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Original Research Paper

Towards nationwide implementation of 40% biodiesel blend fuel in Indonesia: a comprehensive road test and laboratory evaluation

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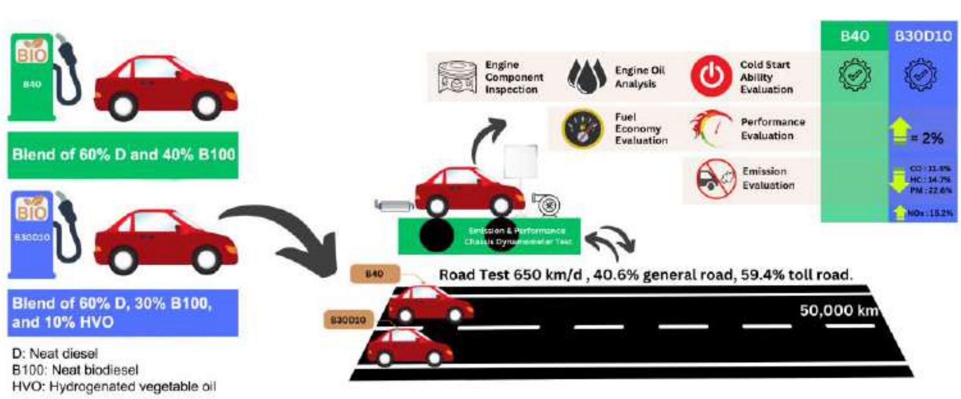
HIGHLIGHTS

- ➢Indonesia will implement 40% biodiesel blend fuel nationwide soon.
- ➢Using 40% biodiesel blend fuel (B40) was studied with road and laboratory tests.
- ➢A blend of 60% diesel fuel, 30% biodiesel, and 10% hydrogenated vegetable oil (HVO) was also investigated.
- ➢Both B40- and B30D10-powered vehicles successfully completed the 50,000 km road test.
- ➢B30D10 had a higher maximum power, less emissions, and better fuel economy than B40.

GRAPHICAL ABSTRACT



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ABSTRACT

This research focused on evaluating the technical viability of using biodiesel with a blending ratio of 40% v/v, which is expected to be implemented soon in Indonesia. Two kinds of biodiesel blends were prepared, a blend of 60% diesel fuel and 40% biodiesel (B40) and a blend of 60% diesel fuel, 30% biodiesel, and 10% hydrogenated vegetable oil (HVO) (B30D10). The fuels were tested on EuroII vehicles without any engine modifications through a 50,000 km endurance road test. Laboratory tests were also performed at certain traveled distances to evaluate various engine parameters, including power, fuel economy, exhaust emissions, and used engine oil properties. Engine components were inspected upon the completion of the road test. Cold-start ability was also examined to confirm the suitability of the investigated biofuels at low-temperature operating conditions in Indonesia. The road test results showed that vehicles fuelled with B40 and B30D10 could reach a distance of 50,000 km without encountering any technical issues. The laboratory evaluation during the road test indicated that B30D10 had a higher power and fuel economy than B40, with a maximum difference of 2%. Furthermore, B30D10 emitted lower CO, HC, and PM emissions than B40 throughout the distance traveled, with maximum differences of 11.4%, 14.7%, and 22.6%, respectively, but led to 15% higher NOx. Engine component inspection and used engine oil analysis confirmed the fulfillment of the manufacturer's recommendations for both B40 and B30D10. Finally, B40 and B30D10 were suitable for operating at low ambient temperatures in Indonesia, confirming them as practical options to be implemented in the nationwide 40% biodiesel blend fuel.
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Contents

Abbreviations

AVL	Anstalt für Verbrennungskraftmaschinen List/ List Institute for Combustion Engines	NEDC	New European driving cycle
CI	Compression ignition	PM	Particulate matter
CIMAC	Conseil International des Machines à Combustion (International Council on Combustion Engines)	PSS	Particulate sampling system
CLD	Chemiluminescence detector	SMG	Saturated monoglycerides
CVS	Constant volume sampling	TBN	Total base number
DI-DOHC	Direct injection - Double overhead camshaft	THC	Total hydrocarbon
ECE	Economic Commission for Europe	UDC	Urban driving cycle
ECU	Electronic control unit	**Nomenclatures**	
EN	European Norm / European Standards	AMAi60	Exhaust gas measurement device made by AVL
EUDC	Extra-urban driving cycle	B0	Neat diesel
FAME	Fatty acid methyl ester	B10	Blend of 90% diesel fuel and 10% of FAME
FE	Fuel economy	B20	Blend of 80% diesel fuel and 20% of FAME
FID	Flame ionization detector	B30	Blend of 70% diesel fuel and 30% of FAME
HHDDT	Heavy-duty diesel truck transient	B30D10	Blend of 60% diesel fuel, 30% of FAME, and 10% of HVO
HVO	Hydrogenated vegetable oil	B35	Blend of 65% diesel fuel and 35% of FAME
IEA	International energy agency	AMAi60	Exhaust gas measurement device made by AVL
ISO	International organization for standardization	B0	Neat diesel
MG	Monoglyceride	B40	Blend of 60% diesel fuel and 40% of FAME
NDIR	Non-dispersive infrared	B100	Neat biodiesel

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Symbols

Al	Aluminium	mCO	Mass of CO emission
Ca	Calcium	mCO_2	Mass of CO_2 emission
CO	Carbon monoxide	mHC	Mass of HC emission
CO_2	Carbon dioxide	Mn	Manganese
Cr	Chrome/Chromium	Na	Natrium
Cu	Copper/Cuprum	NOx	Nitrogen oxides
Fe	Iron/ Ferrum	Pb	Lead
HC	Hydrocarbon	PM	Particulate matter
Mg	Magnesium	Zn	Zinc

1. Introduction

Indonesia has shifted to a biodiesel blend fuel since 2013 to reduce its significant dependence on fossil diesel fuel. Biodiesel is currently implemented with a volume ratio of 35% (B35). Shortly, Indonesia intends to increase the volumetric percentage of biodiesel in fossil diesel fuel to 40%. Utilization of biodiesel is considered a strategic effort to reduce the amount of oil imported and increase the share of renewable energy to achieve a 23% renewable energy mix by 2025. Moreover, implementing biodiesel is also one strategy to help Indonesia reach net zero CO_2 emissions in the transportation sector by 2060 (IEA, 2022).

Utilizing a high blend ratio of biodiesel has some advantages, including drop-in fuel characteristics, low emission, and good lubricity, but some concerns should also be considered. For instance, Jaroonjitsathian et al. (2016) raised issues of filter clogging, degradation in fuel injection systems, and fuel tank corrosion with 50% of biodiesel blended fuel. They reported that vehicle maintenance schedules should be corrected for biodiesel blending ratios above 20%. Furthermore, biodiesel could also increase the harmful unregulated emission of formaldehyde, acetaldehyde, benzene, toluene, and xylene (Jaroonjitsathian et al., 2016). Metal contaminants, including Cu, Fe, Mn, Na, Mg, Al, and Ca, can be found due to friction wear or biodiesel contaminants, which lead to filter clogging (Patel et al., 2022). The properties of biodiesel, including sources and process, play a significant role in performance, emission, and engine components` lifetime; therefore, it is important to define specific biodiesel characteristics for high blending ratio (Markov et al., 2021) as well as the optimization of engine parameters to achieve better performance and emissions (Vijay Kumar et al., 2018). Moreover, improving biodiesel blend fuel properties could improve engine component lifetime comparable to neat diesel fuel (Reksowardojo et al., 2020).

Cardeño et al. (2020) recommended controlling the saturated monoglycerides (SMG) content of neat biodiesel to below 0.4% to minimize fuel clogging issues for efficiently utilizing a high blend ratio of biodiesel fuel. Paryanto et al. (2022) also reported similar results that high saturation at low-temperature conditions, below the biodiesel cloud point, could increase precipitate formation in fuel filters. The formation of precipitate in biodiesel blend fuel could be suppressed with urea inclusion (Liu and Tao, 2022) and the utilization of hydrotreated vegetable oil (HVO) as a blended fuel (Mansur et al., 2019). HVO is a paraffinic biofuel which results from a hydrotreated process. It does not contain monoglyceride, so that it can be used as an alternative for high biofuel blends. Further, HVO has a higher cetane number and calorific value, better oxidation stability, and lower filter-blocking tendency than fatty acid methyl esters (FAME). HVO has been subject to extensive investigation as a blended fuel with neat diesel fuel, FAME (Mansur et al., 2019; Setiapraja et al., 2019; Shepel et al., 2021), bio-butanol (Rayapureddy et al., 2022), and polyoxymethylene dimethyl ether (Holzer et al., 2022). Di Blasio et al. (2022) reported a study on utilizing neat HVO on a single-cylinder diesel engine with four steady states operating in Euro VI-C. The study revealed that HVO with optimization on engine parameters had better combustion characteristics and lower regulated emissions and CO_2 than diesel fuel. Various studies also reported similar results that adjustment in engine parameters could result in further improvement of combustion, performance, and emissions with HVO (Dimitriadis et al., 2018; Bortel et al., 2019; Szeto and Leung, 2022; Mata et al., 2023).

Overall, enhancing FAME characteristics or the utilization of HVO might be used to implement high-ratio biodiesel blend fuel in real operating conditions. However, few studies have examined high-ratio biodiesel blend fuels without engine modification in real-world road operating conditions. Hence, this study was conducted to fill the gap in existing research by investigating the feasibility of using a 40% biodiesel blend fuel as a substitute for 30% biodiesel blend fuel (B30) in Indonesia's current vehicle technology. To achieve the aims of this research, two types of biodiesel blend fuel were prepared. The first blend consisted of 60% diesel fuel and 40% FAME, designated as B40, and the second blend was a mixture of 60% diesel fuel, 30% FAME, and 10% HVO, designated as B30D10. This study used the improved properties of FAME, including SMG, water content, and oxidation stability, to ensure the proper utilization of 40% biodiesel blends in current vehicles available in Indonesia, which typically operate on B30. Both candidate fuels were evaluated on currently high-population vehicles in Indonesia under 50,000 km road test conditions, as well as in a laboratory at certain traveled distances. Both B40 and B30D10 were thoroughly investigated to ensure they would not negatively impact vehicle performance, emissions, fuel economy (FE), engine components, engine lubricant, and cold start-ability.

2. Materials and Methods

2.1. Investigated fuels

In this study, B40 and B30D10 were used as test fuels, and the properties of B40 and B30D10 were evaluated based on the requirements of the Decree of the Director General of Oil and Gas No. 146.K/10/DJM/2020 (KESDM, 2020). The testing of biodiesel used for blending into B40 and B30D10 was performed based on the requirements of the Decree of the Director General of Renewable Energy and Energy Conservation No. 189 K/10/DJE/2019 (DJEBTKE, 2019). Additional parameters proposed for developing fuel specifications included the water content parameter from a maximum of 350 to 320 mg/kg, the minimum oxidation stability from 600 to 720 min, and the maximum monoglyceride content from 0.55 wt% to 0.50 wt%. Meanwhile, the characteristics of HVO were investigated in compliance with the requirements stated in the Decree of the Director General of Renewable Energy and Energy Conservation No. 95.K/EK.05/DJE/2022 (DJEBTKE, 2022).

2.2. Performance, emission, and fuel economy evaluation

B40 and B30D10 fuels were evaluated on two common rail vehicles that complied with Euro II emissions regulations. The tested vehicle was selected based on its high population in the Indonesian market. **Table 1** shows the vehicle specifications. A road test was conducted on Java Island roads for 50,000 km. The route was selected to represent road characteristics in Indonesia, consisting of 40.6% general road and 59.4% toll road. The traveled distance for each vehicle was around 650 km/d.

The emissions, FE, and vehicle performance tests were conducted in a vehicle laboratory at the National Research and Innovation Agency of Indonesia and according to the ECE-04 R83 (Euro II standard), ECE R101, and ECE R85 standards, respectively. In this study, we modified the carbon balance formulas for B40 and B30D10 to obtain better accuracy in FE

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Table 1.
The specifications of the vehicle used in the present study.

Parameter	Unit	Specifications
Year	-	2011
Bore × Stroke	mm	91.1 × 95
Volume	cc	2.477
Cylinder	-	4
Inertia weight	kg	2.850
Engine type	-	2.5L DI-DOHC

measurements. Reksowardojo et al. (2023) reported that using a standard carbon balance formula for high-ratio biodiesel blends could result in a significant error of FE.

Carbon balance formulas for B40 and B30D10 are shown in **Equations 1** and **2**, respectively.

$$FE = \frac{100 \times D}{0.1214 \times [(0.824 \times m\,HC) + (0.429 \times m\,CO) + (0.273 \times m\,CO_2)]} \quad \text{Eq. 1}$$

$$FE = \frac{100 \times D}{0.1204 \times [(0.831 \times m\,HC) + (0.429 \times m\,CO) + (0.273 \times m\,CO_2)]} \quad \text{Eq. 2}$$

where FE stands for fuel economy in km/L; D is fuel density in g/cm^3; mHC denotes HC emission in g/km; mCO is CO emission in g/km; and mCO_2 stands for CO_2 emission in g/km.

The emissions test and fuel consumption were run by using the New European Driving Cycle (NEDC), which consisted of the Urban Driving Cycle (UDC) and Extra Urban Driving Cycle (EUDC), as shown in **Figure 1**.

A chassis dynamometer was used for road load simulation in the laboratory, and emissions were sampled by constant volume sampling systems. An analysis of carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (HC), nitrogen oxides (NOx), and particulate matter (PM) were performed using non-dispersive infrared, heated flame ionization, chemiluminescence, and particulate sampling systems, respectively. The specification of the testing facility for this study is provided in **Table 2**. In this work, uncertainty was calculated based on a statistical analysis of measurement data and the calibration certificate of measurement equipment. The uncertainty is expressed at a 95% confidence level and a coverage factor 2.

2.3. Engine components evaluation

The analysis of engine components is an essential part of ensuring the safety and reliability of the engine when using alternative fuel. In this study, inspection of engine components was done before (0 km) and after the road test (50,000 km) for both B40 and B30D10.

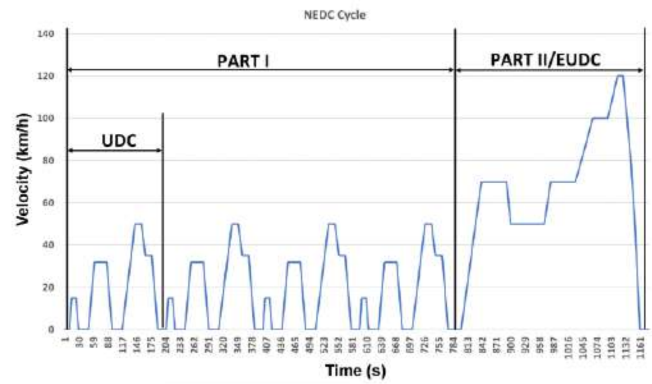

Fig. 1. New European Driving Cycle (NEDC) test cycle for emissions and fuel economy (FE) evaluations. UDC: Urban Driving Cycle, EUDC: Extra Urban Driving Cycle.

2.4. Engine oil analysis

The physicochemical characteristics of used engine oil were evaluated at the Lubricant Laboratory of the Product Application Testing Group (BBPMGB LEMIGAS). Engine oil analysis refers to the quality limits of the International Council on Combustion Engines (CIMAC) Recommendation No. 30 (CIMAC, 2011). Sampling of used oil was carried out when replacing (draining) lubricating oil, following the vehicle manufacturer's recommendations. The scheme for collecting used vehicle lubricants was carried out at a distance of 10,000, 20,000, 30,000, 40,000, and 50,000 km.

2.5. *Cold start ability test*

The cold start ability test was conducted to determine the ability of vehicles to start in low-temperature environments when using B40 and B30D10 fuels. Before the test, eight vehicles were serviced, including fuel filter replacement and fuel tank drainage, followed by the filling of B40 or B30D10 fuels. After filling the tank, the vehicles were driven 100 km to ensure the fuel was evenly distributed. Then, vehicles were grouped to be soaked for 7, 14, 21, and 28 d. After the soaking phase was completed, the engine starting phase commenced with an inspection to ensure the battery was in excellent condition. During this stage, the duration of the engine start was measured using a stopwatch with a resolution of 0.001 s, calibrated with an uncertainty value of 0.3 s.

Table 2.
The specifications of the testing facility used in the present study.

Test Equipment	Type	Maker	Specifications
Chassis dynamometer	48" compact chassis dyno	AVL	- Maximum speed: 200 km/h - Maximum force: 8922 N - Accuracy of force measurement: 0.10% of full scale
Exhaust sampling system	CVS i60	AVL	- Diluted exhaust: max. 30 m^3/min - Bag fill rate: 4, 6, 10 L/min - Absolute pressure sensor accuracy: ± 0.25% of the set range - Temperature sensor accuracy: ± 1 K
Emission Analyzer	AMA i60	AVL	- NOx: CLD i60 type with accuracy 0.05% of full scale. Detector: Chemiluminescence. - THC: FID i60 with flame ionization detector with accuracy 0.19% of full scale. - CO: i60NDIR Analyser, using non-dispersive infrared and solid state detector with accuracy 0.1% of full scale. - CO_2: CO_2 type i60NDIR Analyser, using non-dispersive infrared and solid state detector with Accuracy 0.11% of full scale.
Particulate	PSS i60	AVL	Gravimetric particulate emission measurement with diluted exhaust gas. Flow rate: max. at 65 L/min. Permissible ambient temperature: 5-50 ^{o}C

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3. Results and Discussion

3.1. Fuel characteristics

Table 3 shows the characteristics of the tested fuels used in this study. Generally, it was found that all the tested fuels used in the road test activities complied with the limit determined by the Indonesian government.

B30D10 had a lower density compared with B40, which could be due to the paraffinic chain and lower-end boiling point of HVO (Dimitriadis et al., 2018; Setiapraja et al., 2019). The viscosity of B30D10 was lower than B40; however, both fuels were still in the limit value of 4.5 mm^2/s. The HVO contained in B30D10, owing to its long straight chain molecule structure (Dimitriadis et al., 2018; d'Ambrosio et al., 2022), could lead to a higher cetane number and calorific value than B40, as shown in **Table 3**. Furthermore, B30D10 also offers other advantages, including better filter-blocking tendency value, lower viscosity, monoglycerides, and water content, as well as higher oxidation stability than B40. However, B30D10 has lower lubricity characteristics compared to B40, which could be

Table 3.
The characteristics of the tested fuels used in this study.

No	Parameter	Test Method	Unit	Fuel		Quality Limit for B30*	
				B40	B30D10	Min	Max
1	Cetane number	ASTM D 613	-	53.7	54.2	48.0	-
2	Density at 15°C	ASTM D 4052	kg/m^3	864.0	855.1	815	880
3	Kinematic viscosity at 40°C	ASTM D 445	mm^2/s	3.821	3.789	2.0	5.0
4	Sulphur content	ASTM D 4294	wt%	0.12	0.12	-	0.2
5	Distillation 90% Vol	ASTM D 86	°C	351.0	348.0	-	370
6	Distillation 95% Vol	ASTM D 86	°C	362.0	361.0	-	-
7	Flash point	ASTM D 93	°C	81	80	52	-
8	Cloud point	ASTM D 5773	°C	13.0	13.0	-	18
9	Pour point	ASTM D 5949	°C	9.0	9.0	-	18
10	Carbon residue	ASTM D 4530	wt%	0.02	0.02	-	0.1
11	Water content	ASTM D 6304	mg/kg	170	150	-	425
12	FAME content	ASTM D 7806	% v/v	40.1	30.0	30	
13	Copper strip corrosion (3 h at 50 °C)	ASTM D 130	Class	1a	1a	-	Class 1
14	Ash content	ASTM D 482	wt%	<0.005	<0.005	-	0.01
15	Sediment content	ASTM D 473	wt%	0	0	-	0.01
16	Strong acid number	ASTM D 664	mg KOH/g	0	0	0	
17	Total acid number	ASTM D 664	mg KOH/g	0.11	0.11	-	0.6
18	Visual appearance	Visual		Clear & bright	Clear & bright	Clear & bright	
19	Color	ASTM D 1500	No. ASTM	1.5	1.5	-	3
20	HFRR lubricity (*wear scar dia. @60 °C*)	ASTM D 6079	micron	235.0	242.5	-	460
21	Oxidation stability (*Accelerated Oxidation Method*)	EN 15751	h	81	97	35	-
22	Oxidation stability (RSSOT)	ASTM D 7545	min	280	398	45	-
23	Filter blocking tendency	ASTM D 2068		1.94	1.87	-	-
	a. Volume		mL	180	190	-	-
	b. Pressure		kPa	105	105	-	-
	c. Temperature		°C	24.8	24.5	-	-
24	Particulate contamination	ASTM D 6217	mg/L	11.1	10.3	-	-
25	Cold filter plugging point	ASTM D 6371	°C	10	10	-	-
26	Cleanliness	ASTM D 7619	ISO Code	20/18/16	20/18/14	-	-
	a. Particle > 4 µm		p/mL	5848	5644	-	-
	a. Particle > 6 µm		p/mL	2363	1894	-	-
	a. Particle > 14 µm		p/mL	331	136	-	-
27	Calorific value	ASTM D 240				-	-
	a. *Higher heating value*		MJ/kg	43.935	44.540	-	-
	b. *Lower heating value*		MJ/kg	41.636	42.072	-	-

* The requirements of the Indonesian government as outlined in the Decree of the Director General of Oil and Gas No. 146.K/10/DJM/2020 (KESDM, 2020).

attributed to the very low sulphur content of HVO (Mikkonen et al., 2013). In addition to regulated parameters, fuel cleanliness value was also measured. The result showed that B30D10 had a better fuel cleanliness value than B40 (Table 3).

3.2. Performance and fuel economy

Performance test results of the light-duty vehicles over 50,000 km are shown in Figure 2. B40 achieved maximum power of 78.8, 78.1, and 78.3 kW, while B30D10 exhibited maximum power of 80.5, 80.9, and 83.1 kW at traveled distances of 0, 30,000, and 50,000 km, respectively. No deterioration in maximum power was observed in B30D10 while covering a distance of 50,000 km. Overall, the performance of the vehicles fuelled with B30D10 was approximately 2.14% higher than those powered by B40.

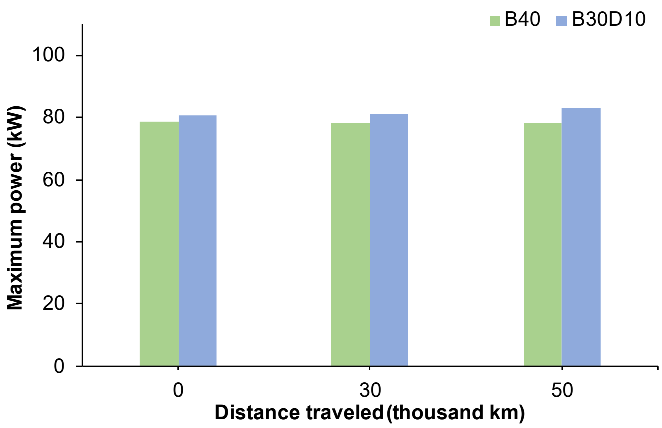

Fig. 2. Maximum power of the vehicle fuelled with B40 and B30D10 at different travel distances of 0, 30,000, and 50,000 km.

Moreover, the B30D10-powered vehicles showed an increase in power of up to 3.26% during the travel distance of 50,000 km. In contrast, the power produced by vehicles operated on B40 fuel did not show a significant change. The presence of HVO in B30D10 fuel could be highlighted as the main reason for higher power compared to using B40, which could be explained by HVO's higher cetane number and higher mass (calorific value multiplied with density) and volumetric calorific value compared to FAMEs (Bortel et al., 2019; Serrano et al., 2021). On the other hand, B30D10 also possessed a lower density and viscosity than B40, which could also potentially result in a higher power through enhancing fuel spray characteristics and the consequent improved atomization (Mujtaba et al., 2020; Ropandi et al., 2022).

Figure 3 shows the FE in km/L based on the R101 test cycle. FE test indicated that the B40 exhibited FE of 9.57, 9.72, and 10.01 km/L, whereas the B30D10 showed FE values of 9.67, 9.91, and 9.95 km/L across the distances of 0, 30,000, and 50,000 km, respectively. Despite the increasing trends observed for both fuels, these differences were insignificant.

The results revealed that the difference in the calorific value between B40 and B30D10 did not influence FE due to characteristics of the EUDC cycle in R101 rarely requiring maximum power for tested vehicles. Karavalakis et al. (2016) also reported similar results where the HVO and FAME blended fuels did not significantly differ in heavy-duty diesel truck transient cycle (HHDDT).

3.3. Exhaust emissions

Exhaust gas emissions of the vehicles fuelled with B40 and B30D10 were evaluated by using Euro II standard test method. Vehicles were soaked at room temperature of 23 ^{O}C before emission testing for one day. Figure 4 shows the result of the exhaust gas emissions test for B40 and B30D10 at travel distances of 0, 30,000, and 50,000 km.

CO and NOx emissions of B40 and B30D10 tended to decrease as travel distance increased (Figures 4a and c), while HC and PM showed a reverse trend (Figures 4b and d). Emission results revealed that both vehicles fuelled

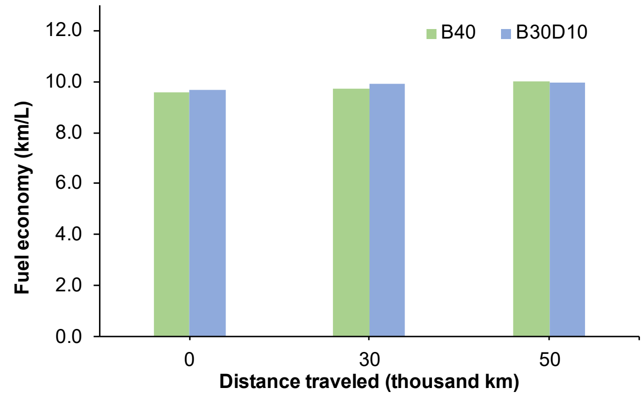

Fig. 3. Fuel economy (FE) of the vehicles fuelled with B40 and B30D10 at different travel distances of 0, 30,000, and 50,000 km.

with B40 and B30D10 could fulfill the emission limit of UN-ECE R83-04 (Euro II) for the whole evaluation distance of the road test. The fuel blends containing HVO or FAMEs, have the advantages of a high cetane number and ultra-low sulphur content, as well as the oxygen content for FAME. These characteristics could lead to better combustion efficiency and improved air-fuel mixing, reducing emissions (Bortel et al., 2019; d'Ambrosio et al., 2022; Szeto and Leung, 2022). B30D10 had lower CO, HC, and PM emissions compared with B40, while NOx emission was higher with B30D10 (Fig. 4). This trend was different from a previous comparative study where B30 and a blend of 70% diesel, 20% FAME, and 10% HVO resulted in comparable exhaust gas emissions (Setiapraja et al., 2019).

Overall, despite B30D10's several superior properties compared to B40, including higher cetane number, lower viscosity, and lower distillation temperature (Table 4), these enhanced properties did not significantly improve exhaust gas emissions. It can also be deduced that the better FE (Fig. 3), resulting in less fuel burned, might have contributed to the lower emission levels of HC, CO, and PM observed in B30D10 compared to B40. Another reason for different trends can be attributed to engine setting, including injection strategy, spray characteristics, and other related parameters to combustion in the ECU of tested vehicles which might have been more suitable for the characteristics of B30D10 (Dimitriadis et al., 2018; Bortel et al., 2019; d'Ambrosio et al., 2022; Holzer et al., 2022).

3.4. Engine oil analysis

Figures 5 - 8 show the results of engine oil analysis conducted on B40 and B30D10 after each travel distance of 10,000 km during the 50,000 km endurance test. The evaluation process involved comparing used and new engine oil as a reference, and the difference obtained was checked against the CIMAC recommendation (CIMAC, 2011). The total base number (TBN) value (determined following the ASTM D2896 standard) of lubricating oil samples obtained at millage of 10,000, 20,000, 30,000, 40,000, and 50,000 km from the vehicles powered by B40 and B30D10, were averaged to calculate a single value. As shown in Figure 5a, the new oil had a TBN value of 10.06 mg KOH/g, while the used oil of B40- and B30D10-powered vehicles had a value of 9.36 and 9.49 mg KOH/g, respectively. These values exceed the minimal required base value of 60% of the total base value of new lubricating oil as per CIMAC Recommendation No. 30 (CIMAC, 2011), confirming the oil enduring the acids generated during combustion. In addition, positive TBN values indicate the absence of strong free acids in the engine oil of the vehicles operated on B40 and B30D10 (Gupta and Agarwal, 2021).

The viscosity value of the used lubricating oil was lower than the new oil (Fig. 5b), which could be attributed to the presence of fuel entering into the lubrication system, known as the fuel dilution phenomenon (Neale, 1996; Gupta and Agarwal, 2021; Taylor, 2021). The used engine oil sample obtained from the B40-powered vehicles showed larger changes in

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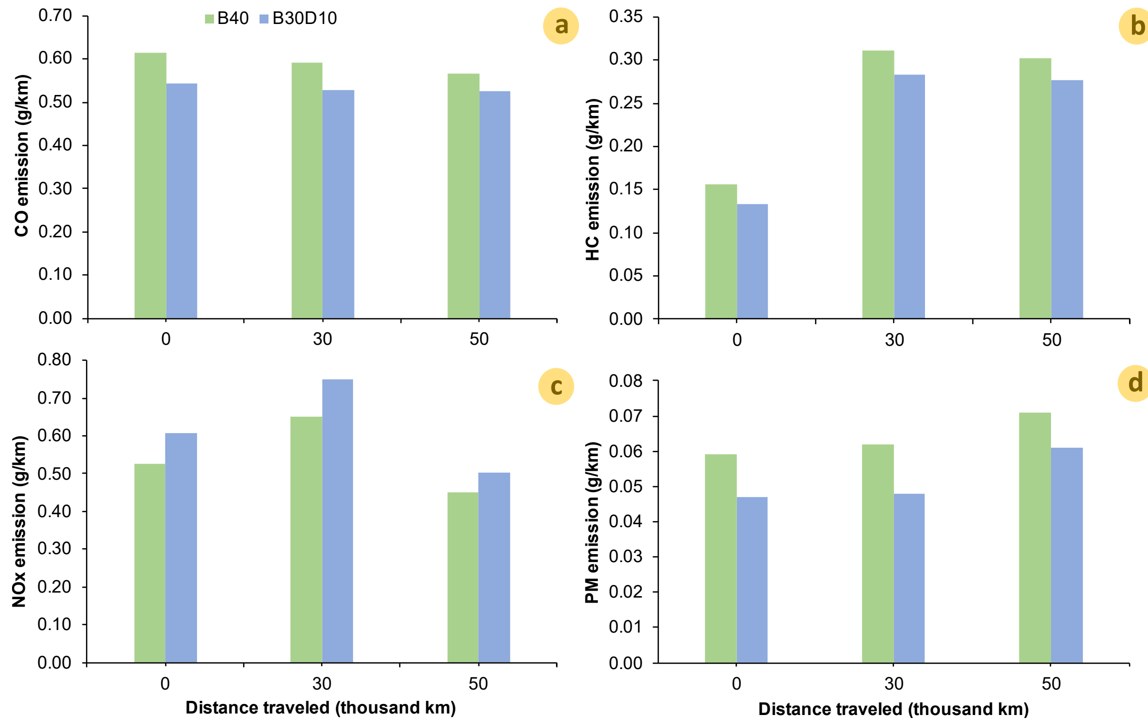

Fig. 4. Exhaust emissions [**(a)** CO, **(b)** HC, **(c)** NOx, and **(d)** PM] of the vehicle fuelled with B40 and B30D10 at different travel distances of 0, 30,000, and 50,000 km.

Table 4.
Possible Sources of metal elements in engine oil*.

Element	Symbol	Origin	Most Common Source
Iron	Fe	Wear metal	Cylinder liner, piston, piston rings, crankshafts, valves, valve guides, gear, rust
Chrome	Cr	Wear metal	Cylinder liners, compression rings, crankshafts, gears, crankshaft, bearings
Aluminum	Al	Wear metal, contaminant	Piston, turbocharger, Plungers, bearings, contaminants, lubricating grease
Copper	Cu	Metal wear, additive	Bearings, bushing, wrist pins, coolant leaks, anti-wear and anti-seized additives
Calcium	Ca	Additive, contaminant	Detergent Additive, Lubricating grease, Water
Zinc	Zn	Additive, wear metal	Additive, bearings, galvanized cases
Lead	Pb	Wear metal, paints, grease	Bearings, bearing matrix, shaft plating, thrust plating, paints, grease

* Source: Lakshminarayanan and Nayak (2011); Amriya Tasneem et al. (2022).

viscosity compared to B30D10, as shown in **Figure 5b**; this can be attributed to the higher oxygen contents of B40 than B30D10, leading to a higher degree of oxidation in the B40 and fuel-engine oil mixture.

Figure 5c presents the percentage of fuel dilution in engine oil, measured before the engine oil change at an interval of 10,000 km. Overall, the fuel dilution percentage trends of both fuel types across the five distance millages are quite constant, which could be due to the regular maintenance of the engine and oil changes keeping the engine in good condition and reducing the risk of fuel dilution. Nevertheless, fuel dilution only slightly affects engine oil properties (Kaminski, 2022), and the presence of a fuel diluent in used lubricating oil could be considered in normal conditions if it does not exceed the specified maximum threshold value.

The insoluble content in engine oil indicates the formation of an insoluble phase containing contaminants. Pentane insolubles can encompass substances not soluble in oil, including materials originating from the degradation of oil or additives, as well as other non-oil soluble resinous matter (Agarwal, 2003; ASTM D893-14, 2018). On the other hand, toluene insolubles can arise from various sources, such as external contamination, carbon deposits from fuel, oil, additive degradation, or materials resulting from engine wear and corrosion.

Any noticeable change in the concentrations of pentane insolubles, toluene insolubles (with or without coagulant), and insoluble resins indicates oil changes that may cause problems with the lubrication system (ASTM D893-14, 2018). According to **Figure 6**, it is clear that the total insoluble values increased noticeably with increasing travel distance using both fuels, especially B30D10. However, they did not exceed the 3 wt% upper limit mandated in CIMAC recommendations No. 30 (CIMAC, 2011).

Metal wear in engine oil is commonly derived from components such as bearings, piston rings, piston cylinders, and other moving metal parts within the engine. Additionally, certain metal compounds like Calcium (Ca) and Zinc (Zn) are commonly added to lubricants as additives to enhance their performance. The analysis of metal content provides valuable insights into the condition of the lubricating oil, revealing the amount of additive content during engine operation and identifying potential wear points. **Table 4**

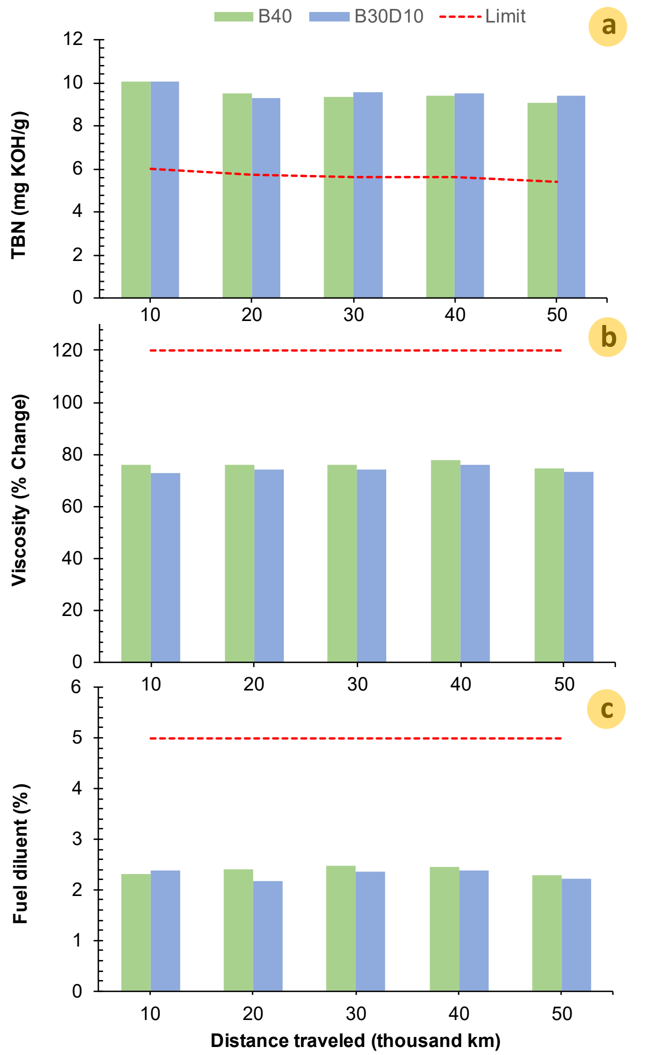

Fig. 5. Influence of the investigated fuels, B40 and B30D10, on **(a)** TBN, **(b)** the change of viscosity, and **(c)** fuel diluent of the used engine oil at various travel distances.

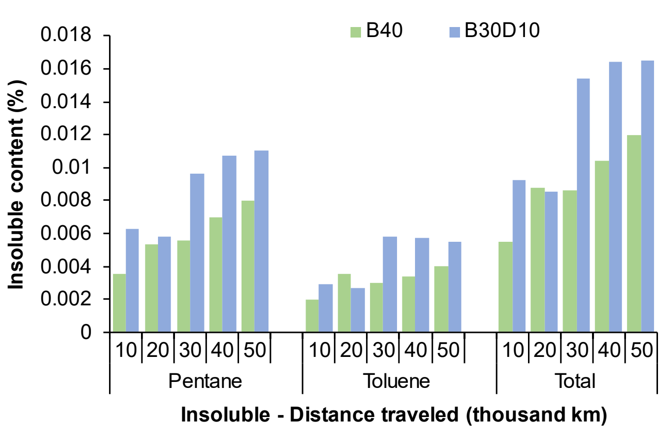

Fig. 6. The effects of B40 and B30D10 on engine oil's pentane and toluene insolubles concentrations at various travel distances.

tabulates the metal elements found generally in the lubricants and their possible sources.

Figures 7 and 8 present the metal analysis results in engine oil during the road test. Based on the data presented in Figure 7, the wear metal contents, including Fe, Cr, Al, and Cu, were still below the wear threshold or warning level, i.e., 100 ppm for Fe, 20 ppm for Al, 10 ppm for Cr and 30 ppm for Cu.

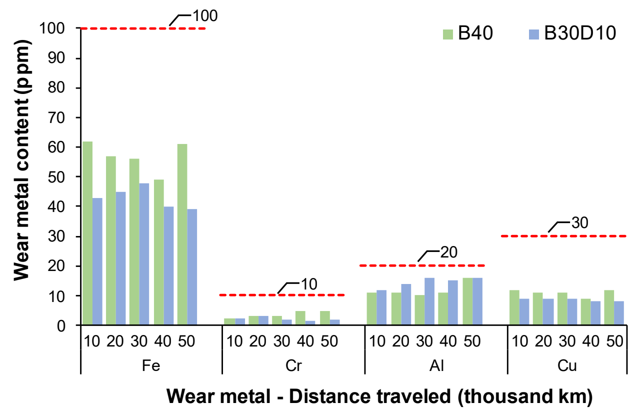

Fig. 7. The effects of B40 and B30D10 on wear metals contents of engine oil at various travel distances.

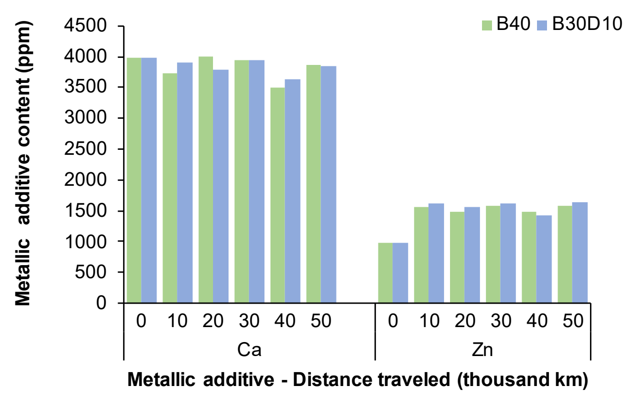

Fig. 8. Influence of B40 and B30D10 on metallic additives of engine oil at various travel distances.

Figure 8 illustrates the contents of commonly found metallic additives in lubricants. The metallic additive Ca is typically employed as a detergent or lubricant dispersant (Lakshminarayanan and Nayak, 2011). The relatively stable Ca content during road tests indicates that the amount of additive remained within the initial specifications, even after lubricant replacement intervals. On the other hand, the Zn content in lubricants can originate from metallic additives, serving purposes such as anti-wear corrosion and anti-oxidation. Additionally, Zn may also originate from alloying elements in components like bearings, thrust washers, and galvanized cases (Lakshminarayanan and Nayak, 2011). The increase in Zn content can be attributed to component wear. Notably, the variation in fuel types B40 and B30D10 did not significantly affect the Ca and Zn metal contents in the lubricants.

Overall, the engine oil analysis results of the samples obtained from the vehicles powered by B40 and B30D10 fulfilled the minimum quality

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standard specified in CIMAC Recommendation No. 30 (CIMAC, 2011). In other words, the currently employed lubricant changing intervals were still adequate to achieve optimal lubricity for vehicles fuelled with B40 and B30D10. This result can contribute to stable vehicle performance and FE over a 50,000 km road test, as described in *Section 3.2*.

3.5. Engine components evaluation after 50,000 km travel distance

The effect of the tested fuels on engine component deterioration following the 50,000 km road test was assessed by comparing engine component conditions before and after the road test. A general visual inspection of the pistons and cylinder liners of the vehicles powered by B40 and B30D10 showed no significant wear of these components (**Fig. 9**). More specifically, none of the piston rings became stuck, indicating that the ring would still work perfectly. The piston skirt and cylinder wall experienced normal wear in the trust position. Superior lubricity was observed for both B40 and B30D10, as indicated by their considerably smaller wear scar diameter of 235 and 242.5 µm, respectively, compared to the 460 µm limit shown in **Table 3**. It should be noted that the high oxidation stability of the tested fuels, B40 and B30D10, would also effectively contribute to preventing excessive wear. Furthermore, the engine oil experienced normal degradation during the 50,000 km endurance tests, as explained earlier (*Section 3.4*), further enhancing its ability to provide optimal protection for engine components.

powered by B40 and B30D10 are shown in **Figure 12**. Carbon deposits on compression ignition (CI) engine components generally originate from thermal and oxidative degradation of lubricating oil and incomplete combustion (Patel et al., 2022).

The normal wear and less deposit formation in the intake valve and combustion chamber during the 50,000 km endurance test can also contribute to improved FE (*Section 3.2*). More specifically, less deposit formation on the intake valve would maintain the air charge mixing pattern and level, resulting in a smaller decrease in engine volumetric efficiency (Ziejewski et al.,1986; Stepien, 2014). On the other hand, less deposit formation in the combustion chamber would prevent reductions in thermal efficiency, maintaining an effective heat transfer during compression stroke (Stepien, 2014; Dong and Truong, 2019). The lower deposit formation of B30D10 compared to B40 (**Fig. 11**) must have also contributed to the observed increased FE of B30D10 over B40. Similar results were also reported by Hidayat and Sugiarto (2020), arguing that the deposit mass was less when the engine was operated on HVO compared to B30.

The deposit formation in an engine is a complex process, and it appears to depend on a combination of different parameters such as fuel, surface material, temperature, pressure, combustion chamber environment, etc. However, wall temperature is one of the most important parameters that affect deposit formation (Arifin et al., 2009). The lower calorific value of B40 compared to B30D10 would result in lower combustion chamber temperatures and component surfaces, resulting in higher deposit formation. The other reason for the higher deposit formation using B40 could be its lower volatility than B30D10, increasing evaporation time. The faster the evaporation time, the smaller the deposit area will be (Suryantoro et al., 2016).

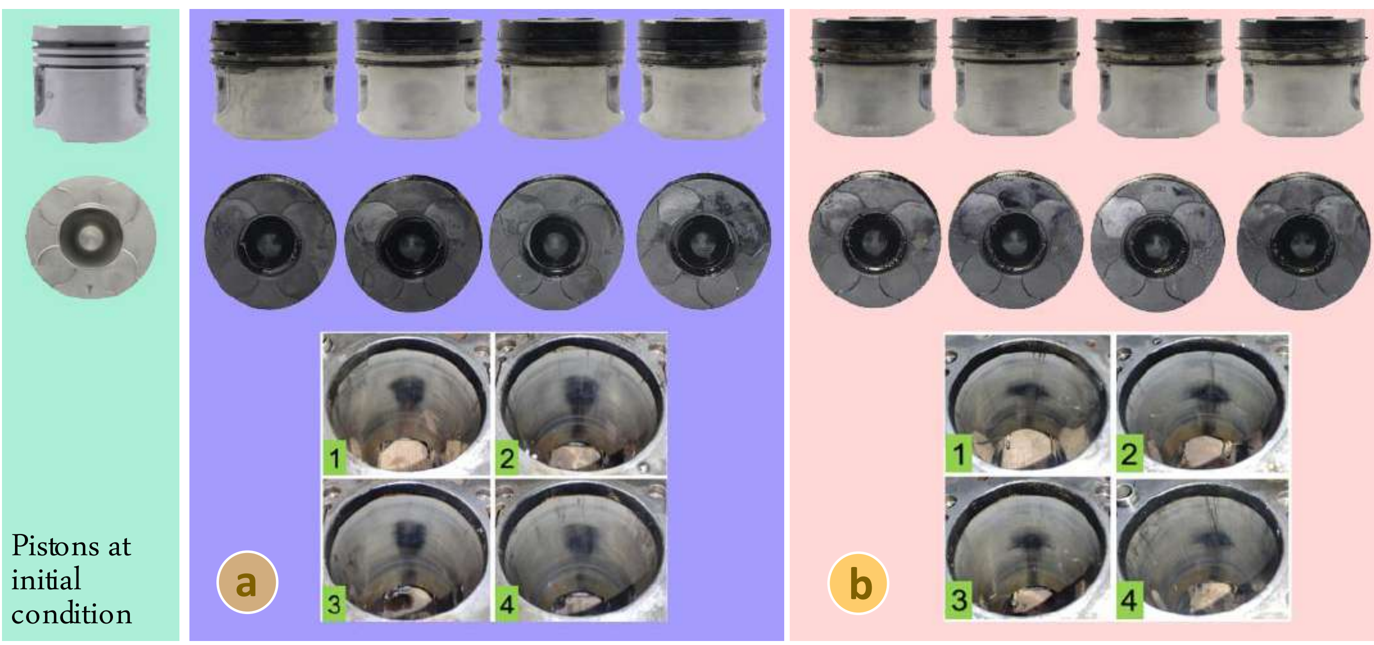

Fig. 9. Pistons and cylinder liners of the vehicles powered by **(a)** B40 and **(b)** B30D10 after the 50,000 km endurance test.

Carbon deposits in the cylinder head of the vehicles powered by B40 and B30D10 are shown in **Figure 10**. The cylinder head top for B40 had a slightly larger deposit formation than B30D10. However, the deposit thickness of each cylinder head was measured less than 0.2 mm, which is still within the manufacturer's recommended limit for the tested vehicle. The low-carbon residues (0.02 wt%) of B40 and B30D10 compared to the quality limit requirement (0.1 wt%) (**Table 3**) could explain the normal deposit formation during the 50,000 km endurance test.

Figure 11 presents the results of carbon deposits measured on the intake valve and combustion chamber after brushing with a soft brush, collecting deposits on paper, and weighing the paper with a microbalance. Combustion chamber deposits for B40 and B30D10 were weighted at 0.423 and 0.417 g, respectively. Further, the average amount of deposits formed on the intake valve using B40 was 0.641 g, compared to 0.231 g when using B30D10. Carbon deposits on the intake and exhaust valves of cylinder 1 of the vehicle

3.6. Cold start ability evaluation

Eight vehicles were prepared for the cold start ability to evaluate cranking time at soaking periods of 7, 14, 21, and 28 d at Dieng of Central Java with an environment temperature range of 13.6-18.1 ºC. B30D10 and B40 did not significantly affect the time required for the engine to start for the different soaking periods (**Table 5**). The time required from engine start until the stable idle condition for the eight tested vehicles was in the range of 0.69 to 2.15 s. These results aligned with the finding of Sugiyama et al.

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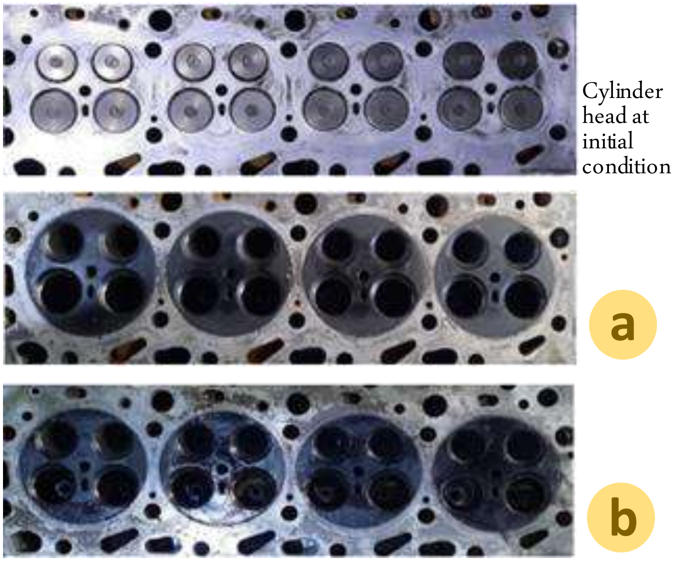

Fig. 10. Cylinder heads of the vehicles powered by **(a)** B40 and **(b)** B30D10 after the 50,000 km endurance test.

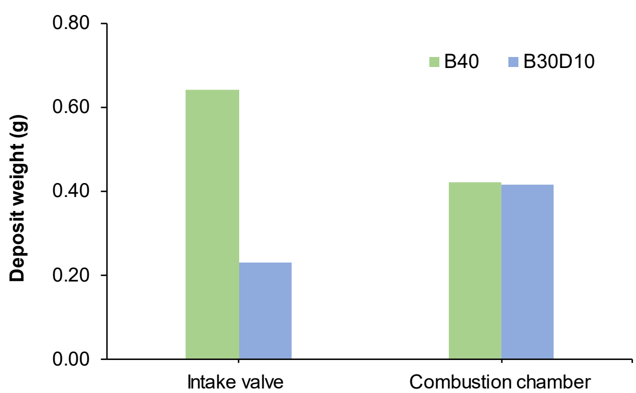

Fig. 11. The results of deposit analysis at the intake valve and combustion chamber for the vehicles powered by B40 and B30D10 after the 50,000 km endurance test.

(2011), who reported that the low-temperature start ability of neat HVO till reaching the stable ide ranged between 1.3 to 2.3 s. At temperatures between 13.6 and 18.1 ºC, the cloud point might have met, but there was still a smooth flow of fuel entering the combustion chamber from the fuel system, causing the engine to start easily. Since B40 and B30D10 did not lead to a significant difference in starting time, it can be concluded that they also did not affect the engine's ignition timing, confirming the safe use of these alternative fuels under Indonesia's operating conditions.

4. Conclusions and Prospects

Based on the evaluation results of the investigated fuels, namely B40 and B30D10, on light-duty vehicles using road and laboratory tests, the following conclusions can be drawn:

I. Vehicles fuelled with B40 and B30D10 encountered no technical problems during the 50,000 km endurance test.

II. Engine components inspection and used engine oil analysis of the vehicles powered by B40 and B30D10 showed normal conditions with all the investigated parameters aligning with the manufacturer's requirements. Therefore, B40 and B30D10 could be implemented in Indonesia without any requirements to modify engine and oil period changing intervals. Moreover, B40 and B30D10 could be used in Indonesia's cold ambient temperature of 13.6 ºC.

III. Laboratory evaluation during the road test showed that B40 has a slightly lower maximum power and FE than B30D10, with the maximum difference at various traveled distances at around 2%. Emission tests showed lower CO, HC, and PM for B30D10 than for B40, with a maximum difference of 11.4%, 14.7%, and 22.6%, respectively. However, B30D10 had a higher NOx emission with a maximum difference of 15.2%. Nevertheless, both B40 and B30D10 vehicles could comply with the Euro II emission regulations.

Fig. 12. Deposits formation on the cylinder 1 valves of the vehicles powered by **(a)** B40 and **(b)** B30D10 after the 50,000 km endurance test.

Table 5.
Cold start ability test of B30D10 and B40 at various soaking periods.

No.	Soaking Period (d)	Start Time (s)	
		B40	**B30D10**
1	0	1.32	1.62
2	7	2.15	1.08
3	14	1.73	2.10
4	21	0.93	1.02
5	28	1.09	0.88

Overall, based on the present study's findings, both B40 and B30D10 are viable options for implementing 40% biodiesel blend fuel in Indonesia. However, it is still crucial to consider the sustainability aspects of Indonesia's biodiesel program by considering various factors, including supply-demand chain analysis as well as techno-economic and environmental impact assessments (Aghbashlo et al., 2022), which were not included in this study.

Biodiesel availability should also be investigated by securing sustainable resources. For instance, in a techno-economic study, Hor et al. (2023) highlighted palm oil waste sludge as a promising resource for biofuel production in Indonesia. In addition, the effect of 40% biodiesel on unregulated emissions such as aldehyde should also be assessed in more detail. The various aspects of HVO utilization at a large scale should also be taken into consideration. For example, Ghadimi et al. (2022) reported that utilizing HVO could increase aerosol emission, a greenhouse gas

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precursor. Additionally, further research should be conducted to explore the implementation of higher biodiesel ratios (>40%), aiming to determine the maximum limit of the biodiesel blending ratio in alignment with advanced vehicle technologies.

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References

[1] Agarwal, A.K., 2003. Lubricating oil tribology of a biodiesel-fuelled compression ignition engine, in: Internal Combustion Engine Division Spring Technical Conference. ICES2003-609. 36789, 751-765.

[2] Aghbashlo, M., Hosseinzadeh-Bandbafha, H., Shahbeik, H. Tabatabaei, M., 2022. The role of sustainability assessment tools in realizing bioenergy and bioproduct systems. Biofuel Res. J. 9(3), 1697-1706.

[3] Amriya Tasneem, H.R., Ravikumar, K.P., Ramakrishna, H.V., 2022. Performance and wear debris characteristics of karanja biodiesel and biolubricant as a substitute in a compression ignition engine. Fuel. 319, 123870.

[4] Arifin, Y.M., Arai, M., 2009. Deposition characteristics of diesel and bio-diesel fuels. Fuel. 88(11), 2163-2170.

[5] ASTM D893-14, 2018. Standard test method for insolubles in used lubricating oils.

[6] Bortel, I., Vávra, J., Takáts, M., 2019. Effect of HVO fuel mixtures on emissions and performance of a passenger car size diesel engine. Renewable Energy. 140, 680-691.

[7] Cardeño, F., Lapuerta, M., Rios, L., Agudelo, J.R., 2020. Reconsideration of regulated contamination limits to improve filterability of biodiesel and blends with diesel fuels. Renewable Energy. 159, 1243-1251.

[8] CIMAC, 2011. Used engine oil analysis-user interpretation guide.

[9] d'Ambrosio, S., Mancarella, A., Manelli, A., 2022. Utilization of hydrotreated vegetable oil (HVO) in a Euro 6 dual-loop EGR diesel engine: behavior as a drop-in fuel and potentialities along calibration parameter sweeps. Energies. 15(19), 7202.

[10] Di Blasio, G., Ianniello, R., Beatrice, C., 2022. Hydrotreated vegetable oil as enabler for high-efficient and ultra-low emission vehicles in the view of 2030 targets. Fuel. 310, 122206.

[11] Dimitriadis, A., Natsios, I., Dimaratos, A., Katsaounis, D., Samaras, Z., Bezergianni, S., Lehto, K., 2018. Evaluation of a hydrotreated vegetable oil (HVO) and effects on emissions of a passenger car diesel engine. Front. Mech. Eng. 4.

[12] DJEBTKE, 2019. Detail Standar dan Mutu (Spesifikasi) Bahan Bakar Nabati (Biofuel) Jenis Biodiesel Sebagai Bahan Bakar Lain Yang Dipasarkan Di Dalam Negeri 189 K/10/DJE/2019.

[13] DJEBTKE, 2022. Standar dan Mutu (Spesifikasi) Bahan Bakar Nabati Jenis Diesel Nabati (Diesel Biohidrokarbon) Sebagai Bahan Bakar Lain yang Dipasarkan di Dalam Negeri 95.K/EK.05/DJE/2022.

[14] Dong, T.M.H., Truong, T.H., 2019. Deposit formation in diesel engine and its effects. World Wide J. Multidiscip. Res. Dev. 5(10), 44-49.

[15] Ghadimi, S., Zhu, H., Durbin, T.D., Cocker, D.R., Karavalakis, G., 2022. The impact of hydrogenated vegetable oil (HVO) on the formation of secondary organic aerosol (SOA) from in-use heavy-duty diesel vehicles. Sci. Total Environ. 822, 153583.

[16] Gupta, J.G., Agarwal, A.K., 2021. Engine durability and lubricating oil tribology study of a biodiesel fuelled common rail direct injection medium-duty transportation diesel engine. Wear. 486-487, 204104.

[17] Hidayat, J.A., Sugiarto, B., 2020. Characteristic, structure, and morphology of carbon deposit from biodiesel blend. Evergreen. 7(4), 609-614.

[18] Holzer, A., Günthner, M., Jung, P., 2022. Performance of pure OME and various HVO–OME fuel blends as alternative fuels for a diesel engine. Automot. Engine Technol. 7, 369-383.

[19] Hor, C.J., Tan, Y.H., Mubarak, N.M., Tan, I.S., Ibrahim, M.L., Yek, P.N.Y., Karri, R.R., Khalid, M., 2023. Techno-economic assessment of hydrotreated vegetable oil as a renewable fuel from waste sludge palm oil. Environ. Res. 220, 115169.

[20] IEA, 2022. An energy sector roadmap to net zero emissions in indonesia. Paris.

[21] Jaroonjitsathian, S., Noomwongs, N., Boonchukosol, K., 2016. Comprehensive experimental study on the effect of biodiesel/diesel blended fuel on common-rail di diesel engine technology. Int. J. Automot. Technol. 17, 289-298.

[22] Kaminski, P., 2022. Experimental investigation into the effects of fuel dilution on the change in chemical properties of lubricating oil used in fuel injection pump of pielstick PA4 V185 marine diesel engine. lubricants. 10(7), 162.

[23] Karavalakis, G., Jiang, Y., Yang, J., Durbin, T., Nuottimäki, J., Lehto, K., 2016. Emissions and fuel economy evaluation from two current technology heavy-duty trucks operated on HVO and FAME Blends. SAE Int. J. Fuels Lubr. 9(1), 177-190.

[24] KESDM, 2020. Standard dan Mutu (Spesifikasi) Bahan Bakar Minyak Jenis Solar yang Dipasarkan di Dalam Negeri 146.K/10/DJM/2020.

[25] Lakshminarayanan, P.A., Nayak, N.S, 2011. Critical component wear in heavy duty engines, First ed. John Wiley & Sons(Asia) Pte. Ltd., India.

[26] Liu, J., Tao, B., 2022. Fractionation of fatty acid methyl esters *via* urea inclusion and its application to improve the low-temperature performance of biodiesel. Biofuel Res. J. 9(2), 1617-1629.

[27] Mansur, D., Fitriady, M.A., Setiapraja, H., Paryanto, I., Haspriyanti, N., Dela, N., Gozan, M., 2019. Precipitation Study of B30 Blended from FAME and/or HVO and Petro Diesel Fuel. SAE Technical Paper. 2019-01-2190.

[28] Markov, V., Kamaltdinov, V., Devyanin, S., Sa, B., Zherdev, A., Furman, V., 2021. Investigation of the influence of different vegetable oils as a component of blended biofuel on performance and emission characteristics of a diesel engine for agricultural machinery and commercial vehicles. Resources. 10(8), 74.

[29] Mata, C., Cárdenas, D., Esarte, C., Soriano, J.A., Gómez, A., Fernández-Yáñez, P., García-Contreras, R., Sánchez, L., Nogueira, J.I., Armas, O., 2023. Performance and regulated emissions from a Euro VI-D hybrid bus tested with fossil and renewable (hydrotreated vegetable oil) diesel fuels under urban driving in Bilbao city, Spain. J. Clean. Prod. 383, 135472.

[30] Mikkonen, S., Honkanen, M., Kuronen, M., 2013. HVO, hydrotreated vegetable oil. a premium renewable biofuel for diesel engines. Germany. 281-291.

[31] Mujtaba, M.A., Masjuki, H.H., Kalam, M.A., Noor, F., Farooq, M., Ong, H.C., Gul, M., Soudagar, M.E.M., Bashir, S., Rizwanul Fattah, I.M., Razzaq, L., 2020. Effect of additivized biodiesel blends on diesel engine performance, emission, tribological characteristics, and lubricant tribology. Energies. 13(13), 3375.

[32] Neale, M.J., 1996. The Tribology Handbook, 2nd Ed. Elsevier, New Delhi.

[33] Paryanto, I., Budianta, I.A., Alifia, K.C.H., Hidayatullah, I.M., Darmawan, M.A., Judistira, Prakoso, T., Indarto, A., Gozan, M., 2022. Modelling of fuel filter clogging of B20 fuel based on the precipitate measurement and filter blocking test. ChemEngineering. 6(6), 84.

[34] Patel, C., Hwang, J., Bae, C., Agarwal, A.K., 2022. Review of regulated, unregulated and particulate emissions from biodiesel fuelled compression ignition engines. Int. J. Automot. Technol. 23(6), 1763-1785.

[35] Rayapureddy, S.M., Matijošius, J., Rimkus, A., Caban, J., Słowik, T., 2022. Comparative study of combustion, performance and emission characteristics of hydrotreated vegetable oil-biobutanol fuel blends and diesel fuel on a CI engine. Sustainability. 14(12), 7324.

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[36] Reksowardojo, I.K., Setiapraja, H., Fajar, R., Wibowo, E., Kusdiana, D., 2020. An investigation of laboratory and road test of common rail injection vehicles fueled with B20 biodiesel. Energies. 13(22), 6118.

[37] Reksowardojo, I.K., Setiapraja, H., Mokhtar, Yubaidah, S., Mansur, D., Putri, A.K., 2023. A Study on utilization of high-ratio biodiesel and pure biodiesel in advanced vehicle technologies. Energies. 16(2), 718.

[38] Ropandi, M., Hayawin, Z.N., Astimar, A.A., Noorshamsiana, A.W., Ridzuan, R., Zawawi, I., 2022. Effect Of biofuel on light-duty vehicles engine performance and lube oil degradation. J. Oil Palm Res. 34(1), 104-115.

[39] Serrano, L., Pereira, N., de Carvalho, P.M., 2021. Comparative performance and efficiency of EURO VI heavy-duty engines fueled by biodiesel, HVO and Diesel, in: da Costa Sanches Galvão, J.R., Duque de Brito, P.S., dos Santos Neves, F., da Silva Craveiro, F.G., de Amorim Almeida, H., Correia Vasco, J.O., Pires Neves, L.M., de Jesus Gomes, R., de Jesus Martins Mourato, S., Santos Ribeiro, V.S. (Eds.), Proceedings of the 1st International Conference on Water Energy Food and Sustainability (ICoWEFS 2021). Springer International Publishing, Cham, pp. 271-279.

[40] Setiapraja, H., Yubaidah, S., Ekasari, M., Haspriyanti, N., Rustyawan, W., Rochim, A., 2019. An effect of utilization B30 from various blends of B0:FAME and HVO on emissions, fuel consumption and power of Euro4 vehicle technology. SAE Technical Paper. 2019-01-2189.

[41] Shepel, O., Matijošius, J., Rimkus, A., Duda, K., Mikulski, M., 2021. Research of parameters of a compression ignition engine using various fuel mixtures of hydrotreated vegetable oil (Hvo) and fatty acid esters (fae). Energies. 14(11), 3077.

[42] Stępień, Z., 2014. Intake valve and combustion chamber deposits formation-the engine and fuel related factors that impacts their growth. Nafta-Gaz. 4, 236-242.

[43] Sugiyama, K., Goto, I., Kitano, K., Mogi, K., Honkanen, M., 2011. Effects of hydrotreated vegetable Oil (HVO) as renewable diesel fuel on combustion and exhaust emissions in diesel engine. SAE Int. J. Fuels Lubr. 5(1), 205-217.

[44] Suryantoro, M.T., Sugiarto, B., Chistian, D., Samudra, B., Gusfa, Z., 2016. Deposit characterization of a diesel engine combustion chamber by droplets at hot chamber temperature: effect of temperature on evaporation time and deposit structure. Int. J. Technol. 7(8), 1373-1381.

[45] Szeto, W., Leung, D.Y., 2022. Is hydrotreated vegetable oil a superior substitute for fossil diesel? a comprehensive review on physicochemical properties, engine performance and emissions. Fuel. 327, 125065.

[46] Taylor, R.I., 2021. Fuel-lubricant interactions: critical review of recent work. Lubricants. 9(9), 92.

[47] Vijay Kumar, M., Veeresh Babu, A., Ravi Kumar, P., Sudhakara Reddy, S., 2018. Experimental investigation of the combustion characteristics of Mahua oil biodiesel-diesel blend using a DI diesel engine modified with EGR and nozzle hole orifice diameter. Biofuel Res. J. 5(3), 863-871.

[48] Ziejewski, M., Goettler, H., Pratt, G.L., 1986. Influence of vegetable oil based alternate fuels on residue deposits and components wear in a diesel engine. SAE Trans. 95, 297-307.

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