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ORIGINAL ARTICLE

The Effect of Blending Ratio on Biodiesel Properties, Emissions, and Engine Performance

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ABSTRACT – This work presents the effects of biodiesel blending on its properties, emissions, and performance. The rubber seed oil (RSO) and waste cooking oil (WCO)-based biodiesel were prepared using a transesterification method in the presence of a heterogeneous catalyst. Several formulations were derived from two types of biodiesels (RSO and WCO) and tested according to the ASTM D6751 specification for acid value, free fatty acid (FFA), kinematic viscosity, pour point, cloud point, density, and calorific value. For the WCO-based biodiesel, the best blend was WCO B5, with properties closely matching those of petrodiesel. Significantly, the formulations with higher WCO content (e.g., B10 and above) suffered from serious drops (above 8%) in calorific value. In contrast, the RSO diesel blend showed less than 5% drops in calorific value for formulations up to a 20% biodiesel blend (B20). In addition, an indiscernible difference was obtained between the WCO B5, RSO B5, and petrodiesel in terms of engine power, torque, and CO_2 emissions, although the RSO B5 did produce less NO_x (158 ppm) than both the WCO B5 (390 ppm) and the petrodiesel (220 ppm). The results showed that blending of WCO and RSO with petrodiesel up to 10%, i.e., B10, is practically applicable for diesel cars with power reduction less than 10%.

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INTRODUCTION

Renewable resources such as vegetable oil or animal fat can be used to produce biodiesel, which has been proposed as a feasible alternative to traditional petrodiesel due to its renewability, local production capacity, and eco-friendliness [1]. The transesterification process is commonly used to produce biodiesel, whereby triglycerides and alcohol react in the presence of a catalyst to produce mono-esters [2]. In recent years, numerous researchers have conducted systematic investigations to determine the viability of vegetable oil and its derivatives as fuel or diesel additives. Balat [3] demonstrated that the properties of biodiesel were similar to those of mineral diesel fuels and could be used without any modification. Azad et al. [4] study indicated that increasing the blend of biodiesel and diesel improved performance, while Akasyah et al. [5] research showed that emissions such as particulate matter, hydrocarbon, and carbon monoxide were reduced by blending diesel with biodiesel. The use of biodiesel was found to significantly reduce CO_2 emissions (65-90%), particulate emissions (39-50%), un-burnt hydrocarbon (70%), soot emissions, and other harmful emissions (e.g., 10% of NOx) according to Lapuerta et al. [6] study. The promotion of blended biodiesel can help mitigate climate change and decrease compound levels.

Blending, emulsification, thermal cracking, and transesterification are the commonly adopted methods to use vegetable oil as fuel in diesel engines. Due to the limited resources of fossil fuel, the increasing prices of crude oil, and growing concern about environmental quality, alternative fuels have recently gained significant attention [7]. Biodiesel has the potential to reduce exhaust emissions, improve lubricity, have a higher flash point, have improved biodegradability, and have reduced toxicity over conventional diesel fuel [8]. Pure biodiesel B100 is not often used directly on a diesel engine because it requires some modifications to the fuel system before it can be used. The use of B100 is associated with many problems, such as high injector pressure arising from the high viscosity of biodiesel compared to diesel fuel, gum formation, excessive carbon decomposition in the engines, and low engine speed and power due to its lower calorific value compared to petrodiesel [9]. In some cases, the use of B100 fuel causes fuel system blockage, seal failures, filter clogging, and deposits at injection pumps [10]. These problems can be negated by blending small amounts of biodiesel with diesel fuel. For instance, Rahim et al. [11] showed a negligible power reduction (ranging from 1.1 to 1.4%) in a diesel engine running on a 5% biodiesel blended fuel. Vashist and Ahmad [12] studied the performance of Jatropha and castor-seed-based biodiesel blends. They reported a minimum thermal power reduction at a blending ratio of 10%, but the power was markedly reduced at a 20% blending ratio. In the meantime, the fuel consumption of 20% blended fuel is much higher than that of petroleum diesel. There are limited comparisons on the properties and performance of blended fuel made of waste cooking oil and rubber seed oil available in the literature, and hence this is the objective of the current work. Moreover, the blending technique is an alternative way to reduce the

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consumption of petrodiesel. Currently, major car manufacturers have approved the use of biodiesel blends from 5% up to 20% without modifications to the engine.

Thus, this work was conducted to evaluate the effect of the physicochemical properties of B5, B10, and B20 blends compared with B100 and pure mineral diesel on engine performance, combustion, and exhaust emission when operating with a 4-cylinder Mitsubishi 4D68 diesel engine.

METHODS AND MATERIAL

Preparation of RSO and WCO Biodiesel

The waste cooking oil (WCO) and rubber seed oil (RSO)-based biodiesels were prepared using the cement clinker-derived catalyst according to the method outlined by Gimbun et al. [13]. The transesterification was performed using a catalyst loading of 5 wt.%, a methanol to oil molar ratio of 5:1, a reaction temperature of 60°C, and a reaction time of 4 hours. The catalyst was dispersed in methanol at 60°C for 24 hours with the aid of agitation prior to contact with the preheated feedstock to provide a robust transesterification process. Water-soluble methanol and glycerol were removed by intensive washing with water. The biodiesel produced was filtered through a 40 μm polytetrafluoroethylene polymer (PTFE) membrane to remove the catalyst, while the residual methanol was vacuum-evaporated. Fuller earth was subsequently used to reduce the moisture content of the product. Finally, the fuller earth, residual catalyst, and glycerol were removed from the biodiesel using an Eppendorf 5810R centrifuge.

Analysis of Diesel and Biodiesel Blend

The biodiesel blends, i.e., B5, B10, and B20, are a mixture of biodiesel and petrodiesel, whereby the compositions of biodiesel are 5%, 10%, and 20%, respectively, on a volume basis. The volume of fuel to be mixed was measured using a measuring cylinder. A predetermined amount of biodiesel was added to the petrodiesel in a Scott bottle (5 L) and stirred to produce a homogeneous solution like the ones shown in Figure 1.

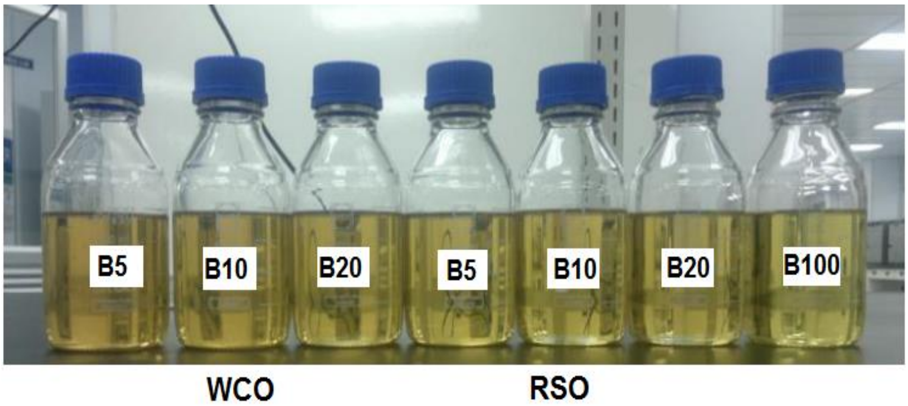


Figure 1. Biodiesel blend and petrodiesel. The first three from left are WCO-based biodiesel, the middle three are RSO-based biodiesel, and the rightmost is petrodiesel

The RSO biodiesel, the WCO biodiesel, and their blend were analysed based on ASTM D6751 specifications. The acid value (ASTM D664) is the quantity of base expressed in mg of potassium hydroxide (KOH) required to neutralise the free fatty acids present in 1 g of the sample. The potentiometric titrators, model 785 DMP titrino (Metrohm) were used to determine the value. The calorific value (ASTM D240) is the thermal energy released per unit quantity of fuel that is burned completely with oxygen (O_2) to form the products of combustion. The apparatus to measure calorific value is the Oxygen Bomb Calorimeter, model 6772 (Parr Instrument Company, USA). The density (ASTM D 4052) was determined using a portable density meter, model DA-130N, from Kyoto Electronic. To ensure an accurate result, this apparatus needs to be cleaned using ethanol 99% before and after each measurement series. Kinematic viscosity (ASTM D445) is the resistance to the flow of oil under gravity due to friction through known size tubing of glass capillary viscometers at a certain temperature. Viscosity baths, Cole-Parmer, with a cannon glass capillary viscometer (350 ml, constant, k_v = 0.4899 mm^2/s^2) were used to measure the kinematic viscosity at 40 ± 0.1°C. The pour point (ASTM D97) and cloud point (ASTM D2500) were examined using the Spark-Proof Freezer (Koehler model). The sample was placed upright in a temperature-regulated chiller bath container and cooled at a specific temperature, which was periodically examined. The triplicate experiment was run on each sample.

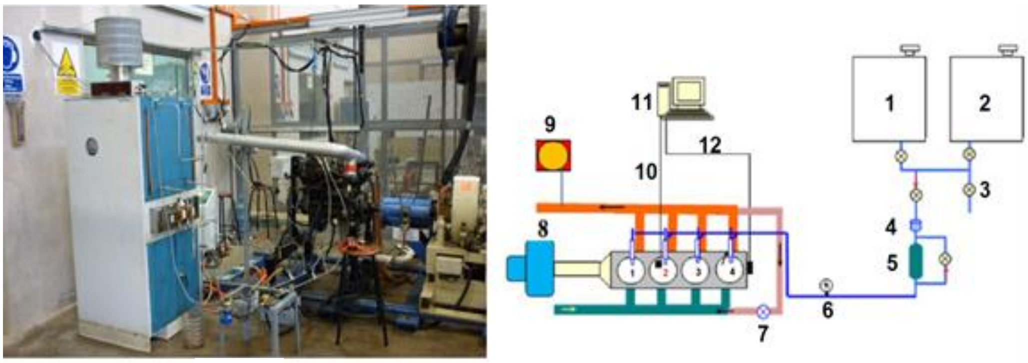
Experimental and Engine Test Rig

The fuel engine tests were conducted with a naturally aspirated, water-cooled 4-cylinder Mitsubishi 4D68 diesel engine with a compression ratio of 22.4:1, a total displacement of 1.998 dm^3, a bore-to-stroke ratio of 0.89, and a mechanically controlled fuel-injection system distributor. The engine specifications are given in Table 1. A schematic diagram of the experimental engine setup and the engine test bed are shown in Table 2 and Figure 2, respectively. The engine was coupled with an eddy current dynamometer with a capacity of 150 kW controlled by a Dynalec controller to measure the effective torque and engine speed. An anemometer (Centerlek) and fuel flow meter (AIC) were used to measure airflow and fuel flow rate, respectively. Meanwhile, the gas analyzer was used to measure and monitor the exhaust emissions of the engine, i.e., NOx, carbon dioxide (CO), and unburned hydrocarbons.

DEWECA software records data on engine operation parameters such as in-cylinder pressure and crankshaft speed. Additionally, DEWESOFT software connected to the thermocouples in the engine records its operating temperature. The tests were conducted at the half-open throttle and variable engine speeds of 1200 and 2400 RPM at partial engine load (50% throttle position). The engine is equipped with an exhaust gas recirculation (EGR) system, but it was turned off in this experiment.

Table 1. Engine specification

Parameter	Specification
Number of cylinders	4 in-line
Combustion chamber	Swirl chamber
Total displacement, cm	1.998 cc
Cylinder bore mm × Piston stroke, mm	82.7 × 93
Bore/store ratio	0.89
Compression ratio	22.4:1
Maximum power	64.9 kW, 4500 RPM
Maximum torque	177.0 Nm, 2500 RPM



(a) (b)

Figure 2. (a) Engine test rig and (b) Schematic diagram of experimental engine test rig: (1) diesel fuel tank; (2) biodiesel fuel tank; (3) drain valve; (4) fuel filter; (5) fuel pump; (6) pressure transducer; (7) EGR valve; (8) dynamometer; (9) gas analyser; (10) in-cylinder pressure transducer; (11) Orion 1624 DAQ; (12) crank angle encoder

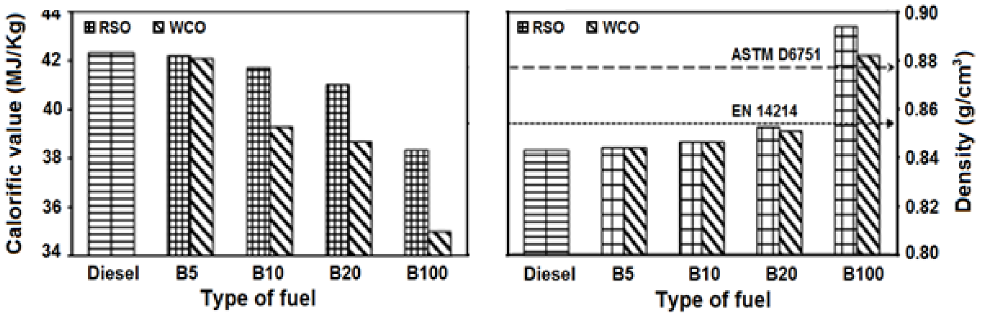
Table 2. Test matrix for fuel testing at 4-cylinder Mitsubishi 4D68 diesel engine

Engine Speed (RPM)	Test designation name
	WCO B5
1200	WCO B10
-	RSO B5
2400	RSO B10
	Diesel

RESULTS AND DISCUSSION

Properties of Biodiesel B100 and its Blends

Three different compositions of biodiesel blends were prepared, i.e., B5, B10, and B20, using WCO and RSO-based biodiesels. The properties of the fuel were tested according to the ASTM 6751 method and compared to those of petrodiesel. The calorific value of B100 WCO biodiesel was 35.00 MJ/kg, which is almost the same compared with the reference value of 35.82 MJ/kg [14]. Meanwhile, the calorific value for B100 RSO biodiesel is 38.326 MJ/kg, which is comparable to the reference value of 37.5 MJ/kg [15]. Normally, the calorific value of biodiesel is lower than that of petrodiesel due to the higher number of carbons and hydrogens in biodiesel molecules (chain length) [16]. A higher calorific value is desired for a diesel engine that produces higher torque and power. Blending biodiesel with petrodiesel is often done to overcome the shortcoming in engine performance due to its lower calorific value (CV). The lower CV is due to the presence of oxygen in the biodiesel fuel [17]. The oxygen content of the biodiesel improves oxygen availability in rich zone flames in the combustion chamber process and decreases its oxidation potential. Figure 3(a) shows the trends of calorific value over different blends. The calorific value decreases with the increasing amount of blending due to the lower calorific value of biodiesel compared to the calorific value of petrodiesel. The biodiesel fuels that are more unsaturated tend to have slightly lower calorific values and energy contents on a weight basis, while those with greater saturation tend to have higher [17]. The lower calorific value would yield lower engine power, which was confirmed by the subsequent engine testing. The B5 biodiesel of both RSO and WCO showed an insignificant calorific value difference compared to that of petrodiesel. Therefore, B5 biodiesel may not significantly affect the engine's performance. Indeed, previous work by Sudrajad et al. [18] also showed no significant reduction in engine performance for B5 blended fuel. In addition, the result from this work also suggests that RSO biodiesel is better than WCO biodiesel because it can be blended up to B20 with very little drop (<5%) in calorific value. In contrast, the calorific value for WCO B20 blended fuel dropped to almost 10%.

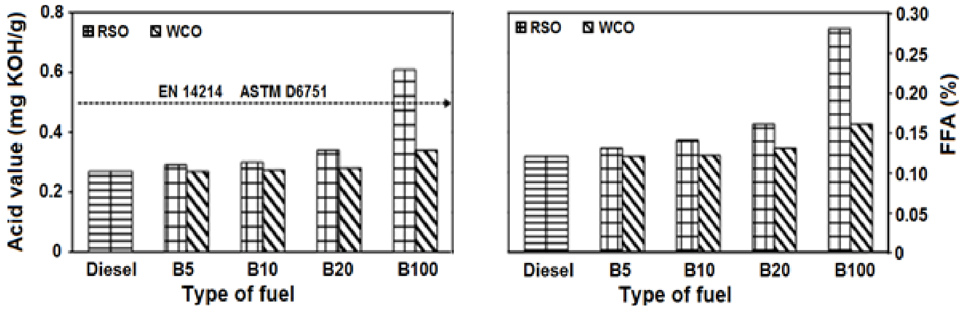


(a) (b)

Figure 3. Properties of WCO and RSO blends. (a) Calorific value and (b) Density

The density of biodiesel blends (WCO and RSO) varies with the percentage of biodiesel used with respect to petrodiesel (Figure 3(b)). The density of B100 WCO biodiesel was 0.882 g/cm^3, which is almost the same compared with the reference value of 0.89 g/cm^3 [19], while the density of B100 RSO biodiesel obtained was 0.894 g/cm^3, which is comparable to the reference value of 0.91 g/cm^3 [20]. It is not known how the WCO biodiesel in Muralidharan and Vasudevan [19] was prepared. However, a similar density (0.89 g/cm^3) was obtained from our recent work on biodiesel synthesis from WCO using a homogeneous catalyst [2]. The WCO biodiesel used in this work was synthesised using a heterogeneous catalyst, which may account for the minor density difference (0.008 g/cm^3). Both WCO and RSO-based biodiesel complied with the standards set forth in ASTM D6751 (0.88 g/cm^3) and EN14214 (0.86–0.9 g/cm^3). Density increases with the increase in the number of double bonds, which means more unsaturated hydrocarbon content. According to Giakoumis [21], the higher the density of the derived methyl ester (biodiesel), the greater the fuel mass needed to inject into the combustion chamber of the diesel engine. The higher density may adversely affect the engine by delaying the time of injection and combustion of the fuel in the engine, thus affecting the efficiency of the fuel atomization for an airless combustion system [10]. Figure 3(b) shows the trends in density for different types of diesel. The density increased with the increasing amount of biodiesel compositions due to the higher density of biodiesel compared to the density of diesel fuel [22]. The density of biodiesel blends B5 and B10 gave almost identical values for both RSO and WCO. However, the difference becomes apparent when the biodiesel content increases to 20% (B20).

The acid value of B100 WCO biodiesel obtained was 0.34 mg KOH/g, which is much lower than the one reported by Phan and Phan [23] of 0.43 mg KOH/g. Whereas, the B100 RSO biodiesel has an acid value of 0.61 mg KOH/g, which is about the same as the value reported by Ramadhas et al. [15] of 0.53 mg KOH/g. The acid value for B100 WCO biodiesel complied with both ASTM D6751 (0.5 max) and EN14214 (0.5 max), whereas this was not the case for B100 RSO biodiesel. The percentage of free fatty acid (FFA) is obtained from the acid value. On the other hand, a higher FFA content leads to a higher acid value. A higher acid value is not preferable for engines as it may cause corrosion in the fuel supply system. Figures 4(a) and (b) show the acid value and FFA trends for various types of diesel. The acid value increased with the increasing amount of biodiesel composition due to the higher acid value of biodiesel compared to the acid value of petrodiesel. The acid value and FFA are related to each other, so the increments in the acid value are also reflected in the value of FFA.



(a) (b)

Figure 4. (a) Acid value and (b) FFA of WCO and RSO blends

The kinematic viscosity at 40°C of B100 WCO biodiesel showed 4.282 mm^2/s, whereas the previous work by Phan and Phan [23] reported a value of 4.89 mm^2/s. Meanwhile, the B100 RSO biodiesel has a kinematic viscosity of 3.95 mm^2/s which is comparable with the reference value of 0.41 mm^2/s [20]. Both the WCO and RSO-based biodiesel complied with both ASTM D6751 (1.9–6.0 mm^2/s) and EN 14214 (3.5-5.0 mm^2/s). The viscosity of diesel fuel (3.6 mm^2/s) is lower than that of biodiesel. Fuels with a higher viscosity provide greater resistance to the flow of fuel, especially at lower temperatures. Kinematic viscosity is important for engine operation because higher viscosity leads to the formation of soot and engine deposits due to insufficient fuel atomization [24]. Figure 5 shows the trends in kinematic viscosity for various types of diesel. The kinematic viscosity of biodiesel is much higher than that of petrodiesel. Therefore, the kinematic viscosity increased with the increasing amount of biodiesel composition from B5 to B20. The WCO blends have slightly higher viscosity compared to the RSO blend, but both fuels comply with both ASTM D6751 and EN 14214 standards. It can be observed that there are no significant differences in the kinematic viscosity of petrodiesel and blended fuel from B5 up to B20. The blending of biodiesel and diesel is done to reduce the density and viscosity of the fuel.

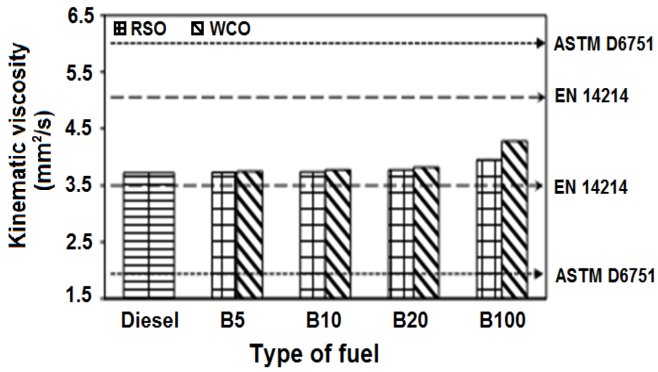


Figure 5. Kinematic viscosity of WCO and RSO blends

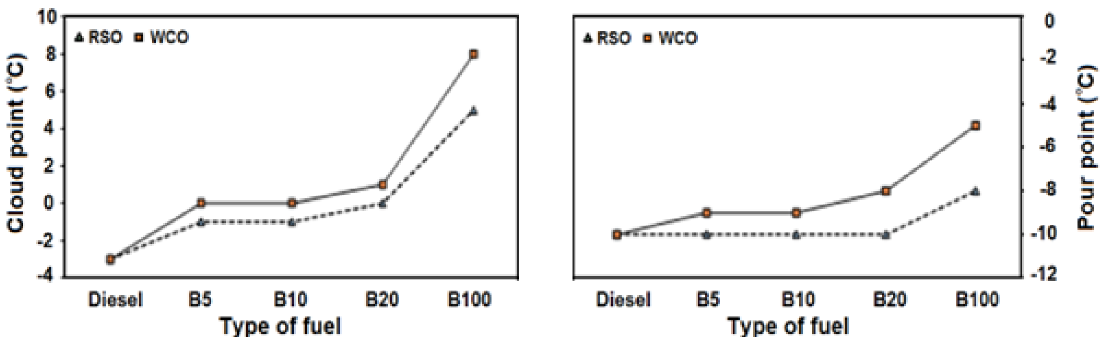


Figure 6. (a) Cloud point and (b) Pour point of WCO and RSO blends

The pour point and cloud point are important behaviours of biodiesel to determine the point where the liquid changes its physical state into crystal wax during cold weather (lower temperature). Fuel with a higher cloud point and pour point may cause blockage in the fuel lines and filters, leading to fuel starvation, engine damage, engine start-up problems, and driving issues [25]. The pour and cloud points of B100 WCO biodiesel were -5°C and 8°C, respectively, which are comparable to the earlier work by Cetinkaya and Karaosmanoglu (2004) of -3°C and 9°C, respectively. Meanwhile, the B100 RSO biodiesel has a pour and cloud point of -8°C and 5°C, respectively. Earlier Bora and Baruah [26] reported almost similar values for B100 RSO biodiesel of -8°C and 4°C for the pour and cloud points, respectively. The cloud and pour points of various fuel types are shown in Figures 6(a) and (b). The cloud and pour points increase with the increasing amount of blending due to the high cloud and pour point values of biodiesel compared to diesel fuel [27].

Engine Test Result

The engine test results for blended and non-blended fuel are shown in Tables 3 and 4. The RSO B5 showed less emission of NO_x (158 ppm) than both the WCO B5 (390 ppm) and petrodiesel (220 ppm) at 1200 rpm. A similar trend was observed even at 2400 rpm and for NO too. WCO is different from virgin RSO because the oil contains higher impurities such as food residue, particles, and other impurities [22]. An observable reduction in power was observed in WCO B5, but it was not observed in RSO B5. According to Vashist and Ahmad [12], the resultant engine power produced from various types of biodiesel blends is generally lower than that of petrodiesel due to the reduction in calorific value; see Figure 3(a). Although the reduction in engine power and torque is minimal at 2400 rpm for biodiesel blends B5 and

B10, respectively. Earlier, Vashist and Ahmad [12] also showed a minimum output power reduction in comparison to petrodiesel for blended biodiesel made of Jatropha and castor seed oil. The inlet temperature may affect overall engine efficiency. The lower inlet temperature often produced more power due to higher efficiency at the theoretical absolute temperature scale [28]. In this work, the inlet temperature for RSO B5 and B10 is slightly lower than the other tests, reflecting the slightly higher resultant engine power produced.

Table 3. Power produced by various blends of RSO and WCO biodiesels

Fuel	Engine speed (rpm)	Intake temperature (°C)	Exhaust temperature (°C)	Ambient temperature (°C)	Engine power (kW)	Engine torque (Nm)
WCO B5	1200	64	231	35	4	31.9
WCO B10	1200	62	158	34	4.2	33.2
RSO B5	1200	60	232	32	4.6	36
RSO B10	1200	61	231	32	4.5	35.9
Diesel	1200	62	227	32	4.4	35
WCO B5	2400	85	403	35	10.8	43
WCO B10	2400	84	405	36	10.4	41.5
RSO B5	2400	69	398	33	11.2	44.5
RSO B10	2400	75	433	34	11.5	45.7
Diesel	2400	84	393	33	11.2	44.6

Table 4. Emissions produced by various blends of RSO and WCO biodiesels

Fuel	Engine speed (rpm)	CO (%)	NO (ppm)	NOx (ppm)	CO_2 (%)	PM (g/m^3)
WCO B5	1200	0.02	372	390	5.1	0.07
WCO B10	1200	0.04	356	371	5.2	0.09
RSO B5	1200	0.02	208	158	3.2	0.115
RSO B10	1200	0.03	218	228	3.3	0.325
Diesel	1200	0.03	263	220	4.2	0.04
WCO B5	2400	0.06	440	451	8	0.275
WCO B10	2400	0.07	416	456	7.8	0.295
RSO B5	2400	0.05	246	258	5.1	0.025
RSO B10	2400	0.04	254	266	5.2	0.04
Diesel	2400	0.05	306	321	6	0.06

CONCLUSION

In this work, it is shown that the blending of biodiesel with petrodiesel has alleviated the issues related to lower engine power and non-compliance with ASTM D6751 and EN 14214 standards. The result has shown that RSO (>10.4 kW) produces higher engine power compared with WCO (4.6 kW) and mineral diesel (4.4 kW). Among the blending ratios tested, the WCO B5 (fuel with 5% WCO biodiesel) provided the best result, which is almost identical to the petrodiesel fuel's characteristics. Moreover, very limited effects on engine performance were observed for B5 blends of WCO and RSO, confirming their suitability for use in automobile engines. Besides that, RSO B20 (fuel with 20% RSO biodiesel) showed excellent compliance in terms of calorific value, kinematic viscosity, and cold flow properties, with a deviation of less than 5% of the petroleum diesel fuel. When the blends were subjected to engine testing, the performance for WCO B5, RSO B5, and petrodiesel in terms of engine power, torque, and CO_2 emissions was similar, although RSO B5 produced less NO_x (158 ppm) than both WCO B5 (390 ppm) and petrodiesel (220 ppm).

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