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Comparative study of diesel engine performance and emission with soybean and waste oil biodiesel fuels

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ABSTRACT

The study investigated the engine performance and emission using biodiesel from soybean oil and waste cooking oil. The fuel properties of these biodiesels were determined using ASTM D6751and EN 14214 standards. The fuels were tested in a multi-cylinder diesel engine with an electromagnetic dynamometer and a 5-gas analyser was used for emission analysis. The result shows that the thermal performance of the engine slightly decreases with increase of the biodiesel blends ratio (i.e. B5, B10, B15, B20 and B50). On the other hand, emission decreases with the increase of biodiesel blends. The reduction in emissions was different for both biodiesels. Waste oil biodiesel showed better trends of emissions reduction with increase of the biodiesel percentage compared with soybean biodiesel. The brake specific fuel consumption (BSFC) of both biodiesels is (6.05%, 9.13%, 12.36% and 18.57% for soybean) and (8.17%, 11.40%, 17.71% and 14.96% for waste cooking oil) higher than diesel, respectively. However, soybean biodiesel consumed less fuel and produced more power and torque compared to waste oil biodiesel. The study concluded that B10 soybean biodiesel blend produced more consistent and expected results than waste oil biodiesel from the performance and emission point of view.

Keywords: Biodiesel; waste cooking oil biodiesel; soybean biodiesel; exhaust emission, BSFC.

INTRODUCTION

Biodiesel is an eco-friendly and renewable source of energy for compression ignition (CI) engines. It can be a potential and sustainable alternative source of fossil fuel with significantly lower emission of greenhouse gases [1]. To determine the suitability of this biodiesel as an alternative source of energy for the CI engine is an interesting research topic today. The use of biodiesel is not new. It was first used by Rudolf Diesel, the inventor of the internal combustion engine, in 1900 [2]. He validated his engine by peanut vegetable oil. At present, most diesel engines run on petroleum-based diesel fuel as it has been cheaper to produce. The energy demand is increasing daily. This increasing energy demand should be met by a cleaner source of energy [3, 4]. Biodiesel is made from renewable plant or animal fats (tallow) that contain fatty acids [5-8], which can be converted into biodiesel using the transesterification reaction [9, 10]. Biodiesel can also be produced from a wide array of feedstocks such as waste cooking oil, edible and non-edible oil seeds, wood and wood waste etc. [11-13]. Research and development is also ongoing to produce biodiesel from microalgae [14]; however, this is still in the development stage. Biodiesel can be used directly in diesel engines or it can be blended with diesel at different strengths [15]. The common way to state biodiesel blends is denoted by the letter B followed by the percent of biodiesel in the fuel [16]. For example, a fuel that has 20% biodiesel will be denoted by B20. When comparing biodiesel to petroleum-based diesel fuel, it is clearly evident that biodiesel is a lot more environmentally friendly [17-22]. A study sponsored by the United States Department of Agriculture and Department of Energy revealed that "Biodiesel yields 3.2 units of fuel product energy for every unit of fossil energy consumed in its life cycle. The production of B20 yields 0.98 units of fuel product energy for every unit of fossil energy consumed" [23]. In the literature it is reported that biodiesel is able to save the environment by reducing harmful emissions, and it can also contribute to the economy [17, 24, 25]. Biodiesel is characterised in generations, namely, first, second and third generation [26]. First generation biodiesel is produced from edible food crops such as mustard oil [27, 28], canola oil [29], sunflower oil etc. [30, 31]. Second generation biodiesel is produced from non-edible feedstocks [32-39]. As food crops are not used to make second generation biodiesel, this type of fuel is more commonly used because it is a more efficient and viable option [40, 41]. Third generation biodiesel is produced from microalgae [14, 42-46]. The research on biodiesel is important from the socio-economic and environmental points of view.

The paper presents a comparative study of engine performance and emission using first generation (soybean) and second generation (waste cooking) biodiesel blends like B5, B10, B15, B20 and B50 with ultra-low sulphur diesel. An experimental study has been conducted on a 4-stroke, 4-cylinder diesel engine fuelled with soybean biodiesel and waste oil biodiesel. Engine performance parameters and emission parameters have been measured and compared with the performance and emission of diesel fuel. The study aims to identify better blends for mining industry engines in Australia.

MATERIALS AND METHODS

Materials

Soybean biodiesel was supplied by National Biodiesel Limited [47], a leading Australian supplier of premium quality biodiesel. The second biodiesel was produced from waste cooking oil, supplied by Central Queensland Technical and Further Education (TAFE) in Mackay, Australia. The biodiesel was blended with petroleum diesel which was used for engine testing.

Fuel Properties of Biodiesel

Analysis of the physical and chemical fuel properties of the biodiesel is very important before use in CI engines. The engine performance and exhaust gas emission depend on the fuel properties, namely density, viscosity, calorific value, cetane number, flash point, pour point etc. These were measured according to the ASTM D6751 and EN 14214 standards. These properties were compared with standard biodiesel and petroleum diesel. The properties of the fuels are presented in Table 1, which shows that almost every property of the fuels is within the acceptable range. The biodiesels have higher density than petroleum diesel, but it has some good fuel properties like higher flash point, pour point and cloud point.

Table 1. Comparison of fuel properties of biodiesels with fossil diesel [10, 48].

Properties	Unit	Diesel	Soybean biodiesel	Waste oil biodiesel	Standard biodiesel
Density at 15°C	kg/m^3	827.2	885	875–900	880
Viscosity	mm^2/s	3.23	4.08	3.77	1.9–6.0
Calorific value	MJ/kg	47.5	39.76	39.78	-
Cetane number	-	58	47–52	39–44	47
Flash point	°C	68.5	69	-	130
Pour point	°C	0	-3	-	- 16
Cloud point	°C	5	-4	-	-3 to -12

Biodiesel Blending

The test biodiesels were blended with ultra-low sulphur diesel in different proportions. For both fuels, the blend samples were prepared by blending 5% biodiesel and 95% diesel denoted as B5, 10% biodiesel with 90% diesel referred to as B10, 20% biodiesel and 80% diesel presented as B20 and 50% biodiesel with 50% diesel denoted as B50.

Test Engine Setup

A Kubota 4-stroke diesel engine was used as the test engine for this study. More specifically the engine is a Kubota V3300 diesel engine with a bore of 98 mm and a stroke of 110 mm. The rated power output of the engine is 50.7 kW at 2600 rpm and the rated torque is 230 Nm at 1400 rpm. The dynamometer used for testing is a Dyno Dynamics engine dynamometer. It works by placing a load on the engine and then measuring the amount of power the engine produces against the load. The dynamometer is coupled with a test bed engine controlled by a computer. The schematic diagram of the test bed engine is presented in Figure 1. Table 2 presents the detailed specification of the test engine and dynamometer.

Table 2. Detailed specification of the test bed engine.

Items	Unit	Specifications
Type	-	Vertical, 4-stroke, liquid-cooled
No. of cylinders	-	4
Bore	mm	98
Stroke	mm	110
Total displacement	L	3.318
Combustion type	-	Spherical type (E-TVCS)
Rated speed	rpm	2800
Compression ratio	-	22.6:1
Rated power	kW	53.9
Fuel injection timing	-	16° before TDC
Injection pressure	MPa	13.73

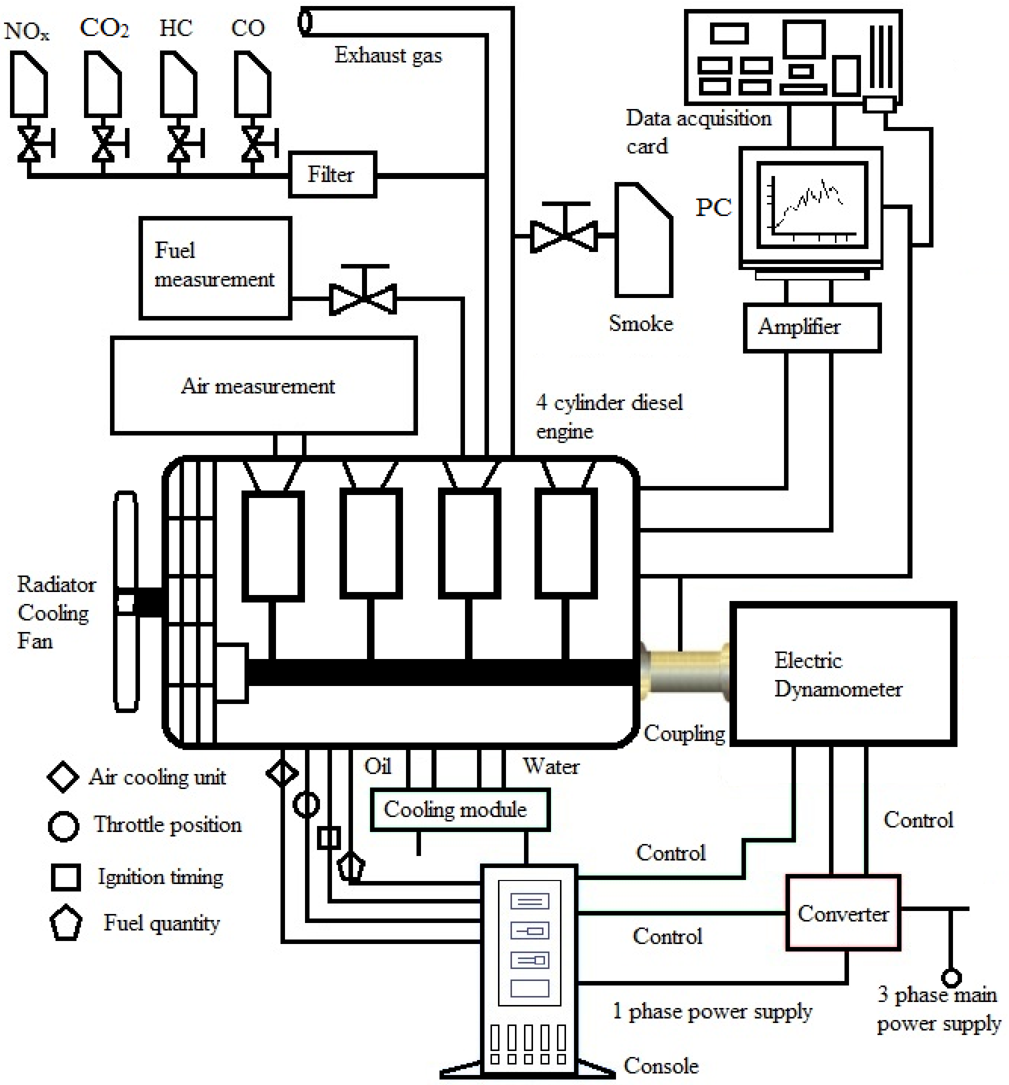

Figure 1. Schematic diagram of the test bed engine setup.

The exhaust gas analyser (EGA) used during testing is an Andros 6241A 5-gas analyser. This EGA takes instantaneous readings of the exhaust gas and can measure carbon monoxide, carbon dioxide and hydrocarbons using a non-dispersive infrared (NDIR) sensor. The EGA can also measure oxygen and nitrogen oxides using an electrochemical sensor. More information like the measurement range, resolution and accuracy of the EGA is presented in Table 3.

Table 3. Detailed specification of the EGA.

Measured gas	Measurement		
	Range	Resolution	Accuracy
HC	0–30,000 ppm (n-Hexane)	1 ppm	±4 ppm abs.
CO	0–15%	0.001%	±0.02% abs.
CO_2	0–20%	0.01%	±0.3% abs.
O_2	0–25%	0.01%	±0.1% abs.
NO_x	0–5,000 ppm	1 ppm	±20 ppm abs.

Testing Method

The International Standard ISO 8178-4 C1 testing method was used in this study. This standard is widely used to measure the exhaust emissions of non-road internal combustion engines. Table 4 shows the testing procedure for the C1 test cycle where the mode is defined as: engine operating point by speed and torque, rated speed. At the start of each test the engine was preconditioned by running the engine at its rated power for 40 minutes. The dynamometer ran a performance curve of the diesel engine and it was found that the engine was not able to reach its rated power of 50.7 kW. From the performance curve it was determined that the maximum torque of the engine occurred at 2300 rpm and as this is less than 60% of the rated speed the intermediate test speed used instead was 60% of the rated speed at 1440 rpm. The idle speed for the dynamometer is 800 rpm, which was chosen as the engine idle speed.

Table 4. ISO 8178-4 test procedure with speed and load values.

Mode	1	2	3	4	5	6	7	8
Speed (rpm)	Rated speed 2400				Intermediate speed, 1440			Idle speed, 80
Torque (N.m)	180	135	90	18	210	158	105	0
Weighting factor	0.15	0.15	0.1	0.1	0.1	0.1	0.1	0.15

RESULTS AND DISCUSSION

Engine Performance Analysis

Figure 2 shows the variation of engine output power with the percentage of biodiesel blends. For both biodiesels, the power production of the engine decreases with increase of the biodiesel percentage. This trend is expected. as biodiesel has a lower energy content (Table 1) than fossil diesel [49, 50]. Figure 2 shows a clear comparison between the two biodiesels, where soybean-based biodiesel has a better power output than waste oil biodiesel. It has been found that B5 and B10 have the maximum power output for both biodiesels, which is close to the fossil diesel output power. Soybean biodiesel blends (B5, B10, B15, B20 and B50) produced 0.22%, 0.44%, 0.85%, 1.52% and 3.05% less power than diesel fuel, respectively. On the other hand, waste oil biodiesel blends (B5, B10, B15, B20 and B50) produced 0.33%, 0.65%, 1.15%, 2.07% and 4.24% less power than diesel fuel, respectively. The result shows that adding biodiesel reduces the power of the engine and the trend of the curve is quite uniform, whereas the value of $R^2 = 0.991$ and 0.988 for soybean biodiesel and waste cooking biodiesel, respectively. For example, the maximum power drops that occurred at B50 for soybean and waste cooking biodiesel were 3.05% and 4.24%, respectively.

Figure 3 illustrates the maximum output torque variation for each biodiesel blend. Waste cooking biodiesel appears to have the expected effect on torque, as the higher biodiesel content consistently results in a lower maximum torque. By comparing Figure 2 and Figure 3, it is evident that the maximum torque and power reflect each other, which is expected as torque and power are directly related [51]. The total torque output decreases gradually with the increase of biodiesel blends [52]. However, the lower torque production for B50 is expected because the property of the biodiesel blends influenced the in-cylinder combustion in the diesel engine [53]. One of the main reasons is that soybean oil contains more than 55% of linoleic acid, which may cause a more viscous fuel when mixing 50% with fossil diesel [54]. The decrease of brake power and torque can be attributed to the biodiesel blends due to the lower energy content (Table 1) and higher viscosity [55]. For soybean biodiesel, 0.45%, 0.91%, 1.59%, 2.27% and 3.18% less torque was produced for the B5, B10, B15, B20 and B50 blends, respectively. On the contrary, waste cooking biodiesel blends (B5, B10, B15, B20 and B50) produced 0.68%, 1.36%, 2.05%, 2.73% and 3.64% less torque compared with diesel fuel, respectively. According to these performance curves (Figure 3), soybean biodiesel (R^2 = 0.999) has better performance than waste cooking biodiesel (R^2 = 0.998). Lambda values from 1.05 to 1.26 have been used for this experiment. The air/fuel ratio was 15.2 to 18.3. Both varied with different rpm.

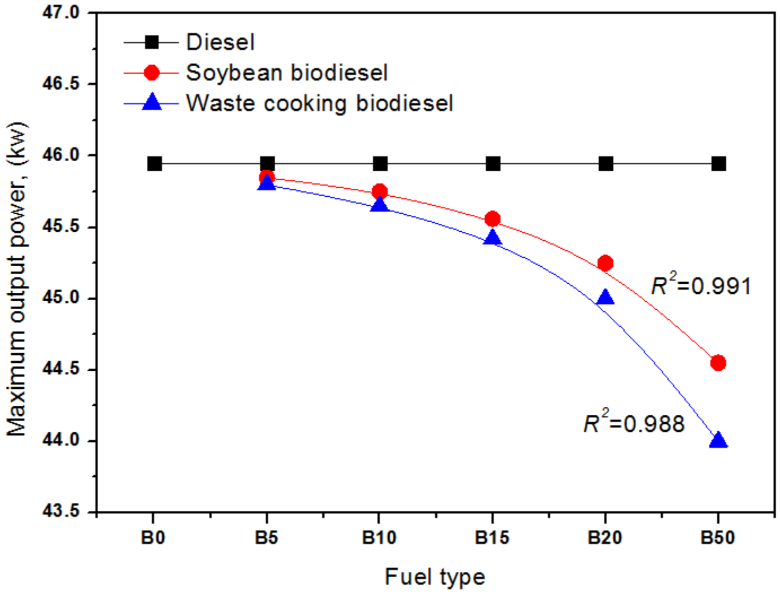

Figure 2. Comparison of maximum output power of diesel and different biodiesel blends.

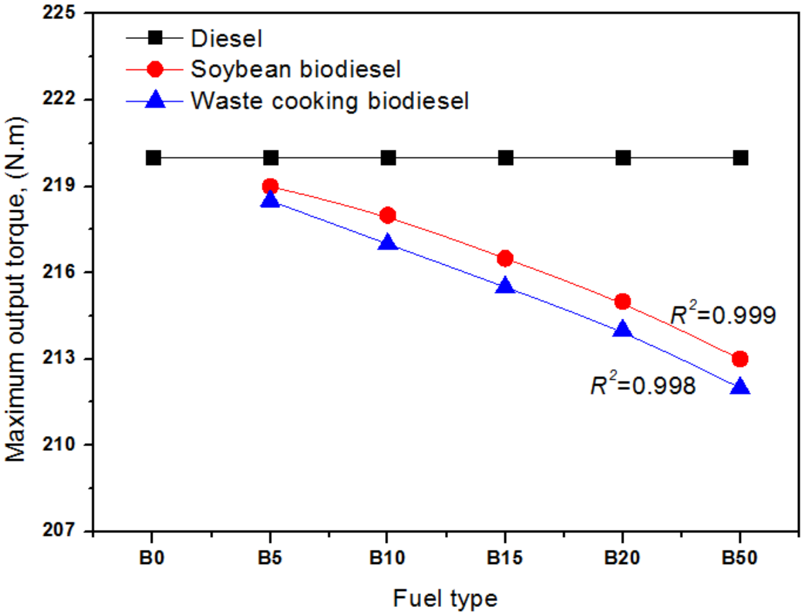

Figure 3. Maximum output torque measured in test engine for diesel and different biodiesel blends.

Brake Specific Fuel Consumption

BSFC is an important factor for engine performance of the fuel. Figure 4 shows the variation of BSFC for different fuel blends over the ISO 8178 test procedure. Fuel flow was calculated in the same way as the emissions, with readings taken at each of the modes and weighting factors applied to get an overall fuel consumption. As shown from Figure 4, biodiesels have higher BSFC than fossil diesel [56]. However, the fuel consumption for B5 soybean biodiesel is lower than other blends. Compared with waste cooking biodiesel blends, soybean biodiesel has lower BSFC except for the B50 blends. The trends of this curve are acceptable according to the literature, as biodiesel has greater fuel consumption due to its lower energy content (Table 1) and higher density [57]. With soybean biodiesel (R^2 = 0.965) the amount of fuel used increases with the biodiesel percentage. BSFC increases for B5, B10, B20 and B50 as 6.05%, 9.13%, 12.36% and 18.57% more than diesel, respectively. For waste oil biodiesel (R^2 = 0.997), BSFC increases from B5 to B20 constantly, but for B50 a slightly lower BSFC has been found. The BSFC is 8.17%, 11.40%, 17.71% and 14.96% higher for B5, B10, B20 and B50 compared with fossil diesel, respectively. It has been reported that BSFC increases with the increase of biodiesel blends [58]. So, the experimental results are acceptable according to the literature [59, 60]. The greater fuel consumption can be attributed to the lower energy content (Table 1) of biodiesel blends compared with fossil diesel. So, soybean biodiesel blends show better performance considering total output power, torque and BSFC compared with waste cooking biodiesel.

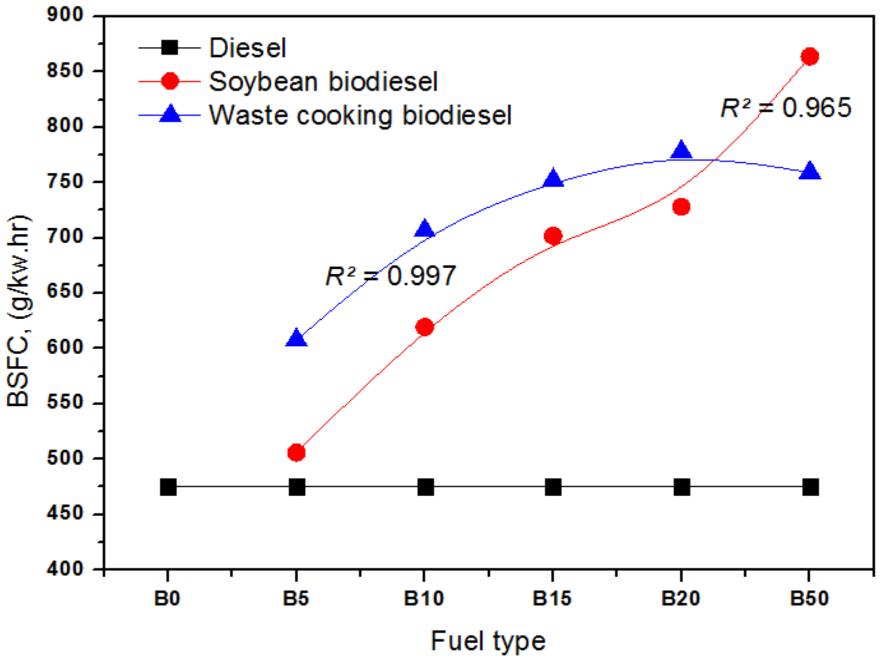

Figure 4. Comparison of brake specific fuel consumption for diesel and biodiesel blends.

Emission Analysis

Emission analysis is an important part of fuel testing in CI engines. In this experiment, CO, CO_2, HC and NO_x emissions have been considered as emission parameters for the diesel and both biodiesels. For this purpose, a gas analyser was installed in the exhaust pipe of the experimental setup. The results of the analysis are briefly discussed below.

Carbon dioxide (CO_2) emission

Figure 5 shows the comparison of CO_2 emissions for the three different test fuels under the ISO 8178 test procedure. It can be seen that the results obtained are different for the two biodiesels. The literature reported that biodiesel is a carbon-neutral fuel and the combustion of biodiesel in CI engines emits lower greenhouse gases than fossil diesel [61, 62].

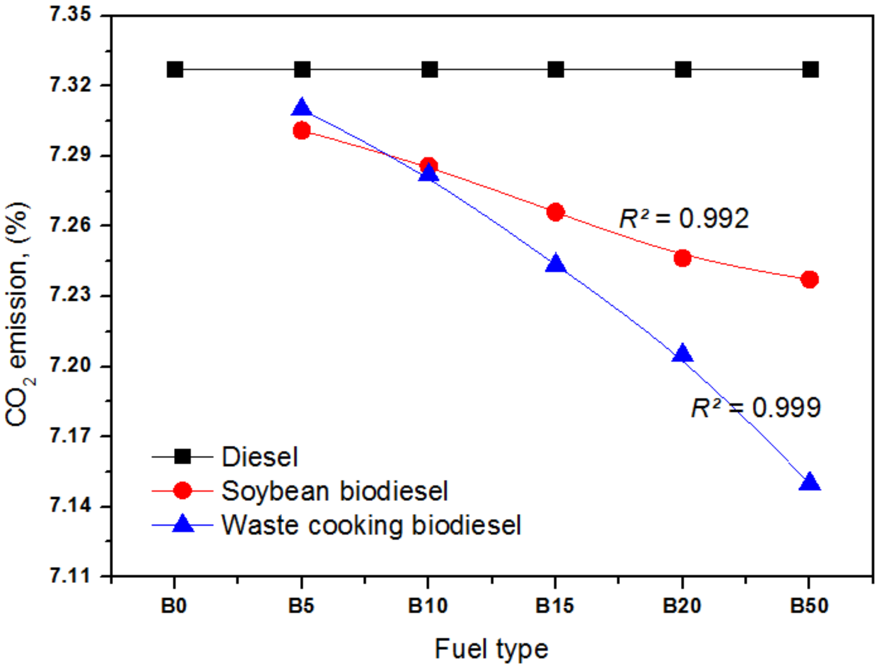

Figure 5. Comparative study of CO_2 emission for diesel and different biodiesel blends.

The trend shows the decrease in CO_2 emission with the increase of biodiesel percentage. For soybean biodiesel, 0.36%, 0.56%, 0.83%, 1.10% and 1.23% reduction of CO_2 emission was recorded for B5, B10, B15, B20 and B50 blends compared with diesel fuel, respectively. Besides, 0.23%, 0.62%, 1.14%, 1.67% and 2.42% reduction of CO_2 emission was observed for waste cooking biodiesel blends, respectively. The trend of reduction for soybean biodiesel (where R^2 = 0.992) is higher than for waste cooking biodiesel (where R^2 = 0.999). The waste cooking biodiesel has a more distinct trend as the more biodiesel is added to the fuel, the more CO_2 emissions are given off. The highest CO_2 reduction occurred using the B50 blend of waste oil biodiesel. The B20 and B50 waste oil biodiesel blends have lower CO_2 readings than diesel fuel.

Carbon monoxide (CO) emission

The literature has reported that CO emissions occur when no excess oxygen is present in the fuel [63]. Some other factors, namely, air/fuel ratio, injection timing, engine speed, injection pressure, fuel characteristics etc. are also related to the CO emission by combustion of fuel in CI engines [64]. Figure 6 shows the variation of CO emissions of the three different fuels, where the majority of the biodiesel emits less CO compared with diesel's CO emissions. For soybean biodiesel, the trend (where R^2 = 0.995) shows 15.49%, 24.83%, 30.48%, 36.13% and 42.79% reduction of CO emission compared with diesel for the B5, B10, B15, B20 and B50 blends, respectively. On the other hand, waste cooking biodiesel emits the lowest CO emission compared with soybean biodiesel. The reduction of CO emission is recorded as 28.45%, 36.03%, 40.96%, 45.89% and 52.32% compared to diesel for the B5, B10, B15 B20 and B50 biodiesel blends, respectively. The trends for CO emission are quite uniform for both biodiesels, where the value of R^2 is 0.995. The experimental data shows that the amount of waste cooking biodiesel has a significant effect on CO, with the results falling between 140 and 180 ppm for blends between 5 and 50% biodiesel. B50 soybean biodiesel has slightly over a 50% reduction in CO emissions. The lower CO reading for the different biodiesels could be attributed to biodiesel having higher oxygen content [65, 66]. A higher oxygen content results in more complete combustion and less CO emission in the exhaust. So, the waste oil biodiesel blends are better from the CO emission point of view.

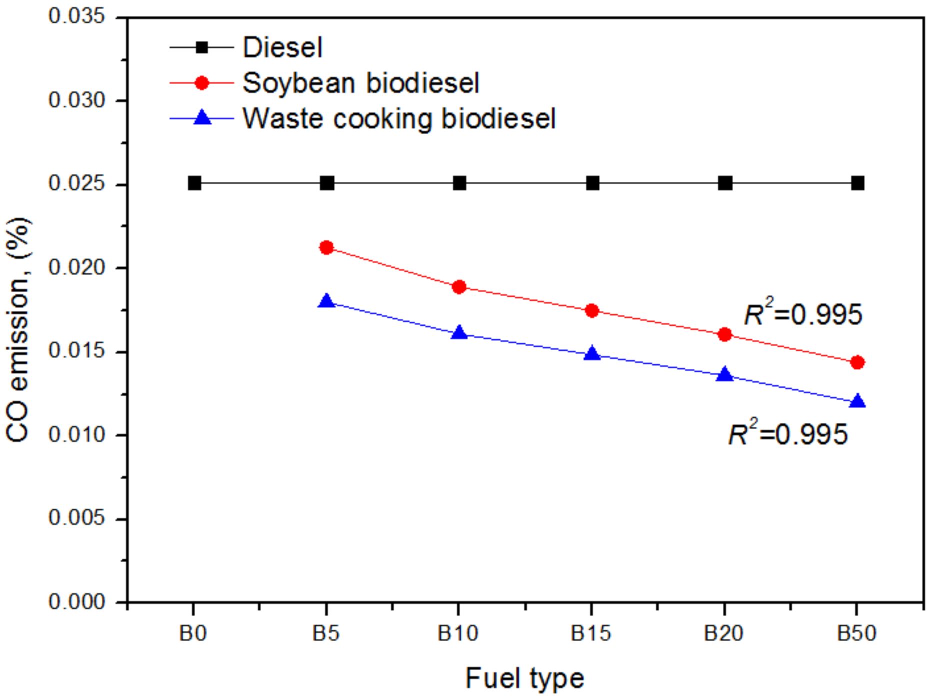

Figure 6. Comparative study of CO emission for diesel and different biodiesel blends.

Hydrocarbon (HC) emission

Figure 7 shows the HC in the exhaust stream for the three different test fuels under the ISO 8178 test procedure. Incomplete combustion of fuel and flame quenching results in the unburned HC emission in CI engines [67, 68]. This occurs when laminar flames enter a region of intense turbulence without a mean flow at instantaneous temperature [69]. As shown in Figure 7, the trends of HC emission for both biodiesels are uniform, where the values of R^2 are 0.988 and 0.995 for soybean and waste cooking biodiesel, respectively. The United States Environmental Protection Agency (US EPA) determined that with an increase in biodiesel the amount of hydrocarbons in the exhaust stream should decrease [70]. The results obtained from this testing for HC emissions are inconclusive and only follow the US EPA statement for the B10, B20 waste oil biodiesel blends and B50 soybean biodiesel. All other blends have a positive impact on HC emission compared with diesel fuel. A reason for these results varying so much is because hydrocarbons make up a very small amount of the exhaust stream [71]. The maximum HC reading was 18 ppm, which equates to 0.0018% of the exhaust gas.

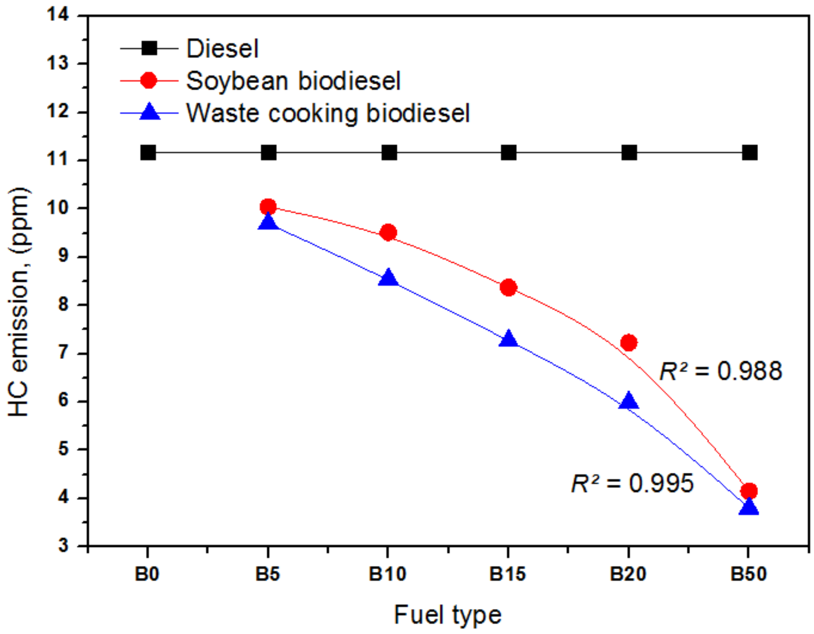

Figure 7. Comparative study of HC emission for diesel and different biodiesel blends.

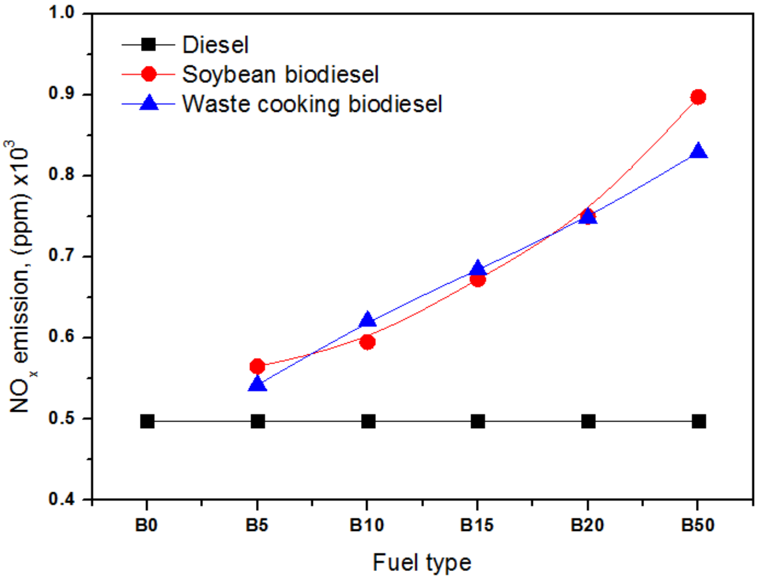

Figure 8. Comparative study of NO_x emission for diesel and different biodiesel blends.

Figure 8 illustrates NO_x emission by combustion of biodiesels in CI engines under the ISO 8178 test procedure. These is evidence from previous studies that NO_x emission is one of the most important problems with the combustion of biodiesel in CI engines [58]. From the graph, it is clearly seen that biodiesels have a positive impact on NO_x emission compared with diesel fuel. For soybean biodiesel, NO_x emission increases by 13.57%, 19.60%, 35.18%, 50.75% compared with diesel fuel for the B5, B10, B20 and B50 biodiesel blends, respectively. Besides, NO_x emission by combustion of B5, B10, B20 and B50 waste cooking biodiesel blends leads to increases of 8.94%, 24.82%, 37.59% and 50.35% of NO_x emission compared with fossil diesel, respectively. The comparison between soybean and waste oil biodiesel shows that the B10 blend of soybean biodiesel emits lower NO_x emission than other blends, as well as other biodiesel. Both biodiesels show increasing trends of NO_x emission. The US EPA report shows that an increase in biodiesel percentage leads to increase of NO_x emissions. As discussed earlier, NO_x has a global warming potential of nearly 300, meaning that it is 300 times worse for the atmosphere than CO_2 emission [66]. So, the small amounts of NOx emission have greater importance than the other exhaust emissions.

CONCLUSIONS

The study experimentally investigated the use of biodiesel as an alternative fuel for diesel engines. The following conclusions can be drawn from the study. The characteristics of these biodiesels and their blends meet the requirement of ASTM D6751 and EN 14214 standards. The ISO 8178 test procedure was followed during the engine performance test and emission study and it was found that biodiesel produced less power and torque and higher BSFC than diesel fuel. The overall performance of B5 and B10 soybean biodiesel was found to be better than other biodiesel blends. These two blends produced 45.85 kW and 218 Nm output power and torque, which are only 0.22% and 0.92% lower power and torque production values compared to diesel fuel. The BSFC of soybean biodiesel is lower than waste oil biodiesel but slightly higher than diesel. With the various emission gases such as CO, CO_2, HC and NO_x, there were no evident trends for the two biodiesels, but for NO_x emission the soybean biodiesel has lower values than waste oil biodiesel. So the soybean biodiesel is better than waste cooking biodiesel.

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NOMENCLATURE

CO_2	[%]	Carbon-di-oxide emission in exhaust gas
CO	[%]	Carbon monoxide emission in exhaust gas
HC	[ppm]	Hydrocarbon emission
NO_x	[ppm]	Nitrogen oxides emission
B5	[-]	5% biodiesel, 95% diesel, by volume
B10	[-]	10% biodiesel, 90% diesel, by volume
B20	[-]	B20% biodiesel, 80% diesel, by volume
B50	[-]	50% biodiesel, 50% diesel, by volume
BSFC	[kg/kw.h]	Brake specific fuel consumption