Journal of Cleaner Production 65 (2014) 304–310

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Performance and emission analysis of *Jatropha curcas* and *Moringa oleifera* methyl ester fuel blends in a multi-cylinder diesel engine

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ARTICLE INFO

Article history:
Received 23 May 2013
Received in revised form
27 August 2013
Accepted 28 August 2013
Available online 5 September 2013

Keywords:
Jatropha curcas
Moringa oleifera
Biodiesel production
Blending
Engine performance
Emissions

ABSTRACT

Research on alternative fuels is increasing due to environmental concerns and diminishing fossil fuel reserves. Biodiesel is one of the best renewable replacements for petroleum-based fuels. This paper examines the potential of biodiesel obtained from *Jatropha curcas* and *Moringa oleifera* oils. The physico-chemical properties of *J. curcas* and *M. oleifera* methyl esters were presented, and their 10% by volume blends (JB10 and MB10) were compared with diesel fuel (B0). The performance of these fuels and their emissions were assessed in a fully loaded multi-cylinder diesel engine at various engine speeds. The properties of *J. curcas* and *M. oleifera* biodiesels and their blends agreed with ASTM D6751 and EN 14214 standards. Engine performance test results indicated that the JB10 and the MB10 fuels produced slightly lower brake powers and higher brake specific fuel consumption values compared to diesel fuel over the entire range of speeds. Engine emission results indicated that the JB10 and MB10 fuels reduced the average emissions of carbon monoxide by 14 and 11%, respectively; and hydrocarbons by 16 and 12%, respectively. However, the JB10 and MB10 fuels slightly increased nitrous oxides emissions by 7 and 9%, respectively, and carbon dioxide by 7 and 5%, respectively compared to B0. In conclusion, *J. curcas* and *M. oleifera* are potential feedstock for biodiesel production, and the JB10 and MB10 blends can replace diesel fuel without modifying engines to produce cleaner exhaust emissions.

1. Introduction

Air pollution is a leading cause of respiratory health problems worldwide. Vehicle emissions are largely responsible for the deterioration of air quality (Zhang and Batterman, 2010). Recently, exhaust emissions have increased substantially due to the rapid growth of the transportation industry. Due to their high energy content, desirable combustion properties and ready availability, fuels derived from petroleum have been the major energy source in the transportation and the machinery sectors (de Vries, 2008; Mofijur et al., 2013a). However, emissions produced by the combustion of petroleum-derived fuels have adverse effects on the environment and human health. The fourth assessment Report of United Nations Intergovernmental Panel on climate change (IPCC) concluded that greenhouse gas emissions such as nitrogen oxides, methane and carbon dioxide are the main cause of global warming. An increase in the average global temperature by 2 °C will result in the deaths of hundreds of millions of people (Shuit et al., 2009). The internal combustion engine emits carbon monoxide (CO), hydrocarbons (HC), formaldehyde (HCHO), nitrogen oxides (NO_x), particulate matter (PM) and organic gases other than methane (non-methane organic gases, NMOG). These emissions are harmful to the environment and human health (Liaquat et al., 2010). The depletion of petroleum-derived fuels, the threat of climate change and increasing prices for petroleum products have influenced researchers to seek alternative energy sources (Tsolakis et al., 2007; Koh et al., 2011; Mrad et al., 2012; Tan et al., 2012). Therefore, for several decades, many researchers have been developing new alternative energy sources that are readily available, technically feasible, economically viable and environmentally acceptable. Biofuel is a feasible, clean alternative energy source that does not contain any harmful substances and produces fewer harmful emissions than diesel fuel (Atabani et al., 2012). Biodiesel is one of the best biofuels that can reduce global dependency on fossil-based diesel fuels and emissions

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http://dx.doi.org/10.1016/j.jclepro.2013.08.034

Nomenclature

ASTM	American society for testing and materials
BP	brake power
BSFC	brake specific fuel consumption
CMOO	crude *Moringa oleifera* oil
CO	carbon monoxide
CO_2	carbon dioxide
HC	hydrocarbon
JCME	*Jatropha curcas* methyl ester
MOME	*Moringa oleifera* methyl ester
NO	nitrous oxide
NO_x	oxides of nitrogen
PM	particulate matter

of environmental pollutants without modifying vehicles (Silalertruksa et al., 2012). Biodiesel is non-explosive, biodegradable, non-flammable, renewable, non-toxic and environmentally friendly, and it has properties that are similar to those of diesel fuel (How et al., 2012; Ng et al., 2012a). Biodiesel can be obtained by applying transesterification processes to vegetable oils, animal fats, used cooking oil and waste grease from restaurants (Shahabuddin et al., 2012, 2013). The most common sources of biodiesel are plant-based oils (palm, rapeseed, sunflower, coconut, peanut, *Jatropha curcas*, neem, cotton, jojoba, rubber, *Moringa oleifera*, Mahua and castor) and animal tallow (Jayed et al., 2011; Mofijur et al., 2012a; Hussan et al., 2013).

Palm oil is the major crop used currently for biodiesel production in Malaysia (Mofijur et al., 2012b; Ng et al., 2012b). Recently, *J. curcas* attracted the attention of the Malaysian Government. In Malaysia, the use of 5% biodiesel (B5) has been already approved by the Malaysian government using palm oil biodiesel. Therefore, increasing the percentage to 10% and using non-edible biodiesel feedstocks (*J. curcas* and *M. oleifera*) will create much interest to the biofuel policy makers in Malaysia. *J. curcas* refers to succulent plants, small or large shrubs and trees, up to 5–7 m tall, belonging to the Euphorbiaceae family, which comprises approximately 800 species that belong to some 321 genera. The seed of *J. curcas*, oval in shape and black in color, contains approximately 66% oil by weight (Silitonga et al., 2011). The oil produced from the seed of *Jatropha* is golden yellow in color. *M. oleifera*, a member of the Moringaceae family, grows mainly in tropical countries. It is a drought-tolerant species. The seeds of *M. oleifera* are triangular in shape and contain approximately 40% oil by weight (Atabani et al., 2013). The oil produced from the seed kernel of *M. oleifera* is also golden yellow in color. Recent studies have indicated that *M. oleifera* is native to Malaysia.

Recently, many investigations have been published (Ndayishimiye and Tazerout, 2011; Wander et al., 2011; Chauhan et al., 2012) about the production of biodiesel from *J. curcas* and its use as a fuel for diesel engines. In addition, several authors (Rashid et al., 2008; Kafuku and Mbarawa, 2010; Rashid et al., 2011) have discussed the potential production of biodiesel from *M. oleifera*, a non-edible oil source. However, a comparative evaluation of *J. curcas* and *M. oleifera* biodiesel blends in diesel engines has not been published. Therefore, the main objective of this paper is to study *J. curcas* and *M. oleifera* oils as potential feedstocks for biodiesel production. The study presents the physical and the chemical properties of *J. curcas* methyl ester (JCME) and *M. oleifera* methyl ester (MOME) and their 10% (by volume) blends with diesel fuel. The performance of these blends is assessed in a diesel engine and compared with diesel fuel.

2. Materials and methods

2.1. Materials

Crude *J. curcas* oil was collected from the Forest Research Institute, Malaysia (FRIM), and *M. oleifera* oil (CMOO) was supplied from University Science Malaysia (USM), through personal communication (USM, 2012). The diesel fuel (D2) was purchased from PETRONAS. All other chemicals, reagents and accessories were purchased from local markets.

2.2. Production of J. curcas and M. oleifera methyl esters

J. curcas and *M. oleifera* methyl esters were produced at the energy lab of the University of Malaya using a 1 L batch reactor, a reflux condenser, a magnetic stirrer, a thermometer and a sampling outlet. Biodiesel was produced using an acid–base catalyst process. Before starting the esterification process, the crude *J. curcas* and *M. oleifera* oils were heated to 60 °C using a temperature-controlled rotary evaporator (IKA) under vacuum to remove moisture. For the esterification process, a 12:1 molar ratio of methanol to crude oil and 1% (v/v) sulfuric acid (H_2SO_4) were added to the preheated oil and stirred at 600 rpm and 60 °C for 3 h. Then, the esterified oil was separated from the excess alcohol, sulfuric acid and impurities using a separator funnel. The separated esterified oil was then heated at 60 °C in the rotary evaporator for 1 h to remove the methanol and the water. For the transesterification reaction, a 6:1 molar ratio of methanol to oil and 1% (m/m oil) of potassium hydroxide (KOH) were mixed with the preheated esterified oil and stirred at constant speed of 600 rpm and at 60 °C temperature for 2 h. After the reaction was complete, the methyl ester was kept in a separation funnel for 24 h. Then, the glycerol in the lower layer was drained out, and the methyl ester was washed with warm distilled water (3 times), dried in the rotary evaporator and filtered using qualitative filter paper to collect the final product.

2.3. Analysis of properties

The physico-chemical properties of the *J. curcas* and *M. oleifera* biodiesels were characterized according to the ASTM D6751 and EN 14214 standards. The cetane number (CN), the iodine value (IV) and the saponification value (SV) were determined using the following equations (Mofijur et al., 2013b):

$$\mathrm{CN} = 46.3 + (5458/\mathrm{SV}) - (0.225 \cdot \mathrm{IV}) \tag{1}$$

$$\mathrm{SV} = \sum (560 \cdot A_\mathrm{i})/M_\mathrm{Wi} \tag{2}$$

$$\mathrm{IV} = \sum (254 \cdot A_\mathrm{i} \cdot D)/M_\mathrm{Wi} \tag{3}$$

Where A_i was the percentage of each component, D was the number of double bonds and M_Wi was the molecular mass of each component.

2.4. Fatty acid composition

The fatty acid composition (FAC) of *M. oleifera* methyl ester was analyzed using gas chromatography (GC) (Shimadzu, Japan) equipped with a flame ionization detector. The results of FAC of *M. oleifera* methyl ester are shown in Table 1.

2.5. Biodiesel blending

The test fuels (JCME and MOME) were blended with diesel using a homogenizer operated at 2000 rpm. The homogenizer was clamped

Table 1
Fatty acid composition of *Jatropha curcas* and *Moringa oleifera* methylester.

Sl. No.	Fatty acid	Molecular weight	Structure	Systematic name	Formula	JCME (%)	MOME (%)
01	Lauric	200	12:0	Dodecanoic	$C_{12}H_{24}O_2$	0.1	0
02	Myristic acid	228	14:0	Tetradecanoic	$C_{14}H_{28}O_2$	0.1	0.1
03	Palmitic	256	16:0	Hexadecanoic	$C_{16}H_{32}O_2$	14.6	7.9
04	Palmitoleic	254	16.1	Hexadec-9-enoic	$C_{16}H_{30}O_2$	0.6	1.7
05	Stearic	284	18:0	Octadecanoic	$C_{18}H_{36}O_2$	7.6	5.5
06	Oleic	282	18:1	cis-9-Octadecenoic	$C_{18}H_{34}O_2$	44.6	74.1
07	Linoleic	280	18:2	cis-9-cis-12 Octadecadienoic	$C_{18}H_{32}O_2$	31.9	4.1
08	Linolenic	278	18:3	cis-9-cis-12	$C_{18}H_{30}O_2$	0.3	0.2
09	Arachidic	312	20:0	Eicosanoic	$C_{20}H_{40}O_2$	0.2	2.3
10	Eicosanoic	310	20:1	cis-11-Eicosenoic	$C_{20}H_{38}O_2$	–	1.3
11	Behenic	340	22:0	Docosanoic	$C_{22}H_{44}O_2$	–	2.8
12	Other					0	0
Saturated						22.6	18.6
Monounsaturated						45.2	77.1
Polyunsaturated						32.2	4.3
Total						100	100

Table 2
Summary of the values of measurement accuracy and the relative uncertainty of BSFC determination.

Fuel samples	Values of measurement accuracy (g/kWh)	Relative uncertainty of BSFC determination (%)
B0	±5	1.30
JB10	±5	1.25
MB10	±5	1.23

Table 3
Details specification of the engine.

Engine type		4 cylinder inline
Displacement	L	2.5
Cylinder bore × stroke	mm	92 × 96
Compression ratio		21:1
Maximum engine speed	rpm	4200
Maximum power	kW	55
Fuel system		Distribution type jet pump (indirect injection)
Lubrication System		Pressure feed
Combustion chamber		Swirl type
Cooling system		Radiator cooling

on a vertical stand, and the height of the homogenizer was adjustable. To mix the fuels, the plug was turned on and the appropriate homogenizer speed was selected.

2.6. Engine tests

The experimental investigation was carried out using diesel fuel (B0), the MB10 (90% diesel and 10% *M. oleifera* methyl ester) blend and the JB10 (10% *J. curcas* methyl ester and 90% diesel) blend. The test engine was a Mitsubishi Pajero (model 4D56T) multi-cylinder diesel engine. The accuracy of the speed, fuel measurement, brake power, and time was ±10 rpm, ±1% of the reading, ±0.07 kW and ±0.1 s respectively. Relative uncertainty of BSFC was determined using the linearized approximation method of uncertainty. Table 2 shows the summary of the values of measurement accuracy and the relative uncertainty of BSFC determination.

Fig. 1 shows the engine test rig. The detailed specifications of the engine are listed in Table 3. The engine was run with diesel fuel for several minutes to warm it up before biodiesel was tested. Likewise, the engine was operated with diesel fuel before it was shut down. The same procedure was used for each fuel test. To carry out engine performance and emission tests, the engine was run fully loaded at various speeds between 1000 and 4000 rpm. Engine test conditions

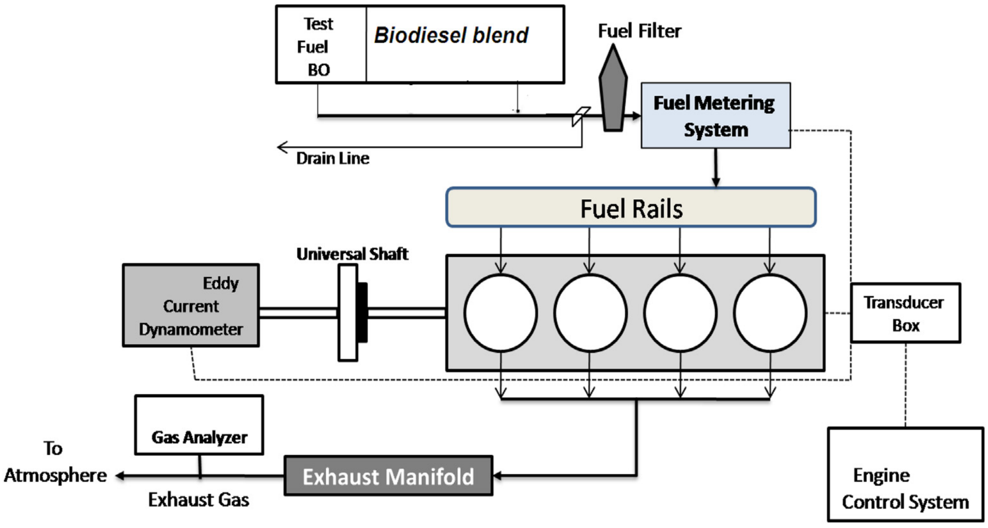

Fig. 1. Engine test bed set-up.

Table 4
Details of the exhaust gas analyzer.

Equipment	Method	Measurement	Upper limit	Accuracy	Uncertainty
BOSCH gas analyser	Non-dispersive infrared	CO	10.00 vol %	±0.001 vol %	0.002 vol %
	Non-dispersive infrared	CO_2	18.00 vol %	±0.001 vol %	0.150 vol %
	Flame ionization detector	HC	9999 ppm	±1 ppm	2 ppm
	Electro-chemical transmitter	NO	5000 ppm	±1 ppm	21 ppm

Table 5
Physico-chemical properties of *Jatropha curcas* and *Moringa oleifera* methylester and their blends.

Properties	Units	B0	MOME	JCME	JB10	MB10	ASTM D6751	EN 14214
Dynamic viscosity	mPa s	2.69	4.34	4.09	2.84	2.94	–	–
Kinematic viscosity at 40 °C	mm^2/s	3.23	5.05	4.73	3.42	3.54	1.9–6	3.5–5
Kinematic viscosity at 100 °C	mm^2/s	1.24	1.84	1.81	1.33	1.35	–	–
Density	kg/m^3	827.2	869.6	865.7	831.0	830.6	–	860–900
Flash point	°C	68.5	150.5	184.5	80.3	79.5	130 min	120 min
Cloud point	°C	8	19	3	6	7	−3 to −12	–
Pour point	°C	0	19	3	0	3	−15 to −16	–
Cold filter plugging point	°C	5	18	10	6	6	+5	–
Calorific value	MJ/kg	45.30	40.05	39.82	44.72	44.74	–	–
Iodine value	g I_2/100 g	–	77.5	99	–	–	–	120 max
Saponification value	–	–	199	202	–	–	–	–
Oxidation stability	h	–	26.2	3.02	–	–	3	6
Cetane number	–	48	56.3	51	–	–	47 min	51 min

were monitored by an REO-DCA controller connected through a desktop computer to the engine test bed (Fig. 1). A BOSCH exhaust gas analyzer (model BEA-350) was used to measure the NO, HC, CO and CO_2 emissions. The details of this gas analyzer are shown in Table 4. Every test was repeated three times, and the results were averaged.

3. Results and discussion

3.1. Characterization of *M. oleifera* methylester and its blends

To characterize the pure *J. curcas* and *M. oleifera* methyl esters (B100), properties such as the density, the flash point, the kinematic viscosity, the viscosity index, the calorific value, the cold filter plugging point, the cloud and the pour points and the oxidation stability were examined and compared with the ASTM D6751 standards. Table 5 shows the detailed physico-chemical characteristics of the *J. curcas* (JCME) and *M. oleifera* methyl esters (MOME) and their 10% by volume blends (JB10 and MB10). All of the studied physico-chemical properties of the *J. curcas* and *M. oleifera* methyl esters met the ASTM D6751 and EN 14214 standards. Thus, the *J. curcas* and *M. oleifera* methyl esters can be used in unmodified diesel engines.

3.2. Engine performance

In this study, engine performance was evaluated in terms of the brake power (BP) and the brake specific fuel consumption (BSFC). The details of this evaluation are discussed as follows:

3.2.1. Brake power (BP)

Fig. 2 shows the engine brake power (BP) output of *J. curcas* and *M. oleifera* methyl ester blends at different engine speeds. For all tested fuels, the brake power increased steadily with the engine speed. Biodiesel blended fuels gave lower BP values than diesel fuel. This observation is consistent with the literature (Sahoo et al., 2009). At all test speeds, the average brake powers of the B0, JB10 and MB10 fuels were 28.72, 27.32 and 27.51 kW, respectively. Compared to diesel fuel, the JB10 and MB10 fuels produced lower brake powers (about 5% and 4%, respectively) due to their lower calorific values and higher viscosities (Table 5), which influenced combustion. The uneven combustion characteristics of biodiesel fuel reduced the engine brake power (Muralidharan et al., 2011). The JB10 fuel produced slightly lower BPs than MB10 fuel because MB10 has a higher calorific value than JB10 fuel.

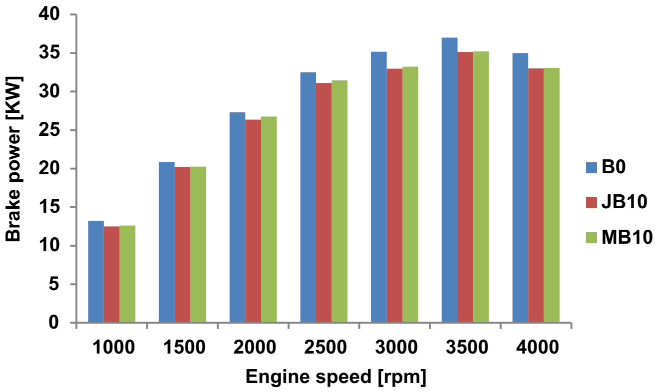

Fig. 2. Variation of the brake power with respect to the engine speed.

3.2.2. Brake specific fuel consumption (BSFC)

Fig. 3 illustrates the variation of the BSFC values for all fuels at different engine speeds. Biodiesel blended fuels gave higher BSFC values than diesel fuel. This observation is consistent with the literature (Chauhan et al., 2012; Shahabuddin et al., 2012; Wang et al., 2013). Factors such as the volumetric fuel injection system, the fuel density, the viscosity and the lower heating value affect the BSFC of the diesel engine (Qi et al., 2010a). At all speeds, the average BSFCs for the B0, JB10 and MB10 were 386, 399 and 406 g/kWh, respectively. Per unit kW of power produced, more biodiesel blend is consumed than diesel fuel because the calorific value of biodiesel is lower than diesel. Compared to diesel fuel, the BSFCs were 3 and 5% higher for the JB10 and MB10, respectively. The blends' BSFCs were higher for the biodiesels because their densities and viscosities are higher, and their energy densities are lower, than diesel

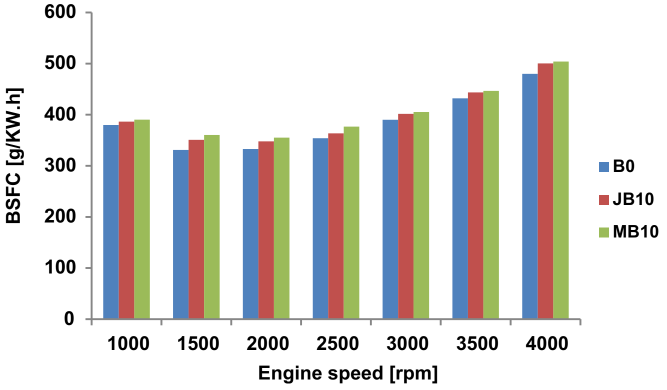

Fig. 3. Variation of the brake specific fuel consumption with respect to the engine speed.

(Mofijur et al., 2013b). Both the viscosity and the BSFC of the MB10 were higher than for JB10.

3.3. Emissions analysis

3.3.1. CO emissions

Due to the absence of molecular oxygen in the fuel, combustion was incomplete and CO was emitted. In general, factors such as the air–fuel ratio, the engine speed, the injection timing and pressure and the fuel type influence CO emissions (Gumus et al., 2012). The variation of CO emissions with diesel and biodiesel blends is shown in Fig. 4. Over the entire range of engine speeds, the JB10 and MB10 reduced the CO emissions by 14% and 11% relative to B0, respectively. This result is consistent with the literature (Rajaraman et al., 2009; Kim and Choi, 2010; Sahoo et al., 2009). This reduction of CO emissions is attributed to the higher oxygen content and cetane number of biodiesel fuel. Biodiesel contains 12% more oxygen that diesel. The higher oxygen content of biodiesel allows more carbon molecules to burn, and fuel combustion is complete. Thus, CO emissions are lower when diesel engines burn biodiesel fuel.

3.3.2. HC emissions

Unburned HC is the result of the incomplete combustion of fuels and flame quenching. The variation of HC emissions for diesel and biodiesel blend fuels is shown in Fig. 5. For the JB10 and MB10, the unburned HC emissions are lower than for diesel fuel. Over the entire range of speeds, the average reductions in HC emission for the JB10 and MB10 are 16 and 12% relative to B0, respectively. This result is consistent with the literature (Rajaraman et al., 2009; Sahoo et al., 2009). These reductions are attributed to the high oxygen contents of these biodiesel fuels. Biodiesel contains more oxygen and less carbon and hydrogen than diesel fuel, which guarantees more complete combustion (Lin et al., 2009; Qi et al., 2010b).

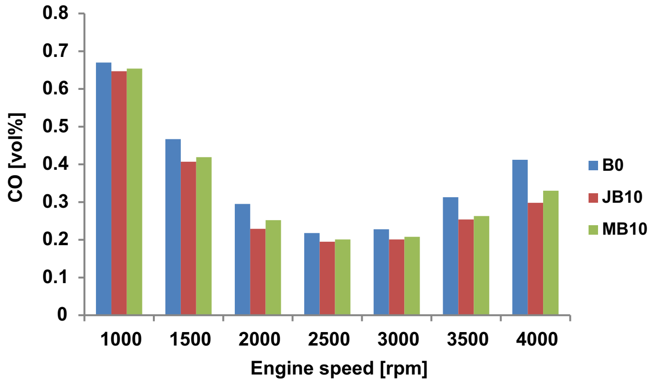

Fig. 4. Variation of CO emissions with respect to the engine speed.

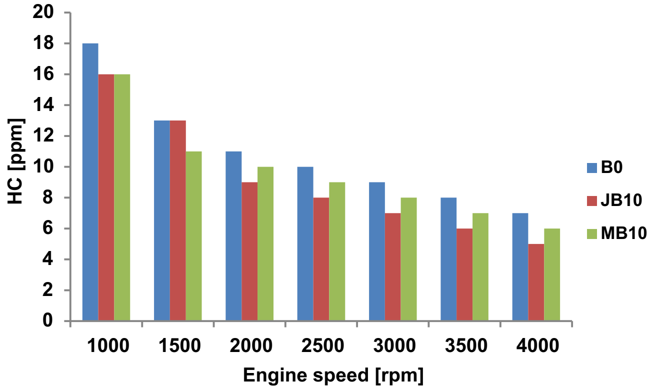

Fig. 5. Variation of HC emissions with respect to the engine speed.

3.3.3. NO emissions

The variation of the NO emissions for diesel and biodiesel blend fuels is shown in Fig. 6. The NO values are higher for biodiesel blends than diesel fuel. This result is consistent with studies published by other researchers (El-Kasaby and Nemit-allah 2013). On average, the JB10 and MB10 produce 7% and 9% higher NO emissions, respectively, than diesel fuel over the entire range of speeds. This result can be attributed to the leaner air/fuel ratio, as biodiesel is an oxygenated fuel and contains 12% more molecular oxygen than diesel, which raises chamber temperatures and improves combustion (Devan and Mahalakshmi, 2009). Thus, NO emissions are higher for biodiesel blends than for diesel fuel. Moreover, the greater NO emissions might be due to the higher adiabatic flame temperature. Biodiesel fuels that contain more unsaturated fatty acids have higher adiabatic flame temperatures, which cause higher NO emissions (El-Kasaby and Nemit-allah 2013).

3.3.4. CO_2 emissions

The variation of CO_2 emissions for all the fuel samples at various speeds are shown in Fig. 7. When the engine speed increased, the CO_2 emissions also increased. The biodiesel fuel blends JB10 and MB10 gave 7 and 5% average increase in CO_2 emissions relative to diesel fuel, respectively. This result is consistent with the literature (Rajaraman et al., 2009). The production of carbon dioxide from the combustion of fossil fuels causes many environmental problems such as the accumulation of carbon dioxide in the atmosphere. Although biofuel combustion produces carbon dioxide, absorption by crops helps to maintain CO_2 levels (Ramadhas et al., 2005).

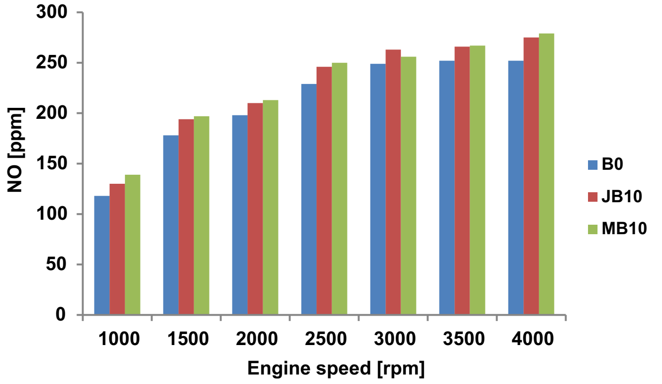

Fig. 6. Variation of NO emissions with respect to the engine speed.

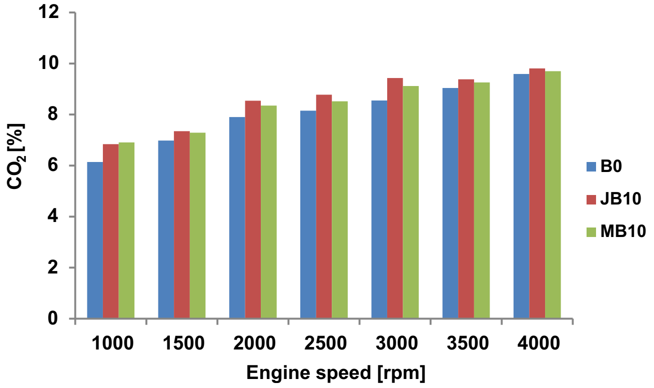

Fig. 7. Variation of CO_2 emissions with respect to the engine speed.

4. Conclusions

Biodiesel is one of the best alternative fuels with the potential to reduce global dependency on fossil-based diesel fuel and environmental pollution, and it can be used in unmodified compression ignition engines. In this paper, biodiesel was produced from crude *J. curcas* and *M. oleifera* oils, and 10% biodiesel blends by volume were evaluated in a diesel engine. Based on this experimental study, the following conclusions were drawn:

- The studied properties of the *J. curcas* and *M. oleifera* methyl esters and their blends agreed with the ASTM D6751 and EN 14214 standards.
- Over the entire range of engine speeds, the JB10 and MB10 biodiesels gave average brake powers of 27.32 and 27.51 kW that were 5 and 4% lower than B0 fuel, respectively. The average brake specific fuel consumptions were 399 and 406 g/kWh for the JB10 and MB10 respectively, which were slightly higher (3 and 5%) than B0 fuel. These results were attributed to the higher viscosity and density and the lower energy content of these biodiesel blends.
- As diesel fuel substitutes, the JB10 and MB10 reduced the average CO emissions by 14 and 11%, respectively; and HC emissions by 16 and 12%, respectively. However, the JB10 and MB 10 slightly increased NO emissions by 7 and 9%, respectively, and CO_2 emissions by 7 and 5% relative to diesel fuel. These results were attributed to the higher oxygen contents and cetane numbers of the biodiesel blended fuels.

In conclusion, the *J. curcas* and *M. oleifera* oils are potential feedstocks for biodiesel production, and the JB10 and MB10 biodiesels can replace diesel fuel in unmodified engines to reduce exhaust emissions into the environment.

Acknowledgments

The authors would like to acknowledge the University of Malaya for financial support through the High Impact Research Grant UM.C/HIR/MOHE/ENG/07.

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