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Lubricating oil degradation and tribological behavior for palm biodiesel fueled engine

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KEYWORDS

Palm biodiesel
Fuel dilution
Friction coefficient
Wear

ABSTRACT

The growing emphasis on biodiesel as a viable alternative to conventional fuels is driven by its potential to reduce environmental impacts. However, a major concern is the compatibility of biodiesel blends with engine lubricants. This study investigates the effect of using a B30 blend, consisting of 30% palm biodiesel and 70% conventional diesel, on engine oil properties and performance during a 500-hour engine dynamometer endurance test. The engine-dynamometer system operated under varying speed and load conditions, following the European Stationary Cycle (ESC), European Load Response (ELR) test cycle, and steady-state (SS) test cycle to simulate real-world driving conditions. Engine oil samples were collected every 50 hours to evaluate oil properties, with oil changes occurring every 100 hours throughout the study. Optical spectroscopy was employed to analyze wear elements, additives, and contaminants in the engine oil, revealing trends over the test duration. The tribological analysis showed that the diluted engine oil exhibited an increased friction coefficient and wear scar diameter, primarily due to the reduced viscosity caused by fuel dilution.

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1.0 INTRODUCTION

The rapid depletion of fossil fuel reserves, increasing pollutant emissions from fuel combustion, and the fluctuating costs of conventional energy sources have driven a global push toward renewable and sustainable energy alternatives. Alarmingly, current petroleum reserves are projected to meet global energy demands for only a few more decades (BP, 2017). This looming energy crisis has intensified the search for renewable energy solutions, with biofuels emerging as a key focus area in alternative energy technologies.

Among biofuels, biodiesel stands out as a viable and sustainable alternative for diesel-powered engines. As of 2020, Malaysia recorded 1,407,823 registered diesel-powered vehicles, with a total diesel consumption of 6.64 billion liters The Malaysian government has actively promoted the adoption of palm-derived biodiesel in line with the National Biofuels Policy (NBP) 2006 and the Biofuel Industry Act 2007. These efforts include the implementation of B10 and B7 biodiesel mandates in the transportation and industrial sectors since 2019, with B20 biodiesel introduced in specific regions like Langkawi and Labuan by 2020.

Palm biodiesel has demonstrated several advantages, such as enhanced engine performance and significant reductions in exhaust emissions (Awang et al., 2021; Aziz et al., 2005; Yusoff et al., 2023). However, its use also presents notable challenges, including carbon deposition, engine oil dilution and degradation, injector coking, fuel filter clogging, storage instability, and long-term wear concerns (Kumar & Chauhan, 2015; Narasimmanaidu et al., 2023). To address these concerns, long-term engine wear assessments during endurance tests can be classified into two main categories. The first focuses on components where fuel serves as a lubricant, reducing friction and wear between mating parts. Biodiesel properties, such as viscosity and lubricity, significantly influence the durability of these components and overall engine performance. Studies have extensively examined the effects of various biodiesels on fuel system components, including fuel lines, injection nozzles, and pumps.

The second category involves engine components primarily lubricated by engine oil, where the fuel type indirectly affects lubricant performance and longevity. Engine oil dilution, combined with contaminants like wear debris, carbonaceous deposits, and air intake impurities, significantly impacts lubricant effectiveness. Evidence shows that all fuel types cause some level of oil dilution , with biodiesel posing higher risks due to its greater viscosity and lower volatility. (Okamoto et al., 2012). During combustion, biodiesel forms larger spray droplets due to its high density, viscosity, and surface tension, resulting in longer spray lengths. Some droplets contact cylinder walls, infiltrating the crankcase and leading to oil dilution. Biodiesel’s lower volatility further exacerbates this issue, as it tends to remain in the crankcase, reducing lubricant quality and effectiveness over time.

Extensive research has been conducted to evaluate the impact of biodiesel on engine oil degradation. Pereira et al. (2020) investigated the effects of biodiesel on seven buses, with four running on pure biodiesel (B100) and three on conventional diesel over an 18-month period. The study revealed that engine oil in biodiesel-fueled vehicles deteriorated more rapidly, primarily due to biodiesel's lower volatility, which led to a significant reduction in oil lubricity. Similarly, Agocs et al. (2021) conducted a field test on 12 passenger vehicles (nine gasoline-powered and three diesel-powered) to examine fuel-related engine oil degradation. The results showed that gasoline vehicles experienced faster oil degradation and higher fuel dilution, whereas diesel vehicles exhibited greater soot loading and more pronounced engine wear.

Dhar and Agarwal (2014) performed a 250-hour engine durability test using a 20% Karanja biodiesel blend (KB20) in a direct injection compression ignition (DICI) engine. Despite no operational issues during the test, the biodiesel-fueled engine displayed higher carbon deposits and increased wear on critical components. Similarly, Gupta and Agarwal (2021) conducted a 274-hour durability and engine oil performance evaluation on an SUV common rail direct injection (CRDI) diesel engine using the KB20 blend. Their findings highlighted increased density, ash content, oxidation, and polymerization of the engine oil, along with viscosity changes. Additionally, biodiesel adversely affected the engine's fuel injection equipment.

The Malaysian government, through the National Energy Transition Roadmap 2023, plans to introduce a higher palm biodiesel blend (B30) in the transportation sector by 2030, supporting carbon emission reduction and sustainable development goals. However, this shift presents challenges in maintaining long-term engine performance and lubricant stability. The novelty of this study lies in its 500-hour engine dynamometer endurance test, designed to simulate extended operational conditions. This approach enables a detailed assessment of the long-term effects of B30 palm biodiesel on engine components and lubricant degradation, particularly under Malaysia's climate conditions, which exacerbate issues like fuel dilution and oil breakdown. While prior studies on higher biodiesel blends (B30 and above) have mainly focused on thermal efficiency and emissions, this research addresses a critical gap by providing insights into the extended operational impacts on engine performance and lubrication systems. The findings will contribute valuable data for assessing the practical application of biodiesel in real-world conditions.

2.0 MATERIALS AND METHODS

2.1 Materials

This study utilized a B30 palm biodiesel blend provided by the Malaysian Palm Oil Board (MPOB) as the test fuel. For lubrication, Shell Rimula Light-duty LD5 10W-40 engine oil was employed, sourced from a Shell fuel station in Kuala Lumpur. This engine oil is specifically recommended for use in the 1.9L ISUZU D-Max diesel engine throughout the testing process. A comparison of the physicochemical properties of the B30 blend with the Malaysian commercial B10 diesel fuel is presented in Table 1.

Table 1: Physicochemical properties of B30 and commercial B10 diesel fuel.

Properties	Unit	B30 (Tested fuel)	B10 (Malaysian Commercial Diesel)	Test method
Kinematic viscosity, 40 ^oC	mm^2/s	3.6855	2.8987	ASTM D445
Density, 15 ^oC	Kg/m^3	849.2	832.4	ASTM D4052
Flash point	^oC	105	81	ASTM D93
Pour point	^oC	9.5	8.0	ASTM D97
Oxidation stability, 110 ^oC	Hr	>24	>24	ASTM D7462
Higher heating value	MJ/kg	44.3	45.3	ASTM D240
Derived cetane number	-	64.08	58.66	ASTM D7668

2.2 Test Procedure

A 500-hour engine dynamometer endurance test was carried out at the Engine Tribology Laboratory, Universiti Malaya, using the B30 palm biodiesel blend. The engine was directly coupled to a Froude Consine AG150 eddy current dynamometer (England), capable of delivering a maximum power output of 150 kW. Detailed engine specifications are provided in Table 2, while the schematic diagram of the engine-dynamometer test setup and its real-world implementation are illustrated in Figures 1 and 2, respectively. Temperature measurements for ambient air, engine oil, coolant, and exhaust gases were recorded using K-type thermocouples installed at strategic points in the test bed. These sensors were linked to a data acquisition (DAQ) system, which facilitated real-time data collection, processing, and analysis through REO-DCA software.

The endurance test was conducted under various operational conditions, adhering to the European Stationary Cycle (ESC), European Load Response (ELR), and steady-state (SS) test cycles, as outlined in Table 3. The ESC test, a widely adopted 13-mode steady-state cycle, is used extensively in Germany to evaluate Euro 3 and Euro 4 diesel engines running on biodiesel. This test provides critical data on emissions, performance, and lubricant characteristics, making it fundamental to engine endurance assessments. The ELR test, introduced with the Euro 3 regulation in 2000, is used to measure smoke opacity under transient engine speeds and is often performed alongside the ESC cycle. It involves three load steps at four defined engine speeds (A, B, C, and D) with varying loads between 10% and 100%. Speed D represents an intermediate speed between points A and C, chosen by certification personnel. The SS test, in contrast, maintains constant engine speed and throttle positions to achieve stable operating conditions. Each test sequence included three repetitions of the ESC cycle, followed by one iteration of the ELR test and one SS test cycle, collectively lasting 2.5 hours. Due to scheduling constraints, the test procedure was adjusted to perform four consecutive sets daily, equating to 10 hours of operation per day.

Table 2: Engine specifications used for engine endurance test.

Engine specifications	**Description**
Model	ISUZU RZ4E
No. of cylinder	4
Cylinder bore x stroke (mm)	80.0 mm x 94.4 mm
Displacement (L)	1.9
Maximum power	110.3 KW @ 3600 rpm
Maximum torque	349.8 Nm @ 1800 to 2600 rpm

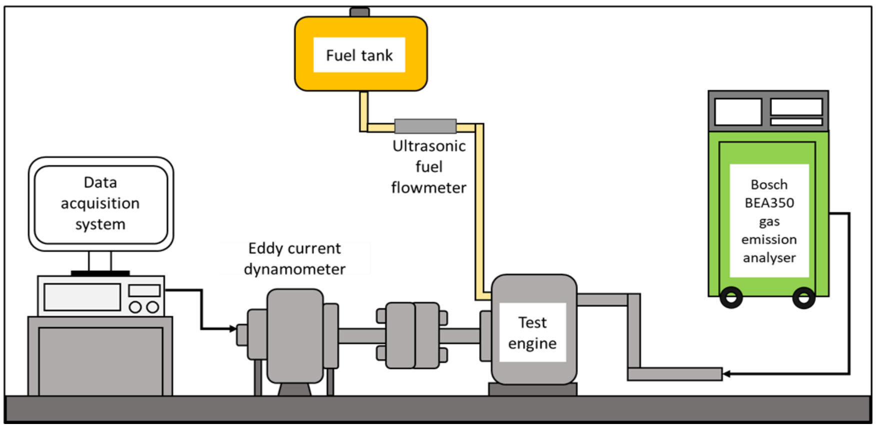


Figure 1: Schematic diagram of engine-dynamometer endurance test bed.

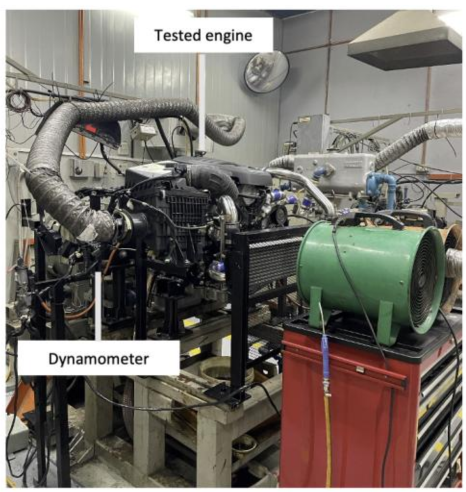


Figure 2: Real setup of the engine-dynamometer endurance test bed.

Table 3: Test cycles for 500-hour engine-dynamometer endurance test.

Step	Test Cycle	Speed	Load (%)	Throttle	Duration (min)
1	ESC (1)	A, B, C	25,50,75,100	Varied	28
2	ESC (2)	A, B, C	25,50,75,100	Varied	28
3	ESC (3)	A, B, C	25,50,75,100	Varied	28
4	ELR	A, B, C, D	10 & 100	Varied	28
5	SS	Rated	Varied	Rated	38
			Total time per a complete set		150 min = 2.5 hr/set
			Total for 4 consecutive sets (per day)		2.5 hr x 4 = 10 hr/day

Notes: The three speeds (A,B,C) in the ESC cycle are determined using the following equations (DieselNet):

$$A = n_{lo} + 0.25(n_{hi} - n_{lo})$$

$$B = n_{lo} + 0.50(n_{hi} - n_{lo})$$
$$C = n_{lo} + 0.75(n_{hi} - n_{lo})$$

Where, n_{hi} refers to the high engine speed at which 70% of the declared maximum net power is achieved, while n_{lo} denotes the low engine speed corresponding to 50% of the declared maximum net power. These values, n_{hi} and n_{lo}, are obtained by mapping the engine's speed and power characteristics.

Speed D is defined as the speed between A and C, with a load ranging from 10% to 100%. The calculated speeds are as follows:
A = 2210 rpm, B = 2840 rpm, C = 3470 rpm, D = 2525 rpm, Rated speed = 2000 rpm

Throughout the 500-hour engine endurance test, it was essential to monitor the engine oil to ensure smooth engine operation. Engine oil samples were taken every 50 hours by extracting a small quantity using an oil pump extractor after a quick engine shutdown. Additionally, oil changes were performed every 100 hours, which is roughly equivalent to 10,000 kilometers of engine operation, assuming an average speed of 100 km/h during the test cycles. This approximation aligns with standardized driving schedules, such as the EPA's Highway Fuel Economy Test (HWFET), which reflects highway driving conditions at an average speed of approximately 60 mph (100 km/h). These periodic oil changes are critical to maintaining proper engine lubrication, cleanliness, and overall engine health throughout the test.

To assess the impact of fuel dilution on engine oil degradation, the physicochemical properties of the collected oil, including viscosity, viscosity index (VI), and density, were analyzed at each sampling interval. Additionally, optical spectroscopy was used to evaluate the elemental composition, including wear elements, oil additives, and contaminants caused by fuel dilution. A post-analysis study further examined the tribological performance of the engine oil samples. A Four-Ball Tribotester (TR30H, Ducom) was used to measure the coefficient of friction (COF) and wear scar diameter (WSD), providing insights into friction and wear between two interacting surfaces. The test followed the ASTM D4172(b) standard. As shown in Figure 3, during the test, a steel ball was rotated on top of three stationary balls submerged in the engine oil, ensuring point contact between the surfaces.

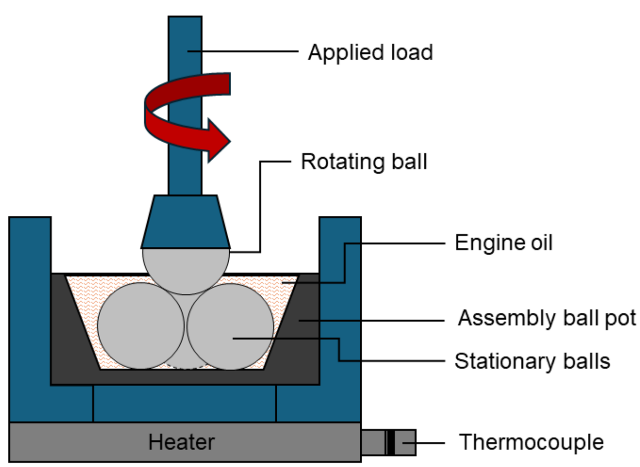


Figure 3: Schematic diagram of fourball test.

The coefficient of friction (COF) was calculated using the following equation:

$$\mathrm{COF} = \frac{\text{Actual friction force (N)}}{\text{Applied load (N)}}$$

The wear scar diameter (WSD), which represents the diameter of the wear scar on the tested ball's surface, was measured using an optical microscope (Panthera Moticam S6, Motic Scientific). These parameters provide crucial insights into the tribological performance of the engine oil samples under test conditions.

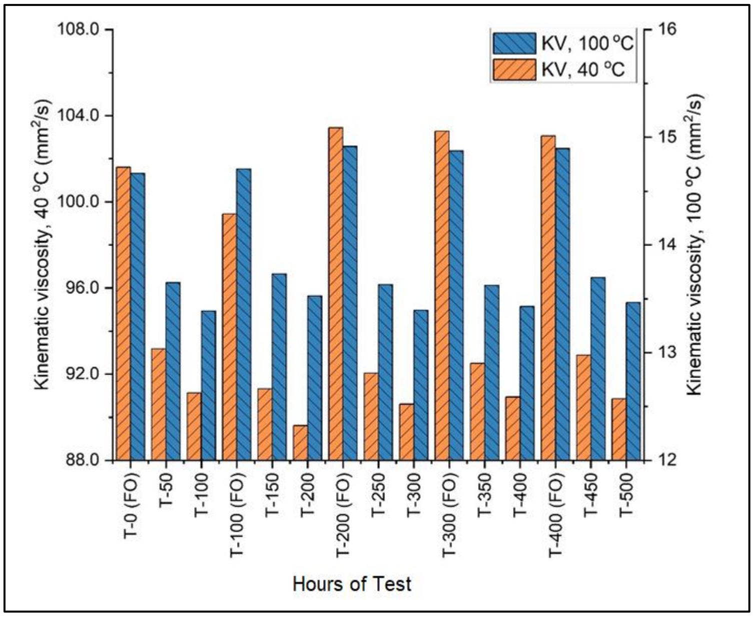
3.0 RESULTS AND DISCUSSION

3.1 Physicochemical Properties of Diluted Engine Oil

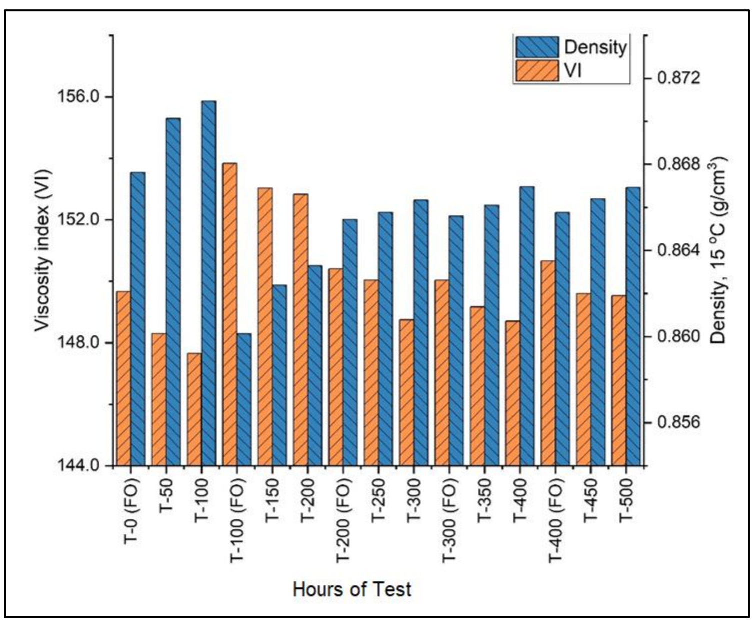
Viscosity plays a pivotal role in the lubrication and overall performance of an engine. Variations in engine oil viscosity due to fuel dilution create challenges for the engine's lubrication system, impacting both lubricating efficiency and oil film thickness (Khuong et al., 2017). Insufficient oil viscosity compromises the lubricating film and load-bearing capacity, potentially accelerating wear on critical components, including bearings, journals, and other moving parts.

The study revealed a degradation in the kinematic viscosity of the engine oil at both 40°C and 100°C, attributed to fuel dilution. As illustrated in Figure 4(a), the kinematic viscosity measured at 40°C decreased by an average of 9.6% after 50 hours and 11.3% after 100 hours compared to fresh engine oil (FO) sampled at oil change intervals. Similarly, the kinematic viscosity measured at 100°C showed a reduction of 7.7% after 50 hours and 9.2% after 100 hours relative to FO. These reductions highlight the influence of the B30 biodiesel blend, which has a lower intrinsic viscosity, on the oil's lubricating properties. The increasing extent of fuel dilution from 50 to 100 hours further exacerbates this viscosity reduction, compromising lubrication efficiency.

In contrast, the viscosity index (VI) and density of the engine oil exhibited minimal variations throughout the endurance test, with changes remaining below 1%, as shown in Figure 4(b). These results suggest that while the kinematic viscosity is significantly impacted by fuel dilution, the VI and density are relatively stable, indicating limited impact from biodiesel blend properties on these parameters.



(a)



(b)

Figure 4: Variation in (a) kinematic viscosity of diluted engine oil at 40°C and 100°C, and (b) Viscosity Index (VI) and density of diluted engine oil for the entire 500-hour endurance test.

3.2 Elemental Analysis Of Diluted Engine Oil

Elemental analysis is critical for assessing both the wear degradation of engine components and the oil's quality over the endurance test period. Wear metals such as aluminum (Al), chromium (Cr), copper (Cu), iron (Fe), lead (Pb), and tin (Sn) predominantly originate from the natural wear of key engine components (Ahmad et al., 2018). Al is mainly linked to pistons, plain bearings, bushes, thrust washers, and the pump. Cr comes from cylinder liners, rings, shafts, and anti-friction bearings. Iron is derived from cylinder liners, piston rings, valve trains, crankshafts, rocker arms, gears, engine blocks, and oil pumps. Cu, widely used as an alloying element, has multiple sources, including plain bearings, bushes, thrust washers, and worn gears. Pb is associated with plain bearings, bushes, and thrust components, while Sn, often alloyed with Cu and Pb, is integral to plain bearings and occasionally used in piston coatings to enhance heat conductivity.

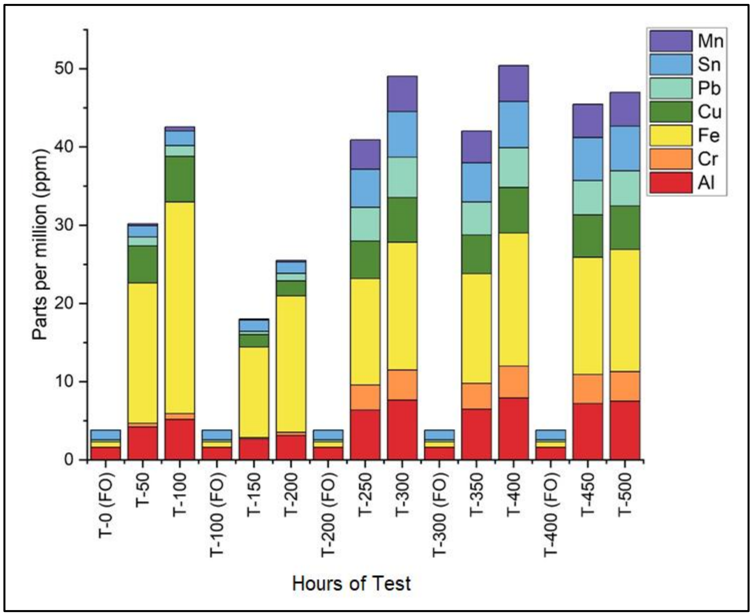
Figure 5 (a) demonstrates a steady increase in all wear metal concentrations over the 50-hour and 100-hour intervals after oil changes, continuing throughout the 500-hour test. This trend indicates wear in various engine components during operation, with iron being the most prevalent wear metal. These findings align with Rahimi et al. (2012), who identified Fe as the predominant wear metal in gasoline engine oil, with significant increases observed during extended operations.

Contaminants such as silicon (Si), sodium (Na), and potassium (K) are also present in engine oil, typically introduced through external sources like dust, dirt, or coolant leaks during testing (Smigins et al., 2023). Figure 5(b) illustrates the rising concentrations of these elements over time. Si concentrations, reaching up to 20 ppm, suggest contamination from dirt particles, while the increased Na and K levels likely result from coolant leakage, as these elements are commonly found in coolant additives like potassium nitrate and sodium molybdate (Turcotte, 2014).

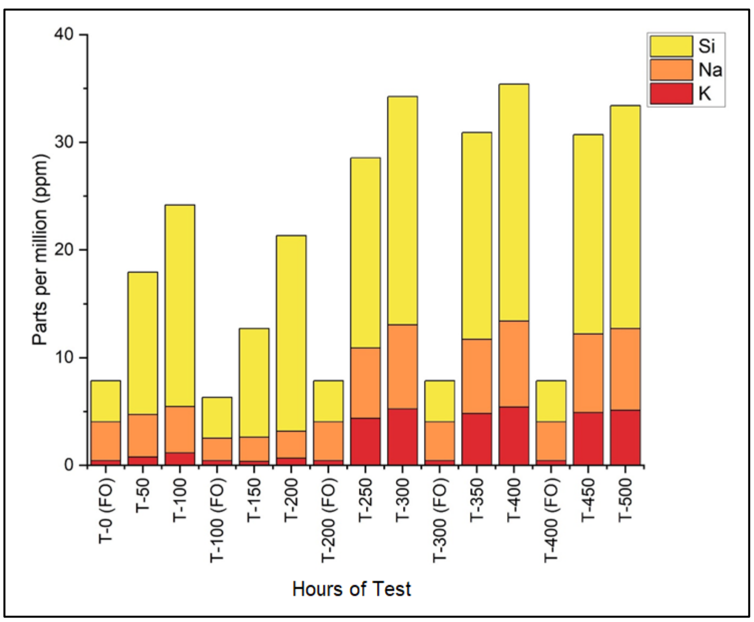
Additive elements such as boron (B), calcium (Ca), magnesium (Mg), phosphorus (P), zinc (Zn), and molybdenum (Mo) serve vital roles in engine oil, acting as detergents, dispersants, anti-wear agents, antioxidants, and viscosity modifiers (Al Sheikh Omar et al., 2024).

Figure 5(c) shows the variation in these additives over the 500-hour test period. Most additive concentrations, except Mg and P, decreased steadily at 50-hour and 100-hour intervals before oil changes, indicating additive depletion due to high operating temperatures and filtration. Despite this reduction, the additives remained effective, maintaining engine cleanliness, controlling acidity, and minimizing friction and wear.

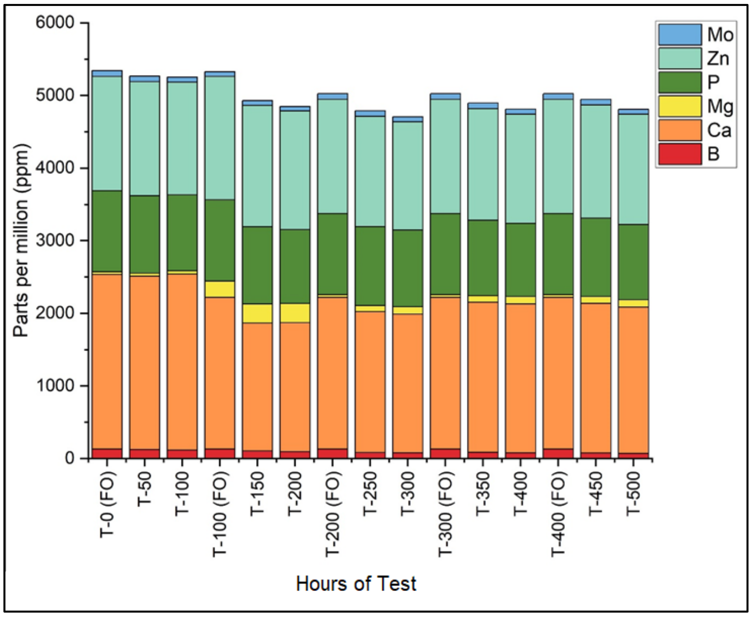
Moreover, additive elements such as boron (B), calcium (Ca), magnesium (Mg), phosphorus (P), zinc (Zn), and molybdenum (Mo) are commonly used in engine oil for various purposes, including acting as detergents, dispersants, anti-wear agents, antioxidants, viscosity modifiers, foam inhibitors, and pour point depressants. Figure 5(c) illustrates the variation in the concentrations of B, Ca, P, Zn, and Mo over the entire 500-hour engine endurance test. The results show a continuous reduction in the concentration of most additive elements, except for Mg and P, at the 50-hour and 100-hour intervals before oil changes. This suggests that the additives degrade, especially under high engine temperatures, with some elements absorbed by the engine oil filter. Despite this reduction, the additives continue to serve their functions, maintaining engine cleanliness, preventing deposits, controlling acidity, and reducing friction and wear.


Mn
Sn
Pb
Cu
Fe
Cr
Al
Parts per million (ppm)
0
10
20
30
40
50
T-0 (FO)
T-50
T-100
T-100 (FO)
T-150
T-200
T-200 (FO)
T-250
T-300
T-300 (FO)
T-350
T-400
T-400 (FO)
T-450
T-500
Hours of Test

(a)


Si
Na
K
Parts per million (ppm)
0
10
20
30
40
T-0 (FO)
T-50
T-100
T-100 (FO)
T-150
T-200
T-200 (FO)
T-250
T-300
T-300 (FO)
T-350
T-400
T-400 (FO)
T-450
T-500
Hours of Test

(b)



(c)

Figure 5: Variation of (a) wear, (b) contaminant and (c) additive elements composition in engine oil for the entire 500-hour endurance test.

3.3 Tribological Performances of Diluted Engine Oil

The tribological performance of diluted engine oil was evaluated by measuring the coefficient of friction (COF) and wear scar diameter (WSD) using four-ball testing, in accordance with ASTM D4172 standards. These measurements provide valuable insights into the lubricating performance of the diluted oil.

Figure 6 presents the variations in the COF and average COF of the diluted engine oil over the 500-hour endurance test. The diluted engine oil consistently showed higher COF values after 50 and 100 hours of operation compared to fresh oil (FO) following an oil change. The average COF of fresh oil was recorded as 0.1036 before the test (0 hr) and increased over time to 0.0866 at 100 hr, 0.1080 at 200 hr, 0.1161 at 300 hr, and 0.1197 at 400 hr (denoted as T-0 (FO), T-100 (FO), T-200 (FO), T-300 (FO), T-400 (FO)).

In contrast, the average COF of the diluted engine oil increased with time. After 50 hours of operation, the COF values were 0.1080, 0.1004, 0.1110, 0.1223, and 0.1205 at 50 hr, 150 hr, 250 hr, 350 hr, and 450 hr, respectively (denoted as T-50, T-150, T-250, T-350, T-450). After 100 hours, the COF values were 0.1174, 0.1008, 0.1191, 0.1264, and 0.1255 at 100 hr, 200 hr, 300 hr, 400 hr, and 500 hr, respectively (denoted as T-100, T-200, T-300, T-400, T-500). The significant increase in COF observed in the diluted engine oil is mainly due to a reduction in viscosity caused by fuel dilution, as shown in Figure 4(a). As the engine operates and fuel dilution increases from 50 to 100 hours, oil viscosity decreases, leading to higher COF values (Milano et al., 2022).

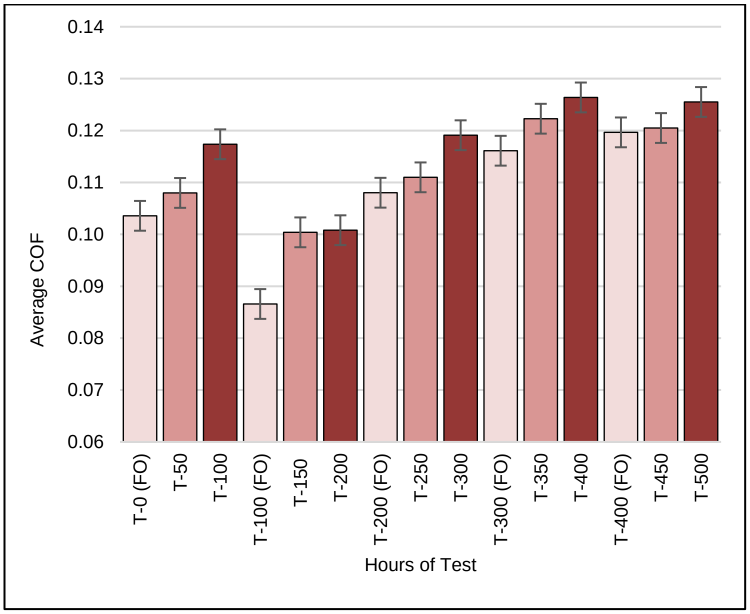


Figure 6: COF and average COF of diluted engine oil during the 500-hour endurance test.

The WSD of the ball is another key parameter for assessing the lubrication performance of engine oil. Figure 7 shows the average WSD values of the worn steel balls, reflecting the wear behavior of engine oil throughout the 500-hour endurance test. The results demonstrate that WSD values consistently increased after 50 and 100 hours of engine operation, compared to FO following an oil change.

Specifically, the average WSD of the tested ball was 421.21 μm before the test (0 hr) and 422.73 μm, 407.40 μm, 432.20 μm, and 423.37 μm after oil changes at 100 hr, 200 hr, 300 hr, and 400 hr, respectively (denoted as T-0 (FO), T-100 (FO), T-200 (FO), T-300 (FO), T-400 (FO)). After 50 hours of engine operation, the WSD values increased to 453.45 μm, 433.88 μm, 455.44 μm, 452.69 μm, and 513.18 μm at 50 hr, 150 hr, 250 hr, 350 hr, and 450 hr, respectively (denoted as T-50, T-150, T-250, T-350, T-450). Similarly, after 100 hours of engine operation, the average WSD values further increased to 465.62 μm, 451.85 μm, 464.29 μm, 483.39 μm, and 519.00 μm at 100 hr, 200 hr, 300 hr, 400 hr, and 500 hr, respectively (denoted as T-100, T-200, T-300, T-400, T-500).

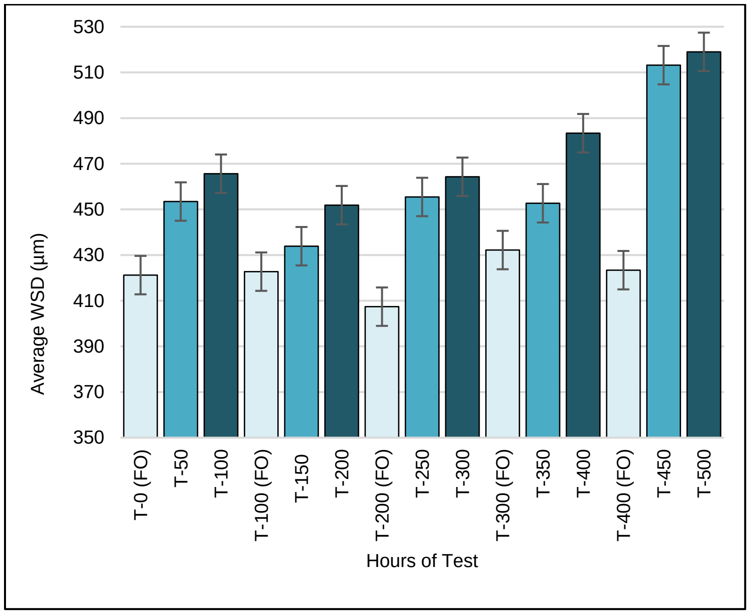
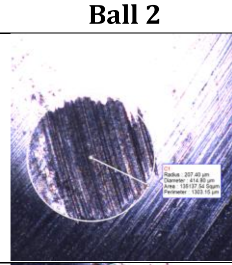
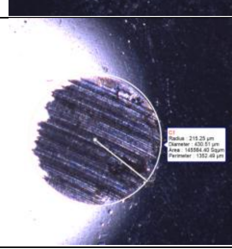
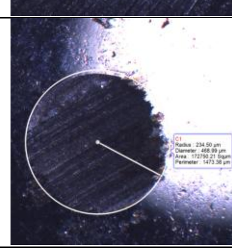
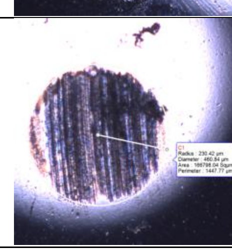
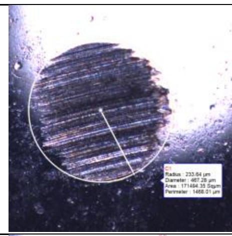
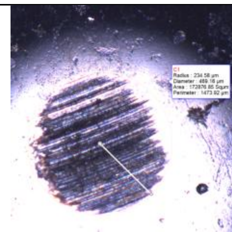
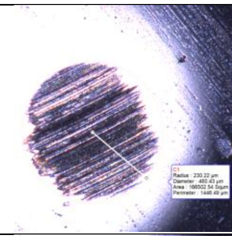
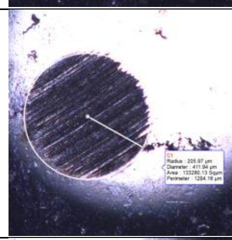
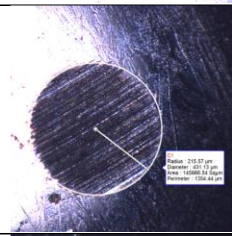
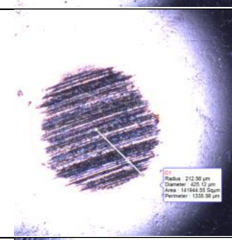
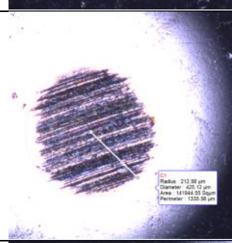
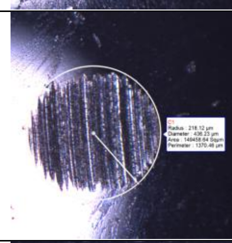
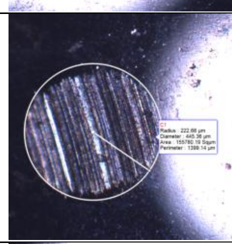
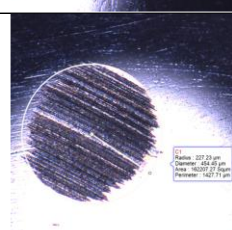
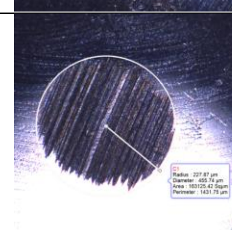
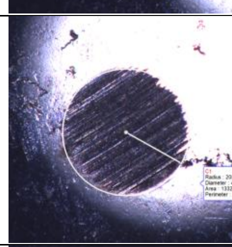
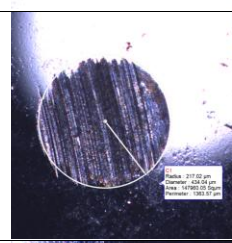
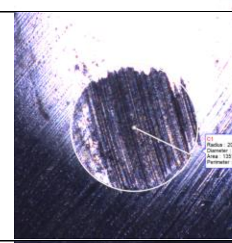
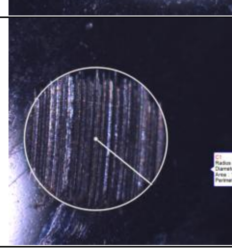
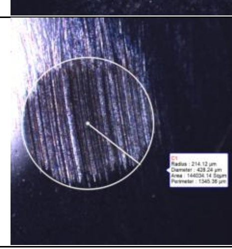
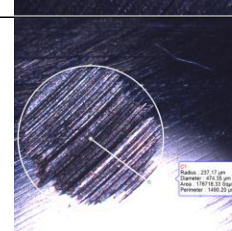


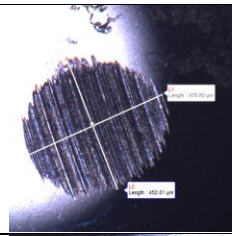
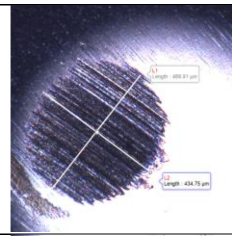
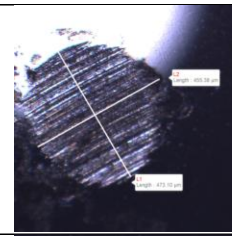
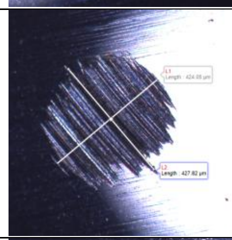
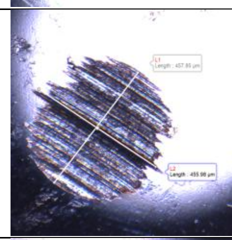
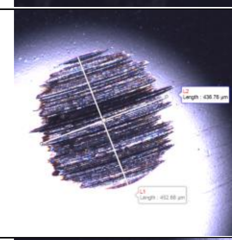
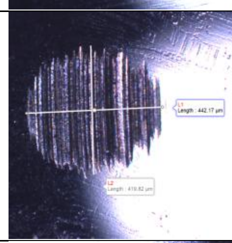
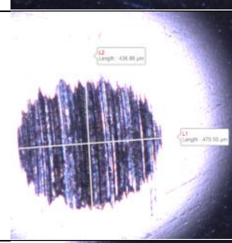
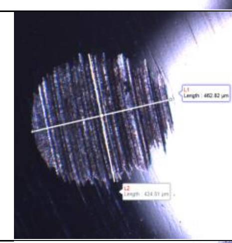
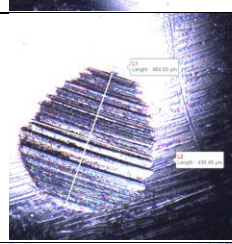
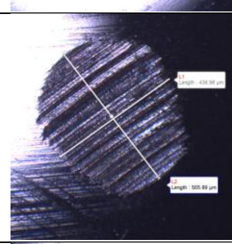
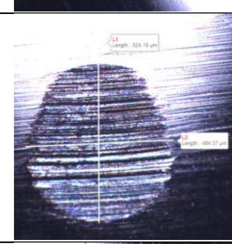
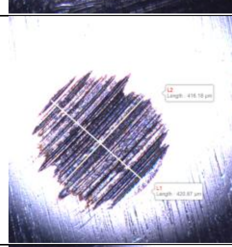
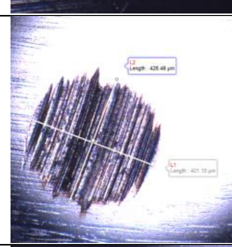
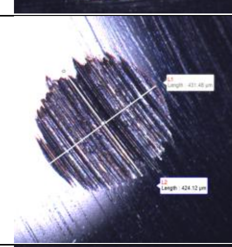
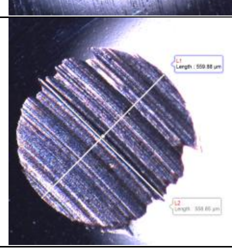
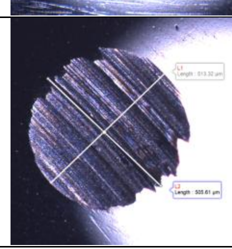
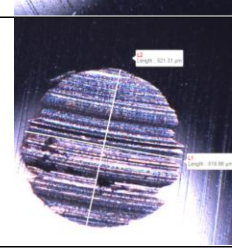
Figure 7: Average WSD of the tested ball for engine oil samples over the 500-hour endurance test.

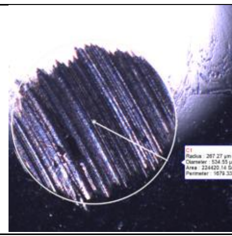
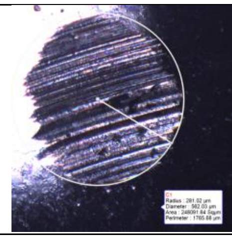
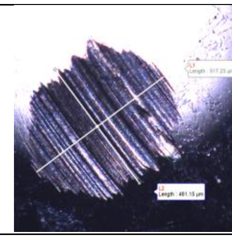
Table 4 shows optical micrographs of the worn steel balls, which correspond to the wear conditions of all engine oil samples throughout the 500-hour test. The micrographs reveal progressively larger and more pronounced wear scars on the balls as engine operation duration increases, with the extent of wear becoming more evident at higher operating hours. These findings align with the increase in COF values. As engine operation continues, fuel dilution reduces oil viscosity, which increases friction, leading to higher WSD values. The elevated WSD in fuel-diluted oils highlights the detrimental impact of fuel dilution on the wear performance of engine oil (Amminuddin et al., 2024; Khuong et al., 2017).

Table 4: Optical micrographs of worn steel balls observed under an optical microscope (OM).

Hours of Test	**Ball 1**	**Ball 2**	**Ball 3**
T-0 (FO)			
T-50			

T-100			
T-100 (FO)			
T-150			
T-200			
T-200 (FO)			
T-250			

T-300			
T-300 (FO)			
T-350			
T-400			
T-400 (FO)			
T-450			

T-500			

CONCLUSIONS

This study presents a comprehensive investigation into the use of B30 palm biodiesel in a diesel engine. A 500-hour engine-dynamometer endurance test was conducted to assess the performance and compatibility of B30 biodiesel under continuous use. Throughout the endurance test, the degradation of engine oil properties, tribological performance, and engine wear characteristics were closely monitored. Based on the findings, the following conclusions are drawn:

a) There is a notable decrease in the kinematic viscosity of engine oil due to increased engine operation, primarily caused by fuel dilution.

b) The elemental analysis of the engine oil provided crucial insights into wear and oil quality, highlighting the impact of B30 fuel contamination observed during the endurance test. The levels of wear metals and contaminant elements consistently increased, while additive elements generally decreased.

c) The investigation extends to the tribological performance of diluted engine oil, specifically examining its coefficient of friction (COF) and wear scar diameter (WSD). The increased COF and WSD observed in the diluted engine oil after 50 and 100 hours of engine operation, compared to fresh oil (FO) post-oil change, can be ascribed to the reduction in oil viscosity caused by fuel dilution.

In conclusion, the findings from this study provide valuable insights into the challenges and considerations associated with the prolonged use of B30 palm biodiesel in diesel engines.

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