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Research paper

Performance and emission characteristics of turbocharged diesel engine fueled with palm biodiesel blends

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Abstract

The exhaustion of fossil fuels and sharp rise in crude oil prices has led to the development of various alternative fuels. Alternative fuels are a necessity to meet rising energy consumption rates and to ensure eco-friendly growth. Alternative fuels that can be regenerated, are sustainable and have clean burning capacity to help promote an eco-friendly development. Whereas there have been various ideas and technologies relating to biodiesel as an alternative fuel, these tend to be restricted to the distant future insofar as compression-ignition engines are concerned. Biodiesel, produced by reacting triglycerides which are the main component of animal or plant-based fatty acids with methanol, is known to be an eco-friendly alternative fuel that can take the place of conventional petroleum diesel. In the present study, biodiesel (palm oil) was mixed at a certain ratio with commercially sold diesel, then introduced into a TCDI engine which was run at low load conditions for engine performance and exhaust gas measurement. Both engine output and torque were reduced, and fuel consumption increased to make up for the reduction in output. There were slight reductions in NOx and CO_2 emissions, but changes in CO and HC emissions were negligible.

Keywords: *Biodiesel; TCDI Engine; Palm Oil; Emission Characteristic; Engine Performance.*

1. Introduction

Substances gained from fossil fuels have applications in a diversity of fields (industrial development, transportation, agriculture, medicine, electronics, fashion etc.), and are widely consumed as fuel for transport. However, increasing energy demands along with increasing trends of modernization and industrialization, and decreasing fossil fuel resources, can be attributed to a rise in renewable alternative fuels. Biodiesel is among the best alternative fuels available to satisfy the world's energy demands.

Many studies on the engine performance and exhaust emission of CI engines, fueled with petro biodiesel and its blends with petrodiesel, have been investigated and are reported in the literature. Altaie et al. [1] tested enriched blends by adding methyl oleate (MO) to palm oil methyl ester (PME) at specified volumetric ratios (vol/vol%). The use of enriched blends reported lower exhaust gas temperature and decreased CO, HC, and NOx emissions, while brake-specific fuel consumption was increased. Phoungthong et al. [2] studied the characteristics of PM, PAHs, and BaPeq emissions from IDI turbo diesel engines using 40%- and 50%-content palm biodiesel blends with petro diesel, operating from 0 to 1000h. Using palm oil blends instead of commercial diesel reduced emissions of PM (8.2%-33.9%), total PAHs (13.3%-40.6%), and total BaPeq (35.4%-67.4%) significantly. Kariklan et al. [3] investigated jatropha-mineral turpentine (JMT) and jatropha-wood turpentine (JWT) blends.

Recently, research has been conducted on various types of biodiesels such as cashew nut shell, moringa, pogamiacamelina, and karanja. Devarajan et al. [4] studied the impact of adding pentanol to cashew nut shell biodiesel (10%, 20% content) on performance and emission characteristics in a constant speed compression ignition engine. CO and HC emission were reduced by 11.1%-12.3% and 3.6%-4.8% for cashew net shell biodiesel/pentanol blends at all loads. Rashed et al. [5] studied the performance and emission characteristics of 20% moringa biodiesel with diesel in a diesel engine at varying engine speeds. The diesel-biodiesel blend fuel with 20% moringa increased BSFC by 5.42%-8.39% and lowered CO and HC by 22.3%-32.7% and 11.8%-30.26%, respectively. M. Prabhahar et al. [6] applied thermal barrier coatings in a 3.7 kW, four stroke single cylinder diesel engine to decrease exhaust emissions and improve combustion and thermal efficiency. It was concluded that a ceramic-coated engine with biodiesel may increase thermal efficiency and reduce harmful emissions.

Engine performance and exhaust emission is emitted differs as the same biodiesel is used for the engine and turbocharger types. In this study, the experiment used turbocharged common rail direct injection (TCDI) diesel engines without significant modification at low load range. The performance and emission characteristics of palm biodiesel blend fuels were studied and compared with petroleum diesel.

2. Bibliographical review

Biodiesel, which has very similar combustion properties to diesel and is therefore able to substitute the diesel that is currently being used, can be transported and sold using existing facilities. This means that it conforms to the recent trends of green growth and green products, and is a strong potential candidate to replace fossil fuels used as energy resources for transportation [7]. Various countries are providing policy support for biodiesel, which is fast growing in terms of the proportion of energy sources it accounts for. Table 1 is a list of the key feedstocks used in the 6 world's largest biodiesel producers. Brazil, which is the fourth largest producer, uses 76.9% soybean oil, 19.8% animal fat, and 2.2% cotton oil as feedstock. The remaining 1.1 % is accounted for by palm oil, peanut oil, oilseed radish oil, sunflower oil, castor oil, sesame oil, waste frying oil and other oil products [8]. Fig. 1 shows currently commercialized methods of producing biodiesel. Biodiesel is a fuel composed of long-chain fatty acid alkyl esters, from vegetable oils or animal fats. Biodiesel is comprised of methyl esters that have been subject to a catalyzed transesterification process. To address the high viscosity of the triglycerides which are its main component, bio diesel is subjected to an esterification reaction and then separated and extracted from water and other impurities to make it suitable for use in diesel engines. Biodiesel is a methyl ester substance with hydrocarbon chain 14 to 24 carbons long. Whereas the hydrocarbon chain is similar to diesel (C10~C21), its molecular structure includes oxygen. Its properties are very similar to conventional petroleum diesel, making perfect mixing possible [9][10]. Advantages of biodiesel include low air-toxins and cancer-causing compounds, no sulfur oxide emissions, less CO_2 emissions, and the inclusion of oxygen in its structure allowing complete combustion. In the ecological aspect, biodiesel causes lower smoke and particulate emissions, and is free of SO_2, CO and aromatic hydrocarbons [11]. Biodiesel includes 11% (Wt%) oxygen, is biodegradable making it safe for the ecosystem, as well having a high cetane number, and can be used in existing diesel motor vehicles without engine modifications.

Table 1: Biodiesel Producer and Its Main Feedstocks

No.	Country	Feedstock
1	United states	Soybeans/waste oil/ peanut
2	Germany	Rapeseed
3	Argentina	Soybeans
4	Brazil	Soybeans/cotton oil/animal fat/palm oil
5	Indonesia	Palm oil/jatropha/coconut
6	France	Rapeseed/sunflower

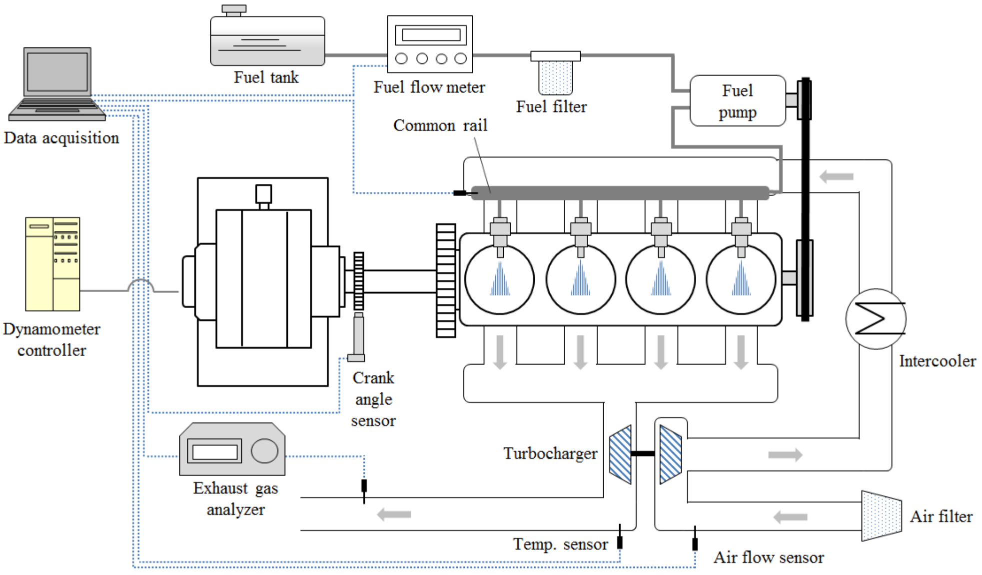


Fig. 1: Schematic Diagram of the Experimental Setup.

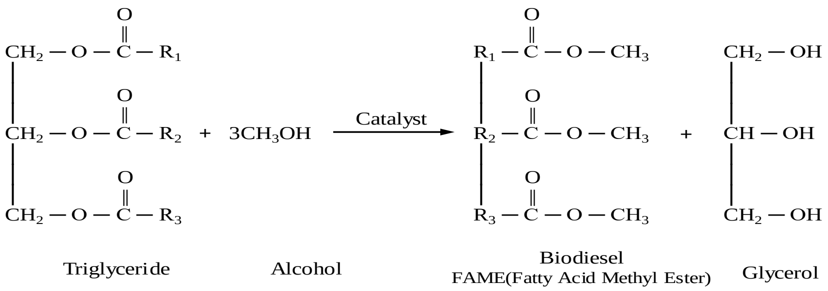


Fig. 2: Synthetic Method of Biodiesel from Triglyceride.

2.1. Experimental setup

The experimental setup used, comprises the experimental engine, engine dynamometer, combustion analysis system, fuel consumption measuring apparatus, and an exhaust gas analyzer. A schematic diagram of the experimental setup for engine performance is shown in Fig. 3.

Facilities to monitor and control engine variables were installed on a test-bed, four-cylinder, direct injection, fur-stroke, water-cooled, diesel engine located at the authors' laboratory. The engine is turbocharged with a fixed geometry turbocharger and intercooler. The basic data for the engine, injection system and turbocharger are shown in Table 2. It is widely used to family sedan and sport utility vehicle. This engine is connected to an eddy-current electric dynamometer with a maximum power absorption capacity of 228 kW / 8,000 rpm to control engine revolutions and load and measure brake torque.

Table 2: Engine, injection system and turbocharged basic data

Engine type	4-cylinder, in-line, 4-storke, compression ignition, direct injection, water-cooled, turbocharged
Speed range	800 - 4500 rpm
Engine total displacement	1991 cm^3
Bore/stroke	83 mm/92 mm
Valve type	SOHC
Compression ratio	17.5:1

Firing order	1 - 3 - 4 - 2
Maximum power	89 kW at 3800 rpm
Maximum torque	280 Nm at 2000 rpm
Diesel injection system	Common rail
Fuel injection pressure	Max. 1600 bar
Turbocharger	Fixed geometry(FGT)

The flow rate of fuel was measured using a Digmesa FHK turbine type flow meter. Exhaust gas, cooling water, inlet flash air and engine oil temperatures were measured by using a K-type thermocouple. Also, for the engine and dynamometer cooling water, water with 2kg/cm^2 pressure and 1,000L/h flowrate was used from a city water facility.

Gaseous emissions were measured by a Horiba MEXA-554JK gas analyzer, a non-dispersive infrared (NDIR) analyzer for CO, HC, and an electrochemical cell for NOx. Measuring instruments accuracies are shown in Table 3. To insure that accuracy of the measured emission values, the exhaust gas analyzer was calibrated before measurement using standard gas.

Table 3: Measuring Instrument Details

Measurements	Measurement range	Accuracy
Load capacity	0-75 kgf	0.25 %
Engine speed	0-7,000 rpm	±5 rpm
Temperature	-200 ºC to 1,000 ºC	±1 ºC
Flow rate	0.027-8.30 L/min	±1.0 %
CO	0-10 % vol.	0.01 % vol.
CO2	0-20 % vol.	0.17 % vol.
HC	0-10,000 ppm vol.	2.0 ppm vol.
NOx	0-5,000 ppm vol.	1.0 ppm vol.
O2	0-25 % vol.	1.0 % vol.

2.2. Tested fuels

The physical properties of the palm oil-based biodiesel fuel used in the present study are shown in Table 5. The biodiesel fuel blend (BD) represents the mix ratio between diesel and biodiesel. DB20 stands for diesel including 20% biodiesel by volume. 0% (DB0), 20% (DB20), and 40% (DB40) samples were prepared and used. Using the samples prepared by mixing biodiesel with diesel at varying ratios, engine dynamometer testing was carried out to analyze engine performance and exhaust gas tendencies depending on the mix ratio between palm oil biodiesel and diesel.

Table 4: Test Conditions

Operation condition	Variation
BD content (vol. %)	0, 20, 40
Load (%)	20
Engine speed (rpm)	1300, 1700, 2000, 2300

Table 5: Properties of Petro Diesel and Biodiesel

Property	Petro diesel	Biodiesel(Palm)
Standard	ASTM D 975	ASTM D 675
Composition	Hydrocarbon (C10~C21)	FAME (C12~C22)
Kinematic viscosity(mm^2/s, 40˚C)	1.9~4.1	1.9~6.0
Specific gravity (mg/L)	0.85	0.88
Flash point (˚C)	60~80	100~170
Cloud point (˚C)	-15~5	-3~12
Pour point (˚C)	-35~15	-15~16
Water (wt. %)	0.05	0.05
Carbon (wt. %)	87	77
Hydrogen (wt. %)	13	12
Oxygen (wt. %)	0	11
Sulfur (wt. %)	0.05	0.05
Cetane number	40~55	48~60

2.3. Experimental methods

As the experiment was devised to compare engine performance and emissions characteristics according to mixed diesel-biodiesel fuel at various ratios, all conditions other than the mix ratios of the mixed fuels used were kept the same. The revolutions of the experimental engine were set to 1300, 1700, 2000 and 2300 rpm, which are the most frequently used revolutions during actual vehicle operation. The load factor was fixed at 20%. All tests were carried out 3 times under the same conditions, and the average values were used as the results. Also, whenever test conditions were changed, the engine was allowed to run for a sufficient time so that the previous experiment would not impact the results of the next. The exhaust gas analyzer was calibrated to match the standard gas concentration, after which various exhaust emissions were measured.

Brake power (PB), brake specific fuel consumption (BSFC) and brake thermal efficiency (BTE) for the biodiesel blend and petroleum diesel were calculated according to Eqs. (1)– (3), respectively:

$$PB\,(kW\,) = \frac{2\pi NT}{60 \times 1000} \tag{1}$$

$$BSFC\,(g \big/ kW\ \cdot h\,) = \frac{m_f}{PB} \tag{2}$$

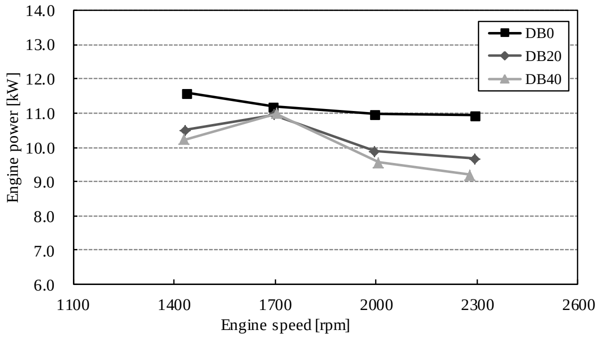
$$BTE\,(\%) = \frac{3600}{BSFC\ \times Q_{HHV}} \tag{3}$$

Where T is brake torque in Nm, N is engine speed in rpm, mf is the mass flow rate of fuel in g/h, and QHHV is the high calorific value of fuel in MJ/kg. The measurements from the experiment were as follow.

3. Result and discussion

In the present study, a water-cooled 4-cycle TCDI engine was used to measure output, torque, fuel consumption, and exhaust gases according to biodiesel mix ratio (BD0, BD20, and BD40) to analyze engine performance and exhaust gas characteristics.

Fig. 2 shows the changes in engine output and torque according to changes in fuel and engine revolutions. For all test fuels, output and torque tended to decrease as rpm increased. Overall, torque and output were lower for BD20 and BD40 compared to BD0. However, at 1700 rpm, it was found that there was almost no difference between BD0 and the mixed fuels.



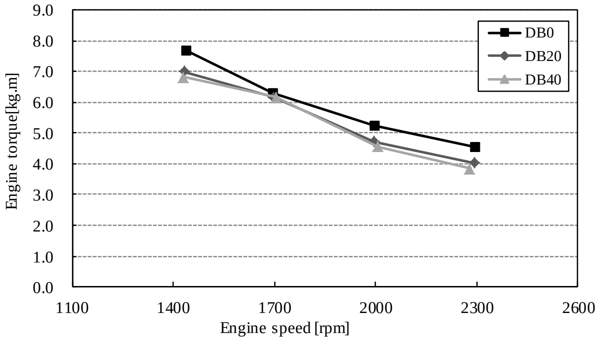


Fig. 2: Change in the Engine Performance in Accordance with Engine Speed.

Brake-specific fuel consumption is defined as the fuel consumed to produce unit power, and its variations with brake power for the tested fuels is shown in Fig.3. As brake power increased, BSFC for all the fuels decreased. The average BSFC for diesel, B10, B20, B30, and B50 over brake power in the range of 0.0 to 30.0kW were 263.5g/kW·h, 282.6g/kW·h, 299.8g/kW·h, 310.3g/kW·h, and 327.6g/kW·h, respectively. Thus, average BSFCs were 7.2%, 13.6%, 17.5%, and 24.0% higher than diesel for B10, B20, B30, and B50. The BSFC of a compression ignition engine depends on the relationships between the volumetric fuel injection system, fuel density, viscosity, and calorific value [14].

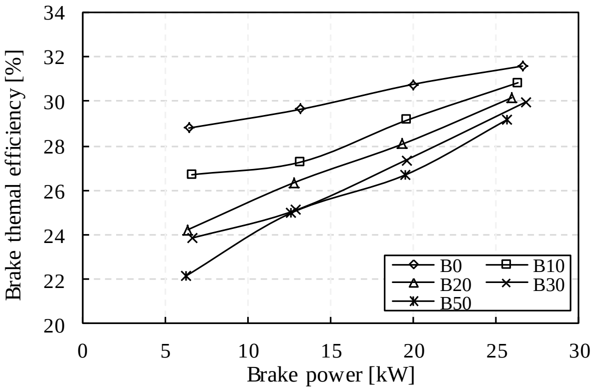


Fig. 3: Variation of BTE with Brake Power for Different Biodiesel Blends and Diesel.

Fig. 4 shows the variations of exhaust gas temperature with brake power in the range of 0.0 to 30.0 kW for diesel and biodiesel blends. Fig. 4 clearly shows that, over the entire range of brake power, all biodiesel blended fuels produced higher exhaust gas temperatures than diesel. The highest exhaust gas temperature values for diesel, B10, B20, B30, and B50 were 435°C, 446°C, 468°C, 494°C, and 514°C, respectively. The maximum exhaust temperature of B10 was very close to the maximum value obtained with petro-diesel. Moreover, ignition delay occurred in fewer periods due to an increase in cetan number [15].

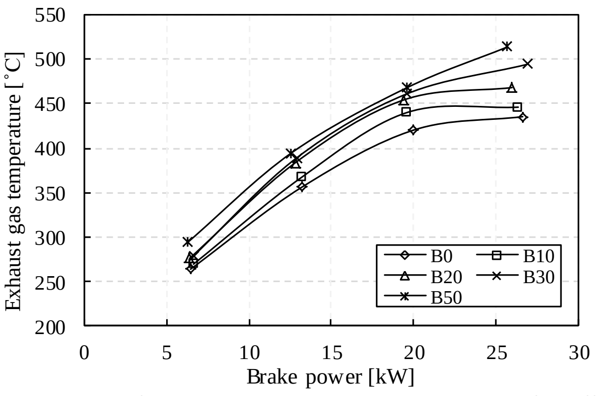


Fig. 4: Variation of Exhaust Gas Temperature with Brake Power for Different Biodiesel Blends and Diesel.

Fig. 5 shows the variations of carbon monoxide (CO) with different loads for diesel and biodiesel blends. CO is an intermediate combustion product and is formed mainly due to incomplete fuel combustion. If the fuel is completely burned, CO is converted to CO_2. If the fuel is incompletely burned due to lack of air or low exhaust gas temperature, CO will be formed [16]. It is observed from brake power in the range of 0.0 to 20.0 kW that there was no definite trend (increasing or decreasing) among biodiesel content increase in the blends. However, it tended to increase at around 25kW. Because of the presence of oxygen in the biodiesel blend, complete combustion was possible, resulting in less CO than diesel [17]. Due to biodiesel being difficult to atomize, the locally rich mixtures of biodiesel caused more CO to be produced during combustion [18].

Hydrocarbon (HC) is one of the important exhaust gas characteristic of biodiesel blends in diesel engine. HC emission appears differently depending on engine operating condition, fuel properties, and fuel spray characteristics [19]. HC emission for biodiesel blends with respect to brake power is presented in Fig. 6. HC emission from B10, B20, B30, and B50 are 9%, 15%, 21%, and 27% lower than diesel. Reduced HC emission for blend fuels can be explained by the higher oxygen content and higher cetane number of biodiesel fuel. Palm biodiesel has a higher cetane number and higher saturated fatty acid content than other biodiesels such as jatropa and moringa [5]. In addition, Altaie et al. reported that a higher cetane number in fuel led to a reduction in combustion delay [1].

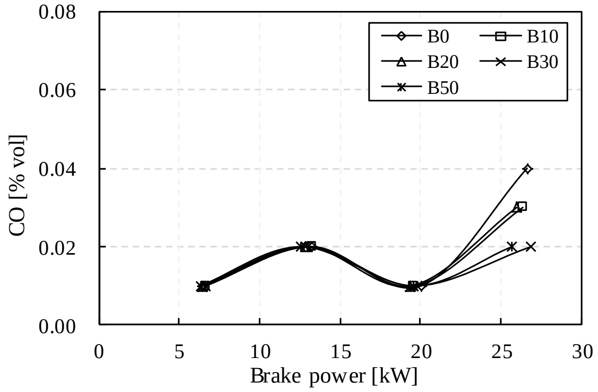


Fig. 5: Variation of CO with Brake Power for Different Biodiesel Blends and Diesel.

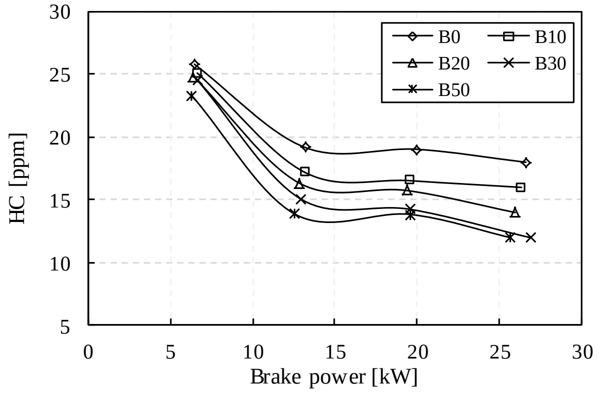


Fig. 6: Variation of BSFC with Brake Power for Different Biodiesel Blends and Diesel.

The NOx (nitrogen oxides) in exhaust gas contain NO (nitric oxide) and NO_2 (nitrogen dioxide). These are produced during engine combustion, especially at a high temperature in-cylinder. Fig. 7 shows the NOx emission from the engine using different diesel-biodiesel blended fuels and diesel. The results show that NOx increased with brake power for different blends and diesel. NOx increases with the increase of biodiesel content in the blend fuel for corresponding brake power. A similar result for NOx emission was reported when a jatropa biodiesel blend in a diesel engine was tested [20]. The highest NOx values for diesel, B10, B20, B30, and B50 were 196ppm, 198ppm, 252ppm, 303ppm and 363ppm, respectively. Among the blends tested, B10 is very close to petro-diesel. On average, B10, B20, B30, and B50 increased NO emission by 4%, 17%, 38% and 56%, respectively. Biodiesel has a higher cetane number than does diesel fuel, which shortens the ignition delay period [21]. The results gained from the experiment show that using vegetable oil in diesel engine increases NOx emissions, which is in accordance with that which was posited by Wang et al .[22].

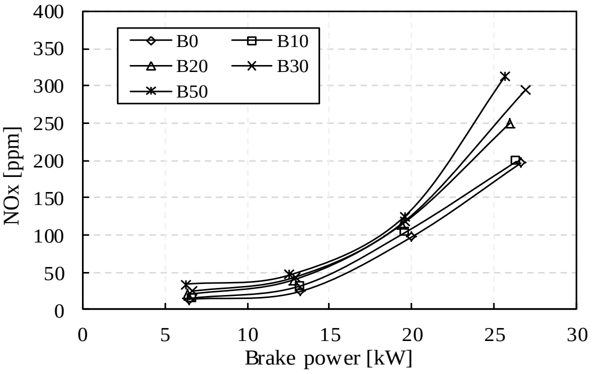


Fig. 7: Variation of BSFC with Brake Power for Different Biodiesel Blends and Diesel.

4. Conclusion

In the present study, mixed fuels of petroleum diesel and biodiesel were used to analyze engine performance and exhaust gas characteristics under the same low load factor experimental conditions. The following conclusions were reached:

- Engine brake-specific fuel consumption (BSFC) increased slightly when the engine was fueled with palm biodiesel blends rather than petro-diesel. The reduction of brake thermal efficiency for blends was found to be lower than diesel due to its higher viscosity and lower calorific value.
- Carbon monoxide and hydrocarbon emissions reduced, which may be due to the higher cetane number and oxygen content in palm biodiesel fuel. However, NOx levels throughout were higher than for diesel fuel.
- A diesel engine as used in this study can perform satisfactorily on biodiesel blends with diesel fuel without any engine modification at low load range. The blends of palm biodiesel and petro-diesel showed similar performance and emission.

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