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Technical and supply chain scheme

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Comprehensive assessment using preheat crude palm oil on endurance test engine diesel: Technical and supply chain scheme

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ABSTRACT

Burdened by oil imports and subsidies for more than 5000 diesel power plants, Indonesia aims to use crude palm oil (CPO) as fuel in the power plants. Previous studies only focused on the technical feasibility of using CPO. Therefore, this study aimed to enrich the existing literature by analyzing the technical feasibility of using CPO, degummed CPO, and bleached palm oil (BPO) fuels on endurance test for 500 operational hours with a 20 kW diesel engine capacity for each type of fuels. Our analysis included component rating and the measurement of specific fuel consumption, emissions, oil dilution, and deposit materials. The assessment concluded that diesel engines using CPO, BPO, and degummed CPO increased specific fuel consumption, deposit formation, and emissions of carbon monoxide and carbon dioxide compared to engines using a 30% FAME blend in HSD or Biodiesel 30. This implies that CPO, BPO, and degummed CPO could be used in diesel engines, though fuel consumption and maintenance costs tend to increase. Based on the test results, we provided an efficient CPO supply chain from CPO mills to diesel power plants.

1. Introduction

Fossil fuel, including diesel fuel, is still essential for electricity generation using diesel engines in developing countries, including Indonesia (IEA, 2022). Diesel engines have several advantages, among: fast construction, reliable performance, easy maintenance, good thermal efficiency, good response, and durability (Ravikumar et al., 2017). Before the 1990 s, when the price of diesel fuel was still low and Indonesia still has a status as a net oil exporter country, the installation of diesel power plants to increase the electrification ratio is very massive (Al Irsyad, 2019). More than 5200 pcs of diesel power plants are used to supply electricity in remote and isolated areas in Indonesia (PLN, 2022).

In 2004, Indonesia became a net oil importer to meet the increasing demand for diesel fuel (besides for electricity, also for transportation, and industrial needs) (MESDM, 2019). The increasing world oil prices resulted in expensive diesel engine operating costs and a burden on state finances (PLN, 2021). Due to these circumstances, and also environmental impacts (Sukra et al., 2022), such as emissions (i.e., black smoke or diesel fuel elements not burning during combustion), NOx, and PM emissions, the country gradually reduced its dependency on diesel fuel. In the other hand, Indonesia is the world's largest producer and exporter of palm oil that can be used to reduce the dependency on diesel fuel

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Table 1
Result summary of previous studies.

Study	Methods	Results							
		1	2	3	4	5	6	7	8
(De Almeida et al., 2002)	• Direct injection of four-stroke 70 kW at 1800 rpm. • 350 operational hours. • HSD and CPO. • The heating temperature is at 50 and 100 °C.	↑	↑	↑	↑		↓	=	↑ =
Bari et al. (2002)	• Direct injection of four-stroke 4.4 kW at 3600 rpm. • HSD and CPO. • Varying heating temperature between 50 and 100 °C.			↑		↑			
(Lim et al., 2002)	• Direct injection of four-stroke 4 kW at 3600 rpm. • HSD and CPO. • The heating temperature is at 60 °C.	↑		↑		↑			
(Pipitone and Costanza, 2018b)	• Direct injection of 8-cylinder 481 kW. • HSD and CPO. • The heating temperature is at 60 and 80 °C.								↑
(PLN, 2019), and (Cahyo et al., 2021a)	• Two low-speed diesel engines (600 rpm) with 10 MW and 27 MW capacity. • 375 operational hours. • B20 and CPO. • The heating temperature is at 70 °C.	↑	↓	↓		↑	↑		↑
(Cahyo et al., 2021b)	• Two diesel engines with a capacity of 2.5 MW and 4.9 MW. • B20 and CPO.			↑			↑		
(Kurniawan et al., 2021)	• Direct injection of four-stroke 4.8 kW at 2200 rpm. • Pure plant oil (PPO) and PPO with Rhodinol and Turpentine.	↑							

Note: (1) Specific fuel consumption (SCF); (2) Exhaust temperature; (3) CO; (4) CO_2; (5) NO; (6) NOx; (7) O_2; (8) Deposits.

through energy diversification toward massive biofuel utilizations (GAPKI; USDA, 2021; dan and ESDM, 2015).

Biodiesel can be utilized in diesel engines without the need for modifications, either by direct use or blending with diesel fuel, with blending being the more prevalent approach (Chen et al., 2021). Indonesia has successfully implemented the blend diesel fuel with biofuel with a composition 70% high-speed diesel (HSD): 30% bio-fatty acid methyl ester (FAME) or known as B30 since 2020 (Supriatna et al., 2021) and increase 65% HSD: 35% FAME (B35), respectively since 2023 (Kementerian Energi dan Sumber Daya Mineral) to reduce HSD consumption in all sectors. For direct uses, Indonesia has built and operated a 5 MW CPO-fueled power plant since 2019, aiming to use crude palm oil (CPO) as fuel. The investment cost of a new and dedicated CPO-fueled power plant is around US$ 1.4 million per MW (Darmawan et al., 2019). This is higher than the investment cost of US$ 1 million per MW needed to convert a diesel to a CPO-fueled power plant (Darmawan et al., 2019). Therefore, converting existing diesel to CPO-fueled power plants is the primary strategy. One of the main concerns for CPO utilizations as fuel in diesel engines is its viscosity (Pipitone and Costanza, 2018a). Diesel fuel and CPO has different viscosity values so that CPO must be heated until its viscosity is nearing the viscosity value of diesel fuel.

In 2019, the State-owned Electricity Company (PLN) conducted experiments to use CPO heated at 70 °C in two conventional diesel power plants with capacities of 2.5 MW and 4.8 MW. The experiments showed that the use of the CPO for conventional diesel power plants fuel still has the constrain. For instance, incomplete CPO combustion created deposits on the cylinder head and piston surfaces. These formations mainly contained carbon and calcium elements for the injector nozzle tip and cylinder head (Cahyo et al., 2021a), respectively. Other reasons have deteriorated engine performances, higher fuel volume consumption, and rapid engine parts replacements, including filters, cylinder heads, pistons, and nozzle. Additionally, CPO combustion produces more NOx emissions and lower lubricant quality (PLN, 2019), (DJK, 2019).

The studies that examine the technical feasibility of CPO usage in diesel power plants are concerned with the heating system temperature level. The heating system reduces CPO viscosity, and boiling at 150 °C reduces its viscosity close to that of the HSD (LIPICO, 2008). Moreover, the high heating temperature reduces deposit formation (Pipitone and Costanza, 2018b). In the experiments, an operational test of 100% CPO

Table 2
The parameter values required by the diesel engine manufacturers and ASTM D975–22.

Parameters	Units	MAN	Wärtsilä	ASTM D975-22
Acid Value	mg KOH/g	< 5	< 15	< 0.050
Iodine Value	g/100 g	< 125	< 120	< 41
Saponification	mg KOH/g	-	-	
Kinematic Viscosity 50 °C	cSt	< 40	< 70	1.3–2.4
Density at 15 °C	kg/m^3	900 – 930	< 940	820–900
Flash Point	°C	> 60	> 60	> 38
Oxidation stability (110 °C)	Hours	> 5	> 17	> 2.5
Carbon Residue	ppm	< 4000	< 500	< 4000
Water Content	ppm	< 5000	< 2000[a])	< 200
Sediment Content	ppm	< 200	< 500	< 500
Silicon	ppm	-	< 15	< 4
Sulfated Ash	ppm	< 100	< 500	< 200
Phosphorus	ppm	< 15	< 100	< 15
S	ppm	-	< 500	-
Na dan K	ppm	< 15	< 30	-
Filterability	°C	< 10[b])	-	-18
Cetane number	-	> 40	-	> 40
Calorific Value	MJ/kg	> 35	-	> 42.5

[a] in v/v, [b]) below the lowest temperature in the fuel system

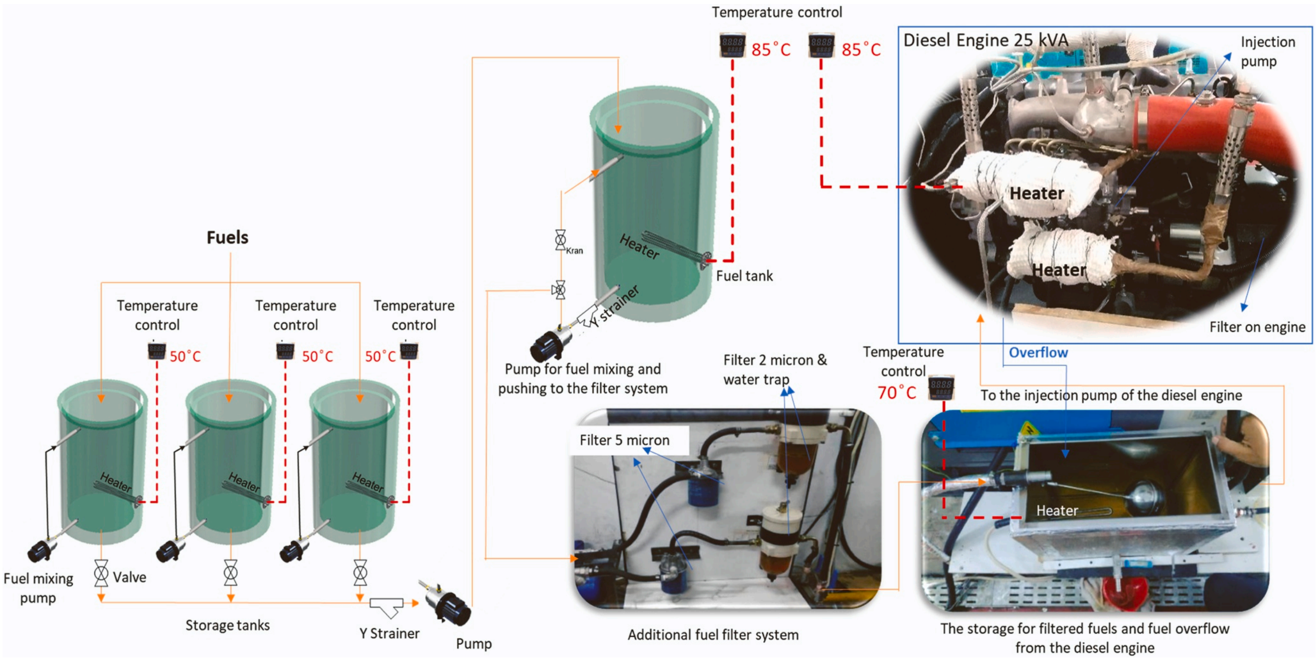


Fig. 1. The testing system configuration.

Table 3
The characteristic comparisons of degummed CPO, BPO, CPO#1, and CPO#2.

No	Parameter	Unit	SNI 8483:2018	Values			
				D.CPO	BPO	CPO #1	CPO#2
1	Density at 50 °C	kg/m^3	870–910	892.2	890.8	891.7	890.2
2	Kinematic Viscosity at 50 °C	mm^2/s	< 40	28.94	28.49	28.32	28.20
3	Flash Point	°C	> 200	248.0	226	240.0	225.0
4	Carbon Residue	% wt	< 0.4	0.02	0.03	0.01	0.03
5	Sulphated Ash	% wt	< 0.01	0.002	0.002	0.004	0.003
6	Phosphorus	ppm	< 10	7.27	0.83	< 0.5	1.5
7	Acid Value	mg KOW/g	< 15	10.5	9.32	11.12	8.20
8	Iodine Value	g I_2/100 g	50–60	10.73	51.83	53.63	51.67
9	Saponification	mg KOH/g	190–205	129.86	194.09	165.10	193.61
10	Water Content	% wt	< 0.45	0.04	0.03	0.19	0.13
11	Sediment Content	% wt	0.05	4.13	0.03	3.27	0.03
12	Copper (Cu)	mg/kg	-	0.57	0.19	0.42	0.18
13	Iron (Fe)	mg/kg	-	1.65	1.4	10.02	4.6
14	Zinc (Zn)	mg/kg	-	8.2	< 0.101	1.23	0.47
15	Nickel	mg/kg	-	0.15	0.92	< 0.101	< 0.101

CPO = crude palm oil; D.CPO = degummed CPO; and BPO = bleached palm oil. The quality standards are SNI 8483–2018 and ASTM D1585-18 for parameters 1–11 and 12–15, respectively.

usages on a 481 kW Genset with a heating temperature of 60 °C caused a 53% greater deposit formation than HSD usages. Increasing the CPO heating temperature to 80 °C effectively reduced the deposits by 41% (Pipitone and Costanza, 2018b).

Several other studies have investigated the impacts of CPO heating temperature on diesel engines when using CPO as fuel. Using 100% CPO in a 70 kW Genset for 350 h obtained significantly lower deposit formation from a test with 100 °C heating temperature compared to the test with 50 °C (De Almeida et al., 2002). However, Bari et al (Bari et al., 2002). had different conclusions after testing 100% CPO usages on a 4.4 kW Genset with heating temperatures between 50 and 100 °C. The tests

Table 4
The specifications of the diesel engines used in the tests.

Parameters	Descriptions
Engine	Isuzu Foton 4JB1
Generator	Winston PI144D
Capacity	25 kVA
Power output	20 kW
Cylinders	4
Bore x Stroke	93 × 102 mm
Piston Displacement	2711 cc
SFC	4.10 Liter/hour (L/h) (75% Load) & 5.60 L/h (100% Load)
Oil Capacity	5.5 Liter
Dimension	2210 × 960×1220 mm

Table 5
Instruments used in the experiments.

Instruments	Range	Accuracy
Pressure Transmitter	0–15 bar	± 0.5%
	0–10 bar	± 0.5%
	0–6 bar	± 0.25%
	0–6 bar abs	± 0.25%
Thermocouple PT 100	-200–500 °C	± 1 °C
Flue Gas Analyser	O2 0.1 – 20.9%	± 0.3%
	CO 0–4000 ppm	± 5%
	NO 0–3000 ppm	± 5 ppm
	NO_2 0–500 ppm	± 5 ppm
	SO_2 0–5000 ppm	± 10 ppm

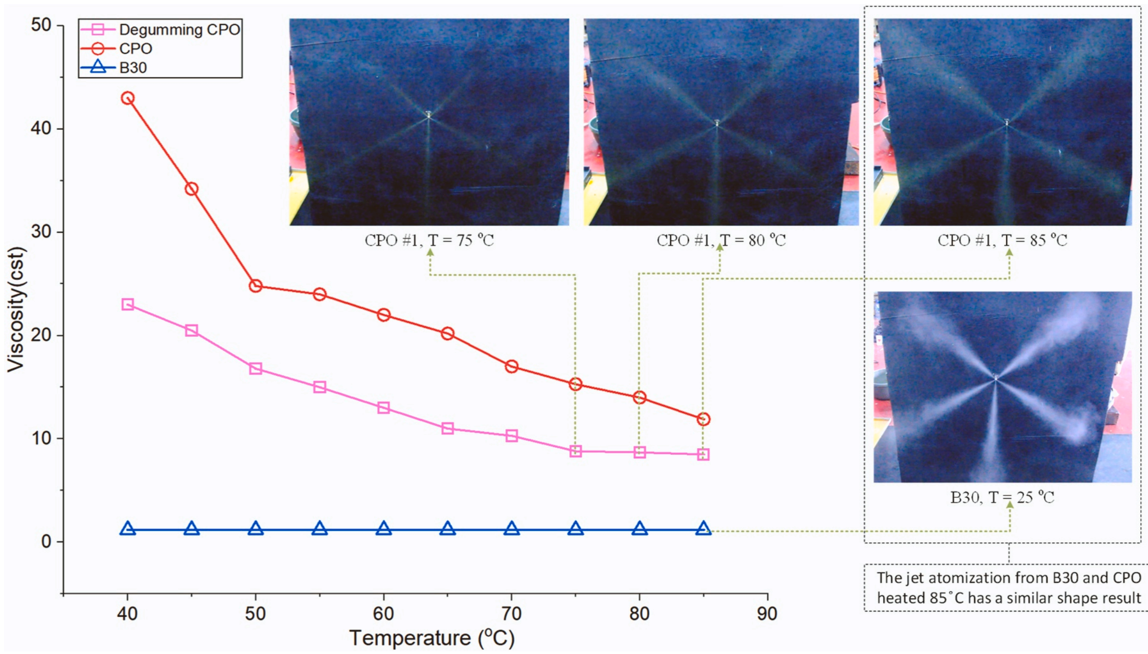


Fig. 2. The viscosity of tested palm oils and the visualization of atomization result from engine injectors.

concluded that the heating temperature difference did not affect friction on HSD engines, brake-specific fuel consumption (BSFC), and thermal brake efficiency (BTE). This implies that the heating temperature at 60 °C is sufficient for CPO's smooth entrance into the engine (Bari et al., 2002), (Lim et al., 2002). Moreover, Bari et al (Bari et al., 2002). did not recommend a temperature exceeding 97 °C because it will release gas from CPO in the fuel inlet. The gas may cause instability and damage vibrations on the engine. According to previous studies, using CPO increases CO emissions (De Almeida et al., 2002)– (Lim et al., 2002), peak pressure, NO emissions (De Almeida et al., 2002), exhaust temperature, specific fuel consumption (SFC), oil replacement frequency, and CO_2 emissions (Bari et al., 2002), (Lim et al., 2002) compared to HSD. The exhaust temperature is higher due to faster deposit formations in the injector. The increased SFC is caused by the low heating value and high density of CPO, making the engine require more fuel volume (De Almeida et al., 2002).

Table 1 summarizes the experimental results on previous studies. According to our literature review results, the endurance test with 500 h with three types of CPO, i.e., B30 (as a baseline), CPO, degummed CPO, and bleached palm oil (BPO) has not been found to analyze the effect on the diesel engine performance and wear material in combustion component. To fill the literature gap, therefore, this study aims to comprehensively determine the feasibility using palm oils as fuel for diesel engine power plants from (i) technical perspective; (ii) financial

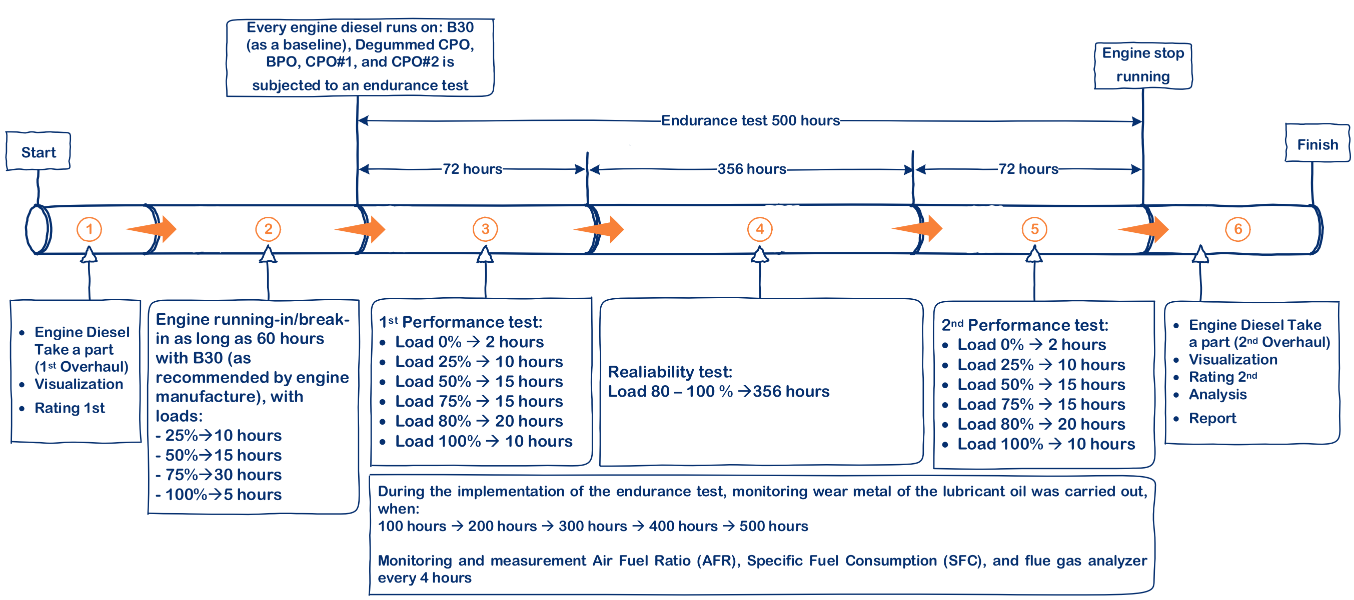


Fig. 3. The endurance operational test cycles.

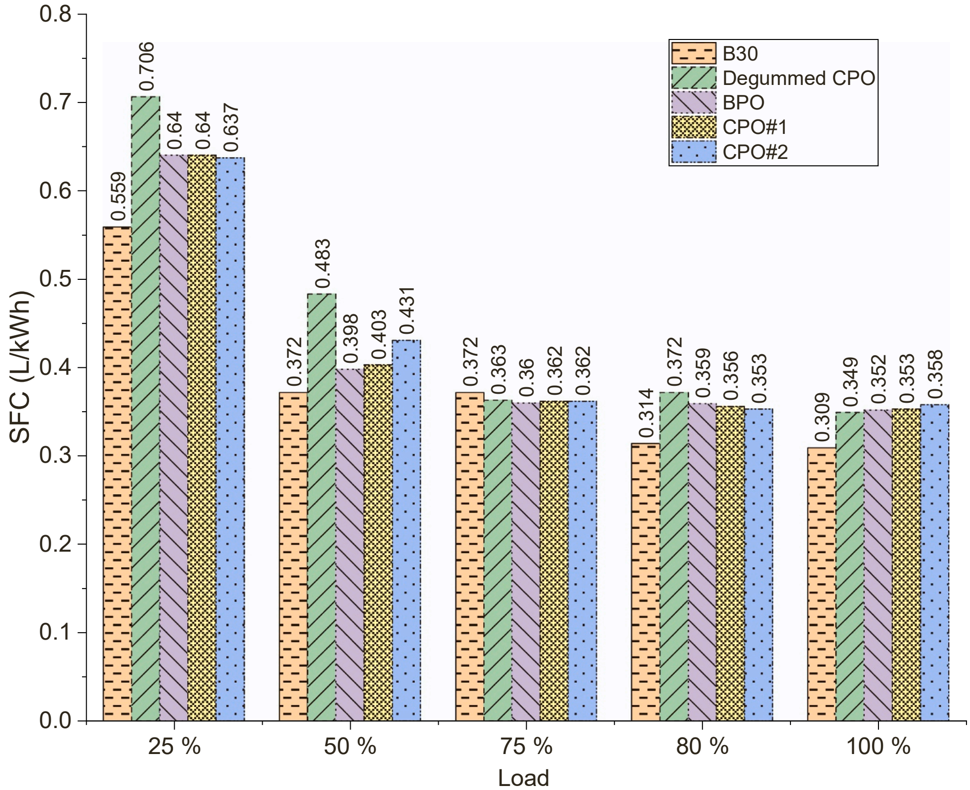


Fig. 4. The SFC at different loads.

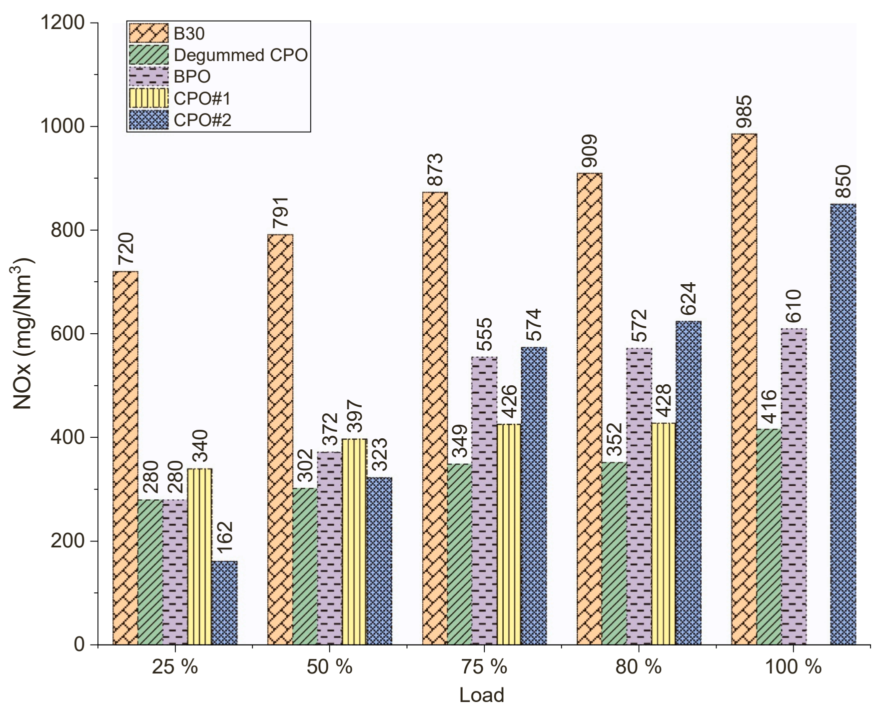


Fig. 5. The NOx emissions at different loads.

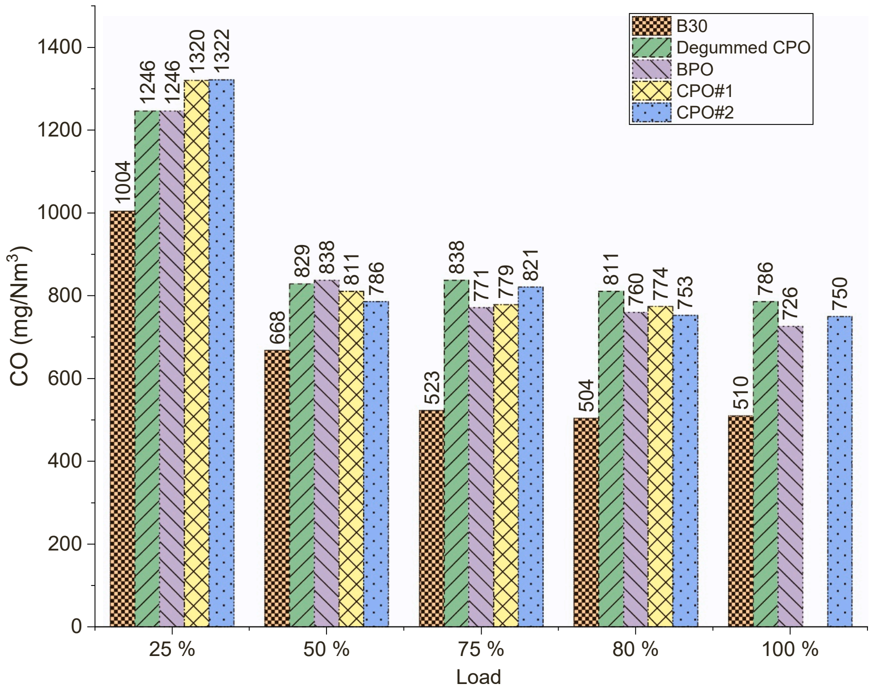


Fig. 6. The CO emissions at different loads.

perspective; (iii) supply chain scheme. Futhermore, these study divided into three sections, i.e., Sections 2, 3, and 4 discuss the methodology, results and discussion, and conclusion, respectively.

2. Methodology

2.1. Fuels characterization

Indonesia sets Indonesia National Standard (SNI) 8483:2018 on the Quality and Test Method of Crude Palm Oil for Low-Speed Diesel Motor Fuel (SNI, :, 8483, 2018, 2018). It is the minimum CPO quality for fuel in diesel engines. Table 2 shows that most parameter requirements in SNI 8483:2018 are better than the fuel specifications for MAN and Wärtsilä engines. Subsequently, PLN (PLN, 2019) used CPO that satisfies the parameter requirements in SNI 8483:2018.

The experiments used biofuels with five different qualities, including B30 with a standard specification (DGNREEC, 2019), degummed CPO, industrial BPO, and two CPOs with different qualities. B30 and BPO

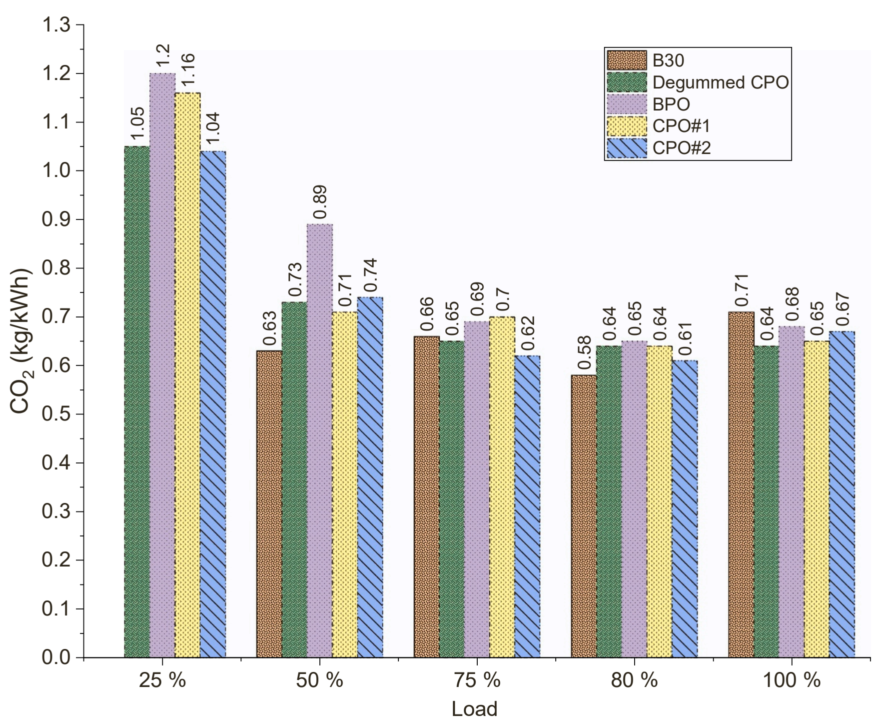


Fig. 7. The CO_2 emissions at different loads.

Table 6
Result summary of this study.

Study	Methods	Results							
		1	2	3	4	5	6	7	8
Experimental result summary (this study)	• Direct injection of four-stroke 20 kW. • 500 operational hours. • B30, CPO, BPO, and degummed CPO. • The heating temperature is 85 °C.	↑		↑	↑		↓		↑

Note: (1) Specific fuel consumption (SCF); (2) Exhaust temperature; (3) CO; (4) CO_2; (5) NO; (6) NOx; (7) O_2; (8) Deposits.

Table 7
The deposit distributions on the top piston.

Fuels	Deposit thickness			
	< 0.05 mm	0.05 – 0.10 mm	0.10 – 0.20 mm	0.20 – 0.40 mm
B30	55%	30%	15%	-
Degummed CPO	10%	20%	20%	50%
BPO	10%	20%	20%	50%
CPO#1	-	10%	30%	60%
CPO#2	10%	20%	20%	50%

were purchased from a fuel station and a palm oil mill accordingly. The degummed CPO was formulated by mixing CPO with phosphate acid 85% for 0.06% w.t. and bentonite for 1% w.t. Table 4 compares the quality of the prepared fuels, where only BPO and CPO#2 met all limits stated in SNI 8483:2018. Furthermore, degummed CPO and CPO#1 had saponification value and sediment content beyond the allowed limit range. The degummed CPO had a high phosphorus value of 7.27 ppm compared to other fuels due to the added phosphate acid. However, this value is below the limit of 10 ppm.

CPO#1 refers to crude palm oil that serves as feedstock for large-scale industries, while BPO represents processed crude palm oil used in the initial stages of large-scale industries. On the other hand, CPO#2 is the feedstock utilized specifically for medium-scale industries.

2.2. Endurance test setup

Fig. 1 shows the configuration of the equipment used for the operational tests, and Tables 4 and 5 show the diesel engine and instrument specification. The equipment comprised six 1000 L storage tanks, a 500 L fuel tank, a 50 kVA electric heater as a dummy load, as well as data acquisition (DAQ) and additional fuel filter systems. All tanks were made from stainless steel and equipped with a heating and mixing system to prevent CPO clotting. The heating temperatures were 40–50 °C and 85 °C in the storage and fuel tanks, respectively. As a comparison, the CPO heating temperature used by PLN was 70 °C (PLN, 2019). The selection of 85 °C temperature reduces corresponds to the maximum fuel viscosity value (around 8 cst) that can enter the test engines. Fig. 2 shows the results of three fuel viscosity tests and fuel jet atomization/nebulization from fuel injectors testing.

Experiments in this study used a data acquisition (DAQ) system containing a 20-channel logger, a personal computer, pressure transmitters, and temperature sensors PT 100. These transmitters measured oil storage pressure, fuel pressure before and after the fuel filter, exhaust gas, and airflow exertions. The sensors measured ambient temperature and temperatures at the engine oil storage, coolant inlet and outlet, exhaust gas exit, and fuel entrance. Table 5 show the accuracy of the sensors that used in this study.

The additional fuel filter system had 5-micron and 2-micron filters equipped with a water trap. The efficiency of the water trap was 81%, reducing the water content from 0.48% to 0.09%wt. CPO after the filter system has a higher low heating value (LHV), lower auto ignition and flash point from 230 °C before the filter system to 200 °C, and higher calorific value from 39.1 kJ/g before the filter system to 39.2 kJ/g. Emissions measurement for NOx, CO, and CO_2 is conducted using the Bacharach PCA3 Portable Combustion Analyzer, while opacity is approached using the Bacharach True Spot Smoke Test Kit.

2.3. Endurance test procedure

The endurance test procedure had two operational test cycles, as shown in Fig. 3. First, the running-in cycle used B30 for the first 60 h, including 10, 15, 30, and 5 h at 25%, 50%, 75%, and 100% load, respectively. This cycle lubricated all components because new diesel engines were used for each analyzed fuel. The second cycle is for the performance and reliability tests when using the analyzed fuel. This cycle lasted 500 h according to requirements by MMER (MEMR, 2018) and PLN (PLN, 2015). It started with 0%, 25%, 50%, 75%, 80%, and 100% load for 2, 10, 15, 15, 20, and 10 h, respectively. The reliability test was conducted for 356 h at 80% load with the load reversal process from 100% to 0% at the end of the cycle. Temperature, SFC, airflow

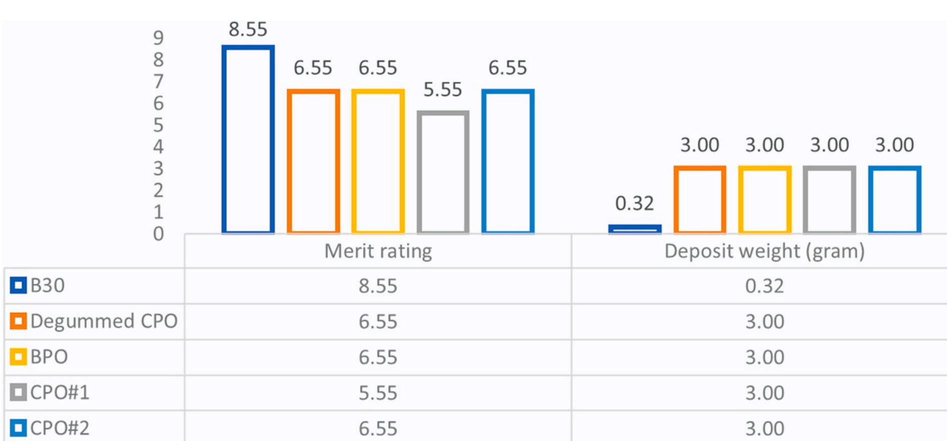
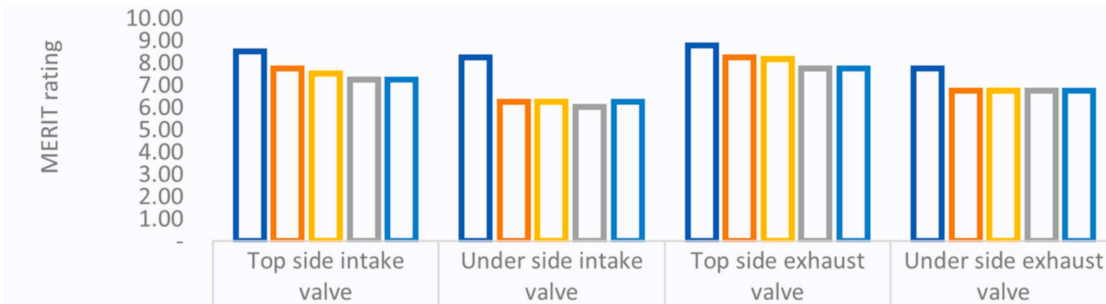


Fig. 8. The merit rating and deposit weight on the cylinder head.



	Top side intake valve	Under side intake valve	Top side exhaust valve	Under side exhaust valve
B30	8.50	8.25	8.75	7.75
Degummed CPO	7.75	6.25	8.25	6.75
BPO	7.50	6.25	8.15	6.75
CPO#1	7.25	6.00	7.75	6.75
CPO#2	7.25	6.25	7.75	6.75

Fig. 9. The merit rating for the intake and exhaust valve.

speed, fuel pressure, rotating speed, torque, electricity generation, and emissions were measured using procedures on ISO 15550:2016 ("ISO - ISO 0:, 1555, 2016, 2022) and ASME PTC 17:1991 (ASME PTC 17:, 1991, 1991).

Rating assessments were conducted on the piston and its ring, cylinder head, as well as the intake and exhaust valves following the ASTM Deposit Rating Manual (Cahyo et al., 2021b). These assessments were performed before and after the operational tests to analyze deposit formation, wear, and tear.

2.4. Supply chains analysis

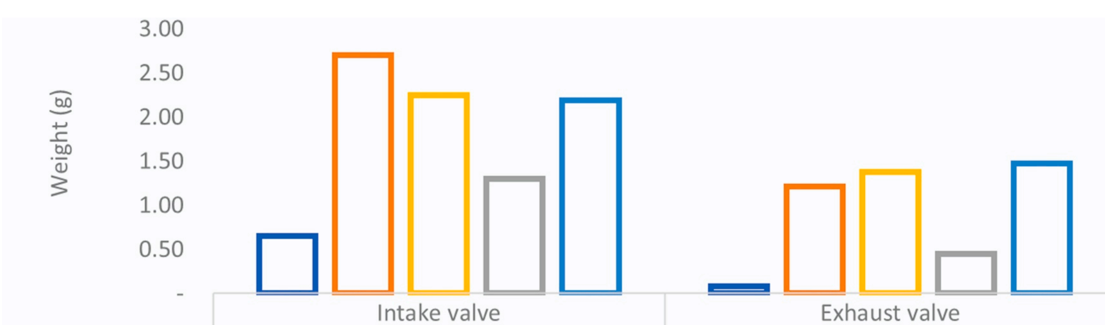
This study will be the first study that uses the Phyton API on Google Collaboratory for analyzing supply chains of feasible diesel power plants using CPO. Conventional analytical tools used for analyzing the supply chains of palm oil products are the mathematical models in linear programming (García-Cáceres et al., 2015; Babazadeh et al., 2017; Peña González et al., 2021). The Python API on the Google Collaboratory, due to being a programming language operated on Google Cloud (Brandolini et al., 2020; Bisong, 2019), offers a superior advantage. It is an application on the Google Earth Engine, which utilizes satellite images such as Landsat and Copernicus Sentinel database (Brandolini et al., 2020). Several studies used the Google Earth Engine for CPO analysis but limited to issues of landscape (Brandolini et al., 2020), land mapping and commodity volume estimation (Shaharum et al., 2020; Campos-Taberner et al., 2018; Zhang et al., 2020; Minasny et al., 2019), and harvest scheduling (You and Dong, 2020). Utilizing this application to estimate the transportation costs will use real-world routes from the CPO mills to the diesel power plants.

The optimization process produced a pair of diesel power plants and CPO mills, based on the shortest distance, CPO production capacity, and fuel requirements, as shown in the following mathematical formula:

$$Minimize \quad Z = \sum_{i=1}^{m} \sum_{j=1}^{n} c_{ij} x_{ij} \tag{1}$$

subject to:

$$\sum_{i=1}^{m} x_{ij} \geq b_j, \nabla j = 1, \ldots, n \tag{2}$$



	Intake valve	Exhaust valve
B30	0.65	0.08
Degummed CPO	2.70	1.21
BPO	2.25	1.37
CPO#1	1.30	0.44
CPO#2	2.19	1.47

Fig. 10. Valve deposit weights.

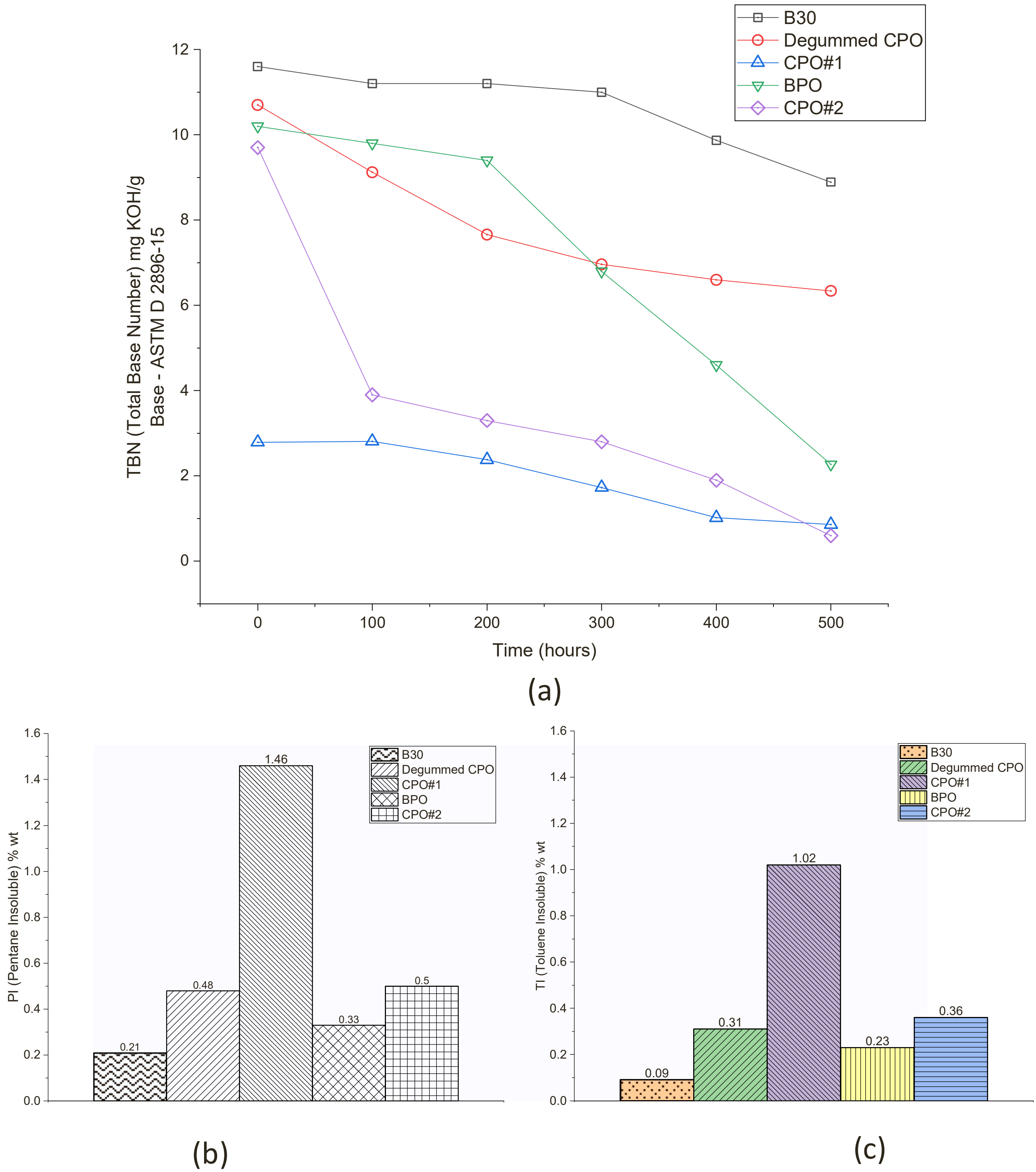


Fig. 11. (a) Total Base Number; (b) Pentane Insoluble; (c) Toluene Insoluble.

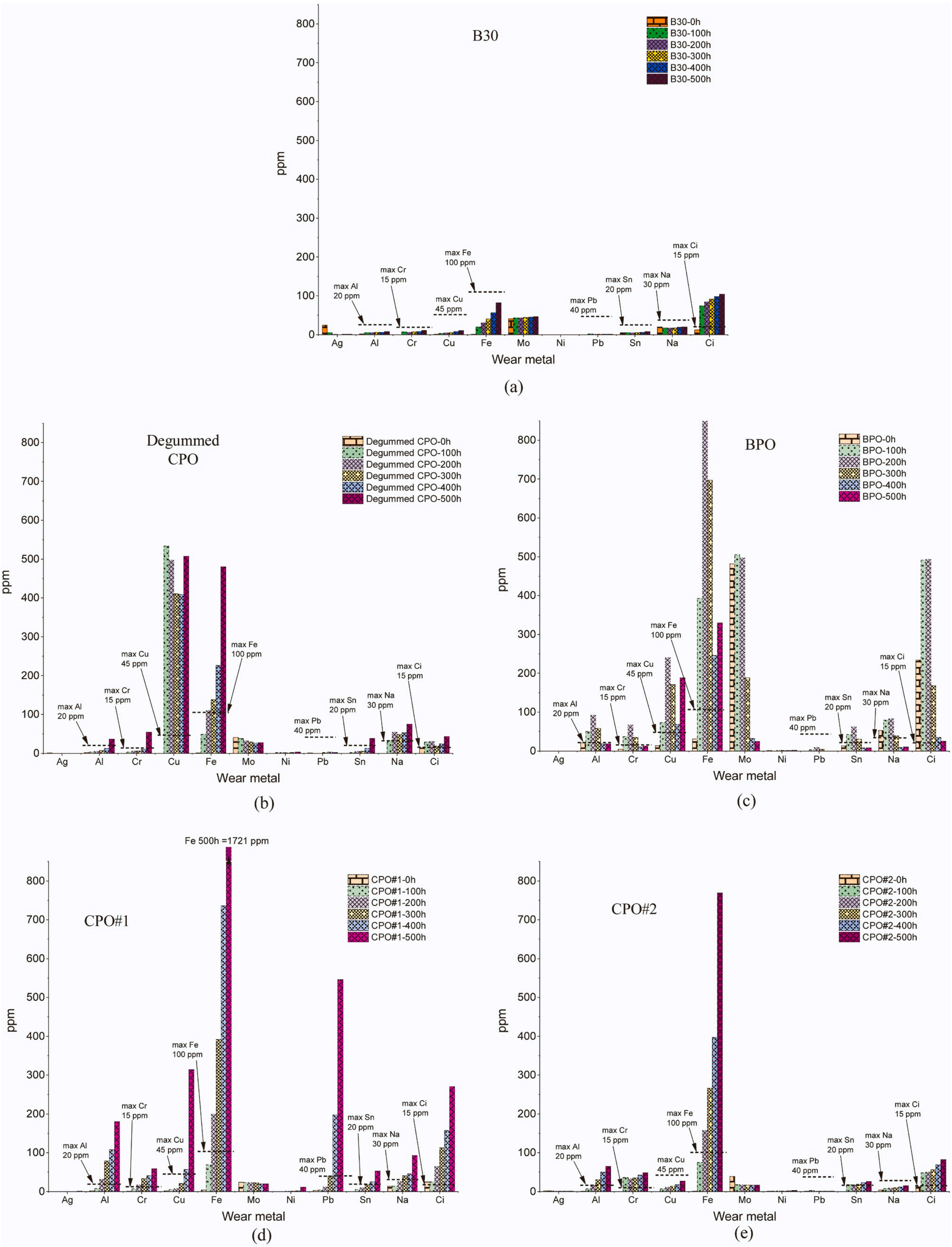


Fig. 12. Wear element on the engine oil when the engine fueled by (a) B30; (b) Degumming CPO; (c) BPO; (d) CPO#1; (e) CPO#2.

Table 8
The consumption of biofuels, electricity, and filters during the 500 operational hours.

Descriptions	B30	Degummed CPO	CPO#1	BPO	CPO#2
- Volume (L)	2400.9	3576.4	2949.0	2920.0	2919.0
- Engine filter (units)	1	53	14	13	12
- Racor filter (unit)	-	8	9	6	6
- Electricity for the heating system (kWh)	-	672	770	709	719

Table 9
The sensitivity analysis of CPO and MFO prices on the percentages of diesel power plants using CPO.

CPO price decreases	MFO price increases				
	0%	20%	30%	50%	70%
0%	0.00% Scenario 1	0.00% Scenario 2	0.00% Scenario 3	0.00% Scenario 4	14.29% Scenario 5
30%	0.00% Scenario 6	6.53% Scenario 7	49.21% Scenario 8	53.97% Scenario 9	53.97% Scenario 10
40%	6.53% Scenario 11	53.97% Scenario 12	53.97% Scenario 13	53.97% Scenario 14	53.97% Scenario 15
50%	53.97% Scenario 16	53.97% Scenario 17	53.97% Scenario 18	53.97% Scenario 19	53.97% Scenario 20
70%	53.97% Scenario 21	53.97% Scenario 22	61.90% Scenario 23	100.00% Scenario 24	100.00% Scenario 25

$$\sum_{j=1}^{n} x_{ij} \leq a_i, \nabla i = 1, \ldots, m \tag{3}$$

Where c, b, and a = the distance, fuel volume requirement, and the CPO production capacity. Also, x = the CPO volume transported from a CPO mill *i* to a diesel power plant *j*.

The next step was to calculate the fuel costs by considering the transportation and energy prices as follows,

$$CPO\ fuel\ cost = \sum (CPO\ price + Transportation\ cost\ )x\ CPO\ Volume) \tag{4}$$

$$B30\ fuel\ cost = \sum (B30\ price\ x\ B30\ Volume) \tag{5}$$

The optimization process was continuously performed for different CPO and B30 prices through the sensitivity analysis of the prices on the supply chain network. The required B30 volume referred to the unpublished 2019 data from the Directorate General of Electricity–the Ministry of Energy and Mineral Resources. The CPO requirements were calculated by using the B30 volume data and the operational tests results. Other data used for the analysis was the average CPO price in April 2021 (i.e., US$ 73 ¢/kg or US$ 67 ¢/liter) from DGNREEC (DGNREEC, 2021), regional marine fuel oil (MFO) prices from PLN (PLN, 2020), and the maximum CPO transportation costs between regions as regulated by MEMR (MEMR, 2020). The MFO price was used because the first phase of the plan was to use the CPO on MFO-fueled diesel power plants.

3. Results and discussions

3.1. Performance analysis

The test results in Fig. 4 showed a negative relationship between the SFC and the load. The lowest SFC was observed at 80% and 100% loads. The combustion efficiency was the highest at these loads because B30

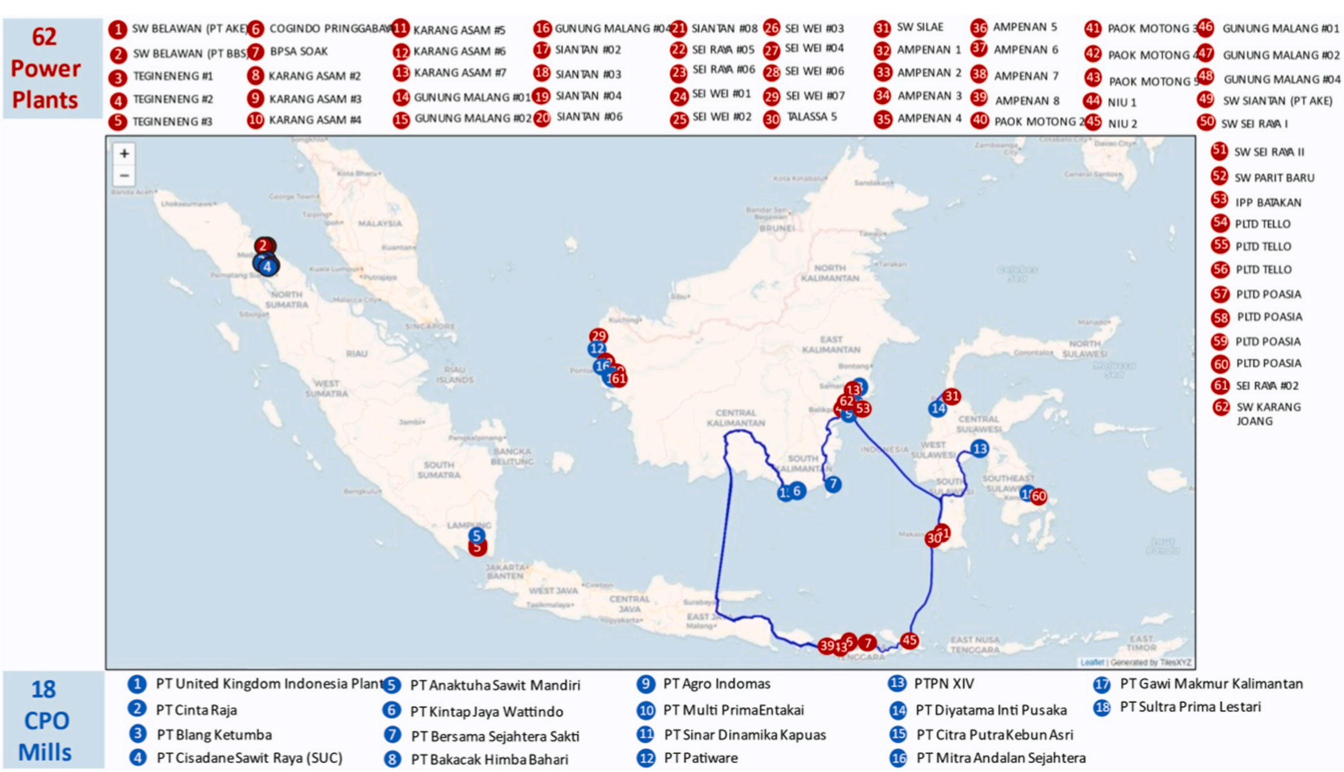


Fig. 13. Transportation route for scenarios 24 and 25.

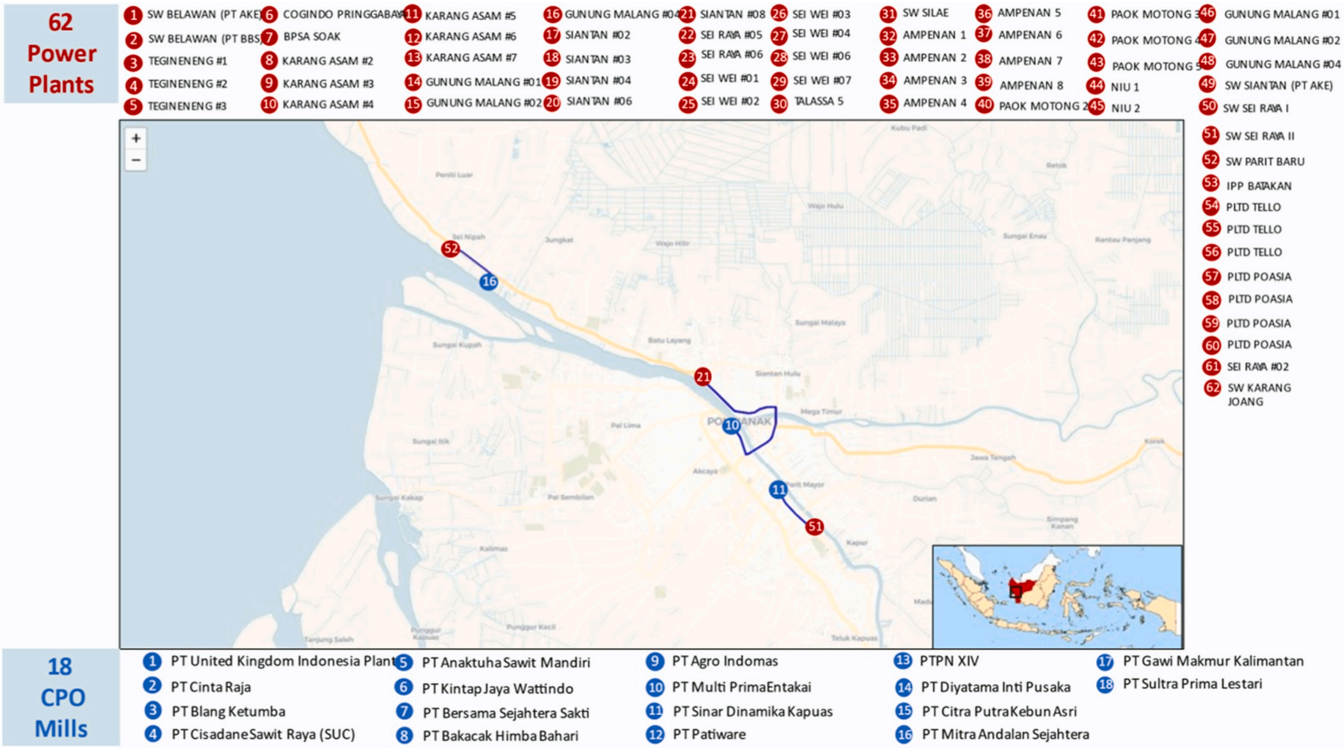


Fig. 14. The comprehensive transportation route in West Kalimantan Province for scenarios 24 and 25.

quality was consistent with the engine specification at a 100% electricity load of 5.6 L/h. At 25% load, SFC at B30 usages was 22.2% lower than degummed CPO usages and 20% lower than BPO and CPO usages. SFC from the B30 usage test is the most efficient SFC because of its calorific value of 43.1 kJ/g. This value was 10% higher than degummed CPO, BPO, and CPO. Additionally, tests of all fuels at 75% load or higher improved SFC and diminished SFC differences. This trend is similar to previous studies (PLN, 2019; De Almeida et al., 2002). SFCs measured by PLN (PLN, 2015) using B20 (and CPO) were 0.2829 (0.2968) liter/kWh and 0.3350 (0.3389) liter/kWh at 100% and 50% loads, respectively. In comparison, Almeida et al. (2002) obtained SFCs from HSD (and CPO) usage tests for 0.29 (0.31) liter/kWh and 0.43 (0.47) liter/kWh at 100% and 25% loads, respectively. The higher SFC, lower calorific value, and increased viscosity of biodiesel lead to a lower brake thermal efficiency (BTE) compared to HSD (Atabani et al., 2013).

Higher load increased NOx emissions, as shown in Fig. 5. The B30 usage tests at the 50% and 100% loads emitted NOx emissions at 791 mg/Nm^3 and 985 mg/Nm^3, respectively. In contrast, the tests of degummed CPO, BPO, and CPO usages released lower NOx emissions. This is because biofuels have a lower calorific value and ignition delay than B30. Moreover, the water content in degummed CPO, BPO, and CPO chilled the combustion chamber, reducing the emitted NOx more than that on the B30 usage test. The factor causing the NOx formation still needs to be clarified to explain (Varatharajan and Cheralathan, 2012). However, related to each fuel property used in this study, that can be seen in Table 3, and also from several conclusions from research conducted before by McCormick et al. (2001). Wyatt et al. (2005), B et al. (2006), Alptekin and Canakci (2008). that the number of iodine value, viscous fuel, and fuel density affect the combustion and emission, especially NOx emission. The unsaturated fatty acid molecule has a high bulk modulus or low compressibility, which affects the pressure in the injection pump; besides, because of the fuel density, that result in the injection time. Added the fuel density properties that affect the fuel spray characteristic, as shown in Fig. 2. However, all of the fuel formations above also effects depend on combustion temperature (Varatharajan and Cheralathan, 2012; Reksowardojo et al., 2018). The result

Fig. A1. The initial condition of skirt piston and top piston.

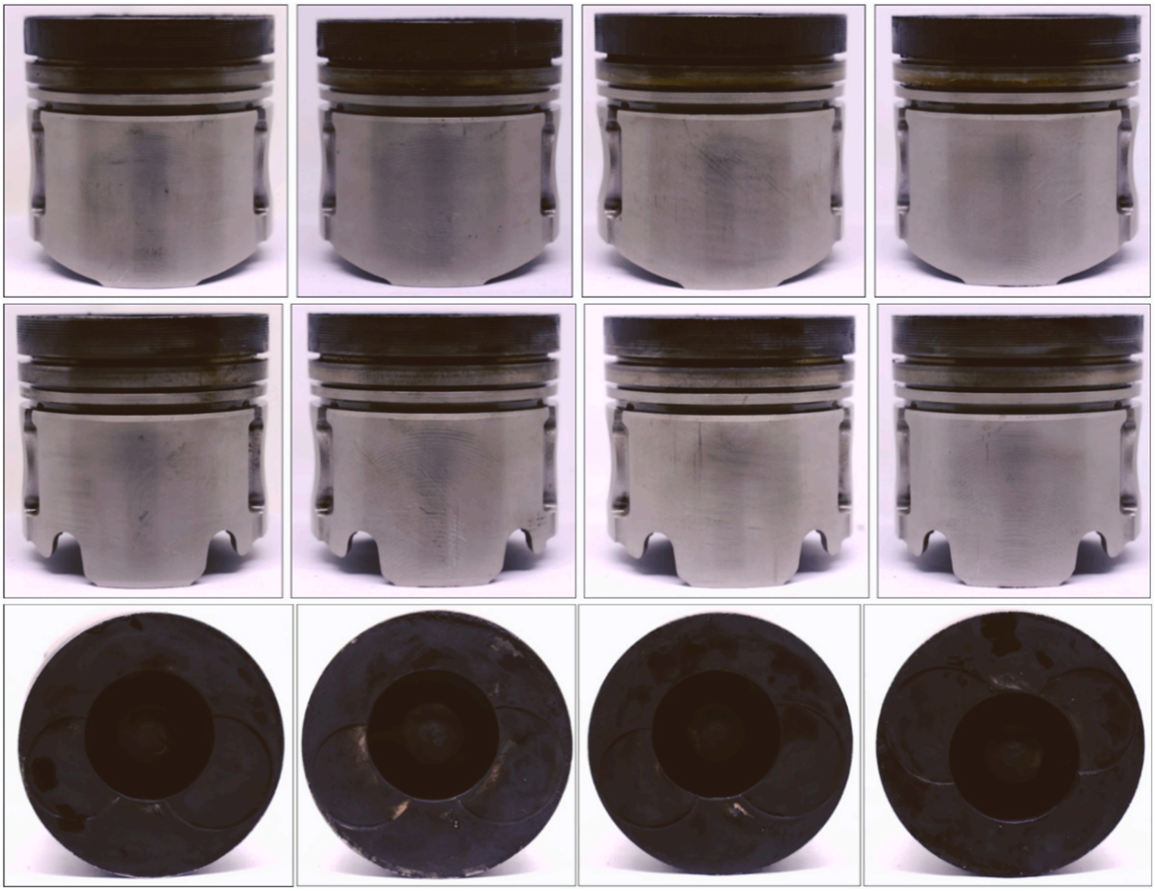


Fig. A2. The condition of skirt piston and top piston of the B30 engine after 500 operational hours.

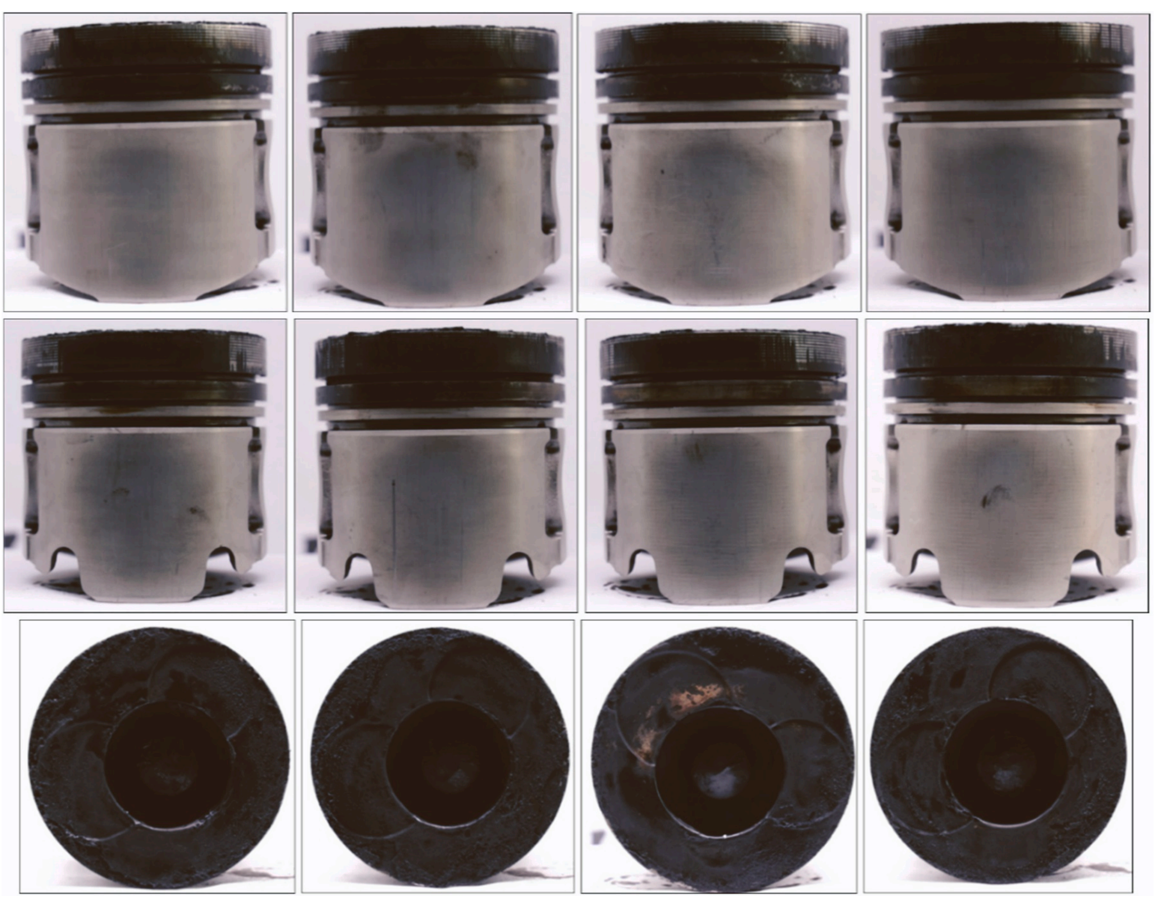


Fig. A3. The condition of skirt piston and top piston of the degummed CPO engine after 500 operational hours.

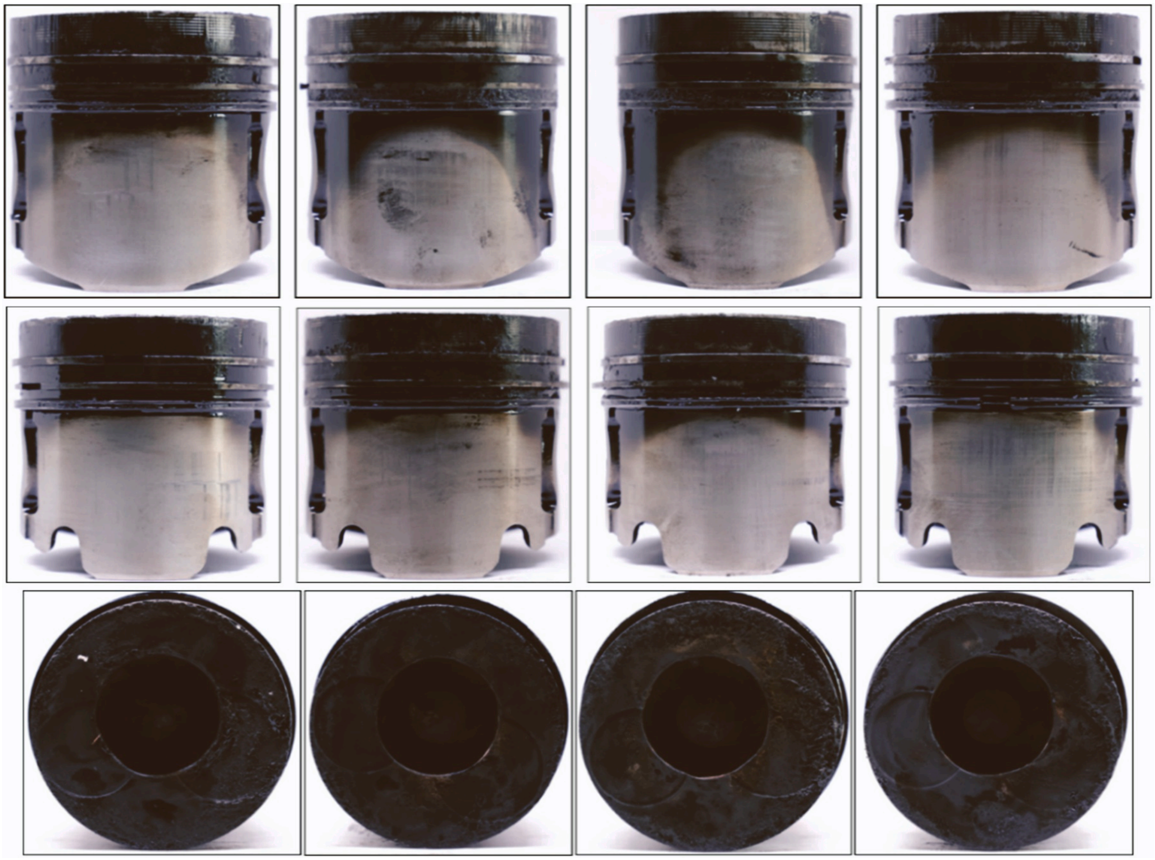


Fig. A4. The condition of skirt piston and top piston of the CPO#1 engine after 500 operational hours.

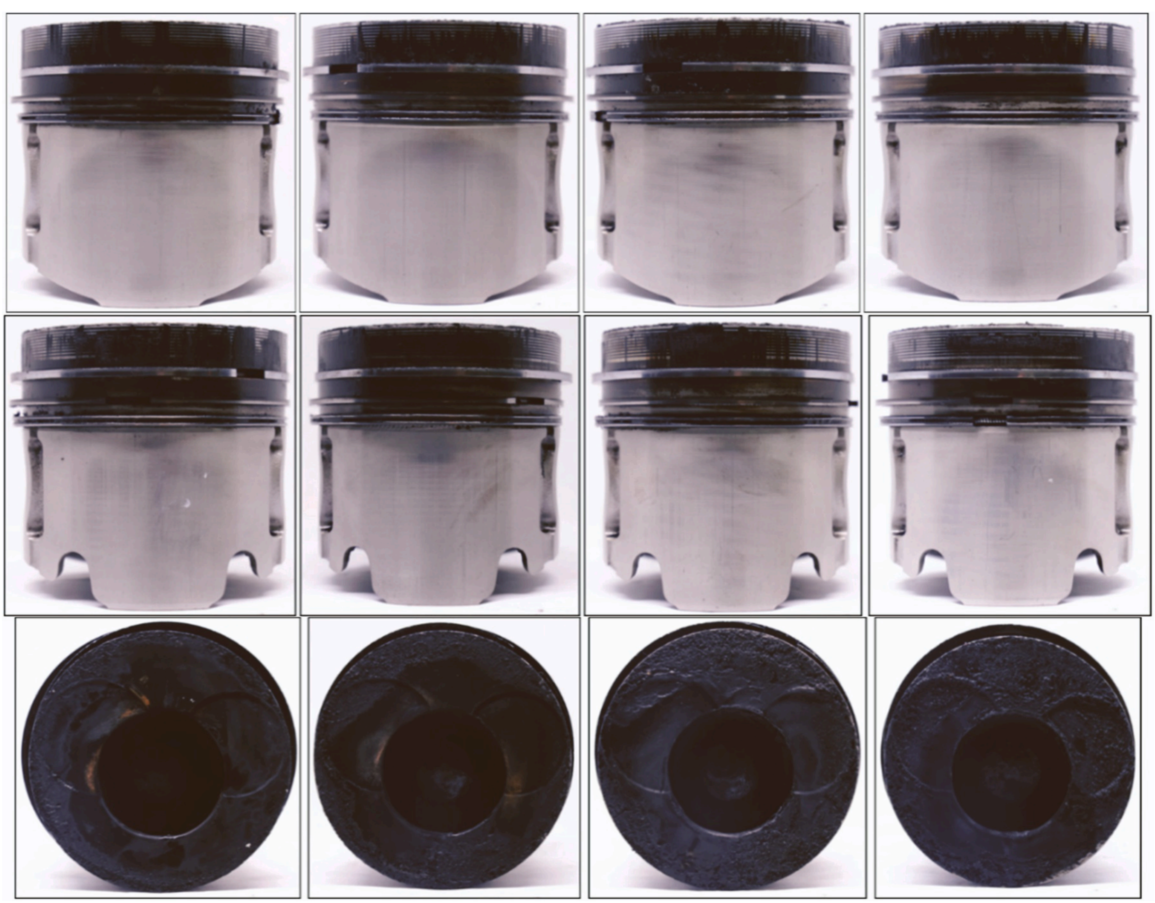


Fig. A5. The condition of skirt piston and top piston of the BPO engine after 500 operational hours.

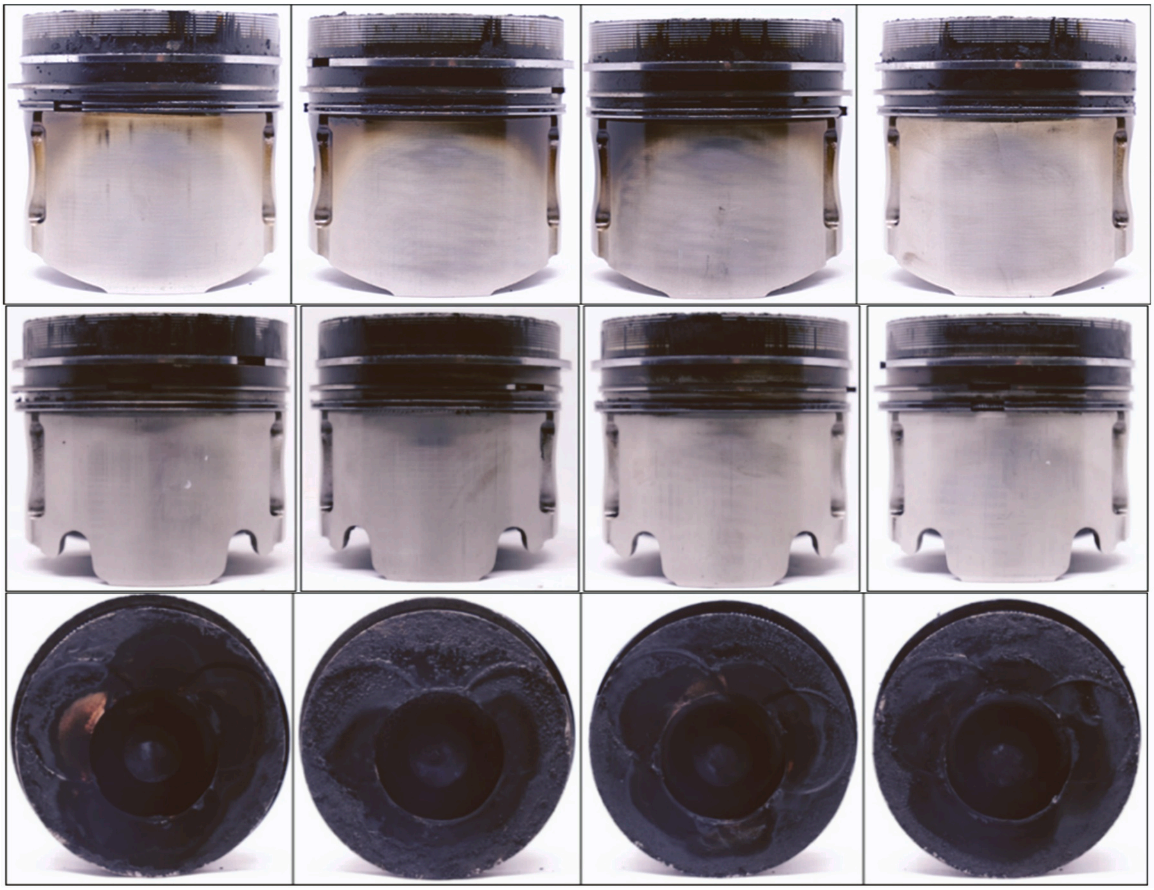


Fig. A6. The condition of skirt piston and top piston of CPO#2 engine after 500 operational hours.

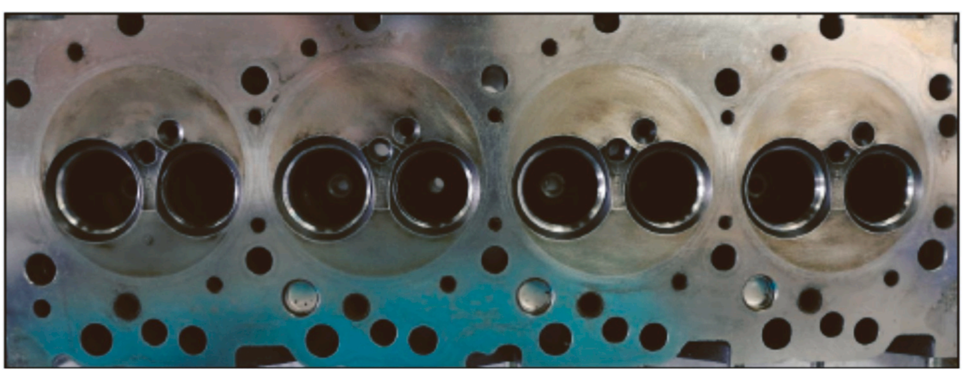


Fig. A7. The initial condition of cylinder head.

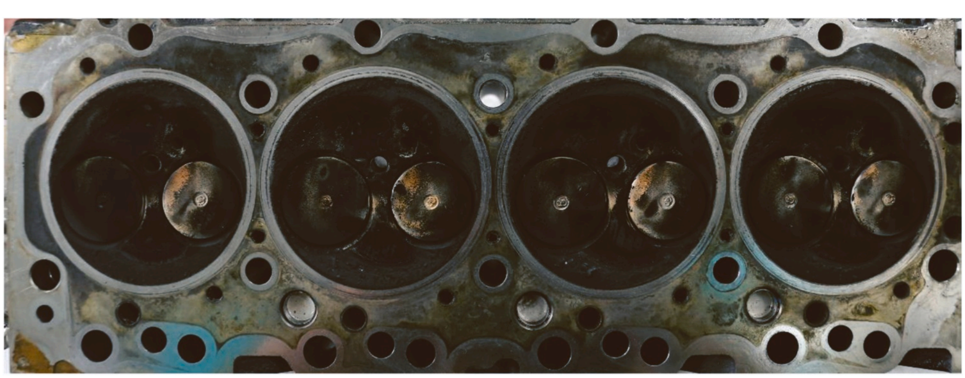


Fig. A8. The condition of cylinder head of the B30 engine after 500 operational hours.

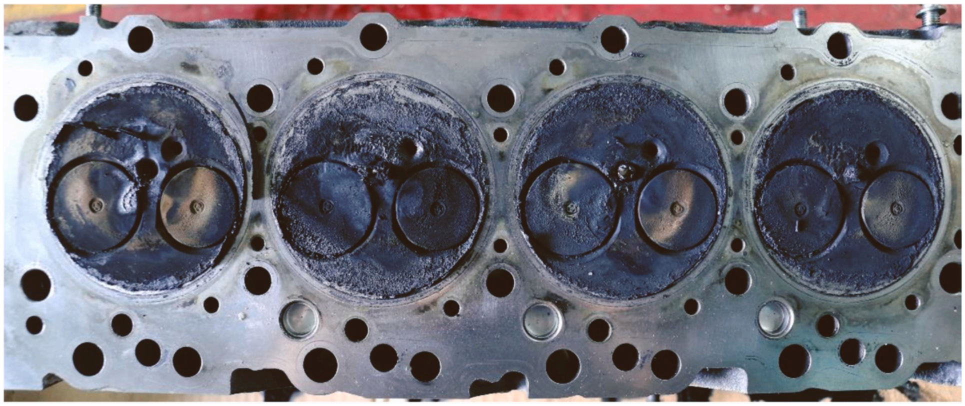


Fig. A9. The condition of cylinder head of the degummed CPO engine after 500 operational hours.

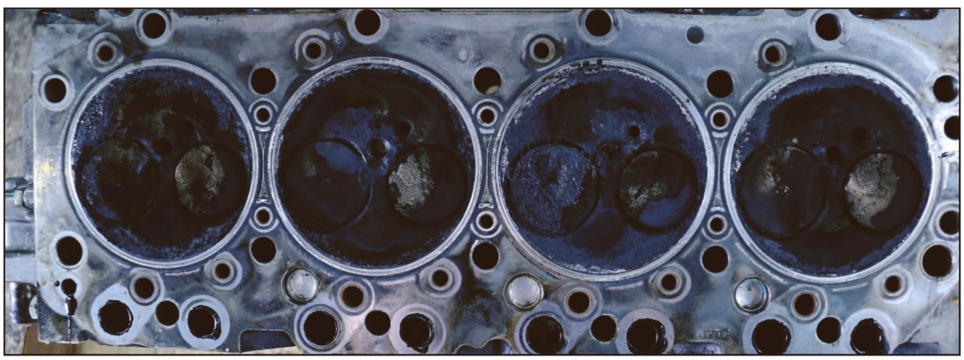


Fig. A10. The condition of cylinder head of the CPO#1 engine after 500 operational hours.

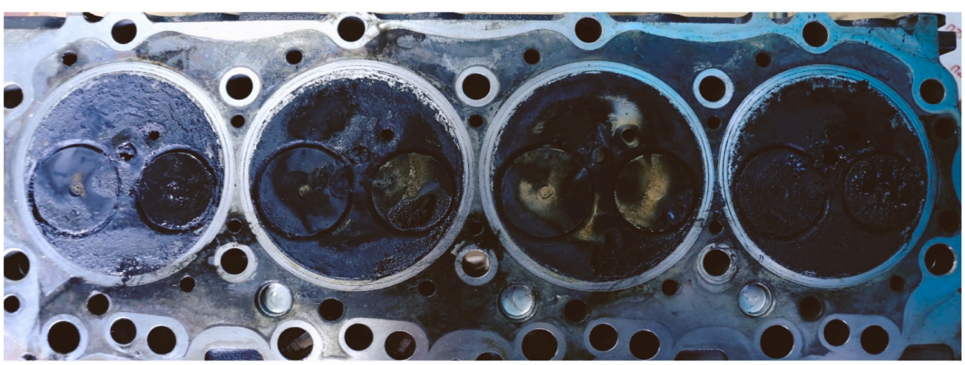


Fig. A11. The condition of cylinder head of the BPO engine after 500 operational hours.

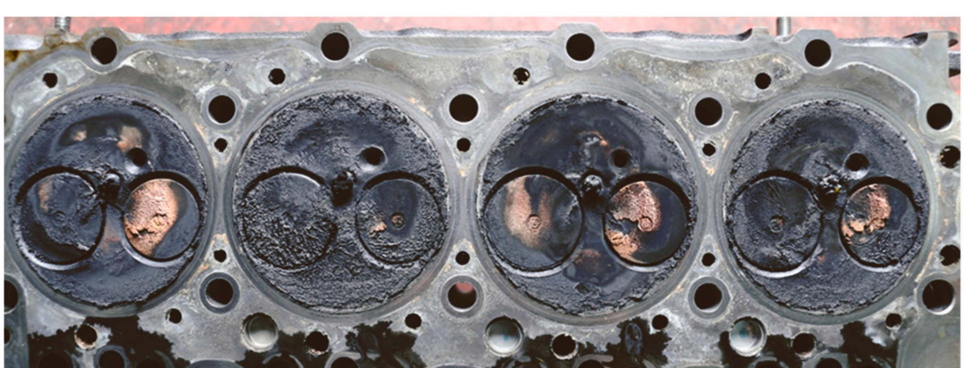


Fig. A12. The condition of cylinder head of the CPO#2 engine after 500 operational hours.

Fig. A13. The initial condition of intake valve and exhaust valve.

of the NOx formation supported several previous studies (De Almeida et al., 2002; Varatharajan and Cheralathan, 2012; Reksowardojo et al., 2018), but contradicted the PLN test results obtaining 25.6% higher NOx emissions when using CPO compared to when using B20 (Cahyo et al., 2021a; PLN, 2019).x.

Fig. 6 compares the CO emissions of diesel power plants using the analyzed biofuels. CPO, BPO, and degummed CPO tests emitted higher CO emissions than B30 because of their viscosity and density of these fuel higher than B30 so causing poor air-fuel mixing (Abedin et al., 2014; Mofijur et al., 2014). The high viscosity also results the improper spraying in the injector, making the fuel unable to atomize (Sisi et al., 2020; Song et al., 2015), making the fuel challenging to reach for combustion, and causing poor air-fuel mixing where the fuel contains higher molecular oxygen than B30. On the contrary, the higher viscosity of biofuel than diesel fuel can potentially reduce fuel leakage around the injector needle, which is required for lubrication (El-Adawy et al., 2013). This resulted in a fuel-rich mixture but no oxygen, cutting short or delaying the fuel to combustion resulting in incomplete combustion also producing more CO emissions. The subsequent impact is higher exhaust gases, including CO. Previous studies reported a similar finding (De Almeida et al., 2002; Lim et al., 2002), and only PLN's study had a contradicting finding (Cahyo et al., 2021a; PLN, 2019). Moreover, PLN reported suspicious stable CO emissions when the load varied from 50% to 100%. CO emissions using CPO were 143.2 ppm and 144.3 ppm at 50% and 100% loads respectively. Meanwhile, emissions using B20 were 159.2 ppm and 157.6 ppm at 50% and 100% loads.

Fig. 7 compares CO_2 emissions emitted by tests of all biofuel types. The test of B30 usages at 50% and 100% loads emitted CO_2 emissions for 0.63 and 0.71 kg/kWh, respectively. The CO_2 emissions emitted by the tests of degummed CPO, BPO, and CPO usages were higher for 0.71 – 0.89 kg/kWh and 0.65 – 0.68 kg/kWh at 50% and 100% loads, supporting De Almeida et al. (2002). The higher CO_2 emissions were caused by higher oxygen contents in degummed CPO, BPO, and CPO. From Fig. 4, it can be seen that the SFC values, or fuel consumption, for diesel engines fueled by degummed CPO, BPO, CPO#1, and CPO#2 tend to be higher than those for B30, which confirms that the extra oxygen molecular content for these four fuels is more elevated, especially in load 25%, 50%, and 80%. The gas analyzer encountered an error during data retrieval at 100% load when measuring the value of NOx and CO in the fuel type of CPO#1 (Fig. 5 and Fig. 6); however, the operational test must continue uninterrupted and cannot be repeated. As a result, the erroneous data is not displayed in the Figures.

Table 6 summarizes the experimental results on this study which is could be compare with previous studies that summarizes in Table 1, where generally the result of the exhaust gas from engine diesel when fueled by preheated CPO that conduct in this study similar with the result from De Almeida et al. (2002).

3.2. The Rating Analysis

The piston rating included the observations of deposits and scratches in various areas. Figs A.1 to A.6 in the Appendix show the conditions of the skirt and top piston of engines used in the experiments. The skirt and top piston conditions had no significant visual difference when using B30, degummed CPO, and BPO. Furthermore, an average numerical

Fig. A14. The condition of intake valve and exhaust valve of the B30 engine after 500 operational hours.

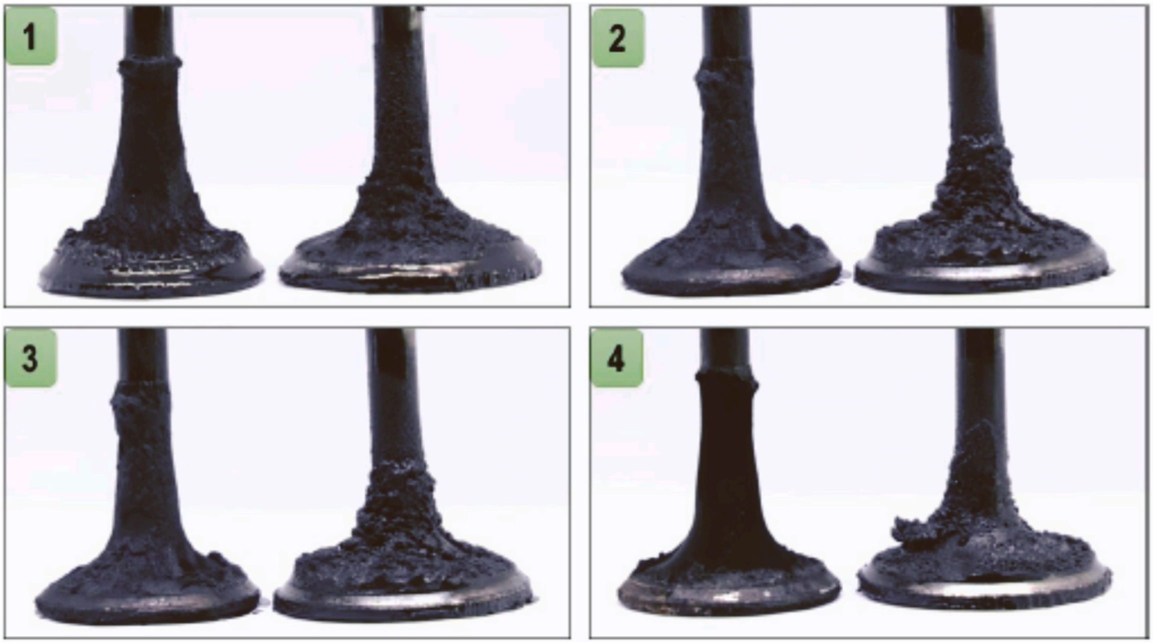


Fig. A15. The condition of intake valve and exhaust valve of the degummed CPO engine after 500 operational hours.

value of 1–2 indicated the presence of scratches on the crown and skirt areas after 500 h of operation testing with various biofuels. The pistons of the CPO#1 and CPO#2 engines had a varnish color change due to the mixture of fuel with lubricant. In comparison, the piston underside on the B30 degummed CPO and BPO test engines had a reasonable varnish color change. The piston undersides on the CPO#1 and CPO#2 engines transformed to a dark color due to the abnormal lubricant burning.

The rings of the B30 and CPO#2 engines were firmly attached to the pistons without sticking, hardening, or easily breaking. The abnormal sticking condition was observed on the 1st compression ring of the degummed CPO and BPO engines. The B30 test engine piston had less deposit formation, of which 55% of the deposits had a thickness of less than 0.05 mm, as shown in Table 7. In contrast, the pistons of diesel engines using Degummed CPO, BPO, and CPO#2 fuel, visually still looks good, but the top surface of the piston is covered flat by 50% deposits with a thickness of between 0.2 and 0.4 mm. The piston deposit thickness of the CPO#1 engine was approximately between 0.2 and 0.4 mm (60% of the deposits) and 0.1–0.2 mm (30%). Furthermore, the pistons of test engines using B30 degummed CPO, CPO#1, BPO, and CPO#2 had similar wear in diameter area of piston at approximately 0.01 mm. The piston diameter of all engines did not significantly change after the test. The changes complied with the standard limits of the Isuzu 4JB1 test engine.

Deposits also occurred on compression and oil rings. The clearance

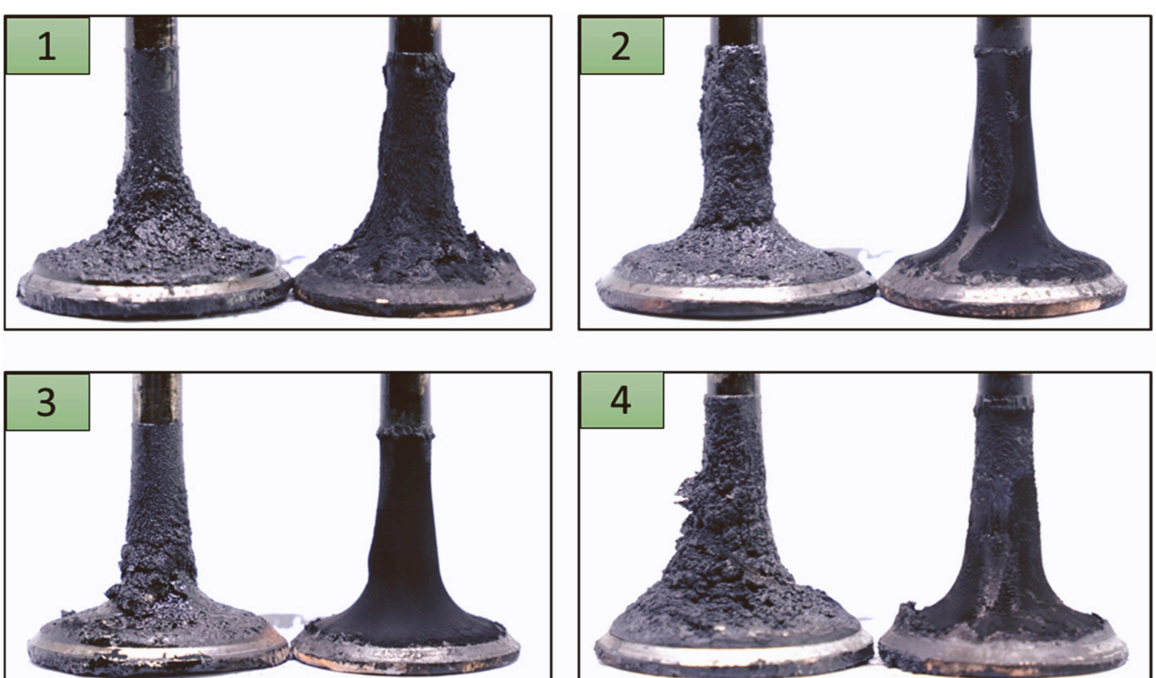


Fig. A16. The condition of intake valve and exhaust valve of the CPO#1 engine after 500 operational hours.

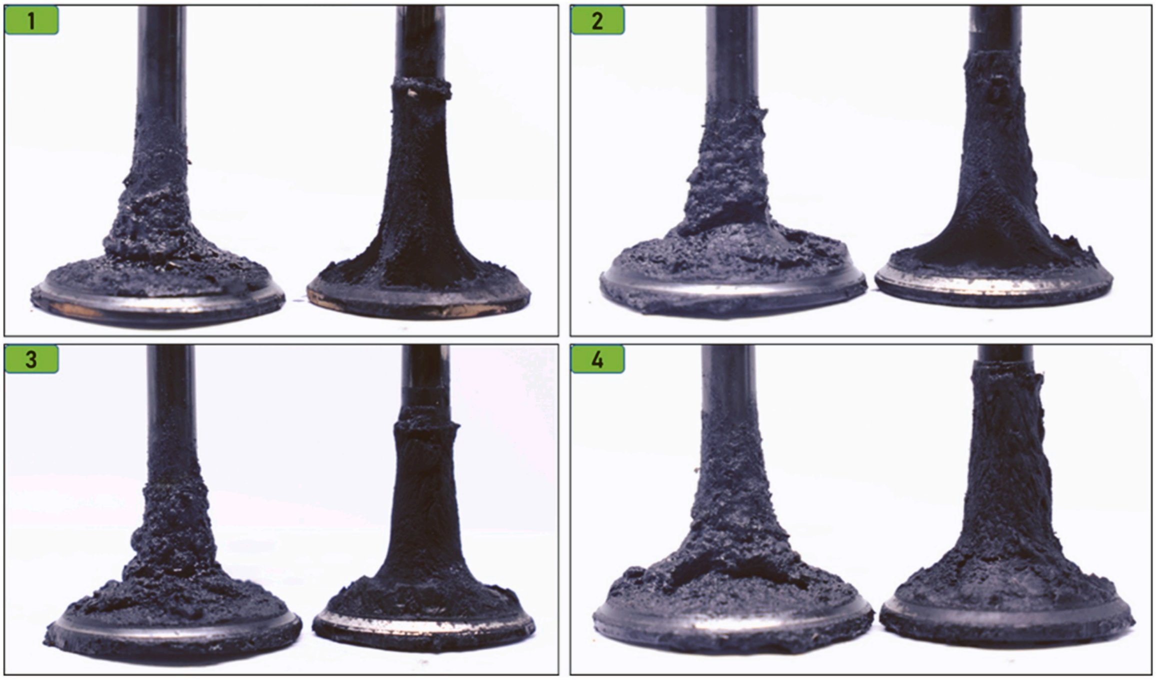


Fig. A17. The condition of intake valve and exhaust valve of the BPO engine after 500 operational hours.

on the compression rings 1 and 2, as well as the oil ring on the B30, degummed CPO, BPO, and CPO#2 engines, met the factory standard of 1.5 mm. Meanwhile, the ring clearance on the CPO#1 engine did not move in the groove locations due to high deposit accumulation in ring areas 1, 2 and 3. The ring gaps of the B30, degummed CPO, BPO, and CPO#2 engines complied with the factory standard. However, the oil ring 3 of these engines exceeded the standard. The ring gap on the CPO#1 test engine was not measured due to the sticking condition from high deposits in ring areas 1, 2, and 3. The measuring data of the clearence ring piston, available in Table A1, A2.

The cylinder liner was eroded due to the friction between it and the piston ring. The erosion was estimated by measuring the liner's inner diameter using a cylinder bore gauge at a depth of 10 mm, 65 mm, and 120 mm from the diagonal position. The average wear values of the cylinder liner were 0.0065–0.0085 mm, 0.0071–0.0090 mm, 0.005–0.013 mm, 0.0065–0.0072 mm, and 0.01–0.013 for the B30, degummed CPO, BPO, CPO#1, and CPO#2 test engines, respectively. The wear values were still less than the factory standard limit of 0.04 mm.

Fig. 8 shows the merit rating and deposit weight on the cylinder head. The visual observations of the cylinder head are shown in Figs A.7 to A.12 in the Appendix. In Fig. 8, higher merit rating values mean lighter deposit mass. The cylinder head surfaces of degummed CPO, BPO, and CPO engines had thicker deposits than the B30. The merit

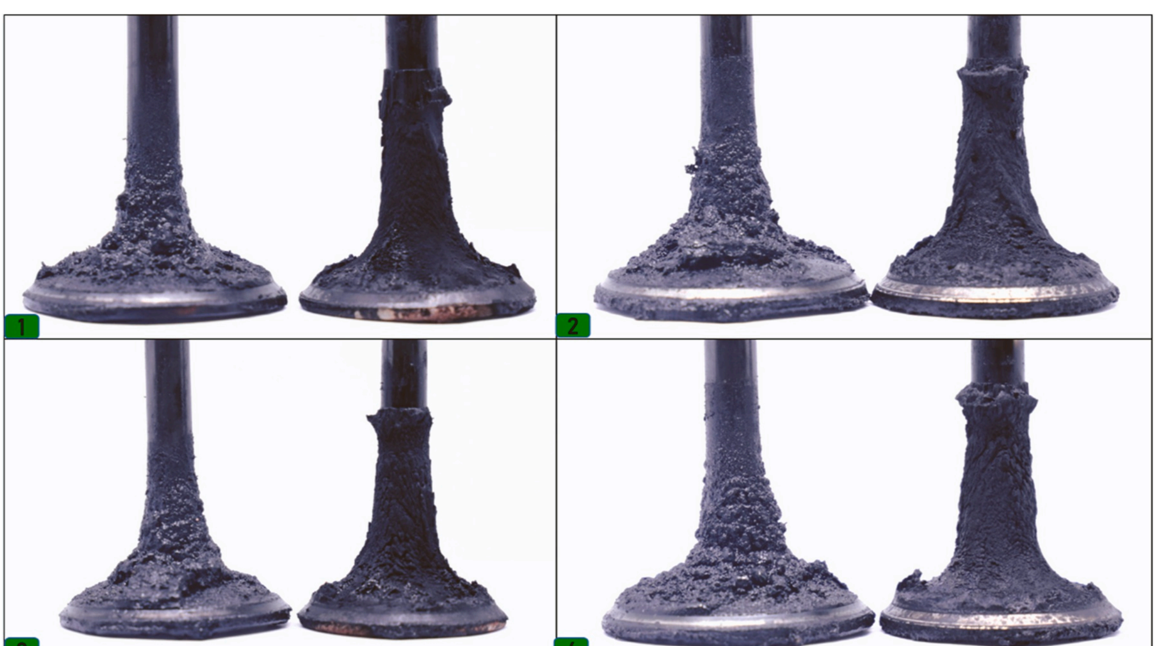


Fig. A18. The condition of intake valve and exhaust valve of the CPO#2 engine after 500 operational hours.

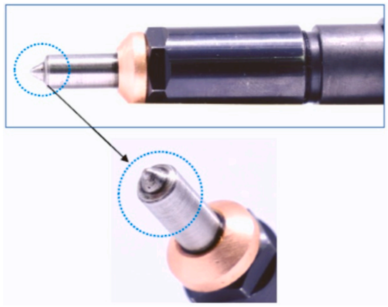


Fig. A19. The initial condition of injectors.

value for the B30 engine cylinder head was 8.55, with black carbon deposit thickness and weight of 0.05–0.15 mm and 0.32 g, respectively. Furthermore, the merit values for the cylinder head of the degummed CPO, BPO, and CPO#2 test engine were similar at 6.55. The deposit thickness and weight correspondingly for 0.15–0.45 mm and 3.00 g. The cylinder head of the CPO#1 engine had a merit value of 5.55 and a deposit distribution. It had a thickness of 0.20–0.60 mm and a weight of 3.00 g.

Figs. 9, 10 and A.13 to A.18 show the four intake and exhaust valves' rating results. In Fig. 9, engines using degummed CPO, BPO, and CPO had a higher deposit formation than the B30 engine. The results also showed that the deposit thickness on the intake valves of the B30 and other engines were approximately 0.1–0.15 and 0.2–0.4 mm, respectively. Moreover, Fig. 10 shows that the deposit weight of the B30 test engine was 0.65 g, lighter than those on the degummed CPO, BPO, CPO#1, CPO#2, which had 2.70 g, 2.25 g, 1.3 g, and 2.19 g, respectively. The injectors of all test engines had deposits covering the tip, as shown in Figs A.19 to A24. Deposits in the B30 test engine did not significantly interfere with the injector holes during the fogging process. In contrast, deposits on the other testing engines significantly covered injector tips, disrupting the fuel fogging process in the combustion chamber.

3.3. The oil dilution and wear metal

Fig. 11 (a) shows the Total Base Number, which is a number that indicates the ability of lubricating oil to absorb corrosive acids. As can be seen in Fig. 11 (a), the TBN value for D.CPO, BPO, CPO #1, and CPO#2 fuel is lower than the TBN B30 value, and this indicates that the lubricating ability of the lubricating oil decreases, resulting in corrosive wear or the formation of varnish, lumps, and deposits, where metal wear due to this phenomenon can be seen in Fig. 12.

Pentane insoluble consists of particles of soot from combustion, oxidation of lubricants, dust particles, and the wear and tear of engine components that occurs. At the same time, insoluble Toluene is the same as insoluble pentane but is not accompanied by insoluble (solid) oxidation results. It can be seen in Fig. 11. (b) and 11. (c), each of which is the value of insoluble Pentane and Insoluble Toluene, where the PI and TI values for engine lubricants that operate with D.CPO, BPO, CPO #1 fuel, CPO#2 value is higher than the PI and TI values of lubricating oil with B30 fuel. This shows that the condition of the lubricating oil with D.CPO, BPO, CPO #1, and CPO#2 fuel has undergone a higher oxidation process than the engine with B30 fuel.

The oil dilution test showed that the B30 engine oil had a constant water content of 0% vol. In contrast, the degummed CPO engine oil had a water content of 1.34% vol, which was higher than the required maximum value (i.e., 0.2% vol). The oil also contained metal (i.e., Al, Cr, Cu, Fe, and Sn) and contaminant (i.e., Na and Si) elements, which exceeded the permissible values, as can be seen from Fig. 12. The result of the engine oil monitoring in Fig. 11 and Fig. 12 shows that the CPO#1 was highly corrosive, subsequently causing the test machine to wear out rapidly. For instance, the degummed CPO engine oil had a higher metallic element than the B30 engine oil. Due to the differences in fuel quality, the CPO#2 engine oil was relatively better than that of CPO#1. For example, the Na, Cu, and Pb values of the CPO#1 and CPO#2 oils were above and below the maximum limits, respectively. A similar trend occurred for other metal content values, including Si, Al, Cr, Fe, and Sn. The effect of using BPO-type fuel on the quality of lubricating oil is better than the effect of lubricating oil quality when using CPO#2 fuel. It can be seen in Fig. 12 that the results of the TBN and Insoluble Content (PI and TI) tests for lubricating oil quality in BPO have a better value than CPO#2, even though the wear metal content (especially for Cu, Sn, Na, and Ci) in the lubricating oil at CPO#2 is less than the content in the lubricating oil at BPO.

Table 8 compares the consumptions of biofuel, electricity for the heating system, and filters during the operational test. Biofuel consumptions were 2.4, 3.6, 2.9, 2.9, and 2.9-kilo liters of B30, degummed CPO, CPO#1, BPO, and CPO#2, respectively. Experiments using degummed

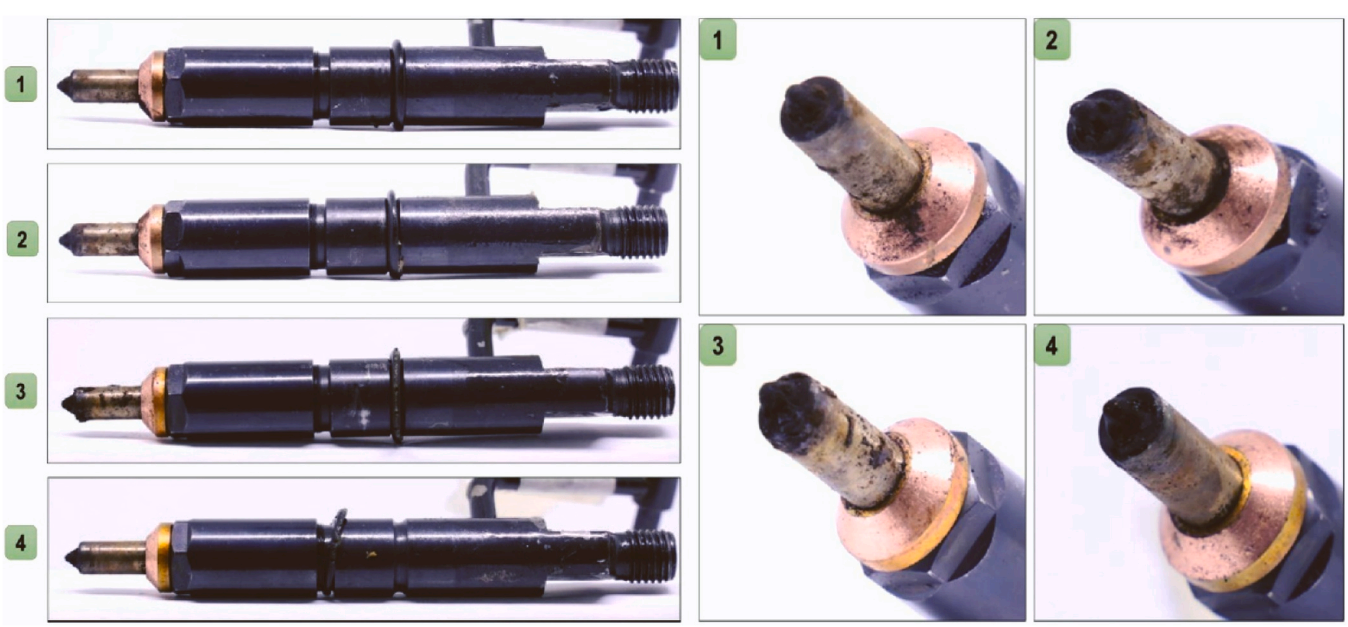


Fig. A20. The condition of injectors of the B30 engine after 500 operational hours.

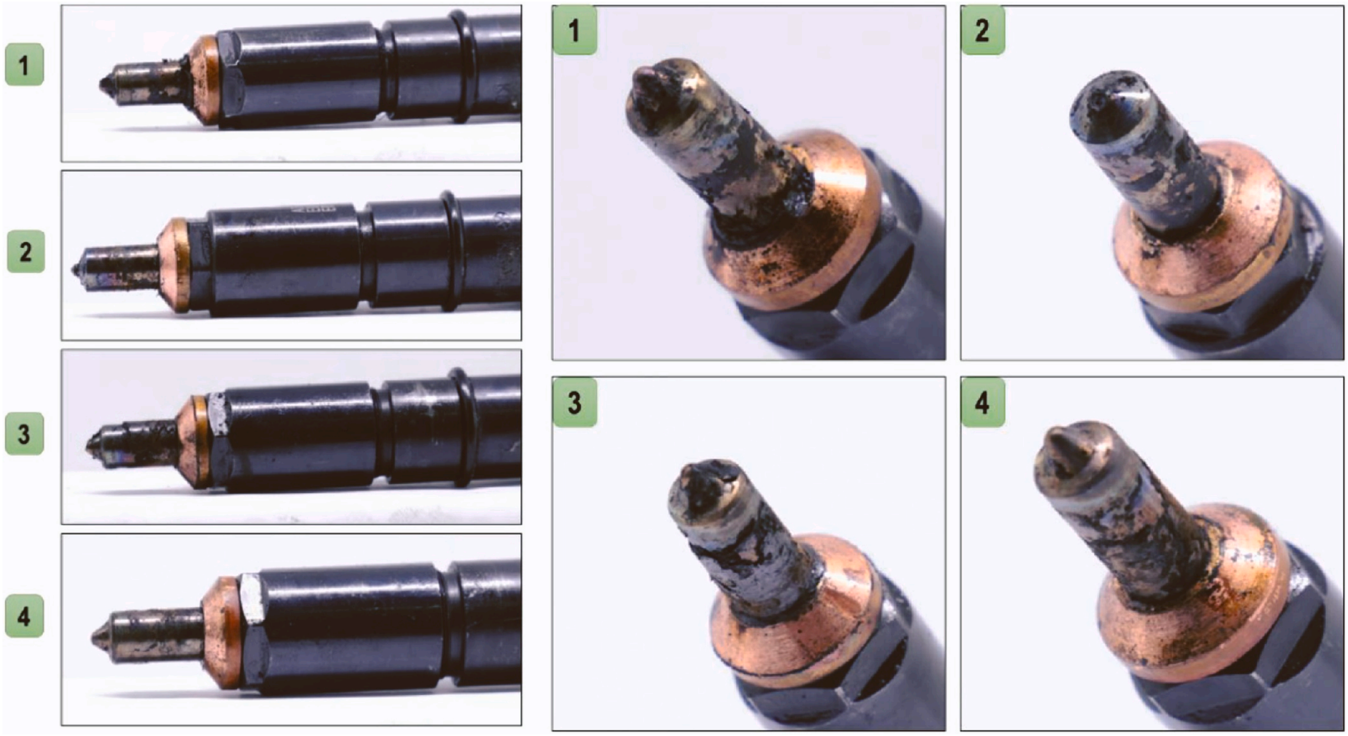


Fig. A21. The condition of injectors of the degummed CPO engine after 500 operational hours.

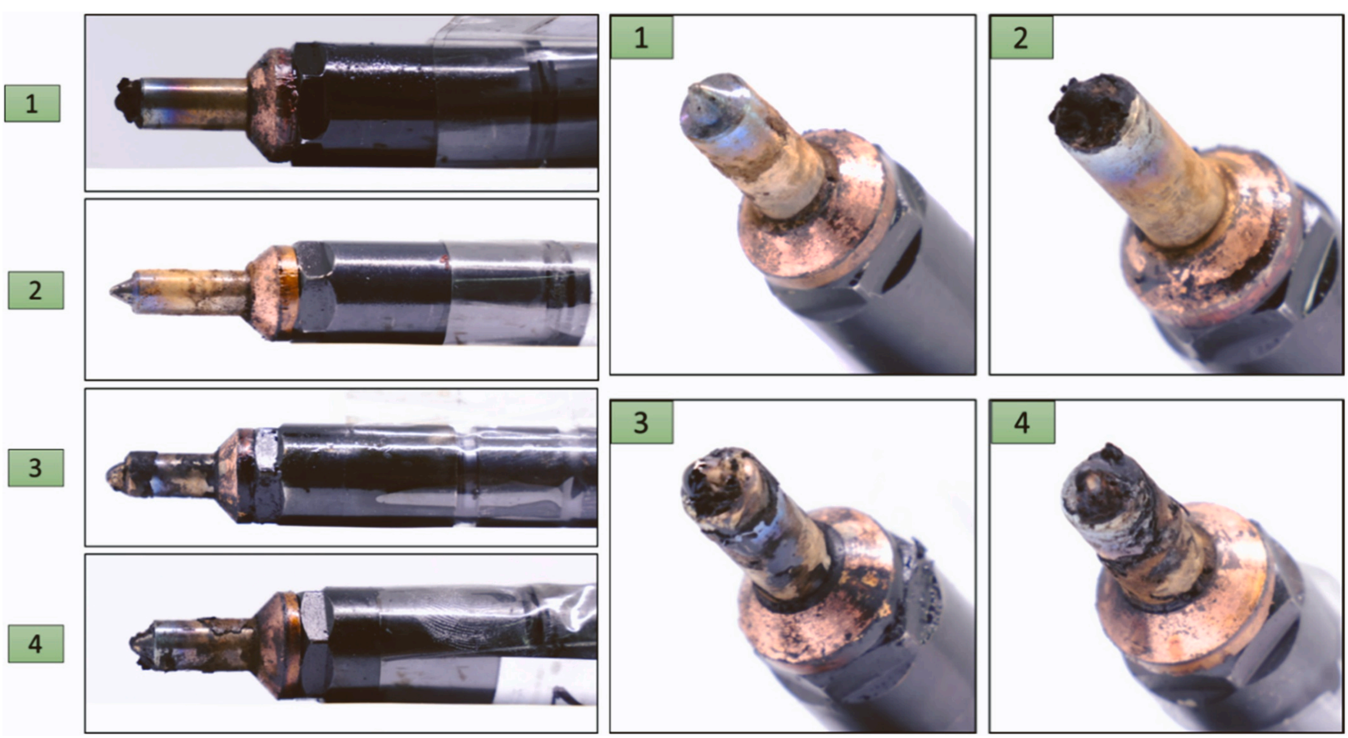


Fig. A22. The condition of injectors of the CPO#1 engine after 500 operational hours.

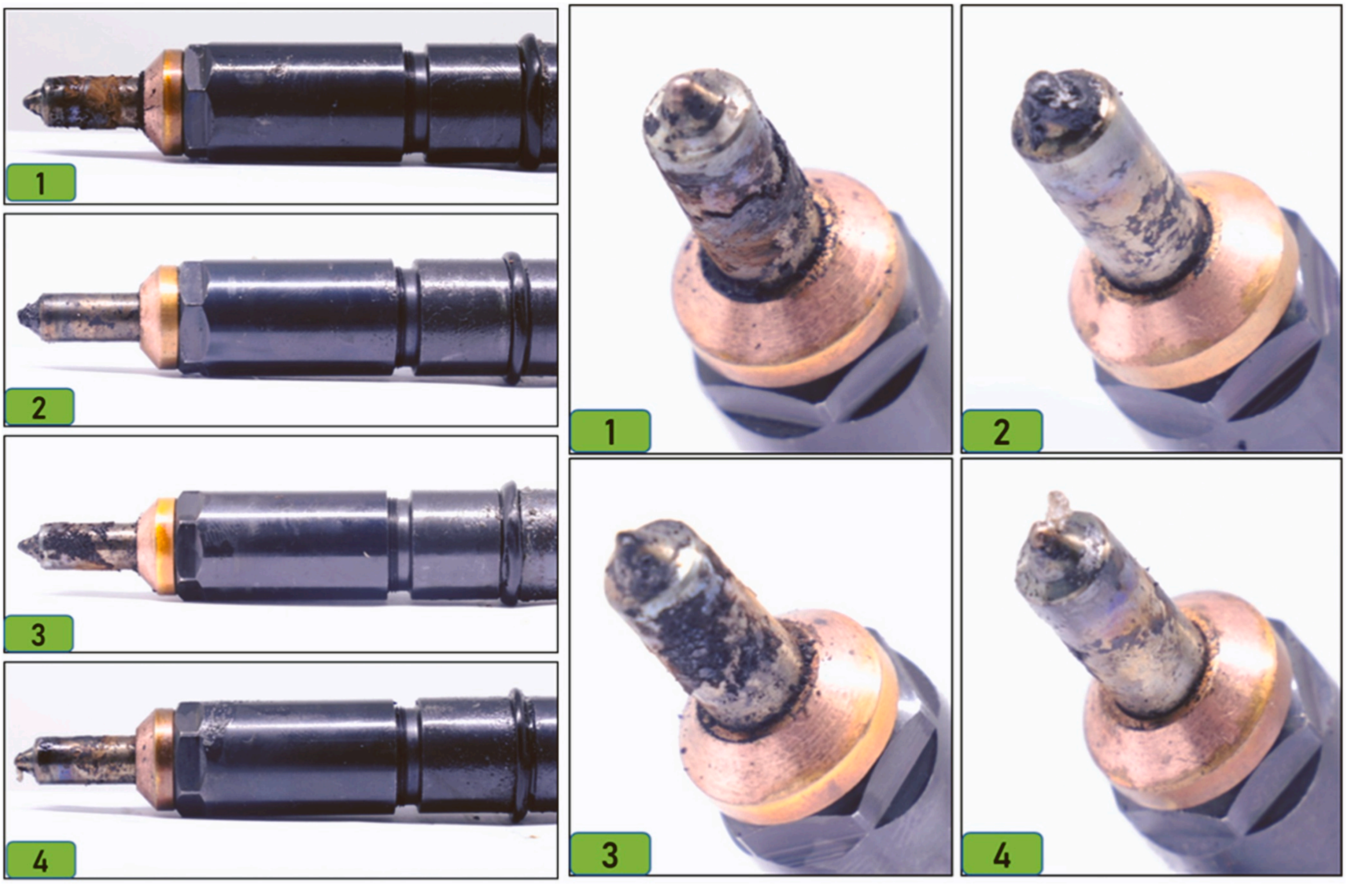


Fig. A23. The condition of injectors of the BPO engine after 500 operational hours.

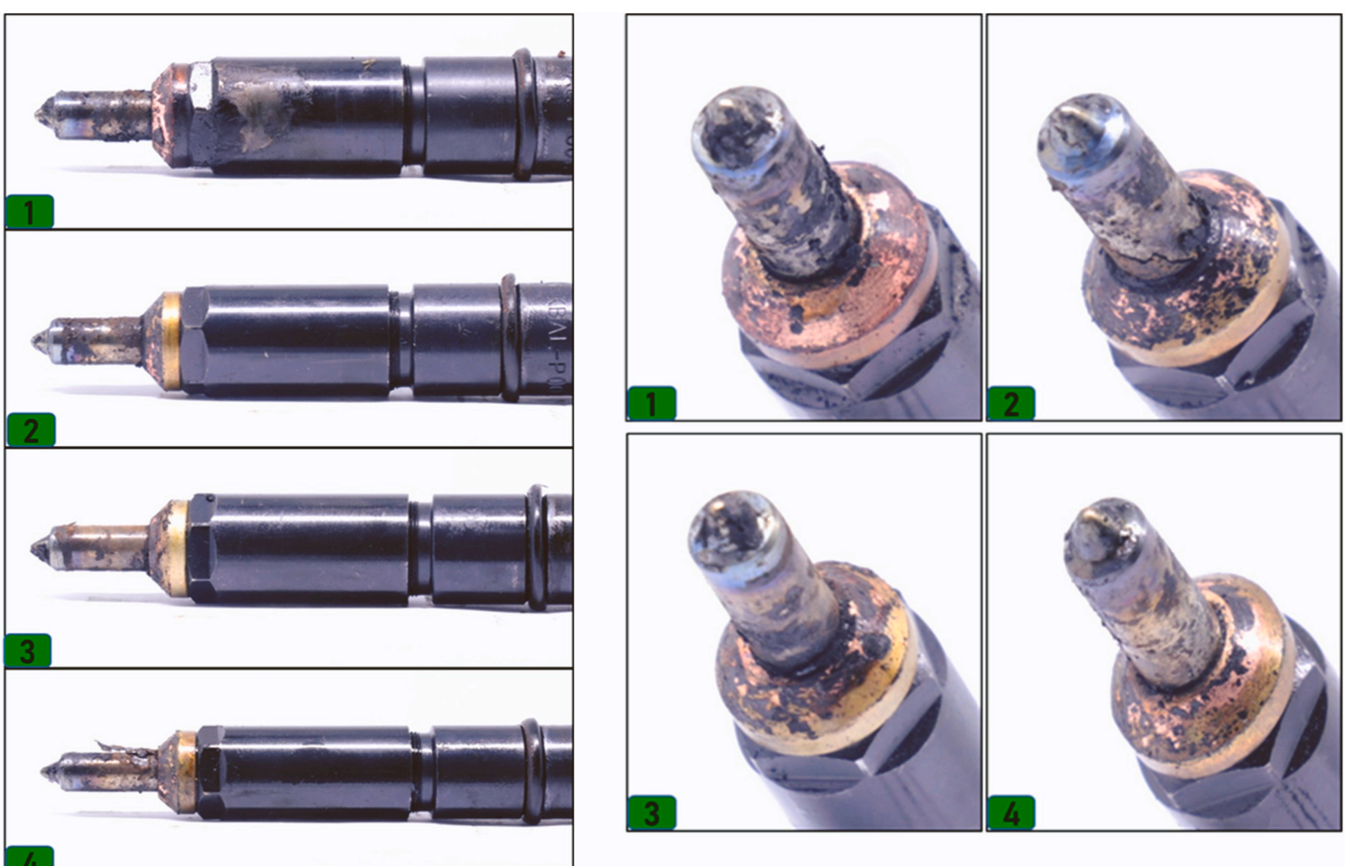


Fig. A24. The condition of injectors of the CPO#2 engine after 500 operational hours.

Table A1
Ring grove clearance measurement data.

Fuel	Ring reference	Maximum limit (mm)	*Ring grove clearance* (mm)			
			Cylinder 1	Cylinder 2	Cylinder 3	Cylinder 4
B30	A	1,5	< 0,05	< 0,05	< 0,05	< 0,05
	B	1,5	< 0,05	< 0,05	< 0,05	< 0,05
	C	1,5	< 0,05	< 0,05	< 0,05	< 0,05
Degummed CPO	A	1,5	< 0.05	0.06	0.09	0.07
	B	1,5	0.06	0.05	0.06	0.06
	C	1,5	< 0.05	< 0.05	< 0.05	< 0.05
CPO#1	A	1,5	*Sticking*			
	B	1,5	*Sticking*			
	C	1,5	*Sticking*			
BPO	A	1,5	1,0	1,0	1,0	1,0
	B	1,5	0,05	0,05	0,05	0,05
	C	1,5	< 0,05	< 0,05	< 0,05	< 0,05
CPO#2	A	1,5	0,05	0,05	0,05	0,05
	B	1,5	< 0,05	< 0,05	0,05	0,05
	C	1,5	0,05	0,05	< 0,05	< 0,05

CPO needed 53 units of engine filters. In contrast, in experiments using other biofuels, filter replacements were 14, 13, and 12 units for CPO#1, BPO, and CPO#2, respectively. The replacement of the Racor fuel filter was relatively similar between experiments using degummed CPO, CPO#1, BPO, and CPO#2. Additionally, electricity usage for the heating system varied between 672 and 770 kWh, with an average of 717.5 kWh.

3.4. Supply chain analysis

The higher SFC when using CPO will affect the fuel cost component. The price of the CPO should be lower than the HSD, due to investment costs and higher SFC. Simaremare et al. estimated the equivalence of CPO and HSD prices in order to obtain equal fuel cost in generating electricity (Simaremare et al., 2021). As a result, HSD prices between US $ 35–76.9 ¢ per liter were equivalent to CPO prices at US$ 23.6–62.4 ¢ per kg. Simaremare et al. concluded that the conversion of diesel power plants to CPO power plant was only feasible when the project lifespan and average HSD price were approximately 5 years and US$ 69.9 ¢/liter respectively (Simaremare et al., 2021). However, the conclusion was derived from a simple assumption of the CPO transportation cost from a mill to a diesel power plant for US$ 3.5 ¢/kg, regardless the distance. In the reality, the transportation cost is a significant cost component and, for that, the Indonesia government uses tariffs in MEMR (MEMR, 2020) as the maximum CPO transportation costs in various cities for calculating biofuel supply costs.

The supply chain analysis optimized the transportation costs of CPO from 790 mills to 62 diesel power plants using MFO. The sensitivity analysis combined the MFO price increase at 0%, 20%, 30%, 50%, and 70% with the decrease in CPO prices at 0%, 30%, 40%, 50%, and 60%. Table 9 shows that the business as usual (BaU) scenario or Scenario 1, for example, using the average price in 2021, indicated that no diesel power plant was feasible by using CPO. A similar occurrence was also observed when MFO price increased by less than 50% (Scenario 2–4) or CPO price decreased by less than 30% (Scenario 6). Approximately 14.29% of diesel power plants were feasible using CPO when MFO prices increased by 70% (Scenario 5). In addition, a 30% decrease and a 20% increase in CPO and MFO prices (Scenario 7) enabled better CPO utilization for 6.53% of the diesel power plants. Scenarios 24 and 25 were cases of 100% diesel power plants to use CPO, due to CPO and MFO prices decreasing and increasing at least 70% and 50%, respectively.

Fig. 13 shows the transportation route produced by the Google Collaboration for Scenarios 24 and 25. 18 mills supplied CPO requirements to 62 power plants. The diesel power plants in Sumatera, Kalimantan, and Sulawesi obtained CPO from the mills within the same province. The power plants in West Nusa Tenggara should procure CPO from other islands, which are Kalimantan and Sulawesi Islands. Based on the existing ship routes, the shipment of CPO from Kalimantan to West Nusa Tenggara should initially be performed through the East Java seaport, before using land transportation through Bali. The establishment of new ship routes and seaports will decrease the distance. In addition, zooming the map visualized the transportation route within a province, as shown in Fig. 14, where the distance between the diesel power plants and CPO mills in West Kalimantan was suggested.

Table A2
Ring gap measurement data.

Fuel	Ring reference	Maximum limit (mm)	*Ring gap* (mm)			
			Cylinder 1	*Cylinder* 2	*Cylinder* 3	*Cylinder* 4
B30	A	1,5	0,90	0,90	0,90	0,90
	B	1,5	0,45	0,45	0,45	0,45
	C	1,5	0,60	0,60	0,60	0,60
Degummed CPO	A	1,5	0,95	0,95	0,95	0,95
	B	1,5	0,55	0,55	0,55	0,55
	C	1,5	1,65	1,65	1,65	1,65
CPO#1	A	1,5	*Sticking*			
	B	1,5	*Sticking*			
	C	1,5	*Sticking*			
BPO	A	1,5	0,95	0,95	0,95	0,95
	B	1,5	0,55	0,55	0,55	0,55
	C	1,5	1,55	1,55	1,55	1,55
CPO#2	A	1,5	0,95	0,95	0,95	0,95
	B	1,5	0,55	0,55	0,55	0,55
	C	1,5	1,65	1,65	1,65	1,65

4. Conclusions

This study aimed to analyze the technical and economic feasibility of using CPO as a fuel in diesel power plants. The technical analysis was performed through the operational tests on five CPO-based biofuels, including B30, degummed CPO, industrial BPO, and two CPOs with different quality. The operational tests were conducted in four-stroke 20 kW diesel engines with the heating systems at 85 °C for 500 operational hours. Our performance analysis focused on the SFC, emissions, oil dilution, engine component rating, injection pump condition, and deposit evaluations. The SFC value when using B30 was in accordance with the diesel engine specifications (i.e., 6 liter /hours at the maximum load). This was 22.2% lower than the SFC of the degummed CPO and 20% lesser than CPO#1, CPO#2, and BPO. The skirt and top pistons of the B30 degummed CPO, and BPO engines did not have a significant visual difference. However, the CPO#1 and CPO#2 pistons had varnish color changes due to the fuel and lubricant mixture. The cylinder head surface of the degummed CPO, BPO, and CPO#2 engines had thicker deposits (0.15–0.45 mm with a weight of more than 3.00 g) than that of the B30 system (0.05–0.15 mm with a weight of 0.31 g). The deposit on the cylinder head surface of the CPO#1 engine was also thicker (0.20–0.60 mm with a weight of more than 3.00 g) due to its lowest quality. From the results of technical analysis, the most suitable type of CPO for replacing diesel fuel in the first power plant is Degummed CPO, but with additional treatment, such as replacement of lubricating oil and fuel filters with better quality or increased frequency of replacement.

According to the economic analysis, the feasibility was more sensitive to the changes in CPO prices, compared to the MFO costs. For example, a 50% CPO price reduction led to 53.97% of diesel power plants being more economical to use CPO. In contrast, no diesel power plant was economically feasible to use CPO when MFO price increased by 50%. The government should prioritize the conversions of diesel power plants in South, Central, and Southeast Sulawesi, as well as North Sumatra, NTB, and Lampung. The conversions of diesel power plants in these provinces were economically feasible when the MFO or CPO prices increased or decreased by 70 or 40%, respectively. Other provinces, especially Kalimantan, had lower MFO price (i.e., US$ 19.6 ¢/litre) than the average national MFO price (i.e., US$ 44.9 ¢/litre) in 2019 (PLN, 2020). Consequently, diesel power plants in Kalimantan were economically converted to use CPO only when the MFO and CPO prices increased and decreased by 50% and 70%, respectively.

CRediT authorship contribution statement

Arridina Susan Silitonga: Supervision, Writing – review & editing draft. **Yohanes Gunawan:** Conceptualization, Methodology, Investigation, Visualization, Data curation, Validation, Writing – review & editing draft. **Muhammad Indra al Irsyad:** Conceptualization, Writing – original, Visualization, Writing – review & editing draft. **Arfie Ikhsan Firmansyah:** Conceptualization, Methodology, Investigation, Writing – original, Data curation. **Nina Konitat Supriatna:** Conceptualization, Visualization, Data curation, Validation. **Khalif Ahadi:** Investigation, Visualization, Data curation, Validation. **Ikrar Adilla:** Investigation, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The data that has been used is confidential.

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Appendix

Rating Visual Observations

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