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Impact of CPO and B35 on Diesel Engine Rocker Arm Wear During Long-Term Operation

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ABSTRACT

The increasing number of motor vehicles has led to higher fossil fuel consumption, contributing to greenhouse gas emissions, climate change, and environmental degradation. As a renewable alternative, biodiesel offers a way to reduce these impacts. Indonesia, with its abundant natural resources, has significant potential for biodiesel production. Crude palm oil (CPO) is a promising feedstock due to its availability and relatively low environmental impact. However, the high costs associated with the transesterification process make direct use of pre-heated CPO an area worth exploring. This study investigates the impact of pre-heated pure CPO compared to B35 ("*Dexlite*") on rocker arm wear in a Kubota RD 65 DI-NB diesel engine connected to a Denyo FA-5 alternator. The engine was operated for 300 hours at an average speed of 2000 rpm under a 100% load condition from 4000 watts of halogen lamps. Wear on the rocker arm was evaluated based on dimension loss, mass loss, and visual morphology. The results showed that the CPO-fueled engine exhibited a 38.69% lower wear rate compared to the B35-fueled engine. These findings suggest that pre-heated CPO can reduce component wear, extend engine lifespan, and lower maintenance costs, making it a viable alternative fuel for diesel engines. Further research is recommended to assess its long-term effects on engine performance and efficiency.

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Keywords: *Biodiesel, CPO, diesel engine, long-term operation, rocker arm, wear.*

I. Introduction

The increasing population in Indonesia correlates with a rise in fuel oil (BBM) consumption, which significantly impacts the depletion of crude oil reserves. To meet energy demands, Indonesia's fuel oil imports have escalated from 2018 to 2023 [1]. Furthermore, crude oil reserves have shown a declining trend from 2013 to 2022, reaching 4.2 billion barrels in 2022 [2]. This decline is corroborated by the reserve replacement ratio (RRR), which indicates a reduction in proven oil reserves and a corresponding decrease in oil production from 2016 to 2021 [3]. Globally, the use of fuel oil adversely affects the environment, contributing to the greenhouse effect, air pollution, and rising global temperatures [4]–[6]. Diesel fuel, in particular, is the highest-selling fuel oil compared to other types [7], yet its use increases emissions of CO, NO_x, SO_x, HC, and other harmful substances [8]–[10]. Consequently, there is an imperative need for transitioning to alternative fuels [11].

Biodiesel emerges as a viable alternative fuel, produced from plant or animal materials [12], [13]. This fuel is biodegradable, environmentally friendly, and derived from renewable

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resources [15],[16]. Biodiesel can be produced from various sources, including soybean, fish oil, papaya seed, chicken fat oil, neem, linseed, jatropha, and crude palm oil (CPO) [17]–[25]. Notably, Indonesia became the world's largest biodiesel producer from 2016 to 2022, surpassing Europe, the United States, Brazil, and India [25]. Indonesia's substantial potential as a global producer of alternative energy is evident, and it became the leading producer of palm oil (*Elaeis guineensis*) in 2022, with production increasing by 65% from 1980 to 2022 [26]. CPO, extracted from the mesocarp of palm oil, has versatile applications in cooking oil, cosmetics, soap, and pharmaceuticals. Since February 1, 2023, the Indonesian government has implemented a 35% biodiesel blend derived from CPO mixed with 65% diesel, known as "Dexlite" [27]. This commercial fuel undergoes transesterification in accordance with national fuel standards [28]. However, the transesterification process for CPO is costly, time-consuming, and produces significant environmental waste [29], [30]. Additionally, the quality of CPO depends on specific characteristics such as an acid number <0.4 mg-KOH/g, Free fatty acid (FFA) <2%, peroxide value <1 meq/kg, Deterioration of bleachability index (DOBI) >2.2, and total contaminants <20 mg/liter to be deemed suitable for production [31],[32]. High FFA CPO can reduce production quality, pose carcinogenic risks if consumed by humans, and lower the price of cooking oil [32]. Utilizing high FFA CPO or off-grade CPO directly without the transesterification process can significantly reduce production costs and time. While Indonesia's biodiesel blending mandate (B35) addresses energy security and emission reduction targets, limited empirical evidence exists regarding the long-term tribological implications of biodiesel use on diesel engine components. In particular, the mechanical consequences of employing off-grade CPO—proposed as a cost-effective substitute to refined feedstocks—remain underexplored. Thus, evaluating its wear characteristics is critical to determine whether such fuels can simultaneously achieve policy goals and ensure engine reliability.

The application of biodiesel in diesel engines significantly influences performance metrics, combustion temperature, emissions, and various engine conditions, including noise, vibration, deposit accumulation, lubrication degradation, and wear rates [22], [34]–[39]. The policy primarily focuses on reducing fossil fuel dependence, emphasizing emissions reduction and fuel blending ratios, without addressing the long-term impact on engine components. Wear of engine components is an inevitable outcome of diesel engine operation, primarily due to the lubricating properties of the fuel and its impact on performance [40],[41]. A study examined the use of lemon peel oil as fuel in relation to piston ring wear and reported that it resulted in higher wear compared to conventional diesel fuel. This increased wear was attributed to the poorer lubrication properties and greater lubricant degradation associated with oxygenated fuels during testing [41]. Additionally, the use of diesel-palm fatty acid distillate ethyl ester-hydrous ethanol blend, as opposed to conventional diesel, led to increased oxidation reactions and corrosive wear on biodiesel engine components due to the higher oxygen content [42]. Conversely, the study by Reddy *et al.* [43] indicated that diesel fuel caused greater wear compared to straight vegetable oil, primarily due to its low sulfur content, which resulted in reduced lubrication and increased component contact. Taken together, these studies demonstrate that biodiesel's influence on wear is inconsistent and strongly dependent on feedstock properties and testing conditions. Some investigations report accelerated wear due to oxidative instability and inferior lubricating performance of oxygenated fuels, whereas others suggest enhanced protection relative to low-sulfur diesel. However, most prior works are limited to short-duration experiments and rarely examine off-grade CPO with pre-treatment. This knowledge gap highlights the necessity of assessing the long-term mechanical effects of Indonesia's policy-

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relevant fuels, particularly off-grade CPO, on engine components. So, this research investigates the long-term effects (300 hours) of using off-grade CPO with heat treatment at 100°C, compared to a 35% biodiesel blend, on diesel engine components, specifically the rocker arm and rocker arm shaft. The study aims to assess dimensional loss, mass loss, and visual wear comparisons to determine the viability and impact of these alternative fuels on engine wear.

II. Material and Methods

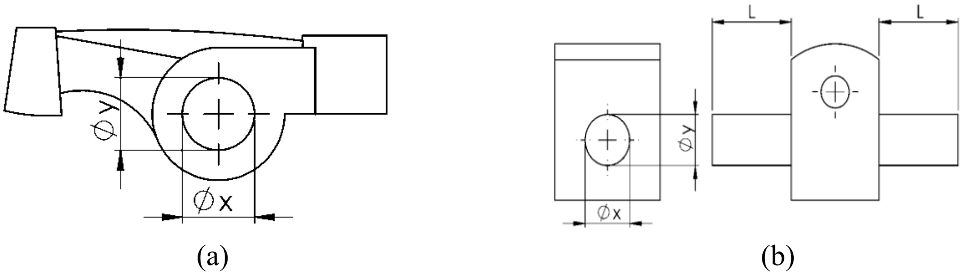
This study used two 6.5 HP Kubota RD 65 DI-NB diesel engines coupled with a 5 kVA Denyo FA-5 alternator, and the engine specifications are shown in Table 1. Lubrication for the engines was supplied by Meditran SX-Bio 15W-40 oil, while cooling was facilitated using Prestone Coolant Antifreeze. The engines were subjected to a load of 4000-watt lamps, selected based on an 80% efficiency factor of the alternator's rated capacity. The CPO used in this investigation was sourced from PT. Salim Ivomas Pratama, Tbk. Comprehensive fuel characteristics for both CPO and the B35 biodiesel blend are outlined in Table 2.

Table 1. Specification of the diesel engine

Name	Kubota RD 65 DI-NB
Type	Horizontal diesel engine, water-cooled, 4-stroke
Number of cylinders	1
Diameter x stroke	80 x 75 mm
Volume of a cylinder	376 cc
Continue power	5.5 x 2200 HP/RPM
Maximum power	6.5 x 2200 HP/RPM
Maximum torque	2.36 x 1600 Kg.m/RPM
Combustion system	Direct injection
Cooling system	Radiator
Coolant volume	1.3 liters
Fuel tank volume	7.5 liters
Lubricant volume	2 liters

1. Methods

The CPO-fueled engine uses a tank equipped with a heater and agitation system set at a temperature of 100°C to ensure that the kinematic viscosity and density at this temperature meet biodiesel standards [28]. Testing was conducted over a long-term period of 300 hours, focusing on mechanical energy transfer components, specifically the rocker arm and rocker arm shaft. These components were analyzed for dimensional loss, mass loss, and visual morphology wear. Dimensional loss was measured using an INSIZE 1108-150 Caliper, with measurement locations illustrated in Figure 1. Mass loss was assessed using an ACIS 600i instrument, and visual morphology was documented using a Canon 14000D camera.



(a) (b)

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Fig. 1. Location of component measurement (a) rocker arm and (b) rocker arm shaft

Table 2. Fuel properties

Property	Biodiesel standard SNI 7182	CPO	B35
Kinematic viscosity (mm²/s)	2.3 to 6.0 @40ºC	5.7 @100ºC	2 – 4.5 @40ºC
Density (kg/m³)	850 to 890 @40ºC	870 @100ºC	780 – 870 @15ºC
Calorific value (Mj/kg)	-	41.733	43.521
Cetane number	Min. 51	37.52	≥51
Sulfur content (mg/kg)	Max. 10	130	≤10

2. Working Setup and Testing Pre-Operational

The engine setup was designed to assess the suitability for long-term testing, specifically focusing on evaluating potential leaks in lubricant, coolant, and fuel valves. Testing was conducted using an iron stand measuring 125 cm x 60 cm x 10 cm. The diesel engine was securely mounted using a 3 cm-thick rubber engine mount to mitigate vibrations and minimize structural stress on the stand. The testing configuration is depicted in Figure 2. The engine operated consistently at 2000 RPM during the trials. Each test session lasted 15 minutes to determine the engine's readiness for prolonged evaluation. Instrument calibration was performed to determine measurement uncertainties, calculated using equations (1) and (2) as detailed in the reference [44]. Measurement uncertainties for the instruments used are documented in Table 3. Because the measurements represent repeated observations of the same components under controlled long-term testing, data variability was reported as mean ± standard deviation, with uncertainty propagated through calibration error. A two-sample t-test was not employed since it is not suitable for dependent, instrument-limited measurements; instead, the emphasis was placed on uncertainty quantification to provide a more rigorous assessment of measurement reliability [45].

$$Standard\ Deviation\ (SD)\sqrt{\frac{m\sum_{m-1}^{n}(X_m-X)^{-2}}{n-1}} \quad (1)$$

$$U=\frac{SD}{\sqrt{n}} \quad (2)$$

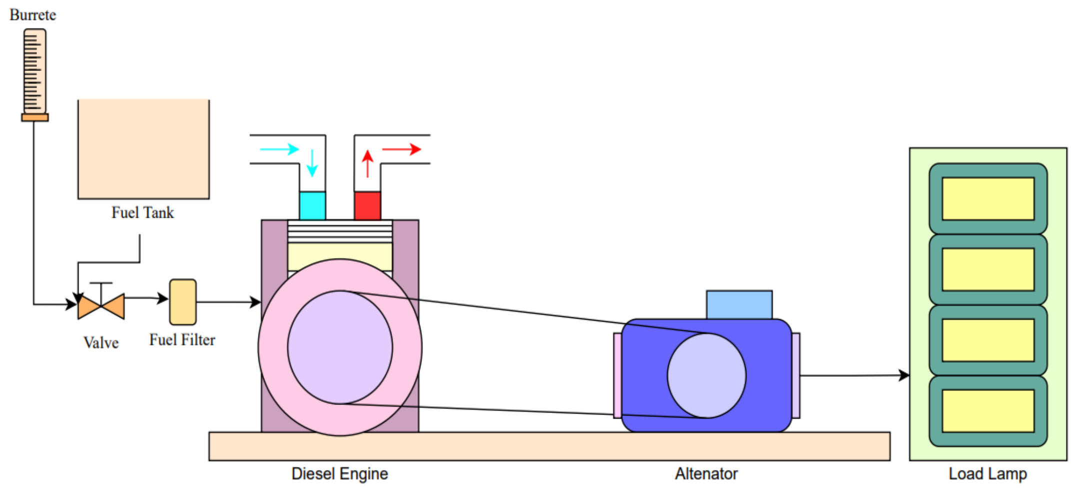


Fig. 2. Schematic diagram of the experimental

Table 3. Uncertainty of each parameter

Parameter	Range of measurement	Device	Accuracy	Uncertainty
Dimension (mm)	0 – 150 mm / 0 – 6”	Caliper meter	±0.02 mm	±0.05%
Weight (g)	0 – 600 gr	Digital precision balance	±0.01 mm	±0.02%
Wear	$U = \sqrt{((dimension)^2 + (weight^2))} = \sqrt{((0.05)^2 + (0.02^2))}$			±0.054%

III. Results and Discussions

The analysis of wear is categorized into three methods: dimensional loss, mass loss, and visual inspection of components. Dimensional loss is quantified using a caliper meter, mass loss is measured with a scale balance, and visual morphology is documented using a Canon 1400D camera.

1. Dimension Loss

Dimensional loss in the analyzed components pertains to areas experiencing the greatest dimensional reduction. The rocker arm and rocker arm shaft play pivotal roles in transferring energy from the camshaft to the valves. Therefore, excessive wear on these components can significantly affect engine performance.

Intake Rocker Arm

The intake rocker arm serves as the linkage between the camshaft and the intake valve. Its operation begins with power transfer from the camshaft to the camshaft follower, followed by transmission through the intake pushrod to the intake rocker, which subsequently actuates the intake valve. Figure 3 presents the dimensional loss results of the intake rocker arm, with measurement details illustrated in Figure 1.

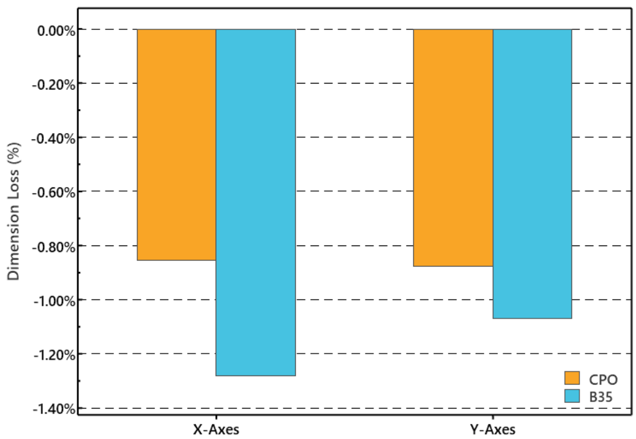


Fig. 3. Dimension loss of the intake rocker arm

This component underwent a 300-hour test at a consistent engine speed of 2000 RPM. The findings revealed dimensional wear on the intake rocker arm along both the x-axis and y-axis, attributed to repetitive contact with the intake rocker arm shaft. Repetitive contact may induce micro-vibrations and intermittent stick–slip phenomena at the contact interface, representing a tribological behavior analogous to the chatter and moan mechanisms described in SAE 2006-01-3270 [46]. These oscillatory frictional interactions accelerate surface degradation, thereby contributing to increased dimensional wear over prolonged operational periods. The rocker arm oscillates between 20° and 50° on the shaft [47], remaining in continuous motion during engine operation. Measurements along the x-axis and y-axis were necessary due to the cylindrical shape of the rocker arm shaft, whereas the intake rocker arm, fueled by B35, exhibited a slightly oval shape. After 300 hours of operation, measurements recorded 13.84 mm on the x-axis and 13.86 mm on the y-axis. In contrast, the rocker arm fueled by CPO showed minimal variation, measuring 13.87 mm on the x-axis and 13.873 mm on the y-axis. These findings have significant implications for the operational performance of the intake rocker arm.

Exhaust Rocker Arm

The exhaust rocker arm performs a function analogous to the intake rocker arm, transmitting mechanical energy received from the camshaft through the exhaust pushrod to actuate the exhaust valve. Figure 4 illustrates the dimensional wear results of the exhaust rocker arm.

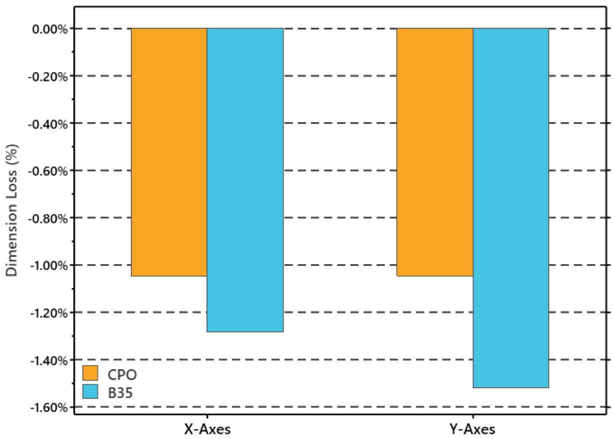


Fig. 4. Dimension loss of the exhaust rocker arm

Figure 4 shows that the exhaust rocker arm operates under elevated pressures during the opening of the exhaust valve, driven by the high pressures and temperatures within the combustion chamber, leading to greater wear compared to the intake rocker arm. B35 fuel exhibits a higher calorific value of 43.521 MJ/kg, whereas CPO possesses 41.733 MJ/kg. Calorific value significantly influences the energy generated during fuel conversion into power, with higher values resulting in increased contact stress and repetitive loading during movements induced by combustion, even though the engine operated at a constant speed of 2000 RPM. This indicates that the wear increase is attributed to higher mechanical loading rather than increased component velocity, impacting components such as the rocker arm and rocker arm shaft. These components undergo repetitive motion due to the energy conversion process derived from calorific value dynamics [48], [49]. Kinematic viscosity also holds substantial importance in combustion; lower kinematic viscosity promotes more efficient combustion [50], [51], thereby yielding higher energy outputs compared to fuels with higher kinematic viscosity like CPO [52]. Despite the optimal lubrication provided by B35-fueled engines, prolonged operation at high engine speeds can still contribute to wear formation.

Intake Rocker Arm Shaft

Dimensional loss on the intake rocker arm shaft, illustrated in Figure 5, serves as a notable indicator of wear. This wear arises from the interaction between the intake rocker arm and the shaft during engine operation. The analysis of dimensional loss on the intake rocker arm shaft involves comparing the use of CPO and B35 fuels over a span of 300 hours.

Dimensional degradation of the intake rocker arm shaft after 300 h in Figure 5 was consistently greater for B35 than for CPO, with longitudinal loss of approximately −1.0% for B35 versus −0.6% for CPO. Morphological inspection corroborates these findings: B35-operated shafts exhibited larger wear scars and increased surface roughness (Table 4). The increased wear under B35 is likely multifactorial. B35's higher cetane number (≈51 vs. 37.5 for CPO) can promote earlier and more complete combustion, which may shift combustion phasing and increase in-cylinder pressure/torque and cyclic contact stresses on valve-train components [53]. In addition, biodiesel's oxygenated chemistry and its oxidation products can alter lubricant performance and accelerate boundary-lubrication breakdown, contributing to abrasive and corrosive wear despite B35's superior baseline lubricity. Other fuel properties (for instance, kinematic viscosity at operating temperature, sulfur content, free fatty acids, and particulate/contaminant load) can further influence lubrication film formation and surface fatigue.

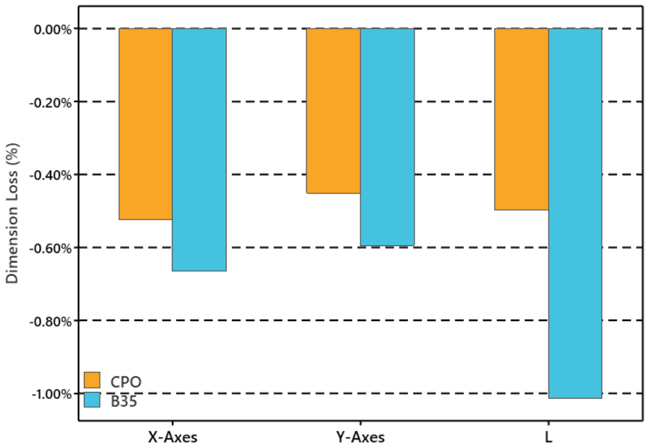


Fig. 5. Dimension loss of the intake rocker arm shaft

Exhaust Rocker Arm Shaft

Following Figure 1(b), the same parameters were measured in the intake rocker arm housing: the x-axis, y-axis, and shaft length (L). The exhaust rocker arm housing accommodates the movement of the exhaust rocker arm, and the data outcomes from this housing are detailed in Figure 6.

The wear observed in the exhaust rocker arm housing follows a similar trend to that of the intake rocker arm housing but is more pronounced, reflecting the greater mechanical and thermal stresses experienced during exhaust valve operation. The exhaust rocker arm undergoes repeated contact with the housing under elevated loads, as the opening of the exhaust valve is associated with higher in-cylinder pressures and temperatures compared to the intake cycle. These operating conditions intensify frictional interactions, resulting in greater dimensional and mass loss in the exhaust rocker arm housing. Fuel characteristics further influence this process; properties such as higher density, lower kinematic viscosity, elevated cetane number, and greater calorific value can increase combustion intensity and torque transfer, thereby amplifying the contact stresses on valve-train components [54]. The resulting wear is manifested as abrasive patterns, with fine circumferential lines on the rocker arm housing surface, indicative of boundary-lubrication breakdown and repetitive sliding under high-pressure conditions [55].

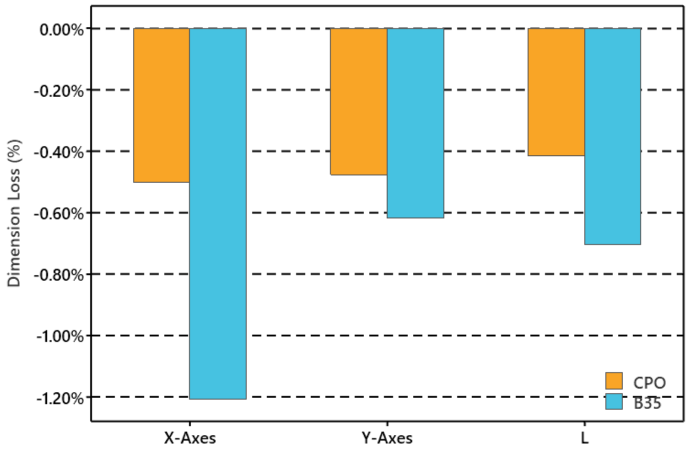


Fig. 6. Dimension loss of the exhaust rocker arm

2. Weight Loss

Weight loss corresponds to dimensional loss in components, with mass loss measurements aimed at quantifying wear occurring in dimensions not directly measurable on the component.

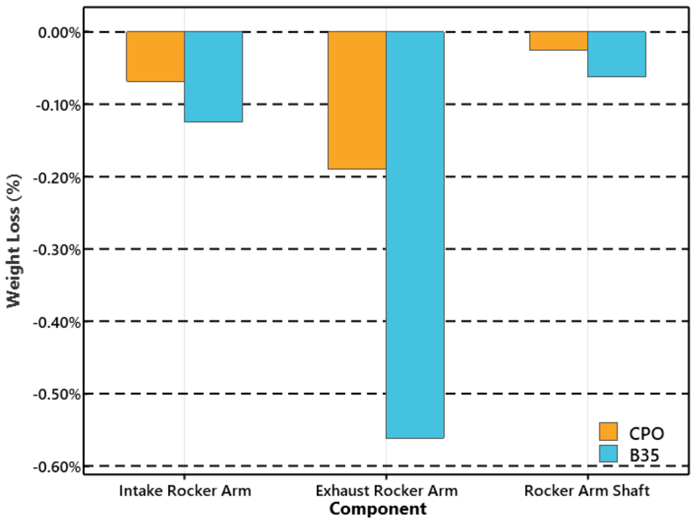


Fig. 7. Weight loss of intake rocker arm, exhaust rocker arm, and rocker arm shaft

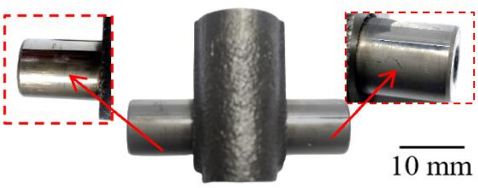
Weight loss, as shown in Figure 7, reflects cumulative dimensional degradation in components where direct measurement is difficult. The mass loss recorded in the intake rocker arm, exhaust rocker arm, and rocker arm shaft is markedly greater in engines fueled with B35 compared to CPO. This difference arises from B35's higher calorific value and superior combustion efficiency, which increases mechanical loading on moving parts [56]. In particular, B35's lower kinematic viscosity promotes finer atomization and more complete ignition, thereby enhancing torque output but simultaneously intensifying contact pressures on the rocker arm assembly. Consequently, the exhaust rocker arm and shaft exhibit higher wear rates under B35 operation, whereas the higher viscosity of CPO provides slightly more lubrication despite less efficient combustion [57].

3. Visual Morphology

Visual examination of components at 4x magnification reveals diverse wear patterns such as scratches, shape alterations, or surface fractures. Detailed analysis of wear morphology aids in maintaining optimal engine performance and preventing significant damage. The visual morphology findings for these components are detailed in Table 4.

Based on Table 4, the exhaust rocker arm and shaft exhibit more pronounced wear than their intake counterparts. This is primarily due to the higher pressure required to actuate the exhaust valve, which increases surface loading and accelerates material degradation. Inadequate lubrication further exacerbates this effect, as reduced oil film thickness elevates friction between sliding contacts. Engines fueled with B35 show greater wear severity, as its higher torque output intensifies the mechanical stresses acting on the rocker assembly. Morphological inspection reveals abrasive wear across all components, characterized by fine scratches produced by repeated sliding contact [58]. Additionally, adhesive wear is observed at the exhaust rocker arm shaft end, where elevated valve pressures induce localized plastic deformation under high contact stresses, leading to material transfer and surface damage.

Table 4. Visual morphology of the rocker arm and rocker arm shaft

Components	Fuel	
	Crude Palm Oil	B35
Intake rocker arm		
Exhaust rocker arm		
Rocker arm shaft		

IV. Conclusions

This study demonstrates that CPO fuel reduces wear on rocker arms and rocker arm shafts by 38.69% compared to B35, with average wear rates of −0.38% and −0.62%, respectively. The lower wear associated with CPO is attributed to its lower calorific value, which moderates in-cylinder pressures and torque fluctuations, and to its inherent lubricating properties that help sustain boundary lubrication films under high contact stresses. In contrast, B35's higher calorific value and combustion efficiency intensify cylinder loading, promoting abrasive and adhesive wear, particularly in exhaust-side components that endure the greatest mechanical and thermal stresses. These results highlight the potential of off-grade CPO as a cost-effective alternative fuel with tribological advantages in diesel engines. However, the study was limited to a single engine type and controlled steady-state operation, and only one batch of off-grade CPO was tested, leaving variability in feedstock quality and real-world duty cycles unaddressed. To validate the broader feasibility of CPO, future investigations should extend to multi-engine trials, long-term endurance under diverse operating conditions, and detailed surface analyses to clarify wear mechanisms across different engine materials and fuel qualities.

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Nomenclature

CPO	: Crude palm oil
B35	: 35% biodiesel + 65% diesel fuel
BBM	: Bahan bakar minyak
DI	: Direct injection
RRR	: Reverse replacement ratio
CO	: Carbon monoxide
No_x	: Nitrogen oxide
SO_x	: Sulfur oxide
HC	: Hydrocarbon
DOBI	: Deterioration of bleachability index
FFA	: Free fatty acid
HP	: Horsepower
kVA	: Kilo Volt Ampere, unit of apparent power
mm	: Millimeter
cc	: cubic centimeter, unit of volume
RPM	: Revolutions per minute
Kg.m	: kilogram-meter, unit of momentum
U	: Uncertainty
SD	: Standard deviation
gr	: Gram, unit of mass
CN	: Cetane number

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