted in decreased SFC. This behavior is probably due to reduced fuel LHV, which is caused by increasing the DP in the various mixed fuels (see **Table 3**) [33]. A decrease in heating value contributed to a reduction in the net heat release rate and energy level of the mixed fuel, which contributed to combustion efficiency and directly affected the SFC [50,51]. Moreover, Arpa et al. [27] have found that lower fuel LHV results in lower SFC at various engine speeds, which perfectly agrees with the present study.

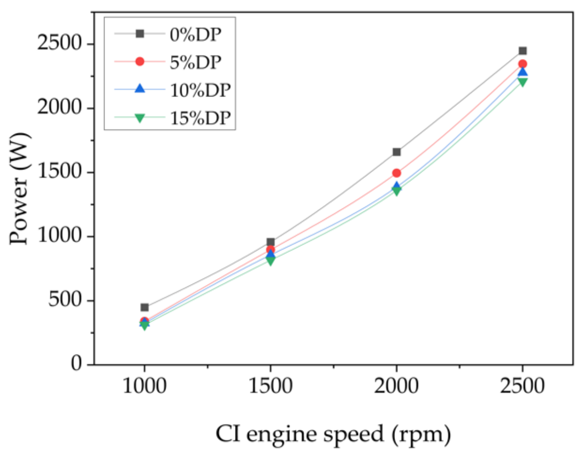


Figure 6. Engine power output for different mixed fuel versus CI engine speed rotating

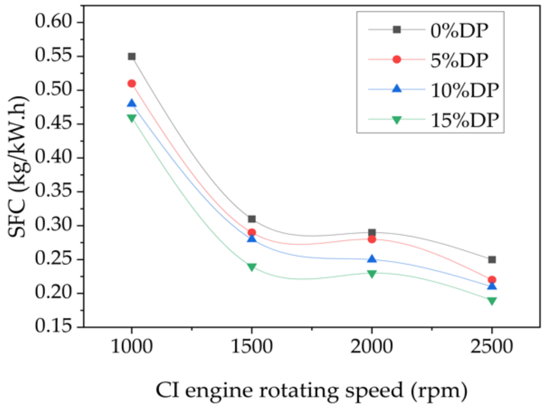


Figure 7. SFC versus CI engine rotating speed

3.2.4. *Thermal Efficiency*

Thermal efficiency was calculated using equation (4). Thermal efficiency vs CI engine speed rotation can be seen in **Figure 8**. All fuels have a similar trend; increasing CI engine speed rotation from 1000 to 2500 rpm could increase thermal efficiency. When comparing thermal efficiency to SFC, it can be seen that it is inversely proportioned, which perfectly agrees with other researchers [7,34,54].

Yadaf et al. [53] found that increased power raised thermal efficiency, which aligns with present research. Moreover, Effendy et al. [26] found that thermal efficiency decreases due to reduced power combined with increased fuel consumption, which perfectly aligns with the present research. Furthermore, Musthafa [55] found that lower fuel LHV resulted in lower thermal efficiency at various brake power conditions. Lower thermal efficiency is affected by lower fuel LHV and promotes a decrease in fuel energy conversion to mechanical power [56]. Compared to **Table 3**, it can be seen that the increased DP composition in the mixed fuel leads to decreased fuel LHV. As mentioned above, reduced LHV contributed to a decrease in the net heat release rate and energy level of the mixed fuel, which contributed to combustion efficiency and, therefore, a reduction in the thermal efficiency [50,51].

3.2.5. *Smoke Opacity*

Smoke opacity vs CI engine speed rotation can be seen in **Figure 9**. The behaviors of all fuels are similar. Increasing the CI engine rotation speed from 1000 to 2500 rpm promoted an increase in smoke opacity. The rise in DP content in the mixed fuel at similar operating conditions caused an increase in smoke opacity (**Figure 9**). Higher smoke opacity indicates incomplete combustion [54]. The reason for this behavior is likely due to the rise of the DP content in the mixed fuel, which resulted in a decrease in fuel LHV. According to Effendy et al. [26], higher LHV leads to a higher contribution to intensifying combustion behavior, resulting in the lowest smoke opacity. Moreover, Rozak et al. [32] found that the smoke opacity of Pertamina Dex at 1500 rpm was around 14-16%.

Besides fuel LHV, fuel density also contributed to pollution, such as smoke opacity [46]. According to Liu et al. [48], enhanced fuel density could increase the emission. The fuel density also contributed to the incomplete combustion, which could strengthen the smoke opacity. Higher fuel density also requires an earlier injection time [43]. Moreover, fuel density value could affect combustion duration; an increase in fuel density could decrease combustion duration [48]. Therefore, there is an increase in smoke opacity by the rise in fuel density.

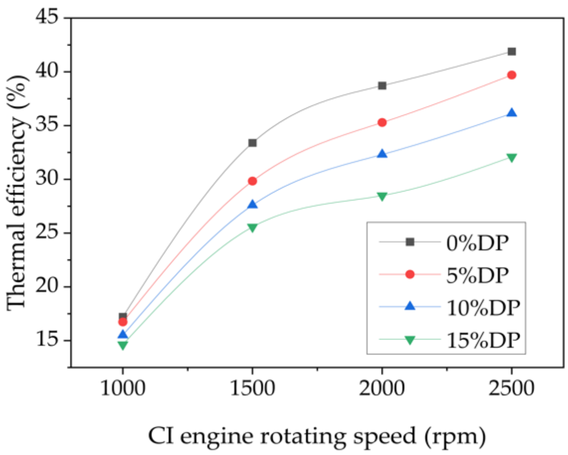


Figure 8. Thermal efficiency versus CI engine speed rotating

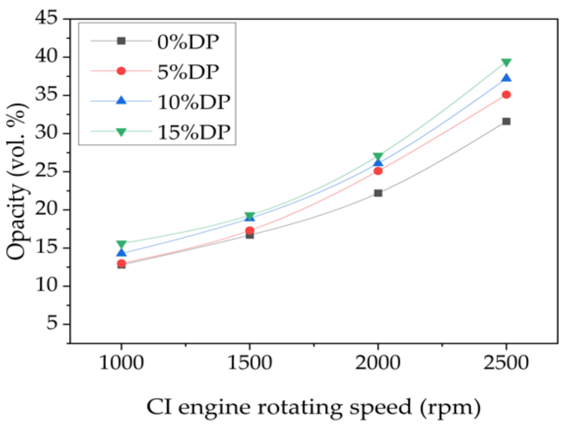


Figure 9. Opacity versus engine speed rotating

4. Conclusion

Distillation of WLO has been successfully conducted. The DP has a lower viscosity, density, LHV, and flash point than WLO. According to the testing of mixed fuel on CI engines, an increased content of DP in the mixed fuel promoted to decreased torque, power, SFC, thermal efficiency, and increased smoke opacity. This behavior is because of the increased density and reduced LHV of mixed fuel. Therefore, the suggested use of a catalyst in the distillation process could probably decrease density and increase the LHV of fuel. Moreover, enhanced CI engine speed would increase linearly of the torque, power, thermal efficiency, and smoke opacity. On the contrary, a rise in CI engine speed promoted decreased SFC.

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Author's Declaration

Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript.

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Availability of data and materials

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Competing interests

The authors declare no competing interest.

Additional information

No additional information from the authors.

References

1. Ibrahim, R.L.; Ajide, K.B.; Omokanmi, O.J. Non-renewable energy consumption and quality of life: Evidence from Sub-Saharan African economies. *Resources Policy* **2021**, *73*, 102176, doi:10.1016/j.resourpol.2021.102176.
2. Zhang, Y.; Li, L.; Sadiq, M.; Chien, F. The impact of non-renewable energy production and energy usage on carbon emissions: Evidence from China. *Energy & Environment* **2024**, *35*, 2248–2269, doi:10.1177/0958305X221150432.
3. Kalghatgi, G. Is it really the end of internal combustion engines and petroleum in transport? *Applied Energy* **2018**, *225*, 965–974, doi:10.1016/j.apenergy.2018.05.076.
4. Arjun, T.B.; Atul, K.P.; Muraleedharan, A.P.; Walton, P.A.; Bijinraj, P.B.; Raj, A.A. A review on analysis of HHO gas in IC engines. *Materials Today: Proceedings* **2019**, *11*, 1117–1129, doi:10.1016/j.matpr.2018.12.046.
5. Nahian, M.R.; Islam, M.N.; Khan, S.M. Production of Biodiesel from Palm Oil and Performance Test with Diesel in CI Engine. In Proceedings of the International Conference on Mechanical, Industrial and Energy Engineering 2016; 2016; pp. 26–27.
6. Onukwuli, D.O.; Emembolu, L.N.; Ude, C.N.; Aliozo, S.O.; Menkiti, M.C. Optimization of biodiesel production from refined cotton seed oil and its characterization. *Egyptian Journal of Petroleum* **2017**, *26*, 103–110, doi:10.1016/j.ejpe.2016.02.001.
7. Yadav, S.P.R.; Saravanan, C.G.; Kannan, M. Influence of injection timing on di diesel engine characteristics fueled with waste transformer oil. *Alexandria Engineering Journal* **2015**, *54*, 881–888, doi:10.1016/j.aej.2015.07.008.
8. Milano, J.; Silitonga, A.S.; Tiong, S.K.; Ong, M.Y.; Masudi, A.; Hassan, M.H.; Nur, T. Bin; Nurulita, B.; Sebayang, A.H.; Sebayang, A.R. A Comprehensive exploration of jatropha curcas biodiesel production as a viable alternative feedstock in the fuel industry – Performance evaluation and feasibility analysis. *Mechanical Engineering for Society and Industry* **2024**, *4*, 17–37, doi:10.31603/mesi.10610.
9. Supriyadi, S.; Purwanto, P.; Anggoro, D.D.; Hermawan, H. The Effects of Sodium Hydroxide (NaOH) Concentration and Reaction Temperature on The Properties of Biodiesel from Philippine Tung (Reutealis Trisperma) Seeds. *Automotive Experiences* **2022**, *5*, 57–67, doi:10.31603/ae.5986.
10. Thanikodi, S.; Rangappa, S.M.; Sebayang, A.H.; Siengchin, S. Performance of IC Engines Using Chicken Waste as Biofuel, CNT and MnO Nano-Biofuels and Diesel Fuel: A Comparation Study. *Automotive*

Experiences **2023**, *6*, 395–406, doi:10.31603/ae.9556.

11. Al-Saadi, A.; Mathan, B.; He, Y. Biodiesel production via simultaneous transesterification and esterification reactions over SrO–ZnO/Al2O3 as a bifunctional catalyst using high acidic waste cooking oil. *Chemical Engineering Research and Design* **2020**, *162*, 238–248, doi:10.1016/j.cherd.2020.08.018.
12. Kolakoti, A.; Setiyo, M.; Waluyo, B. Biodiesel Production from Waste Cooking Oil: Characterization, Modeling and Optimization. *Mechanical Engineering for Society and Industry* **2021**, *1*, 22–30, doi:10.31603/mesi.5320.
13. Suherman, S.; Abdullah, I.; Sabri, M.; Turmuzi, M.; Silitonga, A.S.; Dharma, S.; Yusfiani, M. A Review of Properties, Engine Performance, Emission Characteristics and Material Compatibility Biodiesel From Waste Cooking Oil (WCO). *Automotive Experiences* **2023**, doi:10.31603/ae.10128.
14. Mujiarto, S.; Sudarmanta, B.; Fansuri, H.; Saleh, A.R.; Fajarningrum, N.D.; Hayati, N. Characterization of diesel engines fueled by dual fuel syngas gasification refused derived fuel (RDF) and dexlite. *BIS Energy and Engineering* **2024**, *1*, V124039–V124039.
15. Nugroho, A.; Fatwa, M.A.; Hurip, P.D.; Murtado, H.; Kurniasari, L. Pyrolysis of plastic fishing gear waste for liquid fuel production: Characterization and engine performance analysis. *BIS Energy and Engineering* **2024**, *1*, V124040–V124040, doi:10.31603/biseeng.41.
16. Sunaryo, S.; Suyitno, S.; Arifin, Z.; Setiyo, M.; Hermawan, H.; Irfan, A. Improving oil quality from waste pyrolysis using natural zeolite catalysts: towards sustainable resource recovery. *BIS Energy and Engineering* **2024**, *1*, V124037–V124037, doi:10.31603/biseeng.65.
17. Herraprastanti, E.H.; Ashraf, M.A.; Wahyusari, R.; Alfreda, D.Y. Fuel from plastic waste using the pyrolysis method. *BIS Energy and Engineering* **2024**, *1*, V124011–V124011, doi:10.31603/biseeng.34.
18. Wolak, A.; Zając, G. An empirical study of the variables affecting the frequency of engine oil change in the environmental aspect. *Rocznik Ochrona Srodowiska* **2019**, *21*, 738–766.
19. Waluyo, B.; Pujiarto, B.; Ardana, N.; Sholiah, A.; Rochman, M.L.; Adi, A.T. Optimizing energy harvesting from waste motor oil through steam reforming: A path to efficient combustion and emissions reduction. *Mechanical Engineering for Society and Industry* **2023**, *3*, 86–92, doi:10.31603/mesi.10362.
20. Pinheiro, C.T.; Ascensão, V.R.; Cardoso, C.M.; Quina, M.J.; Gando-Ferreira, L.M. An overview of waste lubricant oil management system: Physicochemical characterization contribution for its improvement. *Journal of Cleaner Production* **2017**, *150*, 301–308, doi:10.1016/j.jclepro.2017.03.024.
21. Gan, X.; Chen, L.; Chen, X.; Pan, S.; Pan, H. Agricultural bio-waste for removal of organic and inorganic contaminants from waste diesel engine oil. *Journal of Hazardous Materials* **2021**, *414*, 124906, doi:10.1016/j.jhazmat.2020.124906.
22. Thanikachalam, J.; Karthikeyan, S. Study on extraction of pollutant free flammable fuel from contaminated automobile waste lube oil. *Journal of Achievements in Materials and Manufacturing Engineering* **2020**, *2*, 78–84, doi:10.5604/01.3001.0014.3348.
23. Wang, X.; Ni, P. Combustion and emission characteristics of diesel engine fueled with diesel-like fuel from waste lubrication oil. *Energy Conversion and Management* **2017**, *133*, 275–283, doi:10.1016/j.enconman.2016.12.018.
24. Zare, A.; Bodisco, T.A.; Jafari, M.; Verma, P.; Yang, L.; Babaie, M.; Rahman, M..; Banks, A.; Ristovski, Z.D.; Brown, R.J.; et al. Cold-start NOx emissions: Diesel and waste lubricating oil as a fuel additive. *Fuel* **2021**, *286*, 119430, doi:10.1016/j.fuel.2020.119430.
25. Maceiras, R.; Alfonsín, V.; Morales, F.J. Recycling of waste engine oil for diesel production. *Waste Management* **2017**, *60*, 351–356, doi:10.1016/j.wasman.2016.08.009.
26. Effendy, M.; Surono, A.; Saputra, E.; Nugraha, N.A. Performance and smoke opacity of compression-ignition engine using used-waste oil. *Case Studies in Thermal Engineering* **2021**, *26*, 101063, doi:10.1016/j.csite.2021.101063.

27. Arpa, O.; Yumrutaş, R.; Argunhan, Z. Experimental investigation of the effects of diesel-like fuel obtained from waste lubrication oil on engine performance and exhaust emission. *Fuel Processing Technology* **2010**, *91*, 1241–1249, doi:10.1016/j.fuproc.2010.04.004.
28. Li, X.; Zhai, J.; Li, H.; Gao, X. An integration recycling process for cascade utilization of waste engine oil by distillation and microwave-assisted pyrolysis. *Fuel Processing Technology* **2020**, *199*, 106245, doi:10.1016/j.fuproc.2019.106245.
29. Dzida, M.; Prusakiewicz, P. The effect of temperature and pressure on the physicochemical properties of petroleum diesel oil and biodiesel fuel. *Fuel* **2008**, *87*, 1941–1948, doi:10.1016/j.fuel.2007.10.010.
30. Özgür, C.; Tosun, E. Prediction of density and kinematic viscosity of biodiesel by artificial neural networks. *Energy Sources, Part A: Recovery, Utilization and Environmental Effects* **2017**, *39*, 985–991, doi:10.1080/15567036.2017.1280563.
31. Cappenberg, A.D. Pengaruh Penggunaan Bahan Bakar Solar, Biosolar Dan Pertamina Dex Terhadap Prestasi Motor Diesel Silinder Tunggal. *Jurnal Konversi Energi dan Manufaktur* **2017**, *4*, 70–74, doi:10.21009/jkem.4.2.3.
32. Rozaq, F.; Wirawan, W.A.; Hari, B.W.; Dadang, S.A.; Nurtanto, M. The influence of centrifugal particulate matter reducer on gas opacity and fuel consumption of inspection train. *Journal of Physics: Conference Series* **2020**, *1700*, doi:10.1088/1742-6596/1700/1/012050.
33. Seifi, M.R.; Hassan-Beygi, S.R.; Ghobadian, B.; Desideri, U.; Antonelli, M. Experimental investigation of a diesel engine power, torque and noise emission using water-diesel emulsions. *Fuel* **2016**, *166*, 392–399, doi:10.1016/j.fuel.2015.10.122.
34. Katekaew, S.; Suiuay, C.; Senawong, K.; Seithtanabutara, V.; Intravised, K.; Laloon, K. Optimization of performance and exhaust emissions of single-cylinder diesel engines fueled by blending diesel-like fuel from Yang-hard resin with waste cooking oil biodiesel via response surface methodology. *Fuel* **2021**, *304*, 121434, doi:10.1016/j.fuel.2021.121434.
35. Prasanna Raj Yadav, S.; Saravanan, C.G.; Karthick, S.; Senthilnathan, K.; Gnanaprakash, A. Fundamental droplet evaporation and engine application studies of an alternate fuel produced from waste transformer oil. *Fuel* **2020**, *259*, 116253, doi:10.1016/j.fuel.2019.116253.
36. Hardiyanto, C.; Prawoto, P. Effect of Diethyl Ether on Performance and Exhaust Gas Emissions of Heavy-Duty Diesel Engines Fueled with Biodiesel-Diesel Blend (B35). *Automotive Experiences* **2023**, *6*, 687–701, doi:10.31603/ae.10311.
37. Ooi, J.B.; Kau, C.C.; Manoharan, D.N.; Wang, X.; Tran, M.-V.; Hung, Y.M. Effects of multi-walled carbon nanotubes on the combustion, performance, and emission characteristics of a single-cylinder diesel engine fueled with palm-oil biodiesel-diesel blend. *Energy* **2023**, *281*, 128350, doi:10.1016/j.energy.2023.128350.
38. Al-Bawwat, A.K.; Gomaa, M.R.; Cano, A.; Jurado, F.; Alsbou, E.M. Extraction and characterization of Cucumis melon seeds (Muskmelon seed oil) biodiesel and studying its blends impact on performance, combustion, and emission characteristics in an internal combustion engine. *Energy Conversion and Management: X* **2024**, *23*, 100637, doi:10.1016/j.ecmx.2024.100637.
39. Pelletier, E.; Brennan, S. Diesel Engine Characterization and Performance Scaling Via Brake Specific Fuel Consumption Map Dimensional Analysis. In Proceedings of the Proceedings of ASME 2019 Dynamic Systems and Control Conference; 2019; p. V002T11A003.
40. Majedi, F.; Setiyaningrum, D.; Hidayahtullah, S.M.T.; Abbas, A. Effects of injection pressure on output power, bte, sfc and opacity in a typical single-cylinder diesel engine. *Automotive Experiences* **2020**, *3*, 20–26, doi:10.31603/ae.v3i1.3006.
41. Predojević, Z.J. The production of biodiesel from waste frying oils: A comparison of different purification steps. *Fuel* **2008**, *87*, 3522–3528, doi:10.1016/j.fuel.2008.07.003.
42. Sathish, T.; Surakasi, R.; KishoreT, L.; Rathinasamy, S.; Ağbulut, Ü.; Shaik, S.; Park,

S.G.; Afzal, A. Waste to fuel: Pyrolysis of waste transformer oil and its evaluation as alternative fuel along with different nanoparticles in CI engine with exhaust gas recirculation. *Energy* **2023**, *267*, 126595, doi:10.1016/j.energy.2022.126595.

43. Pandey, R.K.; Rehman, A.; Sarviya, R.M. Impact of alternative fuel properties on fuel spray behavior and atomization. *Renewable and Sustainable Energy Reviews* **2012**, *16*, 1762–1778, doi:10.1016/j.rser.2011.11.010.
44. Suh, H.K.; Lee, C.S. A review on atomization and exhaust emissions of a biodiesel-fueled compression ignition engine. *Renewable and Sustainable Energy Reviews* **2016**, *58*, 1601–1620.
45. Zhou, X.; Li, T.; Lai, Z.; Wei, Y. Modeling diesel spray tip and tail penetrations after end-of-injection. *Fuel* **2019**, *237*, 442–456, doi:10.1016/j.fuel.2018.10.029.
46. Hoang, A.T. Prediction of the density and viscosity of biodiesel and the influence of biodiesel properties on a diesel engine fuel supply system. *Journal of Marine Engineering & Technology* **2021**, *20*, 299–311, doi:10.1080/20464177.2018.1532734.
47. Taghavifar, H.; Khalilarya, S.; Jafarmadar, S. Engine structure modifications effect on the flow behavior, combustion, and performance characteristics of di diesel engine. *Energy Conversion and Management* **2014**, *85*, 20–32, doi:10.1016/j.enconman.2014.05.076.
48. Liu, H.; Ma, J.; Dong, F.; Yang, Y.; Liu, X.; Ma, G.; Zheng, Z.; Yao, M. Experimental investigation of the effects of diesel fuel properties on combustion and emissions on a multi-cylinder heavy-duty diesel engine. *Energy Conversion and Management* **2018**, *171*, 1787–1800, doi:10.1016/j.enconman.2018.06.089.
49. Dzida, M.; Jężak, S.; Sumara, J.; Zarska, M.; Góralski, P. High pressure physicochemical properties of biodiesel components used for spray characteristics in diesel injection systems. *Fuel* **2013**, *111*, 165–171, doi:10.1016/j.fuel.2013.04.031.
50. Chuah, L.F.; Bokhari, A.; Asif, S.; Klemeš, J.J.; Dailin, D.J.; Enshasy, H. El; Yusof, A.H.M. A Review of Performance and Emission Characteristic of Engine Diesel Fuelled by Biodiesel. *Chemical Engineering Transactions* **2022**, *94*, 1099–1104, doi:10.3303/CET2294183.
51. Chen, H.; Wang, J.; Shuai, S.; Chen, W. Study of oxygenated biomass fuel blends on a diesel engine. *Fuel* **2008**, *87*, 3462–3468, doi:10.1016/j.fuel.2008.04.034.
52. Tesfa, B.; Gu, F.; Mishra, R.; Ball, A.D. LHV predication models and LHV effect on the performance of CI engine running with biodiesel blends. *Energy Conversion and Management* **2013**, *71*, 217–226, doi:10.1016/j.enconman.2013.04.005.
53. Prasanna Raj Yadav, S.; Saravanan, C.G.; Vallinayagam, R.; Vedharaj, S.; Roberts, W.L. Fuel and engine characterization study of catalytically cracked waste transformer oil. *Energy Conversion and Management* **2015**, *96*, 490–498, doi:10.1016/j.enconman.2015.02.051.
54. Arjharn, W.; Liplap, P.; Maithomklang, S.; Thammakul, K.; Chuepeng, S.; Sukjit, E. Distilled Waste Plastic Oil as Fuel for a Diesel Engine: Fuel Production, Combustion Characteristics, and Exhaust Gas Emissions. *ACS Omega* **2022**, *7*, 9720–9729, doi:10.1021/acsomega.1c07257.
55. Mohamed Musthafa, M. Synthetic lubrication oil influences on performance and emission characteristic of coated diesel engine fuelled by biodiesel blends. *Applied Thermal Engineering* **2016**, *96*, 607–612, doi:10.1016/j.applthermaleng.2015.12.011.
56. Fahd, M.E.A.; Wenming, Y.; Lee, P.S.; Chou, S.K.; Yap, C.R. Experimental investigation of the performance and emission characteristics of direct injection diesel engine by water emulsion diesel under varying engine load condition. *Applied Energy* **2013**, *102*, 1042–1049, doi:10.1016/j.apenergy.2012.06.041.