Gaseous and Particle Emissions from a Compression Ignition Engine Fueled with Biodiesel–Diesel Blends

M. Mofijur, M.G. Rasul, N.M.S. Hassan, M.M.K. Khan and H.K. Rashedul

Abstract This chapter investigates the sustainability of rice bran biodiesel from environmental point of view. In this study, 5 and 20% biodiesel was tested in a naturally aspirated four-stroke multi-cylinder diesel engine at different load and speed conditions. It was found that all biodiesel blended fuel reduces the brake power (BP) and increases brake specific fuel consumption (BSFC) slightly than diesel fuel. Engine emission results indicated that blended fuel reduces the average particulate matter (PM), carbon monoxide (CO), and hydrocarbons (HC) except nitric oxides (NO) emissions than diesel fuel. Finally, it can be concluded that up to 20% rice bran biodiesel could replace diesel fuel to help in controlling the air pollution to a great extent without sacrificing engine power significantly.

1 Introduction

Diesel engines are widely used in the transportation sector as a source of power due to their higher efficiency [1]. Despite the advantages, the exhaust emission of the diesel engines has received lots of attention since the first CI engine emissions standards were introduced by the United States Environmental Protection Agency (USEPA) in 1988 [2]. The small fraction of unburnt hydrocarbon fuel in diesel engines produces a number of incomplete combustion products that directly affect human health, urban air quality, and global climate. The main particulate fraction of

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diesel exhaust contains fine particles, and due to their modest size, these molecules can penetrate deep into the lungs [3].

It has been reported that “vehicle emissions account for some 65% of urban air pollution” [4] which causes more than 25,000 chronic bronchitis in adults and more than 290,000 episodes of bronchitis (children); more than 0.5 million asthma attacks. Australia’s air pollution death toll is higher than fatalities from road accidents. “Each year, on average, 2400 of the 140,000 Australians deaths are linked to air quality and its health related issues—much more than the 1700 people who die on Australian roads. That is an average of a death every 4 h. This number increases if long-term effects of air toxics on cancer are included” [5].

Exhaust pollution includes coarse, fine and ultra-fine particles, gaseous irritants, and polycyclic aromatic hydrocarbons (PAHs). Different emissions have different effect on human health. For example, the PM emission causes lung cancer and cardiopulmonary deaths, NOx emission irritates the lungs and cause edema, bronchitis, and pneumonia; and result in increased sensitivity to dust and pollen in asthmatics, CO emission affects fatal growth in pregnant women and tissue development of young children, HC emission has a synergistic action with other pollutants to promote morbidity in people with respiratory or circulatory problems, and PAHs cause eye irritation, coughing and sneezing, drowsiness, and symptoms akin to drunkenness. Some hydrocarbons have a close affinity for diesel particulates and may contribute to lung disease [6].

Therefore, it is imperative to find the ways to mitigate the air pollution by lowering the exhaust gasses from diesel engines. For this reason, researchers around the world have become concerned about the reduction of exhaust gasses emission. Due to the environmental impact as well as the depletion tendency, several alternative sources have been proposed as potential replacement [7]. The most promising option so far seen is the use of renewable fuel such as biodiesel. Biodiesel has several advantages as a renewable energy resource, i.e., biodiesel is safer to handle, less toxic, biodegradable, and a higher flash point than conventional fossil fuel. Biodiesel has decreased the dependency on crude oil and reduced environmental pollution [8]. It has an ideal combustion-emission profile compared to diesel, such as low emission of carbon dioxide (CO_2), particulate matter (PM), and unburned hydrocarbon (HC) [9]. Commonly biodiesel is produced from vegetable oils [10, 11]. Though the biodiesel fuels have a good number of benefits as a future bioenergy, serious concerns have been raised about the sustainability of future bioenergy development. Sustainability involves economic, environmental, and social issues. This study focuses on the environmental issues of a particular biodiesel.

In particular, the study investigates the sustainability of rice bran biodiesel from the environmental aspects. In this present investigation, 20% rice bran biodiesel was mixed with 80% diesel fuel to use in diesel engine as the researchers believe that the introduction of mandatory biofuel blends (petrol with 10% ethanol and diesel with 20% biodiesel) would reduce the negative environment and health impacts [3].

2 Literature Review

2.1 Description of Rice Bran Oil

Rice bran is the outer layer of the husked rice kernel that is obtained at the time of milling to produce polished rice. Rice bran comprises pericarp, tegmen, aleurone, and sub-aleurone. The oil contents of rice bran are 15–23% [12]. The crude rice bran oil is dark in color, and the triglyceride contents are relatively lower compared to other vegetable oils. Rice bran mostly was used as a cattle feed, and the produced oil was used for industrial purposes. Rice bran oil is a non-conventional oil, and among the non-conventional oils, it is cheaper and readily available. So the production of biodiesel from crude rice bran oil is also cheaper compared to other traditional oils [13].

2.2 Emission Study of Different Biodiesel in Diesel Engine

Labeckas and Slavinskas [14] found that 5–30% rapeseed biodiesel reduces the unburned hydrocarbon significantly at 1400 and 2200 rpm. The 5, 10, 20, and 30% Jatropha biodiesel blends lowered the HC, CO, CO_2, and smoke density significantly than diesel fuel [15]. Rajaraman et al. [16] found that (20–100%) Moringa biodiesel blend combustion in a direct injection diesel engine produces lower HC, CO, PM emission, but higher NOx emission than diesel fuel. Pure Jatropha biodiesel and preheated Jatropha biodiesel produce less engine emission except for NOx emission than diesel fuel due to the presence of higher unsaturated fatty acids of Jatropha biodiesel [17]. It has been found that 5% palm and 5% coconut oil blends in diesel reduce CO emission 7.3–21% and HC emissions 17–23%. Apart from this, 5% coconut oil blends reduce 1 and 5% palm oil blends increases 2% of NOx emission [18]. Biodiesel blended fuels (B5–B75) reduce CO, UHC, and smoke density by 24.7%, 32.5%, and 63%, respectively, but increase NOx emission than diesel fuel because of the higher oxygen contents in biodiesel [19]. Venkanna and Reddy [20] showed that *C. Inophyllum* biodiesel blends fuel (CB10–CB30) gives 11–20% reduction of smoke opacity than diesel fuel at lower load operation. Also, blends provide lower CO emission and higher HC emission than fossil diesel fuel. The addition of isobutanol with diesel–biodiesel blends lowers the PM and NOx emission by 22.4–53.1% and 32.5%, respectively. The increase of biodiesel percentages in the blends lowers 3.45% CO emission, 32.5% NOx emission, and 38.5% PM emission [21]. The Oleander oil (OOME), Kusum oil (KOME), and bitter Groundnut oil (BGOME) biodiesel lower the CO, HC emissions, and smoke opacity than diesel fuel. But it gives higher NOx emissions due to the higher oxygen contents and exhaust gas temperature [22]. Man et al. [23] studied the regulated and unregulated emission of waste cooking oil biodiesel blends (B10–B30) at different engine load and speed condition. They reported that the increase of biodiesel fuel in the blends offers the reductions of HC, CO, and particulate mass concentrations, but an increase in NOx emission than diesel fuel. The unregulated emission, acetaldehyde, and formaldehyde emissions increase with increasing the percentage of biodiesel in the blends. But a reduction in the toluene and xylene emissions was reported for biodiesel blends. From all the emission results, it is seen that the emissions are affected by the engine operating condition, biodiesel type, and biodiesel percentages.

2.3 Formation of Gaseous Emission

The emissions are mainly due to the incomplete combustion in the cylinder [24]. So it is important to know the theoretical description of how they are formed so that mitigation steps of the harmful emission to the environment can be undertaken.

The oxidation of nitrogen (from the intake air) under high-temperature conditions is responsible for the formation of nitrogen oxides (NOx). NOx collectively refers to two chemical compounds, namely: nitric oxide (NO) and nitrogen dioxide (NO_2) [25]. The NO_2/NOx ratio is highly dependent on the engine technology and after-treatment system utilized. The theory of NOx formation is best commenced by discussing the well-known extended Zeldovich mechanism, which consists of the following three chemical equations [24]:

$$\begin{aligned}&O + N_2 \leftrightarrow NO + N\\&ON + O_2 \leftrightarrow NO + O\\&N + OH \leftrightarrow NO + H\end{aligned}$$

A notable feature of these three chemical equations is their strong temperature sensitivity.

HCs are another incomplete combustion product found in CI engine exhaust [26]. The primary cause of HC emissions is due to the preparation of an over-rich or over-lean air–fuel mixture that is not able to support complete combustion [24]. Over-leaning predominates under idle and light load conditions; however, over-fueling can occur under high load operation due to decrease in the air–fuel ratio in the spray core and near the combustion chamber walls [27]. Incomplete oxidation of the carbonaceous component of hydrocarbon fuels to carbon dioxide under conditions of low exhaust gas temperatures is responsible for the formation of CO [27]. The primary parameter that governs the formation of CO in internal combustion engines is the air–fuel ratio [24]. Fuel-rich conditions are responsible for forming CO as there is insufficient oxygen available to oxidize carbon to CO_2 fully. Oxidation catalysts are very effective at removing CO emissions from CI engine exhaust, especially under high load conditions.

Diesel particulate matter (DPM) is a complex, multi-pollutant mixture of solid and liquid particles suspended in a gas [28]. DPM is a very dynamic physical and chemical system that exhibits very strong spatial and temporal dependency regarding its composition [29]. DPM is a very dynamic physical and chemical system that exhibits adamant spatial and temporal dependency regarding its composition [30], the engine operating condition (e.g., speed/load, injection timing, and strategy), the presence of after-treatment devices (such as a diesel particle filter), the maintenance status of the engine, as well as the type of fuel and lubricants used.

3 Materials and Method

3.1 Materials

In this study, rice bran oil has been used as a biodiesel source as the crude rice bran oil is a low-cost feedstock, and it is not a common source of edible oil compared to other conventional seed sources. Crude rice bran oil was collected from a colleague through personal communication. All other reagents, methanol, filter paper 150 mm were available in the chemical laboratory.

3.2 Biodiesel Fuel Production Procedure

Free fatty acid (FFA) and acid values are the primary identifiers of the production process. The acid value of crude oil was found 1.6 g/KOH, which indicates that esterification (the chemical reaction in which an alcohol and an acid form an ester as the reaction product) is not necessary to produce biodiesel from crude rice bran oil. Because, if the crude oil contains a higher acid value, then two-step processes are required considering the formation of fatty acid salts during the conversion of FFA into Fatty acid methyl ester (FAME) using an alkaline catalyst [17]. The fatty acid salt prevents the separation of FAME layer from glycerin.

In this study, a small-scale water jacketed laboratory reactor 1.8 L in size equipped with reflux condenser, thermometer, and magnetic stirrer was used to produce biodiesel from crude rice bran oil. Figure 1 shows the flow process of rice bran biodiesel, and Fig. 2 shows the production process of rice bran biodiesel. In this process, 1 L of preheated crude rice bran oil was allowed to react with

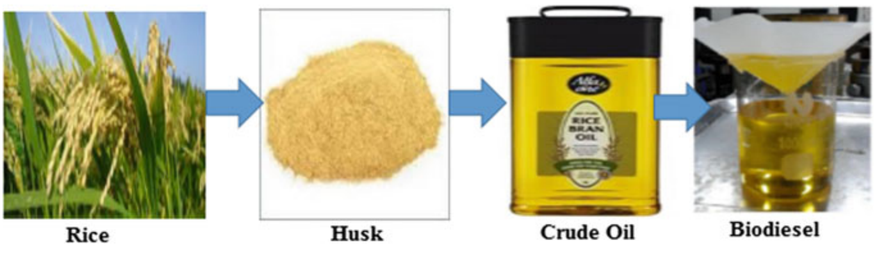

Fig. 1 Flow process of rice bran biodiesel

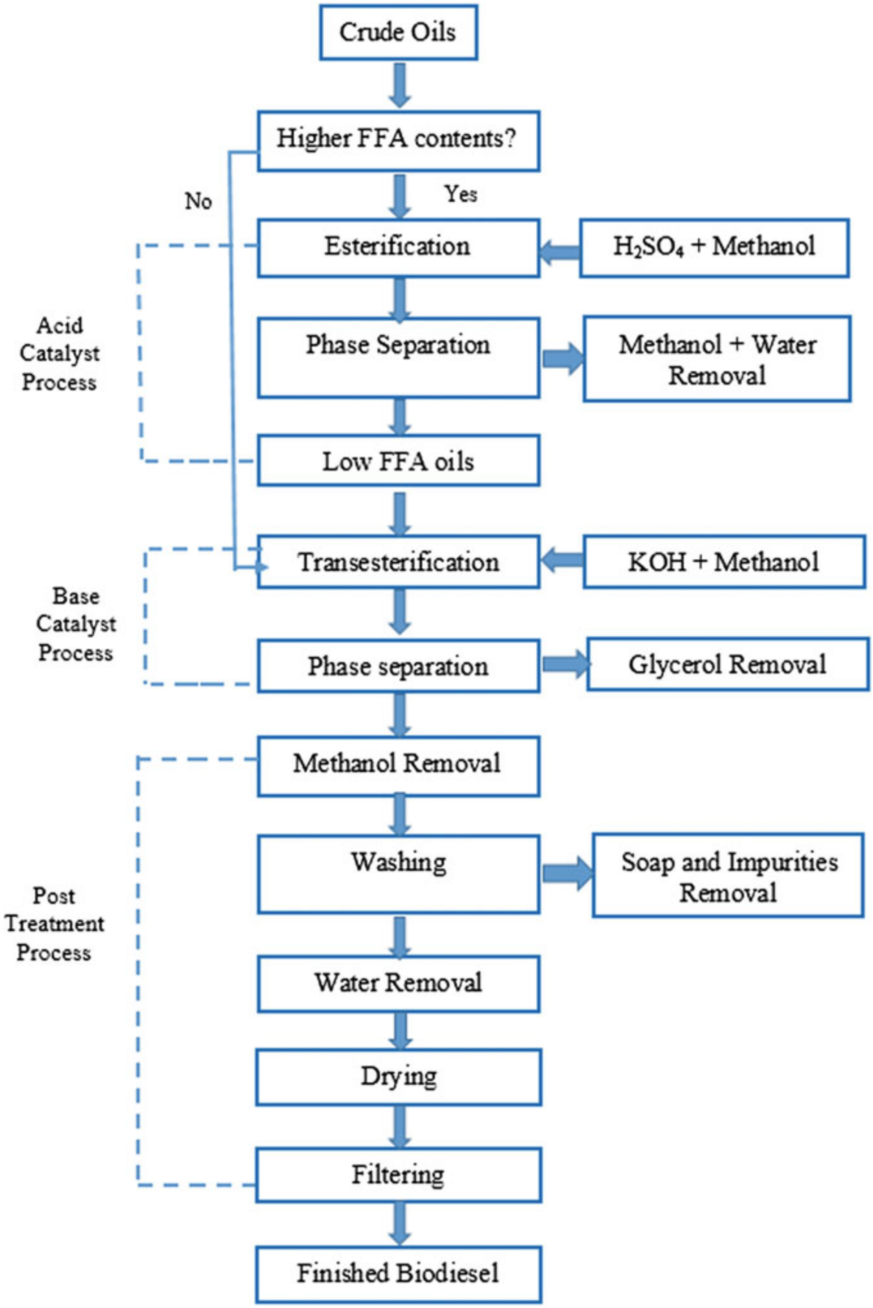

Fig. 2 Production process of rice bran biodiesel

6:1 molar ratio (methanol to oil) in the presence of 1% (w/w) of potassium hydroxide (KOH) catalyst. The reaction was maintained at 60 °C for 2 h at the speed of 800 rpm. After completion of the reaction, the mixture was poured into a separation funnel left for 12 h to be cooled, settled and glycerol to be separated from biodiesel. The upper part of the funnel contains biodiesel, and the bottom was glycerin which contains excess methanol and impurities. The biodiesel was collected, and the glycerin was drawn off. The produced biodiesel was then heated at 65 °C to remove remain methanol. Then the biodiesel was washed using warm distilled water to remove all impurities. Finally, the washed biodiesel was dried using Na_2SO_4 and filtered through a filter paper. The final product was collected and stored for characterization. The biodiesel yield was found more than 90% which was calculated using following formula:

$$\%\,Yield:\left(\frac{amount\ of\ methyl\ ester\ produced}{amount\ of\ oil\ taken}\right)\times 100.$$

3.3 Characterization of Biodiesel Fuel

The physical and chemical properties of the crude oil and biodiesel fuels were tested according to the ASTM D6751 standards. Table 1 shows the list of the equipment used in this study to characterize the biodiesel. Fatty acid composition was tested using gas chromatography (Agilent 6890 model, USA). Cetane number (CN), iodine value (IV), saponification value (SV), degree of unsaturation (DU),

Table 1 List of equipment used in this study

Property	Equipment	Standard method	Accuracy
Kinematic viscosity	NVB classic (Norma lab, France)	ASTM D445	±0.01 mm^2/s
Density	DM40 LiquiPhysics™ density meter (Mettler Toledo, Switzerland)	ASTM D127	±0.1 kg/m^3
Flash point	NPM 440 Pensky-martens flash point tester (Norma Lab, France)	ASTM D93	±0.1 °C
Cloud and pour point	NTE 450 cloud and pour point tester (Norma lab, France)	ASTM D2500	±0.1 °C
Heating value	6100EF semi auto bomb calorimeter (Perr, USA)	ASTM D240	±0.001 MJ/kg
Acid value	Automation titration rondo 20 (Mettler Toledo, Switzerland)	ASTMD664 and EN 14111	±0.001 mg KOH/g
Oxidation stability, 110 °C	873 Rancimat (Metrohm, Switzerland)	EN 14112	±0.01 h

and long chain saturated factor (LCSF) were determined using the following equations [31]:

$$CN = 46.3 + (5458/SV) - (0.225 \times IV) \quad (1)$$

$$SV = \Sigma(560 \times A_i)/M_{wi} \quad (2)$$

$$IV = \Sigma(254 \times A_i \times D)/M_{wi} \quad (3)$$

$$\begin{aligned} LCSF = {} & 0.1 \cdot (C16:0, wt.\%) + 0.5 \cdot (C18:0\,wt.\%) + 1 \cdot (C20:0\,wt.\%) \\ & + 1.5 \cdot (C22:0\,wt.\%) + 2.0 \cdot (C24:0\,wt.\%) \end{aligned} \quad (4)$$

$$DU = \Sigma(Mono\ Unsaturated\ Fatty\ Acid + 2.\,Poly\ Unsaturated\ Fatty\ Acids) \quad (5)$$

where *Ai* is the percentage of each component, *D* is the number of double bonds, and *Mw* is the molecular mass of each component.

3.4 Engine Test

First, the engine was run using diesel fuel for a few minutes to warm up before switching to the biodiesel blend. Furthermore, the engine was run with diesel fuel before it was shut down. Figure 3 shows the engine test bed, and Fig. 4 shows the schematic diagram of the engine test bed. Table 2 shows the specifications of the engine used in this study. A CODA 5 exhaust gas analyzer (Fig. 5a) was used to measure the NOx, HC, and CO emissions from the engine, and an MPM-4 M particulate meter (Fig. 5b) was used to measure the PM emission.

Fig. 3 Engine test bed

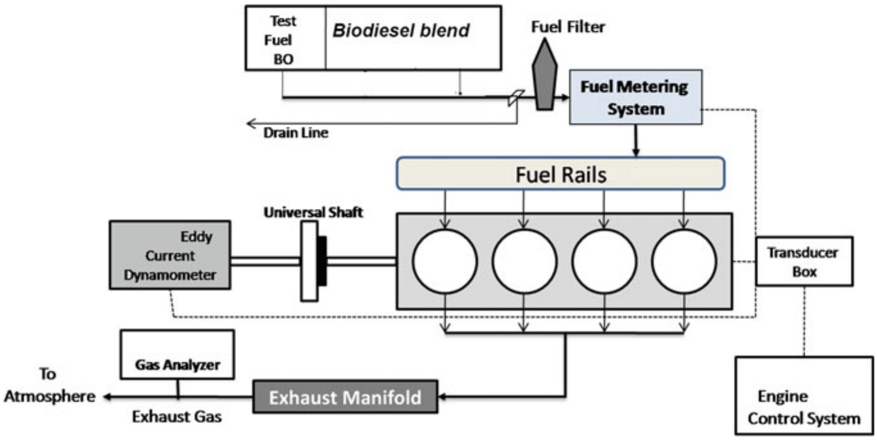

Fig. 4 Schematic diagram of engine test bed

Table 2 The specifications of the engine used in this study

Model	Kubota V3300
Type	Vertical, 4 cycle liquid cooled diesel
No. of cylinder	4
Total displacement (L)	3.318
Bore × Stroke (mm)	98 × 110
Combustion system	E-TVCS
Intake system	Natural aspired
Output	
Gross intermittent (kW/rpm)	54.5/2600
Net intermittent (Rated power output) (kW/rpm)	50.7/2600
Net continuous (kW/rpm)	44.1/2600
Rated torque (N m/rpm)	230/1400
Compression ratio	22.6
No load high idling speed (rpm)	2800
No load low idling speed (rpm)	700–750
Direction of rotation	Counter clockwise (viewed from flywheel side)
Governing	Centrifugal fly weight high-speed governor
Fuel	Diesel fuel No-2-D (ASTM D975)
Starter capacity (V-kW)	12-2.5
Alternator capacity (V-A)	12-60

A Kubota (model V3300) multi-cylinder diesel engine was used to perform the performance and emission test. In the performance and emission study, B5 and B20 fuels were used based on the suggestion from the literature [32, 33] that up to 20%

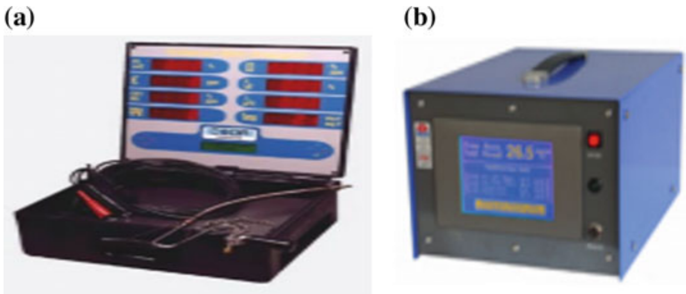

Fig. 5 Equipment for emission test **a** CODA gas analyzer **b** PM monitor

Table 3 Properties of crude rice bran oil

Properties	Rice bran oil
Kinematic viscosity (mm^2/s) at 40 °C	52
Density (kg/m^3) at 15 °C	924
Higher heating value (MJ/kg)	39.5
Acid value (mg KOH/g)	1.3
Flash point (°C)	301
Pour point (°C)	0
CFPP (°C)	16

biodiesel can be used in a diesel engine with no modifications. Engine performance data were collected at full load condition and at different speeds ranging from 1200 to 2400 rpm at an interval of 200 rpm, whereas emission data was collected at a different speed (at idle speed and the speed at which maximum torque was found) and at full load conditions. The emission data also have been investigated at intermittent speed (1800 rpm) and different load conditions (25–100%).

4 Results and Discussion

4.1 Properties of Fuel Samples

The characterization of biodiesel is very important as the suitability of biodiesel as a diesel fuel is determined by the physical and chemical properties. The physical and chemical properties results of crude rice bran oil and rice bran biodiesel are given in the following sections.

4.1.1 Properties of Crude Oils

The crude rice bran oil was characterized by viscosity, density, flash point, acid value, higher heating value. The properties of rice bran oil are presented in Table 3.

The viscosity of crude oil was found 52 mm^2/s which are 15–16 times greater than conventional diesel fuel. The flash point, pour point, and cold filter plugging point were found 301 °C, 0 °C, and 16 °C, respectively. The acid value was determined 1.3 mg KOH/g which is similar with the other conventional biodiesel feedstocks.

4.1.2 Physical Properties of Biodiesel Fuel

The fuel properties of rice bran biodiesel were analyzed and compared with diesel and ASTM D6751 standards. Table 4 shows the fuel properties of rice bran biodiesel. It was found that the kinematic viscosity (KV) of rice bran is 5.37 mm^2/s. However, all these results are within the specified limit ASTM D6751 standards (1.9–6 mm^2/s). The flash point (FP) was found 174.5 °C, which is much higher than diesel fuel (68.5 °C) that indicates rice bran biodiesel fuel is safer to handle and storage. The oxidation stability and higher heating value of rice bran biodiesel were found 1.61 h and 39.50 MJ/kg, respectively.

4.1.3 Chemical Properties of Biodiesel Fuel

Fatty acid composition is an important chemical property of biodiesel fuel. Fatty acids are categorized into saturated and unsaturated fatty acid. A fatty acid that does not contain double bond is known as saturated fatty acid, and that contains double bond is known as unsaturated fatty acid. Table 5 shows the fatty acid composition of rice bran oil. It can be seen that rice bran biodiesel has 24.20% saturated and 75.80% unsaturated fatty acids. Oleic acid (18:1) was the predominant fatty acid (43.5%) in rice bran biodiesel sample. The degree of unsaturation and long chain saturated factor was found 107.40 and 5.08, respectively.

Table 4 Properties of biodiesel and diesel fuel

Properties	Unit	RB100	Diesel	ASTMD 6751 [34]
Kinematic viscosity at 40 °C	mm^2/s	5.37	3.23	1.9–6
Density at 15 °C	kg/m^3	887	827.2	–
Higher heating value	MJ/kg	39.50	45.30	–
Oxidation stability	h	1.61	–	3 min
Flash point	°C	174.5	68.5	130 min
Pour point	°C	−3	0	–
Cloud point	°C	0	8	Report
CFPP	°C	2	5	–
Cetane number	–	51.30	48	47 min
Iodine number	–	97.52	–	–
Saponification value	–	202.55	–	–

Table 5 Fatty acid composition of rice bran biodiesel

Fatty acids	Molecular weight	Structure	Formula	Rice bran biodiesel (wt%)
Lauric	200	12:0	$C_{12}H_{24}O_2$	0.1
Myristic acid	228	14:0	$C_{14}H_{28}O_2$	0.3
Palmitic	256	16:0	$C_{16}H_{32}O_2$	20.3
Palmitoleic	254	16:1	$C_{16}H_{30}O_2$	0.2
Stearic	284	18:0	$C_{18}H_{36}O_2$	2.0
Oleic	282	18:1	$C_{18}H_{34}O_2$	43.5
Linoleic	280	18:2	$C_{18}H_{32}O_2$	31.0
Linolenic	278	18:3	$C_{18}H_{30}O_2$	0.6
Arachidic	312	20:0	$C_{20}H_{40}O_2$	0.8
Eicosenoic	310	20:1	$C_{20}H_{38}O_2$	0.5
Behenic	340	22:0	$C_{22}H_{44}O_2$	0.3
Lignoceric	368	24:0	$C_{24}H_{48}O_2$	0.4
Total saturated fatty acid				24.20
Total monounsaturated fatty acid (MUFA)				44.20
Total polyunsaturated fatty acid (PUFA)				31.60
Degree of unsaturation (DU)				107.40
Long chain saturated factor (LCSF)				5.08

4.2 Engine Performance Study

4.2.1 Brake Torque

Figure 6 shows the engine brake torque (BP) output of B5 (5% rice bran biodiesel and 95% diesel fuel), B20 (20% rice bran biodiesel and 80% diesel fuel), and B0 (pure diesel fuel) at different engine speeds. It is clear that engine torque for diesel fuel is higher than that for biodiesel blended fuel, which is also supported by other researchers [35, 36]. The engine torque lowered with increasing the engine speed and increasing the percentage of biodiesel fuel in the blend. In an average, diesel fuel gives the highest torque followed by the B5 and B20, which is 202 Nm, 195 Nm, and 185 Nm, respectively. The maximum torque for B0, B5, and B20 fuel samples were observed 220 Nm, 214 Nm, and 204 Nm, respectively, at 1400 rpm. At all test speeds, B5 and B20 fuels reduce the torque by 3 and 8% than diesel fuel. The reduction of torque for biodiesel–diesel blended fuel can be attributed to the heating value of biodiesel fuel [37]. The heating value of rice bran biodiesel is lower than diesel fuel (Table 4). Aydin et al. [38] also reported that the engine torque was decreased with the increased percentage of biodiesel in the blends due to the higher viscosity and lower heating value of biodiesel fuel.

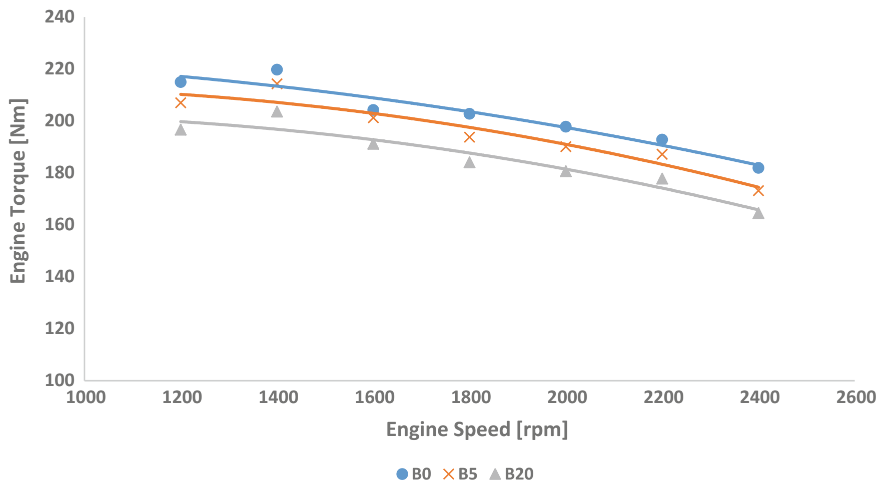

Fig. 6 Variation of brake torque on the speed

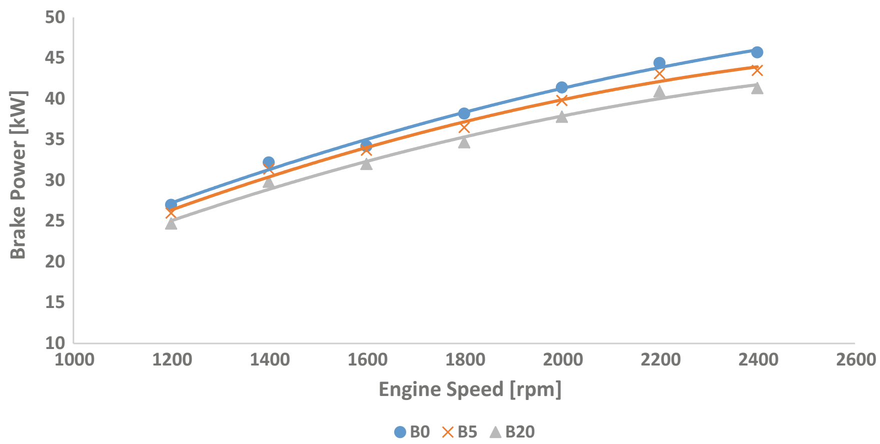

Fig. 7 Variation of brake power on the speed

4.2.2 Brake Power

The engine brake power (BP) output of B5, B20, and B0 at different engine speeds are shown in Fig. 7. It can be seen that the brake power for diesel fuel is higher than that for biodiesel blended fuel, which is also supported by other researchers [35, 36]. The brake power is lowered with increasing the proportion of biodiesel in the blends and increased with increasing the speeds. The average brake power for B0, B5, and B20 is 37.6, 36.3, and 34.5 kW, respectively. The maximum brake power was found 45.7 kW for diesel fuel at 2400 rpm. The blends, B5 and B20 fuels reduce the brake power by 3.46 and 8.29% compared to diesel fuel. The reduction of BP for biodiesel–diesel blended fuel can be attributed to the heating value of biodiesel fuel [37] which is commonly agreed by most of the researchers. The heating value of rice bran biodiesel is lower than diesel fuel (Table 4). Carraretto et al. [39] also found that the increase of biodiesel percentage in the blends resulted in a slight decrease of power over the entire speed range for different combinations.

4.3 Engine Emission Study

4.3.1 Carbon Monoxide (CO) Emission

Figure 8a shows the variation of CO emission by running the engine using B5, B20, and B0 at 1800 rpm and different load conditions. It is seen that CO emission

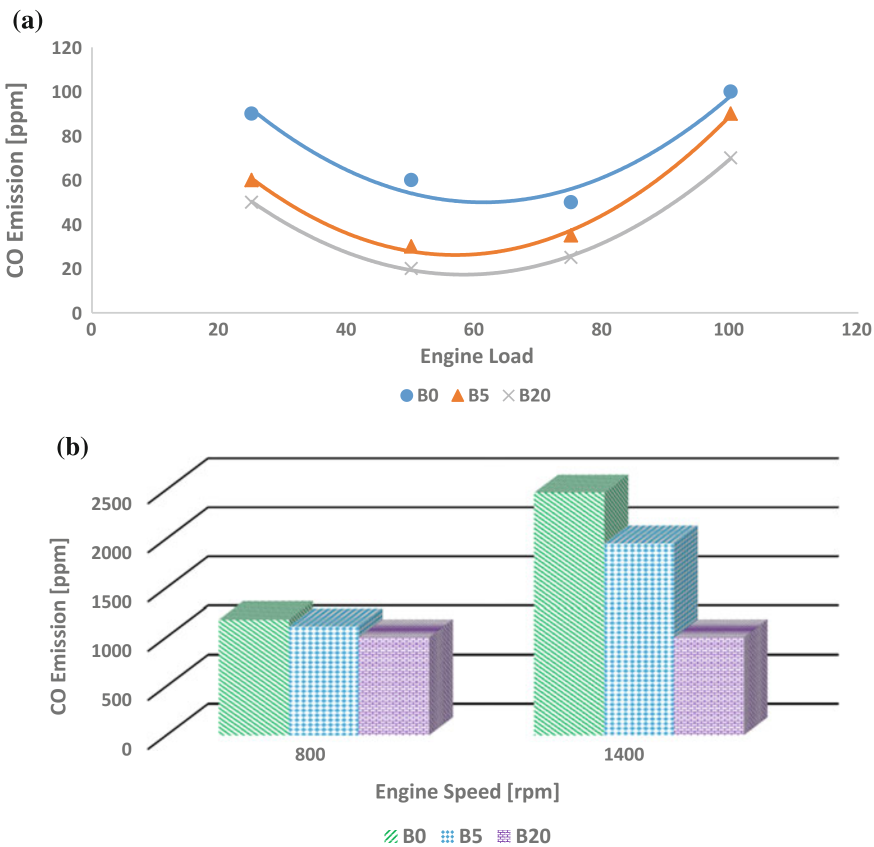

Fig. 8 Variation of CO emission **a** at 1800 rpm and different loads **b** at idle speed and 1400 rpm

increases significantly at lower load condition, decreased at moderate load, and increased slightly at full load. The air–fuel mixing process is affected by the atomization of the blend at low load due to its higher viscosity. The resulting locally rich mixtures cause more CO emission during combustion. Authors in [40] also found that CO emissions decreased as load increased, but they increased slightly at heavy load or full load.

The variation of CO emission of biodiesel blended fuel with engine speed is shown in Fig. 8b. It is seen (Fig. 8b) that over the entire range of speed, the biodiesel fuels provide lower CO emission than diesel fuel. Similar results were also found by the researchers [41]. CO emission is increased with increasing engine speed from idle speed to 1400 rpm. The increase of biodiesel proportion in the blends lowers the CO emission significantly. At 800 rpm fuel samples B0, B5, and B20 produce 1180 ppm, 1110, and 1000 ppm, respectively, while at 1400 rpm B0, B5, and B20 produce 1100 ppm, 1010, and 600 ppm, respectively. Biodiesel blended fuel reduce CO emission by (5.9–59.5%) at both speed condition. Lowering CO emission for biodiesel fuel can be explained by the higher oxygen contents and higher cetane number of biodiesel fuel. Biodiesel fuel contains 12% higher oxygen, which allows more carbon molecules to burn and combustion becomes completed [15].

4.3.2 Hydrocarbon (HC) Emission

Figures 9a, b show the variation of HC emission by running the engine using B5, B20, and B0 at a different speed and different load conditions. It is found that in all operating conditions, HC emission is decreased as the percentages of biodiesel increased in the blends. It is also evident that at lower load condition HC emission is higher, at moderate load is lower, and at a full load slightly higher. Authors [42, 43] also observed that the HC emissions of biodiesel fuel are lower at low load, but it was reported that a greater decrease occurred at intermediate load than lower and higher load condition. However, at lower speed condition, the HC emission is lower compared to the higher speed condition for all fuel samples. Similar results were also reported by the other researchers [41]. For example, Wu et al. [40] found 45–67% reduction in HC emission on average than diesel fuel.

Unlike to the CO emission, the HC emission decreased with the engine speed. At 800 rpm fuel samples B0, B5, and B20 produce 7 ppm, 5, and 2 ppm, respectively, while at 1400 rpm B0, B5, and B20 produce 6 ppm, 4, and 3 ppm, respectively. In average, biodiesel blended fuel reduce HC emission by (28–71%) at all operating conditions. The reason of lowering HC emission could be attributed to the combined effect of oxygen content and cetane number as explained for CO emission [17, 37].

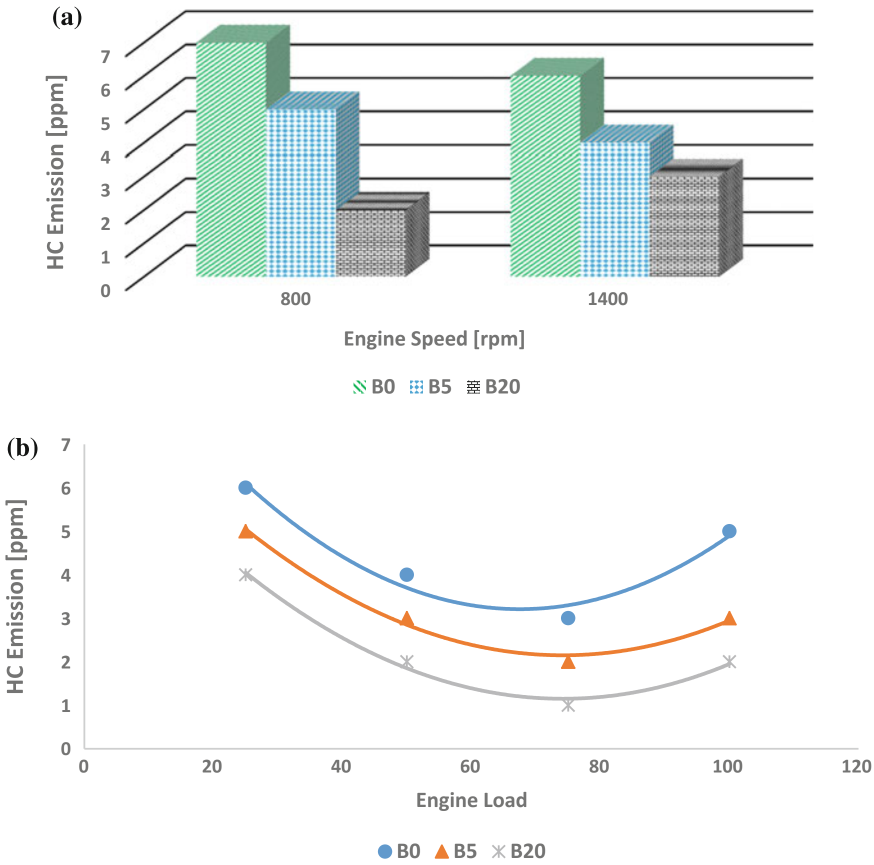

Fig. 9 Variation of HC emission **a** at idle speed and 1400 rpm **b** at 1800 rpm and different loads

4.3.3 Nitrogen Oxides (NOx) Emission

NOx emission is reported by the many authors to be increased for biodiesel blended fuel. The variation NOx emission with different engine speed and load for various blended fuel is shown in Fig. 10a, b. As shown therein, the NOx emission increased with the engine load at intermediate speed due to the higher combustion temperature and local stoichiometry of the blends. It is also found that biodiesel blended fuel gives (6.8–12.3%) higher NOx than diesel fuel and NOx emission is increased as the percentages of biodiesel increased in the mixture.

The NOx variation of fuel samples with engine speed showed a similar trend of load condition. NOx emission also increased with the engine speed. At idle speed condition, B5 gives the highest NOx emission, whereas B20 showed maximum NOx emission at 1400 rpm than diesel fuel. The higher combustion temperatures in the cylinder and presence of oxygen in the blends caused higher NOx emission [25].

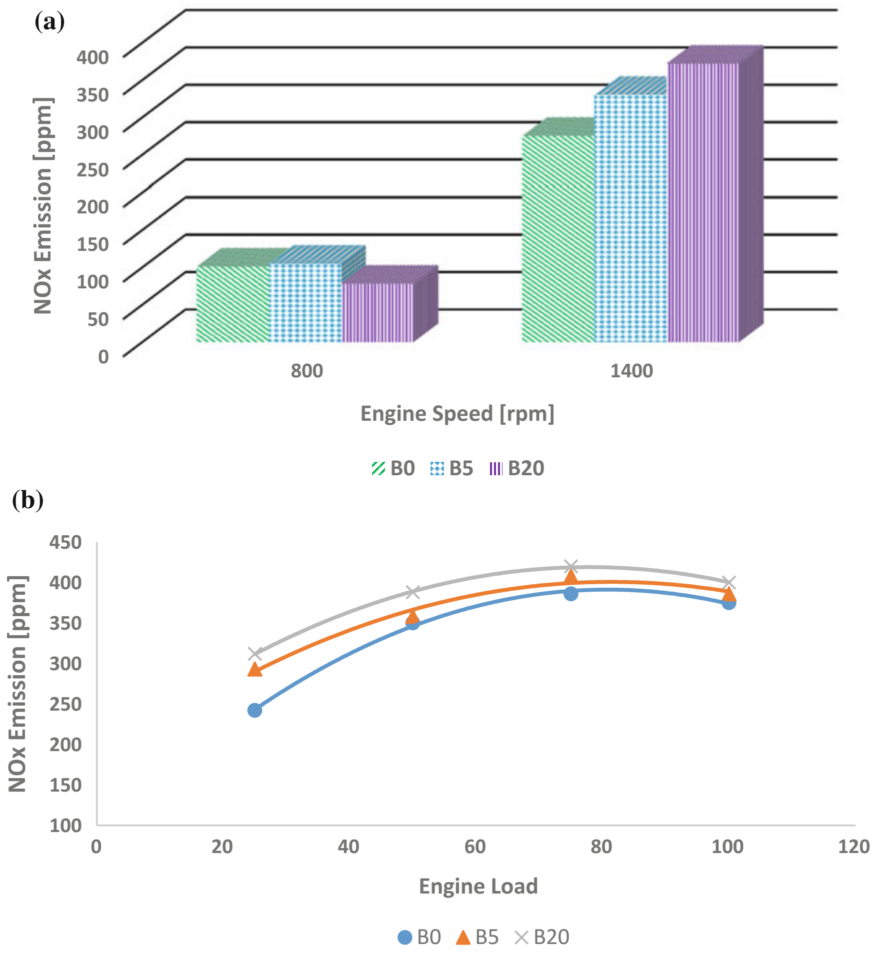

Fig. 10 Variation of NOx emission **a** at idle speed and 1400 rpm **b** at 1800 rpm and different loads

Also, higher exhaust gas temperatures with the fuels provided the higher NOx emission. It is also agreed that inherent oxygen in the biodiesel fuel is more efficient to produce higher NOx than the oxygen supplied with the air [38].

4.3.4 Particulate Matter (PM) Emission

The variation of PM emission for different fuels as a function of load and speed is presented in Fig. 11a, b. It is found that biodiesel fuel lowers 5–9.85 and 60–74% PM emission in both idle speed and 1400 rpm, respectively, than diesel fuel. Also,

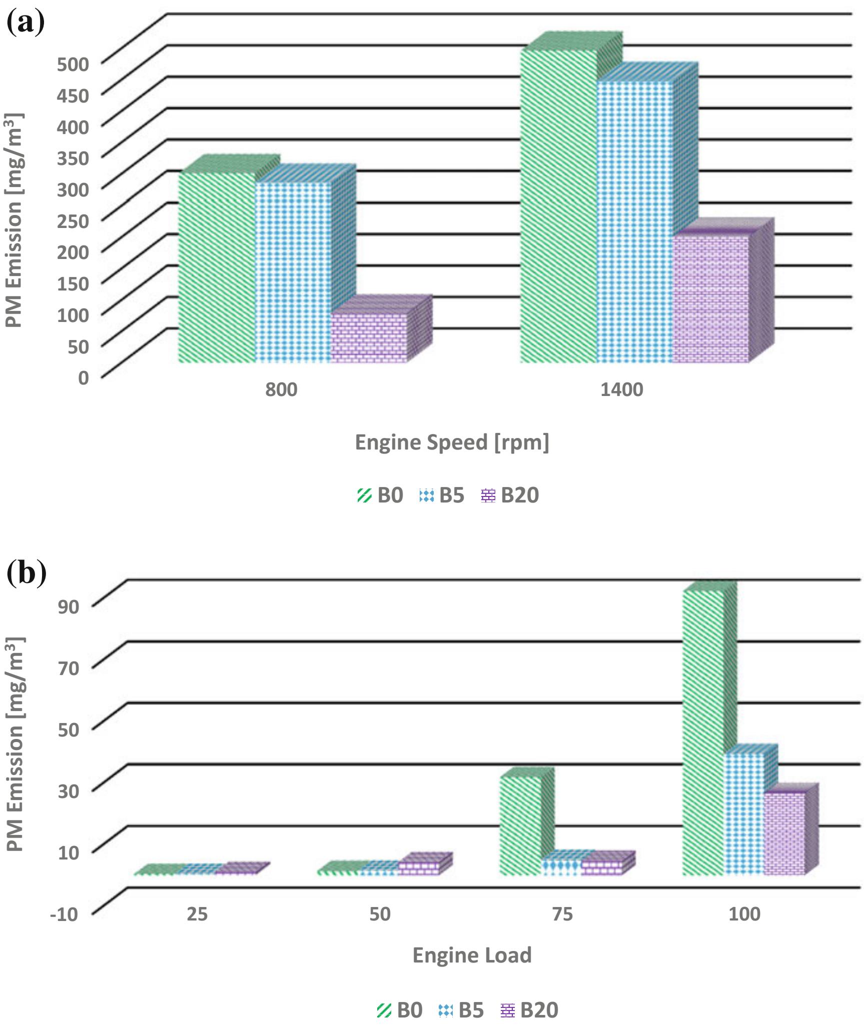

Fig. 11 Variation of PM emission **a** at idle speed and 1400 rpm **b** at 1800 rpm and different loads

PM emission increased as the biodiesel percentage increased in the blends. Similar results were also reported by other researchers [44, 45]. Hass et al. [46] found 30% more reduction in PM emission when then they increased biodiesel percentage from 20 to 100%. The reason of lowering PM emission can be attributed to the higher oxygen contents in biodiesel fuel. The oxygen causes complete combustion of biodiesel in the cylinder. Also, a lack of sulfur and aromatic compound further reduce the PM emissions [47].

The variation of PM emission with load showed a different trend that was in speed. At lower load condition, biodiesel showed a bit higher PM emission, whereas at higher load condition biodiesel fuel reduced the PM emission significantly. It happened because particles are mainly formed during the diffusion combustion, and most of the combustion is diffusive at high load, which means that the oxygen content of biodiesel is more efficient in reducing the PM emission. A significant reduction in PM emission at high load and the increase in the lower load were also found by [48] when they used soybean biodiesel.

5 Conclusions

The development of sustainable liquid transportation fuels is essential to ensure the future security of energy supply in the world. Biodiesel produced from different feedstock represents a sustainable source of energy to be used in the transportation sector. The following conclusions could be drawn from this study:

- The use of rice bran biodiesel in diesel engine favors reducing the 56.5% of CO emission compared to the diesel fuel. Such trend is attributed to the higher oxygen content and lower carbon to hydrogen ratio compared with diesel fuel.
- The HC emission is reduced significantly when rice bran biodiesel blends are used instead of diesel fuel. This reduction is mainly due to the higher oxygen contents and cetane number of rice bran biodiesel.
- The PM emission for rice bran biodiesel is reduced to a large extent compared to diesel fuel. The reduction is mainly due to the higher oxygen and lower aromatic compounds present in the biodiesel.
- An increase of NOx emission in rice bran biodiesel blends was found due to the higher combustion temperature, higher cetane number, and higher oxygen contents of biodiesel fuel.
- The use of rice bran biodiesel blends in the diesel engine lowers the engine power slightly due to the lower heating value of biodiesel fuel compared to diesel fuel.

Finally, it can be concluded that up to 20% rice bran biodiesel could replace diesel fuel to help in controlling the air pollution to a great extent without sacrificing engine power significantly. Therefore, rice bran biodiesel is more sustainable than the existing energy supplies from an environmental perspective as the rice bran biodiesel considerably reduce the harmful emission.

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