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Study of an Indirect Injection Diesel Engine Using Pure Coconut Oil, Pure Tamanu Oil and B-20 as Fuel for Smart Microgrid Applications. Part I: Laboratory Testing

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Novelty: In this paper, we show that biofuels (pure coconut oil and pure tamanu oil as two examples) can be used to replace commercial diesel fuel (B-20) in laboratory testing. This is significant because the engine performance of the two biofuels were found to be nearly the same as B-20 diesel fuel, even better under a few conditions, such as loads. In addition, these biofuels have lower engine emissions, especially pure tamanu oil.

Highlights:

- A diesel engine fueled with pure tamanu oil was found to have relatively low exhaust gas emissions.
- Pure tamanu oil and pure coconut oil can replace B-20 because they have nearly the same results as B-20, both before and after endurance testing.

Abstract. Smart Microgrid (SMG) is a hybrid system based on renewable energy which can use biofuel, taking advantage of local resources, as one of its energy sources. This study was conducted to determine the effect of using pure tamanu oil and pure coconut oil on engine performance, emissions, as well as their effects on particular components before and after endurance testing. The experiments were done using a diesel engine at speeds of 2200 rpm. In this study, engine performance and emission tests were done before and after the accelerated endurance tests, with loads of 800 W to 4000 W. The dimensions of the fuel injector nozzle needle and plunger pump were also measured. The fuel performance and emissions results exhibited marginal disparities before and after the endurance testing. The emissions tests also showed that the two biofuels, especially tamanu, are cleaner than B-20 and have better dimensional measurement results, compared to B-20. Therefore, these biofuels are feasible for replacing B-20, as shown in laboratory testing.

Keywords: *B-20 diesel fuel, coconut oil, pure plant oil, smart microgrid, tamanu oil.,*

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1 Introduction

Fuel and electricity are two examples of basic secure energy components throughout the world. Good access to these is one of the challenges faced by local residents in remote areas, especially in islets. To date, diesel power plants (PLTD) are the most prevalent power source as these have been built as power plants in the smaller islands [1]. Frequent occurrences of delays in the delivery of diesel fuel are often attributed to their strong susceptibility to weather conditions. The high operating costs of PLTDs can be doubled when delays in fuel delivery occur [2].

Numerous innovations have been made to improve the efficiency of energy utilization; one of these is the Smart Microgrid (SMG) system. Various studies have been conducted on this system [3-7]. The SMG system allows grid acceptance of various distributed generators, realizes the complementary advantages of different energy generation units, and improves utilization efficiency [4]. This system can use renewable energy as its primary energy source; for example, pure coconut oil (PCO) and pure palm oil (PPO) [8].

The use of biofuels takes advantage of local resources, which can help increase energy security in remote areas and reduce dependence on commercial fuel [9]. Coconut and tamanu plants are often found on tropical islands, such as the Karimunjawa Islands. Plant oils from both coconut and tamanu plants can be processed into biofuels. According to a number of studies [10–12], test results show that the use of PCO could reduce exhaust emissions but increase BSFC due to its higher viscosity. In addition [13–15], experiments on the use of pure tamanu oil methyl ester show that its BSFC also increases with low thermal efficiency but the smoke opacity and some gas emissions are lower, compared to diesel fuel.

One of the obstacles in using these pure oils as fuel is their high viscosity [16]. Some studies have made a modification to diesel engine to obtain the same characteristics between pure oil and commercial diesel fuel [17, 18]. Viscosity can be reduced by using a preheater with a specific configuration [17]. An experiment based on the literature [18] also verifies this as the results show that PCO at 184.8 °C and PTO at 95.7 °C had the same viscosity as commercial diesel fuel.

Previous studies have been done regarding SMG using many kinds of energy sources to maintain system sustainability; one of these studies uses diesel engine fuel as the backup energy producer [8,19]. Studies were also done regarding the use of pure plant oil: PCO and PTO, in this case, with an evaluation of their use in an engine [10–15, 20]. However, there is a lack of studies about testing PCO and PTO on a laboratory scale that is comparable to existing systems available in field locations. There is also a lack of comparing test results of PCO, PTO, and B-20 diesel fuel before and after endurance testing. Therefore, the aim of this study is to fill those gaps by evaluating the feasibility of PTO and PCO as alternatives for commercial fuel in SMG applications in remote areas. The first part of this twin paper will explain the laboratory test results.

2 Materials and Methods

2.1 Tested Fuel

Table 1 Tested fuel specifications

Parameter	Unit	Values of Testing Results		
		B-20	PTO	PCO
Viscosity @25°C	cSt	2.168	34.965	40.262
Calorific Value	J/g	48.154	38.142	37.951
Density @25°C	g/cm^3	0.84	0.91	0.92
Cetane Number	CN	48 [21]	59[22]	51 [23]

The Combustion Engine and Propulsion System Laboratory (CEPSL), ITB was used to conduct testing. This study was carried out using B-20 fuel and two kinds of pure biofuels: PTO and PCO, and their specific properties are shown in Table 1.

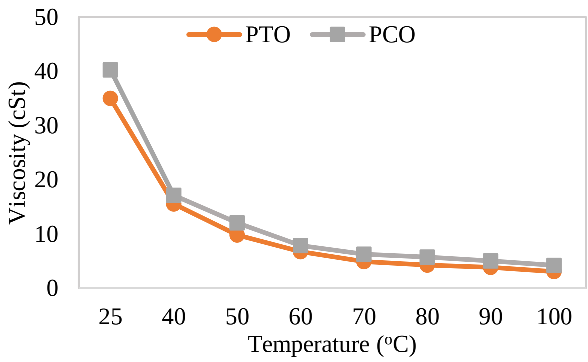


Figure 1 Pure oil viscosity versus temperature

The viscosity of PTO and PCO, as shown in Figure 1, were tested in the Physical Chemistry Laboratory, ITB. Both biofuels have the same range of viscosity as B-20 (25 °C) at temperatures of 70-100 °C.

2.2 Preheater Specification

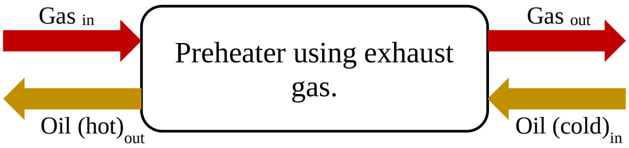


Figure 2 Preheater working principles

A preheater was used to heat the pure biofuels before injecting these into the combustion chamber. This principal heater is hot gas direct heating of the oil by following spiral shaped pipe. This preheater transferred the heat from the exhaust gas to the biofuels so that viscosity was reduced. The preheater used in this study was the same as that used in an experiment based on the literature [18]. The preheater was made of spiral-shaped copper with a diameter of 75 mm and 15 loops. In this experiment, the temperature of the pure biofuels was raised to 110-120$°C$ to obtain the same range of viscosity as that of standard diesel fuel, which is between 2-4.5 cSt [21]. Figure 2 shows the working principles of the preheater.

2.3 Engine and Generator Specifications

The specifications of the engine used in the laboratory experimental are shown in Table 2. The engine was modified by adding a preheater that utilized the exhaust gas of the engine to heat the biofuels.

Table 2 Engine specifications

Parameter	Specifications
Power	16 HP
Rated speed	2200 rpm
Cylinder	1
Displaced volume	901.3 cc
Injection system	Indirect injection
Starting system	Electric and mechanic
Cooling system	Water cooled

The diesel engine was connected to an AC generator with a belt transmission (pulley ratio 1:1). The specifications of the generator are shown in Table 3.

Table 3 Generator specification

Parameter	Specifications
Power	5000 VA
Voltage	220 V
Electric current	22.7 A
Frequency	50 Hz
Rated speed	1500 rpm
Phase	1

2.4 Laboratory Testing

Figure 3 shows the experimental scheme of the laboratory test. The rotational speed of the diesel engine was measured using a tachometer (B). All exhaust gas emissions and opacity were measured by SPTC Auto Check Gas Analyzer (A). The rate of fuel consumption was measured with a volumetric flask; this was recorded manually using a stopwatch for every 50 mL fuel consumed. There was a valve in every outlet of fuel, volumetric flask inlet, and fuel preheater inlet and outlet. In this case, if the biofuel was tested, the V1 and V2 valves would be turned off, and vice versa. Five water heater coils were used as the load of the diesel engine. Each of the coils had a capacity of 800 W and were used as a changing variable in this study.

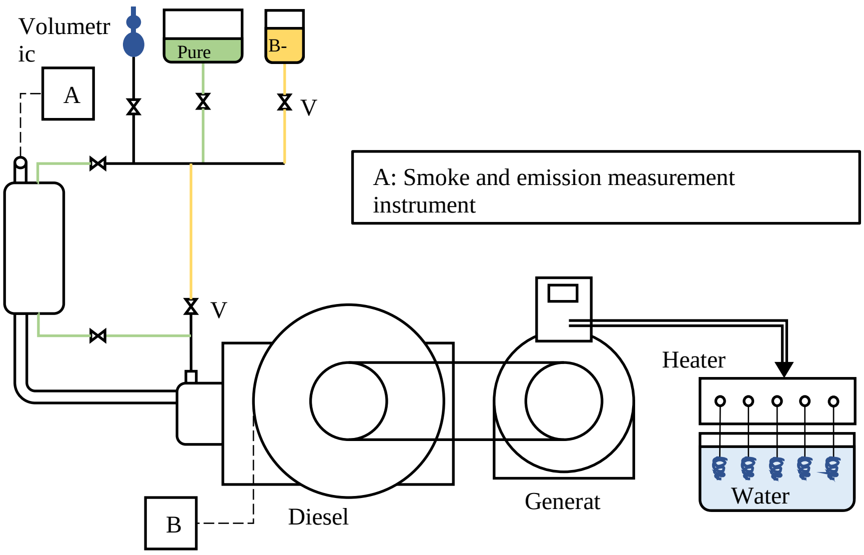


Figure 3 Laboratory experiment schematic diagram

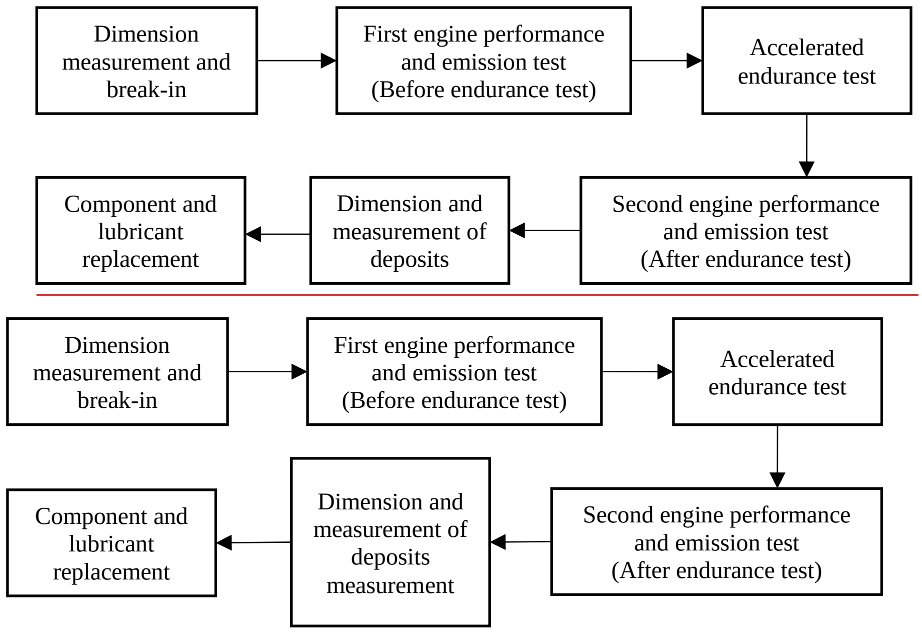


Figure 4 Laboratory procedures scheme

Figure 4 shows the laboratory testing procedures schematic diagram. The break-in step was conducted to adjust the new components of the diesel engine. Engine performance and emission tests were done twice: before and after accelerated endurance testing, with the purpose of finding the effect of the endurance test on the engine. These tests were carried out at different loadings starting from 800 W to 4000 W (with an incremental load of 800 W), at a constant speed of 2200 rpm.

2.5 Endurance Test

The endurance test in this study was carried out according to the technical articles of SAE No. 942010, "Diesel Fuel Detergent Additive Performance and Assessment." The procedure of one cycle for this test, as shown in Table 4, was done 34 times in sequence from steps 1 to 3 for a total of 17 hours.

Table 4 One cycle of the endurance test procedure

Step	Engine Speed (rpm)	Load (W)	Duration (minutes)
1	1000	0	15
2	1500	800	10

3	2000	4000	5

2.6 Measurement of Dimensions and Deposits

These were carried out to assess engine endurance and determine the impact of different fuels; also to determine the after-effect of endurance tests on each fuel.

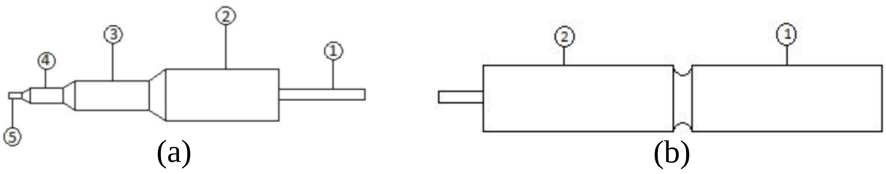


Figure 5 Measurement points of (a) fuel injector nozzle needle, and (b) fuel pump plunger

The dimensional measurement was done to determine the abrasive and lubricative properties of each fuel. In this step, the engine components measured were the fuel injector nozzle needle and the fuel pump plunger. These components were selected because they come in direct contact with the fuel. Figure 5 shows the measurement points of the fuel injector nozzle needle and fuel pump plunger. The measurements were taken using a measuring microscope. The measurements for Points 1 and 2 were done six times, and the average value was recorded; while points 3, 4, and 5, were measured four times because of their smaller areas.

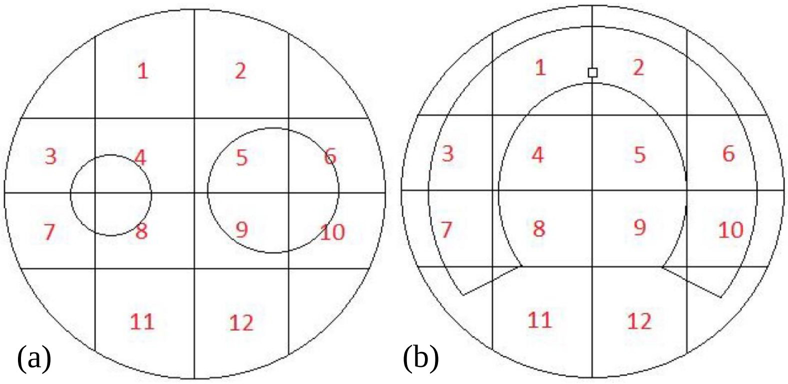


Figure 6 Measurement points of (a) cylinder head and (b) piston

Measurement of the deposits was done at the end of the test procedures to find out how much deposit had formed on the surface of the cylinder heads and pistons. For the purpose of higher accuracy, each component surface was divided into 12 points, as shown in Figure 6. The measurement for each point was done ten times to ensure that the average recorded data was representative.

3 Results and Discussion

3.1 Engine Performance

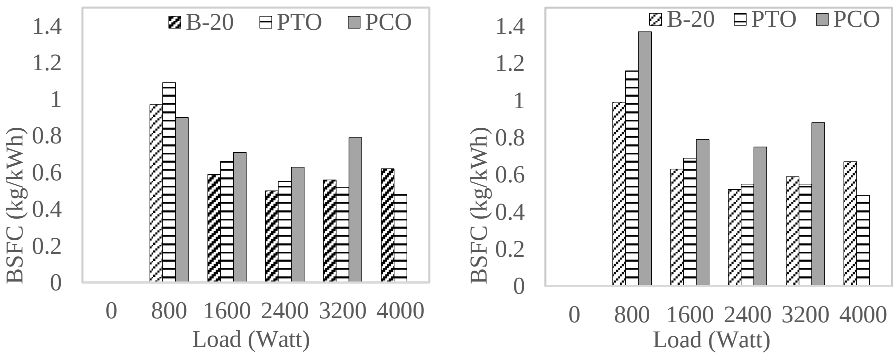


Figure 7 BSFC versus loads before and after endurance testing

Figure 7 shows the BSFC value before and after endurance testing for all fuels. There were no tests for PCO at a 4000 W load, due to high load lead to fluctuating engine speed and unstable fuel consumption rates. The average value of BSFC before endurance testing was 0.66 kg/kWh, 0.71 kg/kWh, and 0.76 kg/kWh for B-20, PTO, and PCO, respectively. Thus, B-20 has the lowest average value of BSFC; this is likely due to the fact that B-20 has the highest calorific value, as seen in Table 1. Both before and after endurance testing results show the same scheme for each fuel in all load conditions, except for the first test with 800 W load; BSFC values for PCO were higher after the endurance test. This was caused by a temperature drop for PCO when coming out of the preheater, which resulted in higher viscosity. Higher viscosity causes worse fuel atomization during fuel injection, so fuel consumption is also raised. The reason for the temperature drop was also indicated by deposits that formed inside the preheater. The BSFC of PTO usage went down along with load increments. This is because of PTO's better lubrication factor, which is also shown in the results of the fuel injector nozzle needle and fuel pump plunger dimensional measurements.

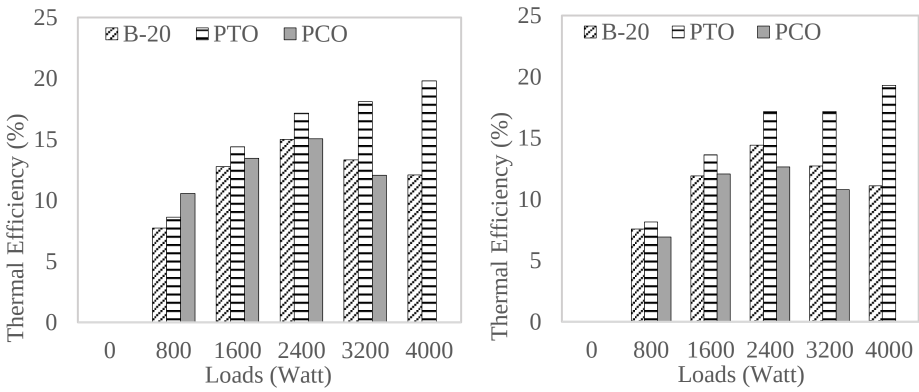


Figure 8 Thermal efficiency versus loads before and after endurance testing

Figure 8 shows the thermal efficiency of the engine when using all tested fuels. Before the endurance test, the average value of thermal efficiency of B-20, PTO, and PCO was 12.2%, 14.6%, and 12.8%, respectively. The average of PCO thermal efficiency went down by 2.18% after endurance testing; this is due to its higher BSFC. On the other hand, PTO has the highest value of thermal efficiency with loads of 4000 W, both before and after endurance testing; this is likely due to its better lubrication and higher oxygen content which lead to better combustion reactions.

3.2 Engine Emissions

CO_2 emissions, as shown in Figure 9, are produced from complete combustion inside the combustion chamber. The average value of CO_2 emissions, as shown in the graph on the left (before endurance testing) is 2.87%, 2.53%, and 3.046% for B-20, PTO, and PCO, respectively. Emissions became higher after endurance testing, which was 3.10%, 2.67%, and 3.58% for B-20, PTO, and PCO, respectively. B-20 is known for having the lowest viscosity of all fuels; therefore, it results in better combustion and higher CO_2 emissions, considering its better atomization. In a few cases, however, PCO had the highest level of CO_2 emissions, which was caused by its higher BSFC.

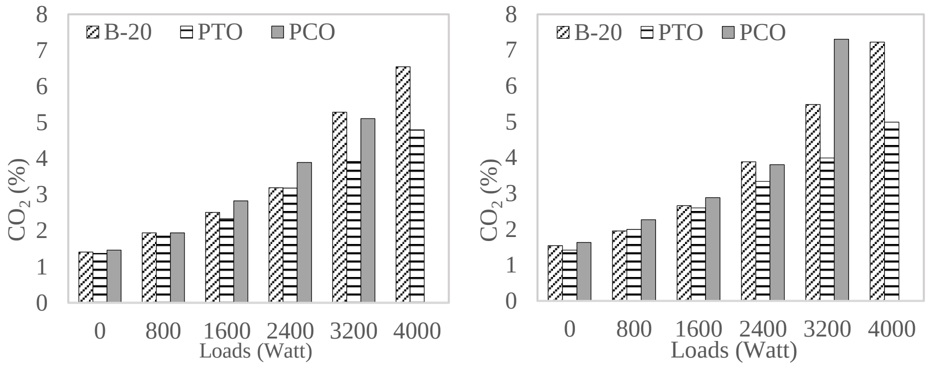


Figure 9 CO_2 versus loads before and after endurance testing

Figure 10 shows the CO emissions for each fuel test. CO emissions result from incomplete combustion; for example, when there is a rich fuel condition. Both tests have nearly the same result. The average results before endurance testing for B-20, PTO, and PCO are 0.02%, 0.02%, and 0.04%. PTO has nearly the same value of CO emissions as B-20; however, PCO has higher CO emissions due to its worse atomization which is caused by higher viscosity. A significant change in B-20 test results at 4000 W loads could have been caused by a low concentration of oxygen and a higher fuel flow rate, which lead to a rich fuel condition.

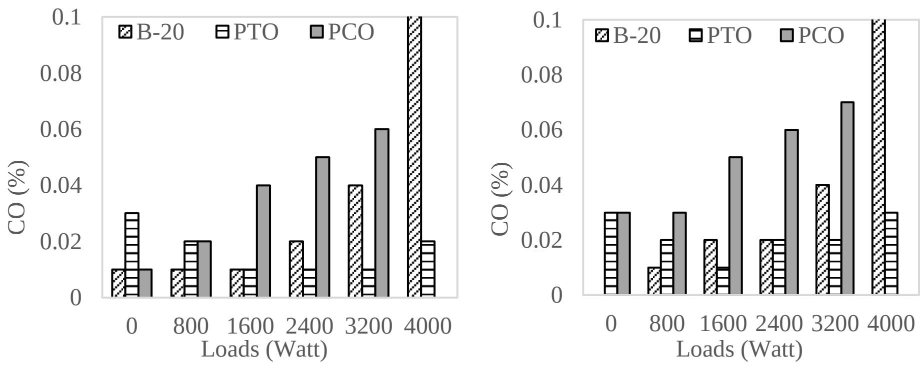


Figure 10 CO versus loads before and after endurance testing

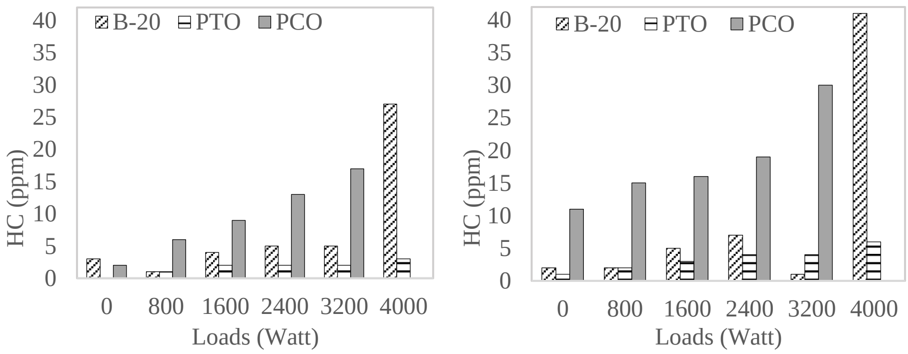


Figure 11 HC versus loads before and after endurance testing

Figure 11 shows the HC emissions results for each fuel. Similar to CO emissions, HC emissions are the result of incomplete combustion. The significant change in the B-20 test result with a 4000 W load also occurred in the HC emission results; this could be caused by low concentrations of oxygen/air and a higher rate of fuel flow entering the combustion chamber. The average values of HC emissions for B-20, PTO, and PCO before endurance testing were 3.6 ppm, 1.4 ppm, and 9.4 ppm. When comparing the PTO and PCO results, PCO has a higher value of HC emissions. This is because its higher viscosity gives worse atomization leaving the injector, resulting in a slightly poorer mixing with oxygen compared to PTO. After endurance testing, all the HC emission values were higher. This is because of higher levels of deposits forming inside the cylinders, resulting in worse combustion processing.

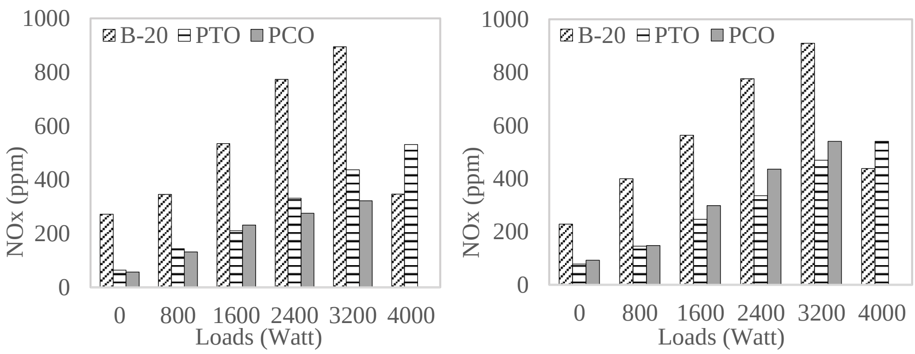


Figure 12 NOx versus loads before and after endurance testing

Figure 12 shows the NOx emissions from each fuel test. NOx emissions are the main product of nitrogen and oxygen reactions at high temperatures. The results show that the average NOx emissions before endurance testing for B-20, PTO, and PCO are 564.2 ppm, 237.2 ppm, and 203.4 ppm, respectively. The high NOx emissions for B-20 are probably due to its higher combustion temperature, compared to the other fuels tested. However, NOx drops significantly at a load of 4000, which is possibly due to the deteriorating combustion process. The deteriorating combustion process is also a factor in thermal efficiency, CO emissions, and HC emissions which have been discussed above.

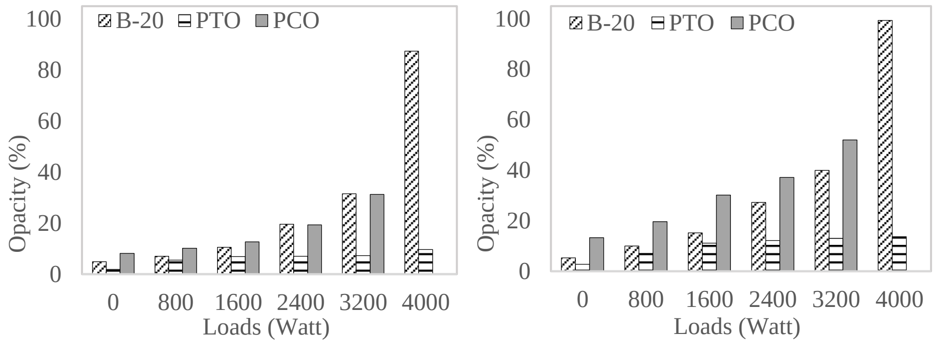
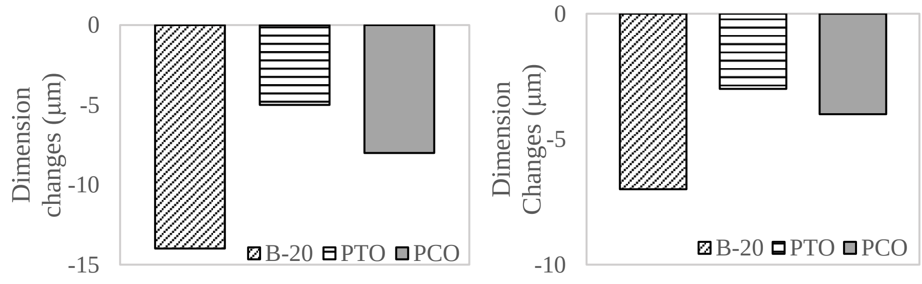


Figure 13 Opacity versus loads before and after endurance testing

The results of opacity measurements, as shown in Figure 13, reveal that the average value of opacity before endurance testing from 0 to 3200 W is 14.7%, 5.7%, and 16.29% for B-20, PTO, and PCO, respectively. The highest value of opacity for B-20 test results is shown in loads of 4000 W; this is affected by high CO and HC emissions. Higher concentrations of biofuel have higher oxygen content, indicating that the fuel oxidation is better and results in lower opacity.

3.3 Dimension Measurements

Figure 14 shows the results of the dimensional measurements of the fuel injector nozzle needle and fuel pump plunger, respectively. Performance and endurance testing that cause friction will add wear to the surfaces of some components. B-20 is known to have the highest dimensional decrement because of its low viscosity, which results in worse lubrication and higher wear levels on component parts. PTO has the lowest component dimensional decrement because of its better lubrication due to its higher viscosity. This shows that the needle and plunger can operate properly with PTO when compared to other fuels; therefore, PTO results in the highest thermal efficiency.

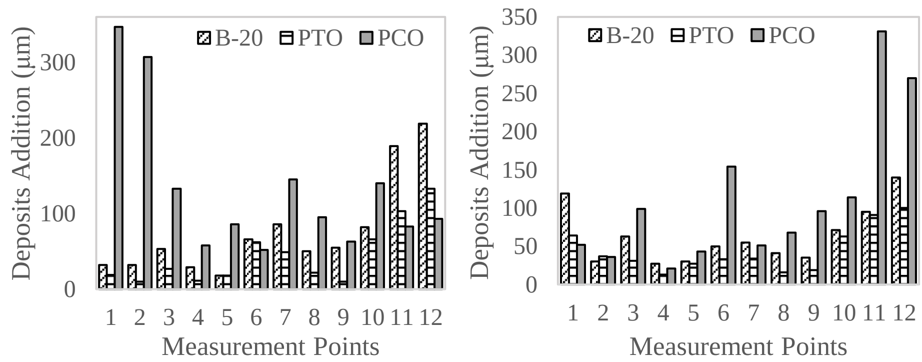


(a) (b)

Figure 14 Changes in the dimensions of (a) the injector nozzle needle and (b) the fuel pump plunger

3.4 Deposit Measurements

Figure 15 shows the amount of deposits on the cylinder heads. The amount of deposit for B-20 usage is the highest in areas 11 and 12, which is caused by high concentrations of fuels coming out of the pre-combustion chamber. PTO combustion has the same pattern as B-20. On the other hand, the PCO combustion formed deposits, mostly on areas 1 and 2; which was caused by PCO having the highest viscosity which made fuels concentrate in the area farthest from the pre-combustion chamber outlet without getting completely burned.



(a) (b)

Figure 15 Deposits on (a) cylinder head and (b) pistons

Deposit formation on the pistons is slightly lower compared to the cylinder head, because the surface of the pistons has a relatively higher temperature, which results in better combustion. In this case, B-20 and PTO share the same pattern of deposit formation. PCO usage has the highest level of deposits formed in areas 11 and 12, which is the same as areas 1 and 2 on the cylinder head.

4 Conclusions

In this study, the effects of B-20, PTO, and PCO fuels before and after endurance testing are compared. These fuels were tested on an indirect injection diesel engine with varied loads. The experiments were done using an engine at speeds of 2200 rpm. Engine performance tests, emission tests, accelerated endurance tests, and measurements of the dimensions of the engine components and deposits were conducted.

The engine performance test results was showed that B-20 has the lowest BSFC, but PTO has the highest thermal efficiency before and after endurance testing. The use of PTO results in higher thermal efficiency which is due to its better fuel lubrication. It is also shown that PTO has the best results as far as CO_2, HC, NOx, opacity in emission, component dimensions, and deposit tests when compared to the other tested fuels. After endurance testing, the component dimension decrements of B-20, PTO, and PCO were 14 µm, 5 µm, 8 µm; while the deposits formed were 6 µm, 2 µm, 4 µm, respectively.

Overall, it can be said that PTO is a good substitute for B-20 because of its better thermal efficiency, cleaner emissions, and because it also has the lowest level of decrement dimension and deposit formation.

5 Nomenclature

BSFC	=	Brake Specific Fuel Consumption
CO_2	=	Carbon dioxide
CO	=	Carbon monoxide
NOx	=	Nitrogen oxides
PCO	=	Pure Coconut Oil
PPO	=	Pure Palm Oil
PTO	=	Pure Tamanu Oil

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References

[1] Kementerian ESDM & Dirjen Ketenagalistrikan, *Statistik Ketenaga Listrikan Tahun 2018,* Jakarta, 2019.

[2] Sekretariat Perusahaan PT PLN (Persero), *Statistik PLN 2018*, Jakarta, 2019.

[3] Chen, Z. & Hu, Y., *Control of Power Electronic Converters for Distributed Generation Units*, in The 31st Annual Conference of the IEEE Industrial Electronics Society, pp. 1317–1322, 2005.

[4] Chen, Z. & Hu, Y., *A Hybrid Generation System Using Variable Speed Wind Turbines and Diesel Units*, in The 29th Annual Conference of the IEEE Industrial Electronics Society, pp. 2729–2734, 2003.

[5] Wang, H. & Li, G., *Control strategy of microgrid with different DG types*, Dianli Zidonghua Shebei / Electr. Power Autom. Equip., **32**(5), pp. 19–23, 2012.

[6] Wang, C.S. & Li, P., *Development and challenges of distributed generation, the micro-grid and smart distribution system,* Autom. Electr. Power Syst, **34**(2), pp. 10–13, 2010.

[7] Chen, Z., Pina, A., Ferrão, P., Fournier, J., Lacarrière, B., & Le Corre ,O., *Smart Micro-grid System with Wind / PV / Battery Micro-grid System with Wind / PV / Battery*, Energy Procedia, **152**, pp. 1212–1217, 2018.

[8] Novitasari, D., *Perancangan dan optimasi sistem smart grid berbasis energi terbarukan di Pulau Nyamuk, Kecamatan Karimunjawa, Jawa Tengah*, Institut Teknologi Bandung, 2016.

[9] Soysal, O. A. & Soysal, H. S., *Energy for Sustainable Society: From Resources to Users*. John Wiley & Sons, Inc., 2020.

[10] Hoang,T. A. & Van Le, V ,. *The Performance of A Diesel Engine Fueled With Diesel Oil , Biodiesel and Preheated Coconut Oil, Int. J. Renew. Energy Dev.*, **6**(1), pp. 1–7, 2017.

[11] Machacon, H. T. C., Shiga, S., Karasawa, T. & Nakamura, H., *Performance and emission characteristics of a diesel engine fueled with coconut oil – diesel fuel blend*, Biomass and Bioenergy, **20**, pp. 63–69, 2001.

[12] Prasad, V. V., *Performance Of 4 Stroke Diesel Engine Using Coconut Oil As Biofuel Material*, Mater. Today Proc., **4**, pp. 5312–5319, 2017.

[13] Miraculas, G. A. & Bose, N., *Effect of compression ratio on diesel engine performance and emission fueled with tamanu oil methyl ester and its blends*, Adv. Mater. Res., 984–985, pp. 850–854, 2014.

[14] Raj, M. T. & Kandasamy, M. K. K., *Tamanu oil - an alternative fuel for variable compression ratio engine,* Int. J. Energy Environ. Eng., 3, pp. 1–8, 2012.

[15] Taylor, P., Mohanraj, T. & Kumar, K. M. M., *Operating Characteristics of a Variable Compression Ratio Engine Using Esterified Tamanu Oil*, Int. J. Green Energy, **10**(3), pp. 285–301, 2013.
[16] Joshi, R. M. & Pegg, M. J., *Flow properties of biodiesel fuel blends at low temperatures*, Fuel, **86**(1–2), hal. 143–151, 2007.
[17] Satrio, N., *Uji Prestasi dan Ketahanan Preheater Motor Diesel Penyemprotan Tidak Langsung Berbahan Bakar Minyak Nabati Murni*, Institut Teknologi Bandung, 2017.
[18] Permatasari, D. P., *Karakteristik Pemanas Awal pada Motor Diesel Penyemprotan Tidak Langsung dengan Bahan Bakar Minyak Kelapa Murni dan Minyak Nyamplung Murni*, Institut Teknologi Bandung, 2019.
[19] Ali, M., *Perancangan dan Optimasi Sistem Smart Micro Grid Berbasis Energi Terbarukan untuk Mesin Refrigerasi (Pembuat Es) Nelayan,* Institut Teknologi Bandung, 2018.
[20] Salmani, M. H., Rehman, S., Zaidi, K. & Hasan, A. K., *Study of ignition characteristics of microemulsion of coconut oil under off diesel engine conditions*, Eng. Sci. Technol. an Int. J., **18**(3), pp. 318–324, 2015.
[21] Kementerian ESDM, *Keputusan Direktur Jenderal Minyak dan Gas Bumi Nomor : 28.K/10/DJM.T/2016*. Indonesia, 2016.
[22] Dinesh, K., Tamilvanan, A., Vaishnavi, S., Gopinath, M. & Mohan, K. S. R., *Biodiesel production using Calophyllum inophyllum (Tamanu) seed oil and its compatibility test in a CI engine*, Biofuels, **10**(3), pp. 347–353, 2019.
[23] Musa, N., Tera, G. & Yaman, S., *Characterization of Coconut Oil and Its Biodiesel,* J. Sci. Res. Reports, **9**(6), pp. 1–6, 2016.