Emissions Study and Estimation of Carbon Dioxide Production from Jatropha Curcas Oil Biodiesel

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ABSTRACT

The goal of this study was to analyse the combustion characteristics and emissions of Jatropha curcas biodiesel (JCB) when run in a diesel engine. Jatropha curcas oil was used to produce Jatropha curcas biodiesel (JCB) through a transesterification process. The major fuel properties of JCB, including the acid value, kinematic viscosity, flash point, gross heating value, and iodine value, were determined and compared with that of soybean biodiesel (SBM), sunflower seed biodiesel (SFM), mackerel fish oil biodiesel (MB), and premium diesel (D). JCB had a higher density, acid value, kinematic viscosity, iodine value and flash point, but a lower gross heating value, than D. JCB was then used to analyze combustion characteristics, CO, CO_2, NO, NO_x, SO_2, and particulate matter (PM), under varied engine speeds and varied engine loads. The experimental results show CO_2 concentration increased with increasing engine loads for all fuels. Engine trials on D exhibited better combustion efficiency at lower engine loads (0 kW–4 kW) but engine trials on JCB exhibited better combustion efficiency for higher engine loads (5 kW–8 kW). JCB emitted more NO and NO_x on a loaded engine. Engine trials on JCB emitted higher PM concentration when the engine was not loaded, while engine trials on MB produced higher PM concentration when the engine was loaded. The estimated CO_2 emissions for JCB, MB, and D are 9221.3, 9617.2, and 10185.0 g (gal fuel)$^{-1}$, respectively.

Keywords: Jatropha curcas biodiesel; Biodiesel emisssions; CO_2 emission.

INTRODUCTION

Biodiesel is a biofuel made from vegetable oils, animal fats or waste cooking oil through transesterification process (Chang *et al.*, 1996; Schmidt and Van Gerpen, 1996; Yu *et al.*, 2002; Dorado, 2003). It is an alternative fuel, the use of which could contribute to energy sustainability (Edlund, 2002). A blend of 2-30% biodiesel and fossil fuel may be used directly in a diesel engine, while it may be necessary to make some minor adjustments to the diesel engine when 100% biodiesel is used (Williams, 2002).

Drenth *et al.* (2014) used a compression ignition engine to evaluate the engine emissions of camelina, carinata, and pennycress seed oils across three fuel types. The three fuel types they studied were triglyceride blends, biodiesel, and renewable diesel. The triglyceride blends used in their study were formed by blending vegetable oil with E10 at a 3: 1 volumetric ratio. Their results showed that the performance of engine using camelina, carinata, and pennycress oils were similar to engine using the traditional oils, soybean and corn,

for each fuel type. Their results also showed that engine using triglyceride blend presented a similar performance as did engine using petroleum diesel, and presented similar emission characteristics as did engine operating on biodiesel. Their study also observed that the engine operating on biodiesel emitted lower level of CO and non-methane hydrocarbons.

In our past work, we derived fatty acid methyl esters (FAME) from animal fat and used cooking oils, and examined the exhaust emitted by the combusting in the diesel engine of these various types of FAME (Wu *et al.*, 2007). The species observed after each run indicated that the sources of the fat and used cooking oil influenced which trace compounds were formed under engine runs. Liu *et al.* (2012) examined regulated pollutants and polycyclic aromatic hydrocarbon (PAH) emissions from heavy-duty diesel engines with a blend of biodiesel from waste cooking oil and ultra-low sulfur diesel. Their results demonstrated that the biodiesel blend produced lower PM, hydrocarbons (HC), and CO emissions, but higher CO_2 and NO_x emissions, when contrasted with the emissions of pure ultra-low sulfur diesel.

Mwangi *et al.* (2015a, b) investigated the production, performance, and emissions reductions of microalgae biodiesel on a diesel engine by using fuels containing varying fractions of diesel, butanol, microalgae biodiesel, and water. All the diesel blends studied exhibited higher brake

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specific fuel consumption (BSFC) and higher brake thermal efficiency (BTE) compared to pure diesel. All the diesel blends showed reductions of particulate matter (PM) and polycyclic aromatic hydrocarbons (PAHs). Most of the blends exhibited decreased hydrocarbons (HC) emissions, however blends with 20% butanol showed increased HC emissions. Blends with 2% microalgae biodiesel caused a decrease in CO emissions, but an increase in NO_x emissions.

Shukla *et al.* (2014) used a common rail direct injection engine fueled with mineral diesel and a 20% biodiesel blend at a constant speed of 1800 rpm for five different loads to analyze the primary and aged particulate matters emitted in the exhaust. In their study, the biodiesel blend emitted lower amounts of primary and aged particulates compared to mineral diesel. The biodiesel blend yielded a significant reduction in aged particulates at higher engine loads (75% and 100%). This study also found that the aged particulates were larger and denser than the primary particulates.

Sahoo *et al.* (2009) investigated the tractor engine performance emission characteristics of pure jatropha, karanja, and polanga biodiesels, as well as of various blends of these biodiesels with conventional diesel. Their results showed that pure karanja biodiesel, karanja/diesel blends, and pure polanga biodiesel all emit less CO than diesel. Pure jatropha biodiesel, jatropha/diesel blends, and polanga/diesel blends yielded higher CO emissions than diesel. This study also showed that both pure and diesel-blended biodiesels emit lower level of PM and HC than diesel. The biodiesels and the biodiesel/diesel blends all produced higher level of NO_x than diesel.

Datta *et al.* (2014) studied the performance and emission characteristics of a compression ignition engine using a mixture of jatropha biodiesel with mineral diesel. According to their results, brake specific fuel consumption increases as the percentage of biodiesel in the blends increases, while brake thermal efficiency decreases as the percentage of biodiesel in the blends increases. CO and hydrocarbon emissions were shown to improve with the addition of biodiesel to diesel. Also, the pure biodiesel emitted 24% more NO_x than mineral diesel.

Bhuiya *et al.* (2016) reviewed studies on the physical and chemical properties of biodiesel produced from non-edible oils, and its effect on engine performances and emissions. They concluded that as the properties of biodiesel vary depending on the sources of feed stocks, the feed stock source affects the engine performance and emissions characteristics. The studies in their review showed that the use of biodiesel can effectively reduce the emission of particulate matter (PM), carbonmonoxide (CO), and hydrocarbon (HC). However, biodiesel causes a slight increase in fuel consumption, and a slight increase in NO_x emission.

Biodiesel can be produced from a variety of edible vegetable oils, for example, soybean, sunflower, or rapeseed oils. However, the use of the edible oils conflicts with human substance needs. There are a few non-edible oils which could be used as a source for biodiesel productions as well. Martin *et al.* (2010) explored the suitability of various non-edible oil seeds for the generation of biodiesel in Cuba. The oil seeds examined were Jatropha curcas, neem, moringa, trisperma, castor beans, and candlenut. As a result of their study, as indicated by the oil yield and the fatty acid composition of the oil, Jatropha curcas was recognized as the most encouraging oil seed for biodiesel generation in Cuba. The investigation of Prueksakorn *et al.* (2010) proposed that an agrarian nation with a high potential for energy crops could use these crops to reduce its dependence on imported fossil energy resources. They showed that although palm oil is currently the major feedstock for biodiesel creation in Thailand, Jatropha curcas is another promising energy crop.

Jatropha curcas crude oil is rich in free fatty acids (FFA). Several authors have reported studies on the development of the two-stage process for the production of biodiesel from Jatropha curcas crude oil. Patil and Deng (2009) analyzed biodiesel creation from different non-edible vegetable oils, including Jatropha curcas and Pongamia glabra (karanja), and from edible vegetable oils, including corn and canola. They utilized a two-stage transesterification procedure to convert the high FFA jatropha and karanja oil to its esters. They found that the high FFA oils could not be transesterified with the alkali catalyst transesterification process. For canola and corn, a one-stage alkali transesterification process was applied. Patil and Deng (2009) showed that one-stage transesterification techniques are suitable for edible oils, while two-stage transesterification techniques are best suitable for non-edible oils.

Corro *et al.* (2010) connected a two-stage catalysis process for biodiesel production from Jatropha curcas oil. In the first step, a solid acid catalyst (SiO_2-HF) was utilized to catalyze the esterification reaction of FFA with methanol. In the second step, sodium hydroxide was added to catalyze the transesterification reaction of the triglycerides with methanol. They asserted that the biodiesel thus produced meets international standards for its utilization and commercialization.

In this study, Jatropha curcas oil was converted into Jatropha curcas biodiesel, and was compared with biodiesels derived from edible vegitable oils and mackerel fish oil. Emissions tests were then conducted, running a diesel engine on pure Jatropha curcas biodiesel and then on premium diesel. The levels of CO, CO_2, NO, NO_x, SO_2, and particulate matter thus formed were then analyzed.

MATERIALS AND METHODS

The reaction scheme of triacyloglycerols transesterification of is shown in Fig. 1, and, for futher reference, is likewise documented elsewhere (Komers *et al.*, 1998; De *et al.*, 1999; Komers *et al.*, 2001; Wu *et al.*, 2007). Transesterification is the procedure of excess alcohol mixed with a catalyst, for example, NaOH, and then mixed with triglyceride to form fatty acid esters and glycerol. Triglycerides are initially broken down to diglycerides, then diglycerides are decomposed to monoglycerides, and then the monoglycerides generate fatty acid esters. 30 L of Jatropha curcas oil were obtained from the Ozone Environmental Technology Co., Ilan, Taiwan. However, since higher free fatty acid (FFA) were contained in the obtained oil, a two-step process, acid-catalyzed esterification process followed by base-catalyzed
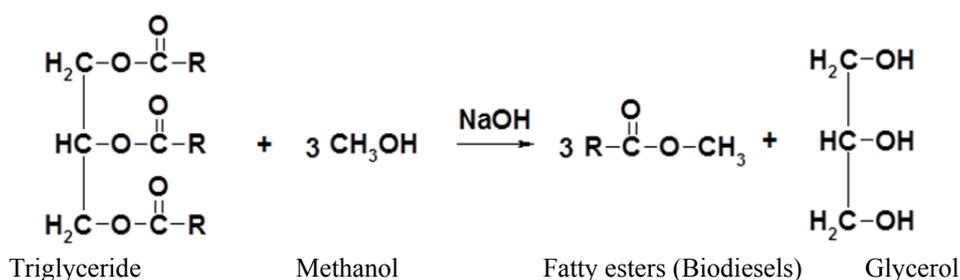
Triglyceride Methanol Fatty esters (Biodiesels) Glycerol

Fig. 1. Transesterification of triglyceride with methanol in the presence of NaOH.

transesterification process, was selected. The first step, acid esterification, was a pretreatment for removing FFA in the oil. Sulfuric acid (H_2SO_4, Sigma-Aldrich Co., USA) was used as an acid catalyst in this step. For the pretreatment process, 200mL methanol (CH_3OH, Malliuckrodt Baker Inc., USA) plus the required amount of H_2SO_4 (1.0% based on the oil weight) in methanol was added for every liter of Jatropha curcas oil, and the reaction was conducted at 65°C for 1.5 hours. The mixture was allowed to settle for 2 hours while the methanol–water fraction at the top layer was removed. The purpose of the process was to reduce the FFA concentration of Jatropha curcas oil to below 2%. A titration of the pretreated Jatropha curcas oil was performed to verify that the FFA content was lower than 2% to ensure the transesterification efficiency of the next step (base-catalyzed transesterification). If the FFA content of the pretreated Jatropha curcas oil was higher than 2%, the pretreatment process was repeated until the FFA content was below 2%. The second step was the production of Jatropha curcas biodiesel (JCB) from the transesterification of the pretreated Jatropha curcas oil with CH_3OH catalyzed by sodium hydroxide (NaOH, Shimakyu, Osaka, Japan). For the base-catalyst transesterification, 200mL CH_3OH and the required amount of NaOH were added for every liter of Jatropha curcas oil, and the reaction was carried out at 65°C.

The water wash process was performed by using a sprinkler which slowly sprinkled water into the biodiesel container until there was an equal amount of water and biodiesel in the container. The water/biodiesel blend was then gently agitated for 10 minutes, permitting the water to settle out of the biodiesel. After the blend had settled, the water was drained out.

A progression of tests were performed to ascertain the properties of the produced biodiesel. Each of the final values used in this study were determined by taking the average of three measurements. The density of the biodiesel at 15°C was measured by utilizing a glass hydrometer cylinder as indicated by ASTM D 1298. Acid value was measured by titration with 0.1 N KOH as indicated by ASTM D 664. The kinematic viscosity at 40°C was determined by a Ostwald type BS/U-tube capillary viscometer as per ASTM D 445. The flash point was analyzed by a manual Pensky-Martens closed cup apparatus as indicated by ASTM D 93. The gross heating value was analyzed by utilizing a isoperibol oxygen bomb calorimeter (model 6200, Parr Instrument Company, USA) as indicated by ASTM D 240. The iodine value was analyzed by titration with 0.1 N sodium thiosulfate

for the mixture of tested fuel and chemical reagents according to ASTM D5554. The chemical compositions of the biodiesels were analyzed utilizing a gas chromatograph-mass spectrometer (ThermoQuest Trace MS, GC/MS) with a 1.0 μm, 0.25 mm, 30 m DB-1 column (J & W Scientific). For emission comparison, fuels used for engine trials in this study were JCB, MB, and D. The biodiesels used for chemical composition comparison were JCB, SBM, SFM, and MB. JCB, SBM, SFM, and MB were all produced in the laboratory, while D were purchased from China Petroleum Corp.

The experiments were carried out in a three-cylinder, four-stroke-cycle 1331 c.c. marine diesel engine (YARMAR 3TN82). The engine characteristics are cited in Table 1. The emission tests were performed at engine speeds of 1000, 1200, 1400, 1600, 1800 and 2000 rpm with no engine load, and at an engine speed of 1800 rpm with engine loads of 0, 1, 2, 3, 4, 5, 6 and 8 kW, respectively. Exhaust gas emissions of CO, CO_2, NO and NO_x were simultaneously measured by an exhaust gas analyzer (IMR 2088P). Exhaust gas emissions of SO_2 were collected in a sampling bag and analyzed by a fluorescent SO_2 analyzer (API 100A). Particulate matter (PM) was pulled back isokinetically from the exhaust pipe and collected on a glass fiber filter following the procedure described in Method 1A, 40 CFR Part 60, U. S. EPA. The emission value presented in this study for each gas or particle was the average taken from three measurements.

RESULTS AND DISCUSSION

A total of 30 L of Jatropha curcas oil was utilized and converted into nearly 30 L of biodiesel. Three cycles of the acid-catalyzed esterification pretreatment process were completed. Fig. 2 demonstrates the FFA content of the Jatropha curcas oil after each cycle. The FFA content came to 0.277% after the third treatment cycle. After the

Table 1. Engine specifications.

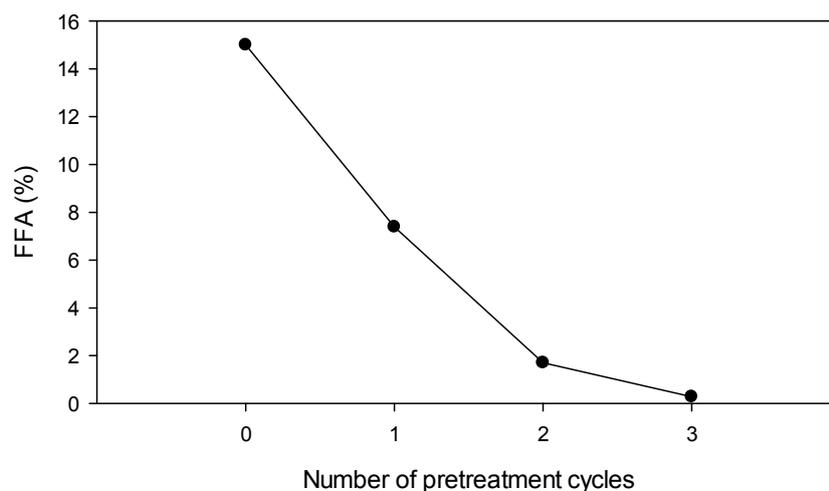| Type	4-cycle, water-cooled diesel
Combustion	Direct injection
Aspiration	Natural
Cylinders	3, in-line, vertical
Bore × Stroke	82 × 84 mm
Piston displacement	1331 cc
Compression ratio	18.1 1

Fig. 2. Content of free fatty acid (FFA%) in Jatropha curcas oil after each pretreatment.

transesterification process, there was a nearly 90% volume ratio of methyl ester phase to a 10% volume ratio of glycerol phase during the separation process, a result similar to the results of our past investigation (Wu *et al.*, 2007; Wu, *et al.*, 2014). The chemical compositions of the biodiesels as investigated by the GC/MS are recorded in Table 2. The results demonstrate that the biodiesels produced from plant seed (JCB, SBM, and SFM) contained mostly C18s (C18: 0, C18: 1, and C18: 2), while MB contains both C16: 0 and the C18s, as well as higher carbon numbers and the more unsaturated bonds C20:5 (11.6%) and C22:6 (16%). JCB, SBM, and SFM contain lower carbon numbers, yielding higher ratios of H/C in JCB, SBM, and SFM at 1.84, 1.84, and 1.85, respectively, while the ratio in H/C of MB was 1.79.

Table 3 compares the major properties of the four biodiesels and premium diesel. The four biodiesels all exhibited higher dentistes and higher acid values than did D. Among these biodiesels, JCB had the highest acid value because Jatropha curcas oil contains more free fatty acids. The biodiesels used in this study likewise demonstrated higher kinematic viscosity values than did D, yet JCB demonstrated the lowest kinematic viscosity value among these four biodiesels. The number of unsaturated bonds in an oil is indicated by its iodine value. As demonstrated in Table 3, and alluded to in Table 2, JCB has the lowest iodine measurement, because it contains more saturated fatty acid methyl esters (C16:0 and C18:0 indicated in Table 2). As demonstrated in Table 3, the flash points of the four biodiesels studied were higher than D's, but the gross heating values of biodiesel were all lower than D's. Fuels with high viscosity may cause the formation of soot and engine deposits due to poor atomization of the fuel spray from the injectors. The acid value is a measure of the fatty acid level in the biodiesel, and a higher content of fatty acids can cause corrosion in the fuel supply system of the engine. The iodine value is an indicator of the total amount of unsaturated fatty compounds in a biodiesel.

A high content of unsaturated fatty acids in the fuels increases the danger of polymerization in the engine oil (Prankl and Wörgetter, 1996). A lower heating value will cause a loss of engine power, requiring a larger amount of fuel to be injected into the combustion chamber to produce the same amount of power.

The fuels used in the engine test were pure Jatrophs curcas oil methyl ester (JCB) and pure premium diesel (D). Engine exhaust tests were carried out at engine speeds of 1000, 1200, 1400, 1600, 1800, and 2000 rpm with no engine load, and at an engine speed of 1800 rpm with engine loads of 0, 1, 2, 3, 4, 5, 6 and 8 kW, respectively. The exhaust concentrations of CO and CO_2, and the combustion efficiency for JCB and D with respect to engine speed and engine load are shown in Fig. 3. As shown in Fig. 3(a), CO formation decreased with increasing engine speeds for both fuels. CO emissions were lower at slower engine speeds for engine trials on JCB. Fig. 3(b) shows that for both JCB and D, at lower engine loads, as engine loads increased, CO formation also increased, and the highest emission of CO was obtained at an engine load 2 kW. However, at higher engine loads, CO emisssion then decreased for both JCB and D. At the highest load (8 kW) for engine trials on JCB, CO emission was not dectected. Fig. 3(c) shows that CO_2 emission decreased by steps when engine speed increased from 1000 to 1200 rpm, and then remained stable with increasing engine speeds for engine trials on JCB, while the CO_2 emissions value remained steady for engine trials on D. Fig. 3(d) shows that CO_2 concentration increased with increasing engine loads for both fuels. Incorporating the results of CO and CO_2 formation, the combustion efficiency was calculated as followed:

$$Combustion\ efficiency = \eta = \frac{C_{CO_2}}{C_{CO_2} + C_{CO}} \times 100\% \qquad (1)$$

where C_{CO2} = concentration of CO_2
C_{CO} = concentration of CO

The combustion efficiencies of JCB and D are shown in Fig. 4. On an unloaded engine as Fig. 4(a) presents, engine trials on JCB yielded lower combustion efficiency than did engine trials on D, except at the engine speed of 1000 rpm. As Fig. 4(b) shows, engine trials on D exhibited better

Table 2. Chemical compositions of the biodiesels investigated in this study.

Component	Name	Formula	JCB	SBM	SFM	MB
C13:0	Tridecanoic acid methyl ester	$C_{14}H_{28}O_2$	-	-	-	0.12
C14:0	Tetradecanoic acid methyl ester	$C_{15}H_{30}O_2$	-	0.01	-	3.32
C15:0	Pentadecanoic acid methyl ester	$C_{16}H_{32}O_2$	0.04	-	-	1.27
C16:0	Hexadecanoic acid methyl ester	$C_{17}H_{34}O_2$	10.6	9.64	6.92	14.9
C16:1	(Z)-9-hexadecenoic acid methyl ester	$C_{17}H_{32}O_2$	-	-	0.11	6.87
C17:0	Heptadecanoic acid methyl ester	$C_{18}H_{36}O_2$	0.24	-	-	-
C17:1	(Z)-10-heptadecenoic acid methyl ester	$C_{18}H_{34}O_2$	0.11	-	-	-
C17:2	(9Z,12Z)-9,12-octadecadienoic acid	$C_{18}H_{32}O_2$	-	-	-	1.96
C18:0	Octadecanoic acid methyl ester	$C_{19}H_{38}O_2$	8.54	2.84	4.14	7.52
C18:1	(Z)-9-octadecenoic acid methyl ester	$C_{19}H_{36}O_2$	21.75	22.27	26.32	27.1
C18:2	(9Z,12Z)-octadeca-9,12-dienoic acid methyl ester	$C_{19}H_{34}O_2$	55.75	64.18	58.18	1.92
C19:1	10-Nonadecenoic acid methyl ester	$C_{20}H_{38}O_2$	-	-	-	0.29
C20:0	Eicosanoic acid methyl ester	$C_{21}H_{42}O_2$	0.45	0.22	-	-
C20:1	(Z)-11-eicosenoic acid methyl ester	$C_{21}H_{40}O_2$	0.152	0.11	0.94	5.06
C20:5	(5Z,8Z,11Z,14Z,17Z)-icosa-5,8,11,14,17-pentaenoic acid methyl ester	$C_{21}H_{32}O_2$	-	-	-	11.6
C22:0	Docosanoic acid methyl ester	$C_{23}H_{46}O_2$	0.06	0.26	0.69	0.92
C22:6	(4E,7E,10E,13E,16E,19E)-docosa-4,7,10,13,16,19-hexaenoic acid methyl ester	$C_{23}H_{34}O_2$	-	-	-	16.0

combustion efficiency at lower engine loads (0 kW–4 kW), but engine trials on JCB exhibited better combustion efficiency for higher engine loads (5 kW–8 kW).

The exhaust concentrations of NO and NO_x against engine speed and engine load from JCB and D are compared in Fig. 5. Fig. 5(a) shows that NO remained stable with increased engine speeds for engine trials on JCB, while NO emission decreased with increasing engine speed for engine trials on D. Fig. 5(b) shows that NO emissions increased as engine loads increased for both JCB and D, with JCB producing more NO with increasing engine loads. Fig. 5(c) presents that NO_x remained stable with increased engine speeds for engine trials on JCB, and that NO_x decreased with increased engine speeds for engine trials on D. Fig. 5(d) shows that NO_x concentration in the emissions from both fuels also increased as engine loads increased, and that JCB emitted more NO_x than did D. The formation of NO_x mainly depends on oxygen availability, and requires high combustion temperatures. The use of biodiesel in an engine can lead to higher flame temperatures, longer reaction times, and a higher cumulative heat release rate, causing higher in-cylinder temperatures (Bhaskar *et al.* (2013)). Hence JCB produced higher NO_x due to the higher combustion temperature and the presence of fuel oxygen.

As shown in Fig. 6, JCB produced a steady amount of SO_2 for engine trials on JCB at varied speeds when the engine was not loaded, while D produced higher concentrations of SO_2 at the three lower engine speeds. JCB emitted more SO_2 than D did at the lower engine loads (1 kW–4 kW). But at the higher engine loads (5 kW–8 kW), JCB emitted less SO_2 than did D. For both JCB and D, SO2 formation increased as engine loads increased. Contrary to expectations, the levels of SO_2 emitted by JCB were similar to the levels of SO_2 emitted by D at all engine loads. This resuls maybe due to a possible residue of sulfur species left in the engine, as the engine utilized in this study was a used one.

The PM concentrations from JCB and D are compared in Fig. 7. JCB emitted higher PM concentrations than D at higher engine speeds for an engine with no load. The reason JCB emitted higher PM than D may be that JCB has a higher viscosity, a lower heating value, and a lower volatility than D causeing engine deposits and heterogeneous combustion. This may also explain the lower CO_2 formation for engine trials on JCB at higher engine speeds. When the engine was loaded, PM concentrations for JCB were much lower than those on the unloaded engine.

The emissions of MB from previous study (Wu *et al.*, 2014) were then compared with the emissions of JCB and D as found in this study. MB, as mentioned above in the discussion of Table 2, contains much higher amounts of high carbon-number products than JCB or other plant seed oil biodiesels. All emissions thus compared are from an engine trials on either pure JCB, MB, or D at the speed of 1800 rpm under engine loads from 0 to 8 kW. Fig. 8 compares the CO emission, CO_2 emission, and combustion efficiency for engine trials on JCB, MB, and D at 0, 1, 2, 4, and 8 kW power loads. As shown in Fig. 8(a), when it was using MB, the engine emitted less CO than when it was using JCB and D under all engine loads. As shown in

Table 3. Major properties of the premium diesel and biodiesels used in this study.

	JCB	SBM	SFM	MB	D	
Density (g cm^{-3})at 15°C	0.863	0.896	0.897	0.893	0.842	ASTMD 1298
Acid value (mg KOH g^{-1})	3.380	0.267	0.145	0.359	0.034	ASTM D 664
Kinematic viscosity at 40°C (mm^2 s^{-1})	3.686	5.171	5.251	4.700	3.110	ASTM D 445
Iodine value (g I$_2$ (100g)$^{-1}$)	93.29	129.1	137.8	139.9	12.74	ASTM D5554
Flash point (°C)	152	184	172	173	70	ASTM D 93
Gross heating value (cal g^{-1})	9473	9460	9464	9388	10592	ASTM D 240
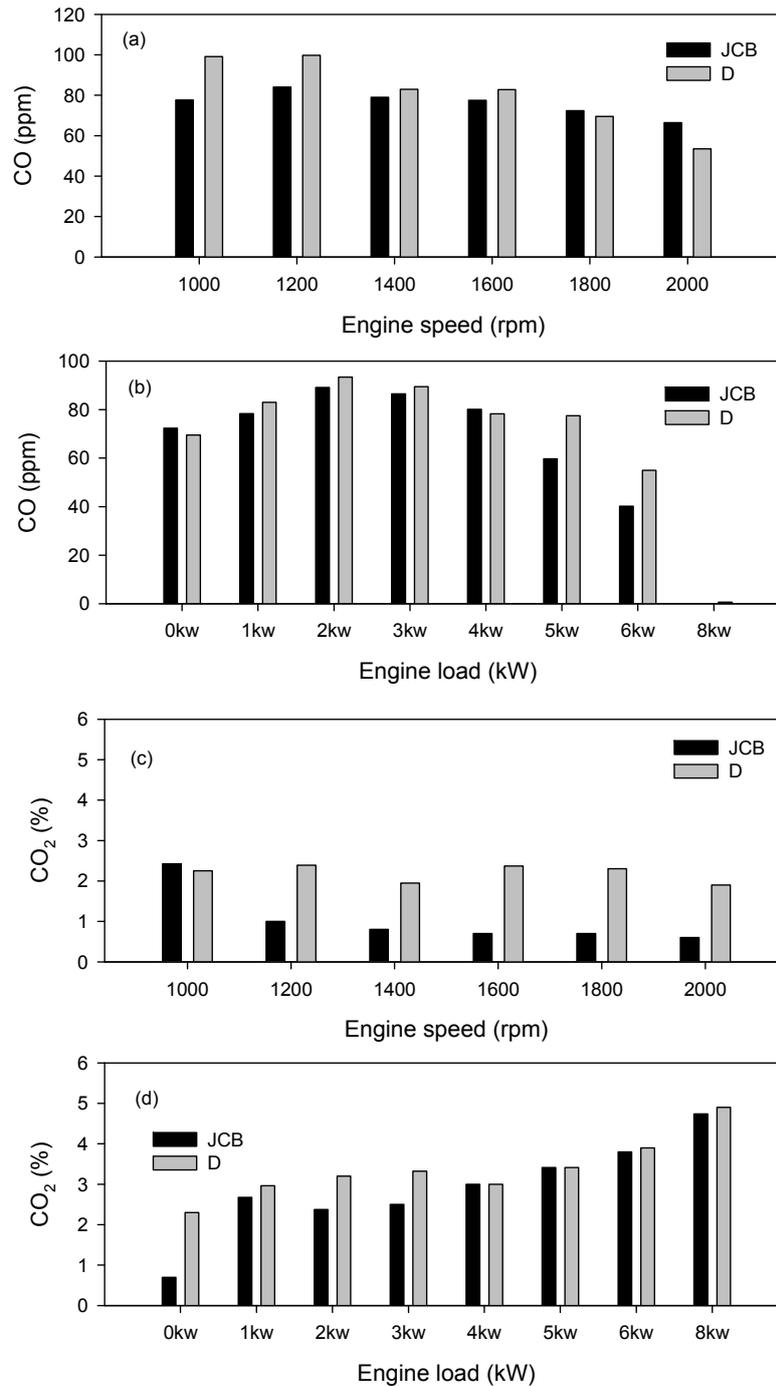
Fig. 3. Comparison of CO emissions (a) under varied engine speeds with no engine load and (b) at 1800 rpm under varied loads, and of CO$_2$ emissions(c) under varied engine speeds with no engine load, and (d) at 1800 rpm under varied loads for JCB and D fuels.
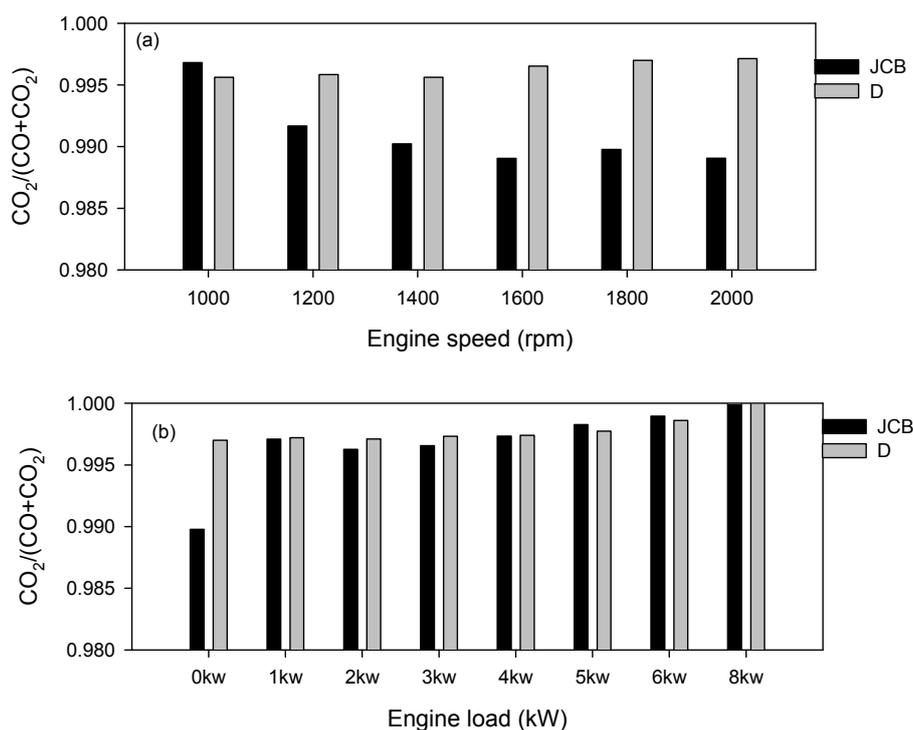
Fig. 4. Comparison of combustion efficiency (a) under varied engine speeds with no engine load and (b) at 1800 rpm under varied loads for JCB and D fuels.

Fig. 8(b), JCB emitted less CO_2 than did MB and D at most engine loads. Fig. 8(c) compares the combustion efficiency (see Eq. (1)) for JCB, MB, and D under engine loads from 0 to 8 kW. As shown in Fig. 8(b), JCB emitted the lowest levels of CO_2, but also showed the poorest combustion efficiency as compare to both MB and D at lower engine loads (0 kW–4 kW).

Fig. 9 presents the NO and NO_x emissions from engine trials on JCB, MB, and D under varied engine loads. Figs. 9(a) and 9(b) show that JCB, MB, and D all emitted increasing levels of NO and NO_x as engine loads increased. JCB emitted higher levels of NO and NO_x than did MB at all engine loads. for the three fuels increased with increased engine loads. Fig. 10 compares the PM emission of JCB, MB, and D under engine loads from 0 kW to 8 kW. JCB emitted the highest levels of PM when the engine was free-loaded (at 0 kW), while at all other loads JCB emitted steady but lower levels of PM. MB, however, emitted higher levels of PM as engine loads increased.

Several studies have been carried out on the estimation of the source for greenhouse gases emissions. For example, Lin *et al.* (2015) used the Organization for Economic Cooperation and Development (OECD) and Tapio methods to analyze the relationship between CO_2 emissions and the Gross Domestic Product (GDP) of South Africa for the period of 1990 to 2012. Dimoula *et al.* (2016) used the conversion factor of 3.06 kg CO_2 per diesel liter in a freight road transport system. The U.S. Environmental Protection Agency (EPA) has developed a series of fact sheets to facilitate consistency of assumptions and practices in the calculation of emissions of greenhouse gases from

transportationand mobile sources. (U. S. EPA, 2005) The Code of Federal Regulations (40 CFR 600.113) provides the values for carbon content which the EPA uses in calculating the fuel economy of vehicles (U.S. EPA, 2005). The provided value for carbon content per gallon of diesel fuel is 2,778 g. According to the fact sheet, the Intergovernmental Panel on Climate Change (IPCC) guidelines for calculating emissions inventories require that an oxidation factor be applied to the carbon content to account for a small portion of the fuel that is not oxidized into CO_2. By assigning the obtained combustion efficiency to oxidation factor, we may calculate the CO_2 emissions from the fuels in this study. Table 4 presents the calculated CO_2 emissions for engine runs on varied fuels and varied loads in this study. As the results in Table 4 show, the CO_2 emissions for JCB, MB, and D are 9221.3, 9617.2, and 10185.0 g (gal fuel)$^{-1}$, respectively. Based on the method od calculation, and assuming that the combustion efficiency of SFM and SBM are 0.9999 for an engine load of 8kW (the same as JCB and MB at 8 kW), the CO_2 emissions for SFM and SBM can be calculated as 9575.7 and 9601.5 g (gal fuel)$^{-1}$, respectively. If one plots the CO_2 emissions (g gal^{-1} fuel) against the gross heating value (GHV, cal g^{-1}) of fuels, as shown in Fig. 11, a symmetrical relationship between CO_2 emission and gross heating value is revealed. There is an emperical equation obtained from Fig. 11 is:

$$CO_2 \text{ emissions (g gal}^{-1}) = 0.9954 \text{ GHV (cal g}^{-1}) \qquad (2)$$

and may be used to estimate the CO_2 emisssion if one knows the GHV of the fuel.
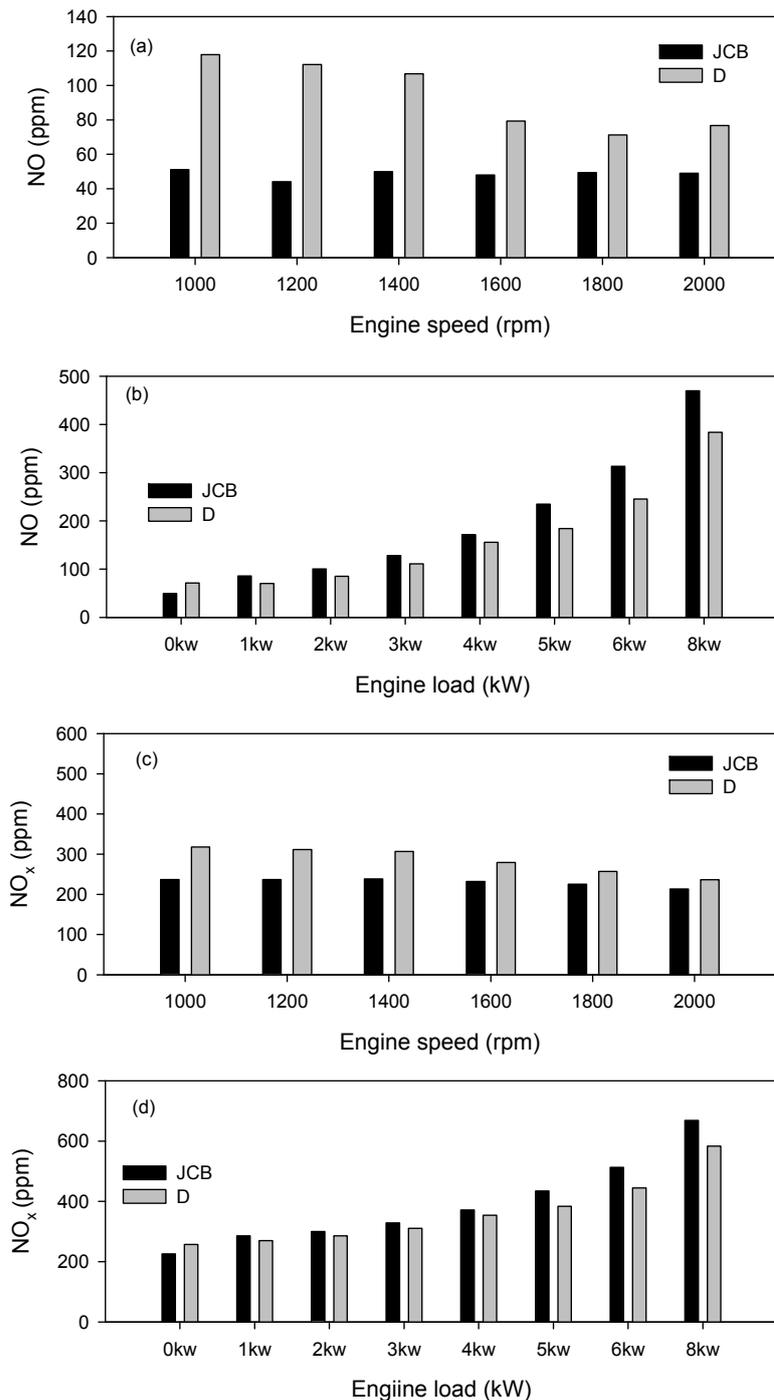
Fig. 5. Comparison of NO emissions(a) under varied engine speeds with no engine load and (b) at 1800 rpm under varied loads, and of NO_x emissions (c) under varied engine speeds with no engine load, and (d) at 1800 rpm under varied loads for JCB and D fuels.

CONCLUSIONS

JCB has a higher density, acid value, kinematic viscosity, iodine value, and flash point than D, but a lower gross heating value than D. JCB has the lowest iodine measurement than other biodiesels, because it contains more saturated fatty acid methyl esters (C16:0 (10.6 wt%) and C18:0 (8.54 wt%)) CO emissions decreased with increasing engine speeds for

JCB and D on an engine unloaded, and at lower engine loads, as engine loads increased, CO formation also increased, and and the highest emission of CO was obtained at an engine load 2 kW. However, at higher engine loads, CO emisssion then decreased for both JCB and D. CO_2 emission was low for engine running on JCB with no engine load. CO_2 emissions increased with increasing engine loads for all fuels, and D exhibited better combustion efficiency. NO

and NO_x emissions increased as engine loads increased for both D and JCB, but JCB emitted more NO and NO_x than did D at all engine loads. For all fuels tested, SO_2 formation increased as engine loads increased. JCB emitted higher PM concentrations than D at higher engine speeds for an engine with no load, while MB emitted higher levels
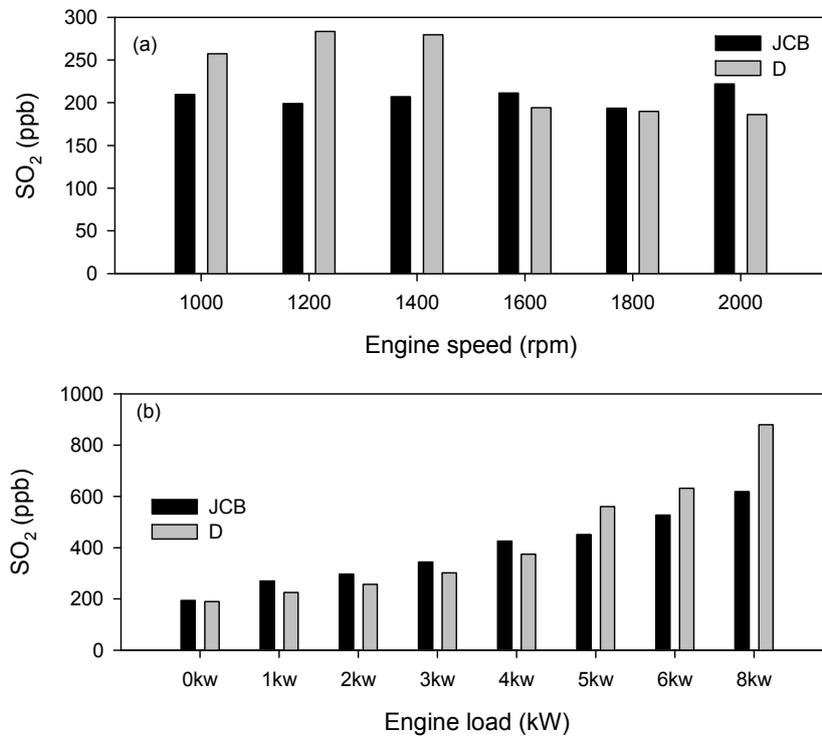

Fig. 6. Comparison of SO_2 emissions from JCB and D fuels (a) under varied engine speeds with no load and (b) at 1800 rpm under varied loads.
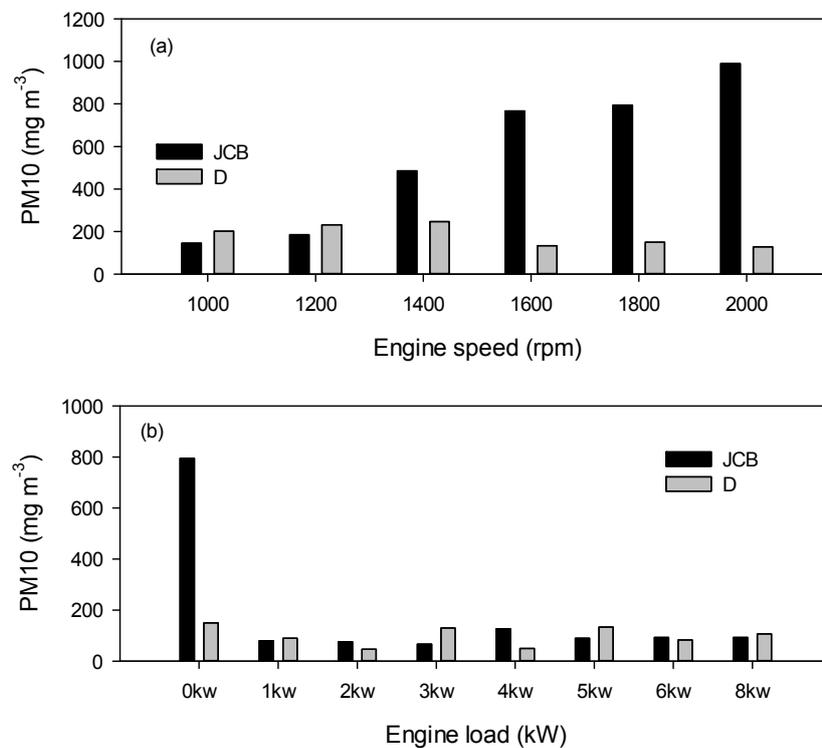
Fig. 7. Comparison of PM emissions from JCB and D fuels (a) under varied engine speeds with no load and (b)at 1800 rpm under varied loads.
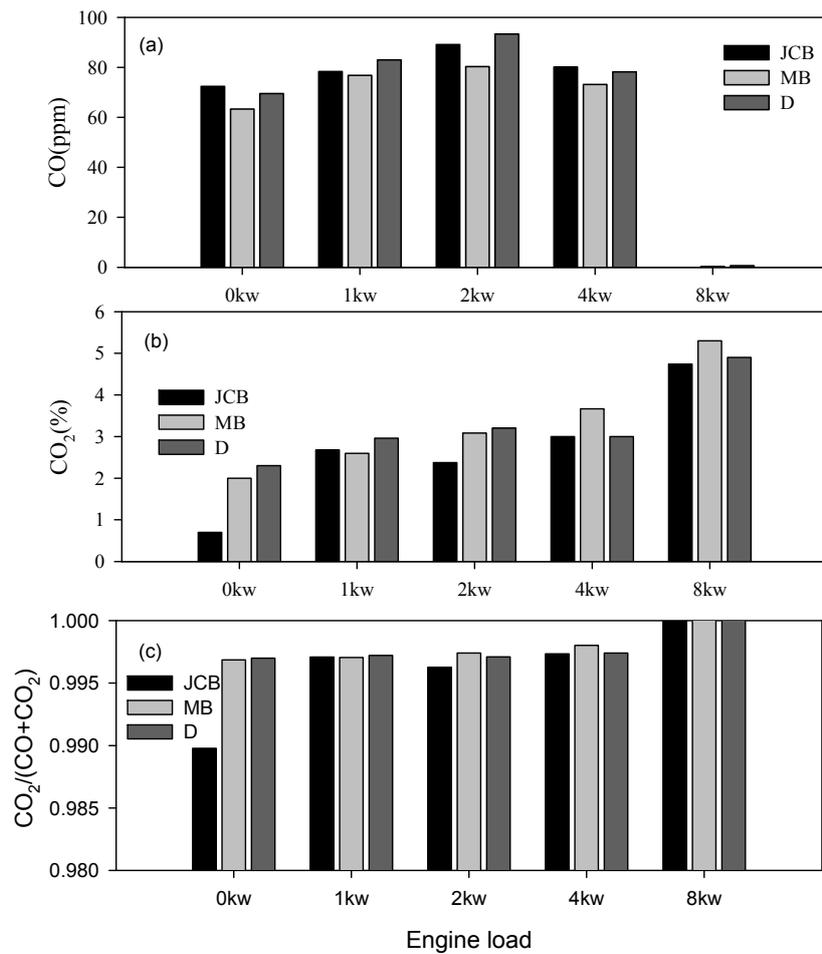
1231

Fig. 8. Comparison of (a) CO emissions, (b) CO_2 emissions, and (c) combustion efficiency from engine trials on JCB, MB, and D at 1800 rpm under varied loads.
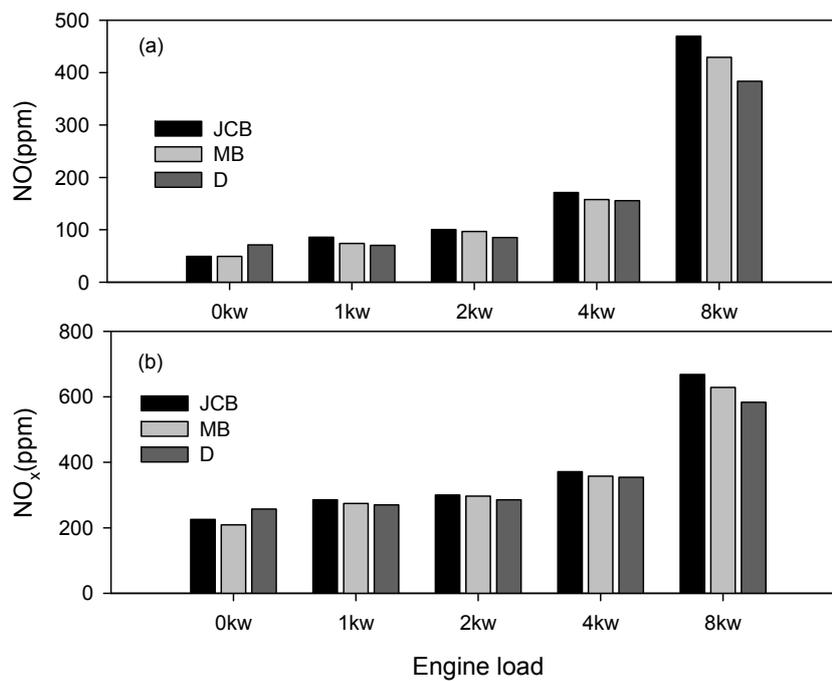

Fig. 9. Comparison of (a) NO and (b) NO_x emissions from engine trials on JCB, MB, and D at 1800 rpm under varied loads.
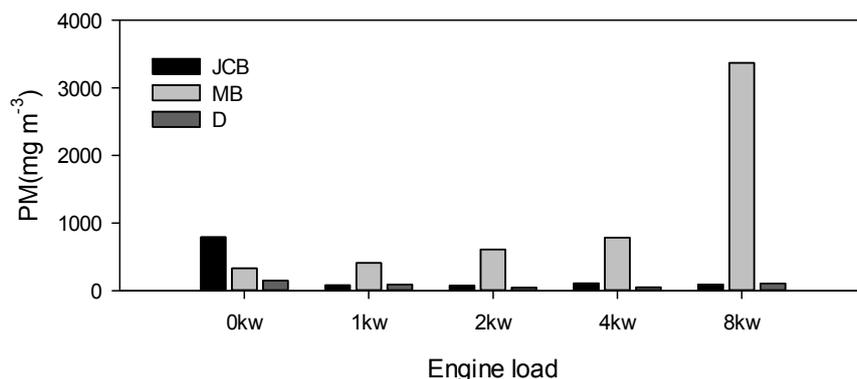
Fig. 10. Comparison of PM emissions from engine trials on JCB, MB, and D at 1800 rpm under varied loads.

Table 4. Calculated CO_2 emissions for JCB, MB, D, SFM, and SBM.

Fuel	Average chemical formula	average MW	g C (gal fuel)$^{-1}$	CO_2 emission (g (gal fuel)$^{-1}$) at engine load			GHV (cal g^{-1})
				0 kW	4 kW	8 kW	
JCB	$C_{18.39}H_{33.91}O_2$	286.59	2514.9	9127.3	9196.4	9221.3	9473
MB	$C_{19.16}H_{34.3}O_2$	296.22	2623.1	9587.4	9599.0	9617.2	9388
D	-	-	2778[a]	10155.4	10159.5	10185.0	10592
SFM	$C_{18.36}H_{34.04}O_2$	286.36	2611.8			9575.7	9464
SBM	$C_{18.84}H_{34.65}O_2$	292.73	2618.9			9601.5	9460

[a] from the Code of Federal Regulations (40 CFR 600.113).
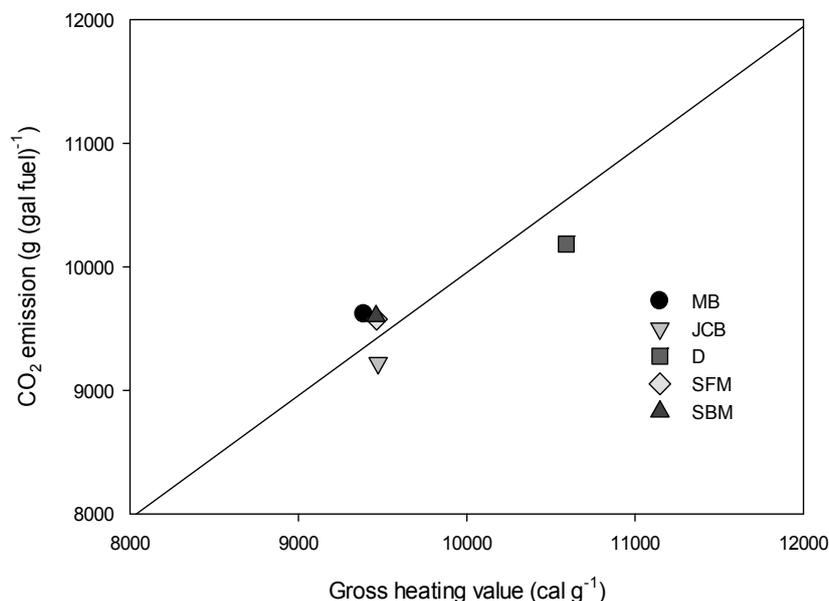

Fig. 11. Relationship between the CO_2 emissions and gross heating values of the various fuels.

of PM as engine loads increased. JCB emitted the lowest levels of CO_2, but also showed the lower combustion efficiency, lower PM and higher emissions of NO_x, but higher PM concentrations as compare to MB. The estimated CO_2 emissions for JCB, MB, and D are 9221.3, 9617.2, and 10185.0 g (gal fuel)$^{-1}$, respectively.

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