 https://doi.org/10.1051/e3sconf/202565001002

Characterization of palm oil-based biodiesel, hydrotreated vegetable oil, and fatty acid methyl esters as alternative renewable fuels to replace petrodiesel in diesel engines

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Abstract. Indonesia has been focusing on the development and utilization of hydrotreated vegetable oil (HVO) as a substitute fuel to increase the use of renewable energy sources and lessen reliance on fossil fuels. This study maps the characteristics of biodiesel fuels, including FAME, HVO, and the mixed-fuel combination, before the fuel is used in performance tests on diesel engines. The study tested nine fuel samples in a laboratory and then compared their quality with the reference standard for each fuel type. The result shows that HVO fuel has a high cetane number, indicating easy ignitability and quick burning, facilitating efficient combustion in diesel engines, while the mixture of biodiesel and HVO contains phosphorus and alkali metals. The high acidity level in FAME biodiesel B100 has the potential to cause corrosion in the fuel system and engine components, such as injectors, fuel pumps, and valves. FAME biodiesel has higher glyceride content, which can disrupt engine performance and cause fuel injector blockages. In summary, the study indicates that it's important to look at different factors when assessing biodiesel fuels, such as cetane number, total acid number, and glyceride content, to reduce any possible negative risks.

1 Introduction

The development and utilization of biofuels, particularly Hydrotreated Vegetable Oil (HVO), has become one of the focal points of energy policy in Indonesia. As one of the largest palm oil producers in the world, Indonesia has enormous potential for HVO production from palm oil mill effluents (POME). It is estimated that Indonesia can produce around 0.9 billion liters of HVO from POME, although the dynamics of supply and demand are still under-researched [1]. The Indonesian government has established energy policies aimed at reducing

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dependence on fossil fuels and increasing the use of renewable energy, including biofuels. This policy aligns with the national CO_2 emission reduction targets and the enhancement of sustainability in the automotive industry [2]. However, the development of biofuels in Indonesia faces various challenges, including higher production costs compared to fossil fuels and distribution obstacles due to geographical constraints. In Indonesia, efforts to implement a blend of biodiesel and HVO have been made to address the emission challenges of conventional diesel fuel and reduce dependence on fossil fuels.

Hydrotreated vegetable oil is becoming increasingly popular as an alternative to fossil fuels. A primary advantage of HVO is its capacity to be synthesized from diverse renewable feedstocks, without affecting the quality of the final product. The HVO production process involves the hydrogenation of vegetable oils, producing pure hydrocarbon fuel with better combustion properties compared to traditional biodiesel, such as fatty acid methyl esters (FAME). Additionally, soybean oil is also used in the production of HVO, especially in Brazil, where life cycle analysis shows excellent environmental performance when processed with hydrogen obtained through electrolysis [3]. Several previous studies indicate that HVO has a higher cetane value, better cold flow properties, lower emissions, and superior oxidation stability, improves the thermal efficiency of engines, and reduces harmful emissions such as carbon monoxide (CO), hydrocarbon (HC), and particulates [4]. Furthermore, using HVO in dual-fuel mode alongside bioethanol or hydrogen can further reduce emissions and improve combustion efficiency. However, to fully utilize the potential of HVO, engine parameter adjustments or recalibrations are often necessary, considering the differences in chemical and physical properties between HVO and fossil diesel. Further research is needed to optimize the use of HVO under various operating conditions and to understand the environmental impact of the full life cycle of this fuel [5]. Overall, HVO offers a promising solution to reduce the carbon footprint of the transportation sector, in line with future low-emission targets.

The use of hydrotreated vegetable oil (HVO) as a biofuel for diesel engines has become a significant focus of research recently. With the rapid growth of population and economy, the need for cleaner and more sustainable alternative fuels is becoming increasingly urgent. HVO, with its superior characteristics, offers a promising solution to meet the sustainable energy needs in Indonesia's transportation sector. In the power generation sector, further research and technological development are needed to maximize the potential of HVO as an environmentally friendly and efficient diesel engine fuel in Indonesia. The advancement of biofuels, specifically HVO derived from palm oil in Indonesia, presents significant potential for diminishing greenhouse gas emissions and reliance on fossil fuels.

This study is part of a comprehensive ongoing research project that evaluates the utilization of biofuel based on FAME, HVO, and their mixtures as alternative diesel engine fuels to support the spread of new renewable energy in the electricity generation sector in Indonesia. The novelty of this study is the mapping of multiple physical parameters that cause potential technical impacts due to fuel parameters with a relatively high biofuel blend ratio (from 40% up to 100% ratio) in diesel engines. The purpose of this research is

- To characterize the critical parameters of biodiesel fuels, specifically FAME (fatty acid methyl esters) and HVO (hydrotreated vegetable oils), including the high blend ratios that differentiate them from pure petrodiesel. These parameters will be utilized as inputs for testing on diesel engines.
- To assess the impact of variations in critical parameters for FAME and HVO biofuels, as well as the high blend ratios, on the performance of diesel engines.

 https://doi.org/10.1051/e3sconf/202565001002

2 Methodology

This study involves the laboratory testing of FAME and HVO samples derived from palm oil and petrodiesel. Existing refineries manufacture HVO without an isomerization reactor. In this study, tests were conducted on 9 fuel samples consisting of pure petrodiesel, pure FAME, pure HVO, a blend of petrodiesel with FAME, a blend of petrodiesel with FAME and HVO, and a blend of petrodiesel with HVO, as shown in Table 1. All of these samples were tested in the LEMIGAS laboratory to be compared with the quality requirements according to the Indonesian National Standard (SNI 7182:2015) and government regulation for fuel quality (Keputusan Dirjen Migas No. 146.K/10/DJM/2020; Keputusan Dirjen EBTKE No. 189k/10/DJE/2019 and No. 95.k/EK.05/DJE/2022). The detailed test method and standards used for each type of fuel are shown in Table 2. Visually, the HVO sample tends to be lighter compared to 100% FAME biodiesel (B100) and petrodiesel (B0), as shown in Fig. 1.

Table 1. Fuel Sample Identication.

Sample Identification	Composition Description
B0	pure petrodiesel
B30	30% FAME 70% petrodiesel
B40	40% FAME 60% petrodiesel
B30D10	30% FAME 10% HVO 60% petrodiesel
B30D20	30% FAME 20% HVO 50% petrodiesel
D40	40% HVO 60% petrodiesel
D50	50% HVO 50% petrodiesel
B100	pure biodiesel FAME
D100	pure HVO

(a) (b)

Fig. 1. Physical appearance of fuel samples (a) pure petrodiesel (B0), pure FAME biodiesel (B100), and pure HVO (D100) (b) Mixture of petrodiesel, FAME biodiesel, and HVO.

Table 2. Laboratory Test Method.

Parameter	Method/Instrument/Standard
Cetana Number	ASTM D 613-18ae1
Density	ASTM D 4052-18a / ASTM D 5453-19a
Kinematic viscosity	ASTM D 445-21
Water Content	ASTM D 6304-20
Flash Point	ASTM D 93-20
Pour Point	ASTM D 5949-16
Atomization/ Pour Point	ASTM D 5773
Phospor Content	SNI 7182:2015 / AOCS Ca 12-55 (2009)

Metal Content (Na+K, Ca+Mg)	EN 14108-2003 (Atomic Absorption Spectrometry)
Total Acid Number	ASTM D 664-18e2
Glyceride	ASTM D 6584-17 / EN 14105

3 Result and Discussion

3.1 Cetane number

All fuel parameters in this study continue to satisfy the criteria limits established by EN 15940:2019 and SNI standards, with the exception of the CFPP parameters, which were not subjected to an isomerization reaction during the preparation of the HVO samples. Cetane number is a measure of diesel fuel quality. This number describes the fuel's ability to produce efficient combustion in a diesel engine. A higher cetane number indicates superior performance of the diesel engine. Figure 2a shows that the biodiesel blends (B30D10, B30D20, D40, and D50) and pure HVO D100 have a higher cetane number than petrodiesel (B0). The cetane number of D100 is the highest compared to other fuels (see Fig. 2(a)). A high cetane number indicates that the fuel has properties that make it easily ignitable and quick to burn, facilitating initial ignition [6]. This allows for more efficient combustion in the combustion chamber of the diesel engine, where the flame propagation is faster. As a result, the diesel engine's efficiency increases, generating more power from the same amount of fuel. In addition, it also tends to produce lower emissions compared to petrodiesel and exerts a beneficial influence on diesel engine performance [7].

3.2 Kinematic viscosity

The kinematic viscosity of HVO can have a significant impact on the performance of diesel engines. For HVO or biodiesel, the kinematic viscosity is influenced by the fuel composition and operational temperature. Figure 2(b) shows that the magnitude of the kinematic viscosity of both the HVO-petrodiesel blend (D40 and D50) and pure HVO (D100) is close to that of pure petrodiesel. The viscosity of each of these fuels only differs within the range of -0.44% to 2.82%. Thus, the viscosity level of HVO is almost the same as that of pure petrodiesel. In general, the kinematic viscosity of the 9 samples still meets the SNI standard limits. High viscosity, such as in FAME biodiesel, has the potential to hinder fuel flow through the fuel system [8], especially through small channels and fuel injectors. These obstacles can cause a decrease in fuel pressure and disrupt efficient combustion in the combustion chamber. Additionally, it requires extra energy to spray the fuel perfectly and achieve excellent mixing with the air. The fuel atomizing process also becomes poor [9]. This process can result in incomplete combustion, leading to higher emissions, increased black carbon, and more combustion residue within the engine. The fuel system circulation can also be hindered due to increased pressure on the fuel pump [10] and affect the return fuel flow to the tank or the return fuel circulation.

3.3 Density and sulfur content

HVO has a density that varies depending on the raw materials and production processes used. In this study, the density of HVO tends to be lower compared to petrodiesel. The magnitude of the density difference between the two is 8.61% (see Fig. 2(c)). Different densities can have different effects on diesel engines, especially in terms of performance and emissions. Furthermore, Fig. 3b shows that the sulfur content in pure HVO and pure FAME biodiesel is much lower compared to diesel.

3.4 Water content

HVO's water content is like petrodiesel's and lower than FAME biodiesel's (see Fig. 2(d)). To avoid the negative impact of water content in FAME biodiesel or HVO on the engine, it is important to maintain the quality and freshness of the fuel. The use of a water separation system can help remove water from biodiesel before it reaches the engine [11]. It is important to properly store and handle fuel to prevent water contamination, especially for FAME [12].

3.5 Flash point, pour point and cloud point

Figure 3a shows that the flash points of HVO mixed with petrodiesel (D40 and D50) and pure HVO (D100) are higher than that of petrodiesel (B0), with increases of 29.31%, 37.93%, and 81.03%, respectively. Meanwhile, the pour point of pure HVO is 183.33% higher compared to pure diesel. For the HVO atomization point, it is also higher by 123.68% compared to pure petrodiesel. This condition shows the characteristics of HVO, which is difficult to ignite and thus requires a longer heating-up process to achieve initial ignition. However, once ignited, it has a faster flame propagation. The flashpoint greatly affects the safety of fuel storage; a higher flashpoint can reduce auto-ignition when the fuel is stored [13]. If the pour point of green diesel is higher than the ambient temperature or the operating temperature of the engine, fuel that freezes can cause blockages in the fuel filter. A high HVO cloud point can cause incomplete combustion in the combustion chamber. Incomplete combustion can reduce the thermal efficiency of the engine, resulting in lower power output, increased fuel consumption, and higher exhaust emissions.

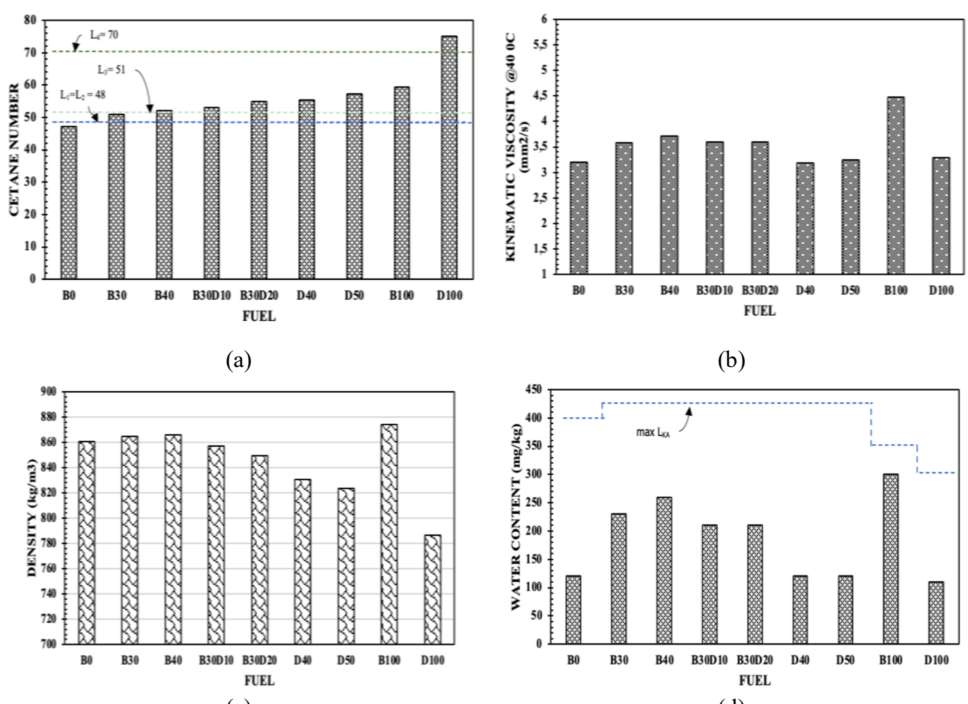


Fig. 2. Comparison parameters: (a) cetane number, (b) kinematic viscosity, (c) density, and (d) water content between solar, biodiesel FAME (B100), HVO (D100), mixed fuel FAME-solar (B30; B40), mixed fuel HVO-solar (D40; D50), and mixed fuel FAME-HVO-solar (B30D10 and B30D20)

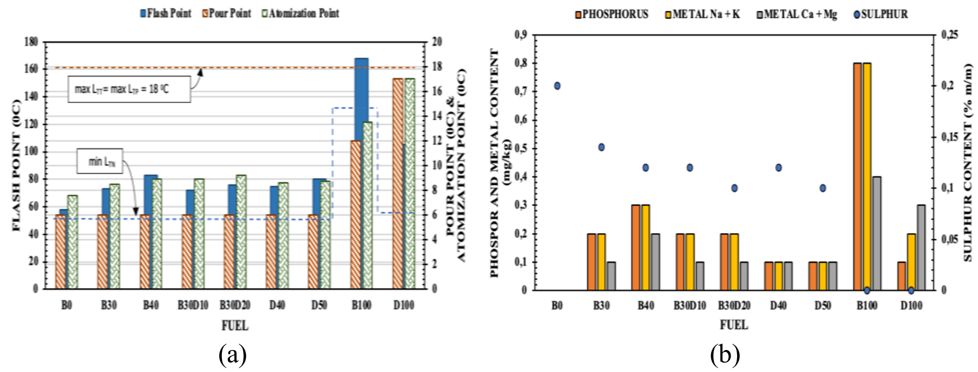


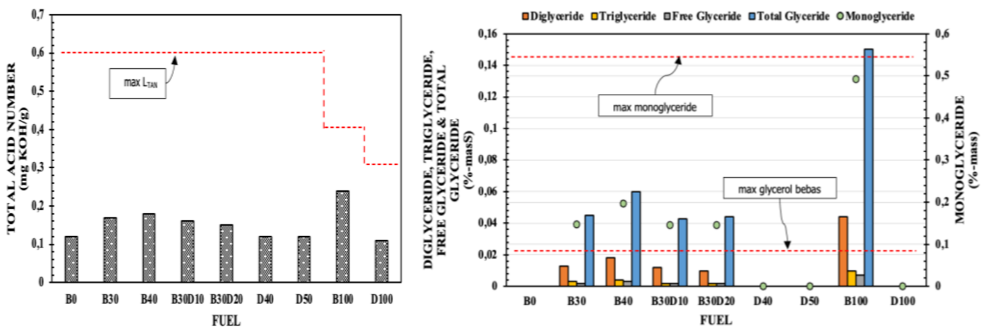
Fig. 3. Comparison parameters: (a) flash point, pour point, and atomization point; (b) phosphorus, metal, and sulfur content between solar, biodiesel FAME (B100), HVO (D100), mixed fuel FAME-solar (B30; B40), mixed fuel HVO-solar (D40; D50), and mixed fuel FAME-HVO-solar (B30D10 and B30D20)

3.6 Phosporus and metal content

In the blend of biodiesel and HVO, there are phosphorus and alkali metal contents Na, K, Ca, and Mg, where the content in HVO tends to be lower compared to FAME biodiesel. This indicates that the potential for corrosion and deposits when using HVO is lower compared to FAME biodiesel. The sodium and potassium content in biodiesel has the potential to cause corrosion on metal components in the engine [14]. Corrosion caused by alkali metals can damage metal surfaces, reduce engine lifespan, and decrease engine efficiency. Meanwhile, calcium and magnesium in certain amounts can play a role in forming a protective layer on the inside of the machine, such as valves and cylinder walls. This layer can help reduce friction and wear that occur during engine operation. However, if the concentration of these metals in the fuel is too high, they can cause the formation of unwanted deposits. These deposits can obstruct the flow of fuel and air within the engine, reducing the engine's efficiency and performance.

3.7 Total acid number (TAN)

D100 has a relatively lower total acid number (TAN) compared to FAME biodiesel; this value is almost the same as B0, D40, and D50 (see Figure 4a). This value indicates that the potential for oxidation or corrosion processes in D100 is still lower compared to other fuels. The high acidity level in biodiesel (B100) has the potential to cause corrosion in the fuel system and engine components that are directly exposed, such as injectors, fuel pumps, and valves. In addition, this condition also tends to form deposits on engine components that block fuel lines and cause a decrease in fuel flow.



(a) (b)

Fig. 4. Comparison parameters: (a) total acid number (TAN); (b) gliseride content between solar, biodiesel FAME (B100), HVO (D100), mixed fuel FAME-solar (B30; B40), mixed fuel HVO-solar (D40; D50), and mixed fuel FAME-HVO-solar (B30D10 and B30D20)

3.8 Glyceride content

The glyceride content in biodiesel generally comes from vegetable oils, which contain triglycerides (glycerol esters with fatty acids) as their main component. The effect of biodiesel's glyceride content on engines depends on the raw material quality, production process quality, and fuel-engine compatibility. Figure 4b shows that in HVO, both mixed fuels (D40 and D50) and pure HVO (D100) have almost no glyceride content. The characteristics of lower glyceride content, improved viscosity, and faster ignition significantly reduce the potential for gum formation. The glyceride content in FAME biodiesel is much higher compared to other fuels that tend to have the potential to dissolve and clean deposits or contaminants in the engine fuel system [15]. As a result, there will be deposits and contaminants that can disrupt engine performance and cause fuel injector blockages. This type of problem needs to be a main concern when using FAME biodiesel fuel, especially during the initial implementation phase.

4 Conclusion

Recently, Indonesia has been focusing on the development and utilization of hydrotreated vegetable oil (HVO) as an alternative fuel. HVO exhibits the most promising balance between combustion efficiency and environmental safety among tested blends. HVO fuel has a high cetane number, indicating easy ignitability and quick burning, facilitating efficient combustion in diesel engines. HVO's density is lower than petrodiesel, with a difference of 8.61% between the two. HVO's water content is similar to petrodiesel's and lower than FAME biodiesel's, making it crucial to maintain fuel quality and freshness. Flashpoints of HVO mixed with petrodiesel and pure HVO are higher than those of petrodiesel, affecting fuel storage safety and causing incomplete combustion. The high acidity level in B100 has the potential to cause corrosion in the fuel system and engine components, such as injectors, fuel pumps, and valves. FAME biodiesel has higher glyceride content, which can disrupt engine performance and cause fuel injector blockages. In conclusion, the study highlights the importance of considering various factors when evaluating the characteristics of biodiesel fuels, including cetane number, flash points, total acid number, and glyceride content, so that the potential negative risks that may arise can be well mitigated. Future studies are needed regarding the engine recalibration or modification when using a high blend ratio of biofuel, life cycle emission analysis, and long-term storage trials. With environmentally friendly characteristics, reduction of carbon dioxide emissions, and the potential for utilizing industrial waste, the use of palm oil-based biodiesel, hydrotreated vegetable oil (HVO), and fatty acid methyl esters (FAME) as alternative fuels in diesel engines can support the achievement of national energy targets and Indonesia's decarbonization while also strengthening energy resilience through the utilization of abundant domestic resources.

Acknowledgments

The authors are grateful to PT PLN (Persero), Diponegoro University, and PT Pertamina (Persero), which supported this study until completion.

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