Energy 55 (2013) 879–887

Contents lists available at SciVerse ScienceDirect

Energy

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

Evaluation of biodiesel blending, engine performance and emissions characteristics of *Jatropha curcas* methyl ester: Malaysian perspective

M. Mofijur*, H.H. Masjuki, M.A. Kalam, A.E. Atabani**

Department of Mechanical Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

ARTICLE INFO

Article history:
Received 1 December 2012
Received in revised form
15 February 2013
Accepted 16 February 2013
Available online 10 April 2013

Keywords:
Jatropha curcas
Blending
Physico-chemical properties
Engine performance
Emissions analysis

ABSTRACT

Currently, the main crop for biodiesel in Malaysia is palm oil. Recently, *Jatropha curcas* has drawn the attention of the Malaysian Government. This paper aims to study the feasibility of *Jatropha* as a potential biodiesel feedstock for Malaysia. Physico-chemical properties of *Jatropha* biodiesel and its blends with diesel followed by engine performance and emissions characteristics of B_{10}, B_{20} and B_0 were studied. The results show that viscosities of B_{10} and B_{20} are closer to diesel. Moreover, only the oxidation stability of B_{10} and B_{20} meet the European specifications (EN 590) of 20 h. Therefore, only B_{10} and B_{20} have been used to evaluate engine performance and emission. Compared to B_0, the average reduction in brake power (BP) is 4.67% for B_{10} and 8.86% for B_{20}. It was observed that brake specific fuel consumption (BSFC) increases as the percentage of biodiesel increase. Compared to B_0, a reduction in hydrocarbon (HC) emission of 3.84% and 10.25% and carbon monoxide (CO) emission of 16% and 25% was reported using B_{10} and B_{20}. However, the blends give higher nitrogen oxides (NO_x) emission of 3% and 6% using B_{10} and B_{20}. As a conclusion, B_{10} and B_{20} can be used in a diesel engine without any modifications.

© 2013 Elsevier Ltd. All rights reserved.

1. Introduction

Historically, fossil diesel fuel has successfully contributed in all sectors such as agricultural, transportation and industrial sectors because of their adaptability, high combustion efficiency, availability, reliability as well as the handling facilities. However, their reserves are wiping out every day [1]. The emissions come out by burning of fossil diesel fuel are considered as one of the major sources of the environment pollution. Pollutant emissions from diesel engines have a serious impact on ecological system as well as human health. Several factors such as world-wide environmental concerns, price hiking of the petroleum products as well as the expected depletion of fossil diesel fuel have promoted to look over the clean combustion of diesel engine using alternative fuel sources [2–4]. Since last decades researchers around the world have been trying to find new alternative fuels that are available, technically feasible, economically viable and environmentally acceptable [5].

Biodiesel as an alternative fuel is one of the best choices among other sources due to having immense potential to reduce pollutant emissions and to be used in compression ignition engines [6,7]. Biodiesel is non-explosive, biodegradable, non-flammable, renewable, non-toxic as well as environment friendly. It has similar properties with diesel fuel. The major advantages of biodiesel are; it can be blended with diesel fuel at any proportions, can be used in a diesel engine without any modification, does not contain any harmful substances and produce less harmful emissions to the environment [8,9].

Biodiesel is alkyl esters of fatty acids and can be obtained by employing the transesterification treatment of vegetable oils, animal fats, waste cooking oil and waste restaurant greases. Vegetable oil can be obtained from both edible (palm oil, rapeseed oil, sunflower oil, coconut oil, peanut oil etc) and non-edible (jatropha, neem, cotton, jojoba, rubber, Mahua and castor etc) oil sources [10,11].

1.1. Current status of biodiesel fuel in Malaysia

Currently, the major crop for biodiesel production in Malaysia is palm oil. In 2006, Malaysian Government agreed to use 40% (~6 million tonnes) of palm oil production (15.8 million tonnes) for the production of biodiesel. Recently *Jatropha curcas* has drawn the attention of the Malaysian Government. The government has planned on a demonstration project on cultivation of *Jatropha curcas* to establish the economic feasibility study of the crop for biodiesel production [12].

* Corresponding author. Tel./fax: +60 3 79674448.
** Corresponding author. Tel.: +60 122314659.
E-mail addresses: mofijduetme@yahoo.com (M. Mofijur), a_atabani2@msn.com (A.E. Atabani).

0360-5442/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.energy.2013.02.059

Nomenclature

ASTM	American society for testing and materials
BP	brake power
BSFC	brake specific fuel consumption
BTE	brake thermal efficiency
CCR	Conradson carbon residue
CO	carbon monoxide
FAC	fatty acid composition
FT-IR	fourier transfer-infra red
HC	hydrocarbon
JBD	*Jatropha* biodiesel
MJ/kg	Mega joule/kg
mm	millimeter
NO_x	nitrogen oxides
PBD	palm biodiesel
rpm	revolution per minute

1.2. Objectives of the study

The aim of this paper is to produce biodiesel from *Jatropha curcas* as a promising biodiesel feedstock for Malaysia. This was followed by characterizing the fuel properties of *Jatropha* biodiesel and its blends with diesel. Finally, engine performance and emission characteristics of *Jatropha* biodiesel blends (B_{10} and B_{20}) and diesel fuel (B_0) have been conducted in an unmodified diesel engine.

2. Literature review

The plant of *Jatropha curcas* grows on well-drained soils with good aeration and is a well adapted to marginal soil with low nutrient content [13]. The seed of *Jatropha* is oval in shape and black in color. The oil produced from the seed of *Jatropha* is golden yellow in color. The high oil content (66%) of *Jatropha curcas* seeds is one of the main reasons that promote biodiesel production from *Jatropha curcas* seeds oil [14].

In recent years, investigations have been carried out by several researchers [15–22] regarding the engine performance, emission and combustion characteristics of diesel engine using biodiesel from edible oil source. Hasimoğlu et al. [21] studied the performance characteristics of a low heat rejection diesel engine at full load and different speeds using biodiesel from sunflower oil. They found a significant improvement in the BSFC and BTE of the engine when biodiesel was used. Combustion and emission characteristics of soybean oil methyl ester and diesel were studied by Canakci [22]. He reported that the soybean oil biodiesel significantly reduced the unburned HC, CO, and PM. However, NO_x increased by 11.2% compared to diesel fuel.

Nonetheless, few authors [14,23–25] have reported on the engine performance and combustion characteristics of diesel engine using biodiesel from *Jatropha*. Sahoo and Das [23] compared the combustion characteristics of biodiesel fuel derived from jatropha, karanja, and polanga in a small 6 kW air-cooled, single cylinder, four-stroke diesel engine at different load conditions. The authors reported that the pure polanga biodiesel was the optimum fuel blend as far as the peak cylinder pressure is concerned. However, they also reported that the ignition delay for pure *Jatropha* biodiesel (JB_{100}) was shorter than for diesel fuel, varying between 5.9°and 4.2°crank angles. Likewise, the ignition delay for pure karanja biodiesel varied between 6.3° and 4.5° crank angles, and between 5.7° and 4.2° for pure polanga biodiesel, all of which are lower than diesel fuel. Chauhan et al. [24] studied the performance and emission characteristics of *Jatropha* biodiesel and its blend in a single cylinder diesel engine. They found that the performance of the engine is comparable with that of diesel fuel. They also reported that *Jatropha* biodiesel and its blend emitted lower exhaust emissions except NO_x with compare to diesel fuel.

It is remarkable that since the physico-chemical properties of biodiesel are different from diesel fuel, both the engine performance and the exhaust emissions are influenced. If an unmodified compression ignition engines are operated using biodiesel, further investigation about biodiesel properties and its impact on the fuel system and the combustion system is required [16]. The viscosity of *Jatropha* biodiesel is higher than that of diesel fuel, which leads to higher carbon deposits in the automotive components and some durability problems in the engine. However, the properties of *Jatropha* biodiesel meet the ASTM D6751-02 specification, which is the standard specification for biodiesel (B_{100}) fuel and indicates that it is suitable to be used in diesel engines.

Table 1
Properties of crude *Jatropha* oil.

Properties	Units	Standards	*Jatropha* oil	*Jatropha* oil[a]
Kinematic viscosity at 40 °C	mm^2/s	ASTM D445	52	47–54.8
Density at 15 °C	kg/m^3	ASTM D4052	921	–
Flash point	°C	ASTM D93	220	210–240
Pour point	°C	ASTM D97	4	−3
Cloud point	°C	ASTM D2500	9	2
Calorific value	MJ/kg	ASTM D240	38.66	37.830–42.050
Iodine value	g Iodine/100 g	–	94	92.0–112.0
FFA	%	–	15	0.18–3.40
Cetane number	–	ASTM D613	45	38.0–51.0

[a] Data obtained from ref [2].

Table 2
Summary of the equipment used to measure the properties.

No.	Property	Equipment	Test method[a]
1	Kinematic viscosity	SVM 3000 (Anton Paar, UK)	ASTM D445
2	Flash Point	Pensky-martens flash point - automatic NPM 440 (Norma lab, France)	ASTM D93
3	Oxidation stability	873 Rancimat (Metrohm, Switzerland)	EN ISO 14112
4	Cloud and Pour point	Cloud and Pour point tester - automatic NTE 450 (Norma lab, France)	ASTM D2500 ASTM D97
5	CCR	Micro-Carbone Conradson Residue Tester - automatic NMC 440 (Norma lab, France)	ASTM D4530
6	Total Sulfur	Multi EA 5000 (Analytical Jena, Germany)	ASTM D5433
7	Density	SVM 3000 (Anton Paar, UK)	ASTM D1298
8	Caloric value	C2000 basic calorimeter (IKA, UK)	ASTM D240

[a] Data obtained from Ref. [11].

Table 3
Summary of biodiesel production process from *Jatropha* oil.

No	Process parameter	Process specification
01	Process selected	Acid-base catalyst process
02	Reaction temperature	60 °C
03	Catalyst used	98% pure sulfuric acid (1%v/v) & 99% pure potassium hydroxides (1%m/m)
04	Alcohol used	Methanol (6:1 M ratio)
05	Reaction time	1 h
06	Setting time	12 h
07	Stirring speed	600 rpm

Table 4
GC operating conditions.

Property	Specifications
Carrier gas	Helium at 23.8 psi
Linear velocity	44 cm/s @ 100 °C
Flow rate	Air = 450 ml/min H_2 = 40 ml/min He = 20 ml/min
Detector temperature	250 °C
Column head pressure	23.8 psi
Column dimension	30 m × 250 mm × 2.5 μm
Injector	Split injector, 50:1 ratio, 0.3 μL injection volume
Temperature ramp 1	100 °C hold for 0 min
Temperature ramp 2	10 °C/min to 250 °C, hold for 5 min

3. Materials and methods

3.1. Materials

Crude *Jatropha* curcas was collected from Forest Research Institute Malaysia (FRIM). Table 1 shows physico-chemical properties of crude *Jatropha* oil beside a comparison with existing literature. It was observed that viscosity of the crude oil is very high (52 mm^2/s) and it is 11 times higher than that of diesel fuel. Moreover, the free fatty acids (FFA %) of the crude oil were reported to be high (15%).

3.2. Equipment list

Table 2 shows a summary of the equipment used in this study to perform the shows physico-chemical properties of crude *Jatropha* oil, *Jatropha* biodiesel and *Jatropha* biodiesel–diesel blends.

3.3. Biodiesel production

Free fatty acid (FFA) is the main identifier of production process. If the crude *Jatropha* oil contains higher FFA then two step processes is required because of forming fatty acid salts during the conversion of FFA into FAME (Fatty acid methyl ester) using alkaline catalyst. The fatty acid salt prevents to separate FAME layer from glycerin [11,26]. Therefore two step (acid-base catalyst) processes were select-ed to convert crude *Jatropha* oil into *Jatropha* oil methyl ester/jatropha biodiesel (JBD). The production of biodiesel was conducted in the laboratory scale using 1L batch reactor. The summary of biodiesel production process is given in Table 3.The next section will explain in detail the production processes used in this study to produce biodiesel.

3.3.1. Acid-catalyzed process

This process was used mainly to reduce the acid value of *Jatropha* oil prior to the transesterification step. In this process, the molar ratio of methanol to *Jatropha* oil was 6:1. 1% (v/v oil) of sulfuric acid (H_2SO_4) was added to the oil at 60 °C for 1 h under 600 rpm stirring speed in the reactor. On completion of this reaction, the products were poured into a separating funnel to separate the excess alcohol, sulfuric acid and impurities presented in the upper layer. The lower layers were separated and entered into a rotary evaporator and heated at 95 °C under vacuum conditions for 1 h to remove methanol and water from the esterified oils.

3.3.2. Alkaline-catalyzed process

In this process, the esterified *Jatropha* oil was reacted with methanol (6:1 M ratio) and 1% (m/moil) of potassium hydroxide

Table 5
Fatty acid composition of *Jatropha* biodiesel.

Sl. no.	Fatty acid	Molecular weight	Structure	Systematic name	Formula	JBD (Wt %)	PBD[a] (Wt %)
1	Lauric	200	12:0	Dodecanoic	$C_{12}H_{24}O_2$	0.1	–
2	Myristic acid	228	14:0	Tetradecanoic	$C_{14}H_{28}O_2$	0.1	–
3	Palmitic	256	16:0	Hexadecanoic	$C_{16}H_{32}O_2$	14.6	40.3
4	Palmitoleic	254	16.1	Hexadec-9-enoic	$C_{16}H_{30}O_2$	0.6	
5	Stearic	284	18:0	Octadecanoic	$C_{18}H_{36}O_2$	7.6	4.1
6	Oleic	282	18:1	cis-9-Octadecenoic	$C_{18}H_{34}O_2$	44.6	43.4
7	Linoleic	280	18:2	cis-9-cis-12 Octadecadienoic	$C_{18}H_{32}O_2$	31.9	12.2
8	Linolenic	278	18:3	cis-9-cis-12	$C_{18}H_{30}O_2$	0.3	–
9	Arachidic	312	20:0	Eicosanoic	$C_{20}H_{40}O_2$	0.3	–

[a] Data obtained from Ref. [27].

Table 6
Major physico-chemical properties of *Jatropha* biodiesel compared to palm biodiesel.

Properties	Units	Standards[a]	ASTM D6751	JBD	PBD	Diesel
Kinematic viscosity at 40 °C	mm^2/s	ASTM D445	1.9–6	4.723	4.617	3.619
Density at 15 °C	kg/m^3	ASTM D1298	860–900	864.8	859.2	832.8
Flash point	°C	ASTM D93	>130	182.5	172	77
Cloud point	°C	ASTM D2500	–	3	16	−20
Pour point	°C	ASTM D97	–	3	–	−35
Sulfur content	ppm	ASTM D5433	0.05%	4.59	5.23	–
Calorific value	MJ/kg	ASTM D240	–	40.536	39.907	44.66
Iodine value	g I/100 g	EN 14111	120 max	99	61	–
Saponification value	–	–	–	202	206	–
Acid value	mg KOH/g	ASTM D664	0.05	0.05	0.24	–
Oxidation stability	h	EN ISO 14112	3	3.02	2.7	110
Cetane number	–	ASTM D613	47 min	51	59	48
Carbon Conradson	%	ASTM D4530	0	0	0	–
Molecular weight	–	–	292	296	296	170

[a] Data obtained from ref [11].

(KOH) and maintained at 60 °C for 1 h and 600 rpm stirring speed. After completion of the reaction, the produced biodiesel was deposited in a separation funnel for 12 h to separate glycerol from biodiesel. The lower layer which contained impurities and glycerol was discarded.

3.3.3. Post-treatment process

The methyl ester formed in the upper layer from the previous process was entered into a rotary evaporator to remove the excess methanol. This was followed by washing with distilled water to remove the entrained impurities and glycerol. In this process, 50% (v/v oil) of distilled water at 60 °C was sprayed over the surface of the ester and stirred gently. This process was repeated several times until the pH became neutral. The lower layer was discarded and upper layer was poured into a flask and dried using rotary evaporator.

3.4. Fatty acid composition

Fatty acid without double bond is known as saturated fatty acids and Fatty acid containing double bond is termed as unsaturated fatty acids. The fatty acid composition (FAC) of *Jatropha* biodiesel was tested using gas chromatography (GC) (Agilent 6890 model, USA). Table 4 shows the operating conditions of the GC. The results of FAC of *Jatropha* biodiesel in comparison with palm biodiesel (PBD) are shown in Table 5. It was found that *Jatropha* methyl ester contained (22.6%) saturated and (77.4%) unsaturated fatty acids while palm biodiesel contained (44.4%) saturated and (55.6%) unsaturated fatty acids [27].

3.5. Properties analysis

The physico-chemical properties of the produced biodiesel were characterized according to the ASTM D6751 standards. The major physico-chemical properties of *Jatropha* biodiesel are comparable with those of diesel fuel and palm biodiesel. Table 6 shows the important physico-chemical properties of *Jatropha* biodiesel. Cetane number (CN), iodine value (IV) and saponification value (SV) was determined using the following equations [28]:

$$\mathrm{SN} = \mathrm{SUM}\left(\frac{560 \times A_i}{M_{wl}}\right)$$

$$\mathrm{IV} = \mathrm{SUM}\left(\frac{254 \times D \times A_i}{M_{wi}}\right)$$

$$\mathrm{CN} = \left(46.3 + \left(\frac{5458}{\mathrm{SN}}\right) - (0.225 \times \mathrm{IV})\right)$$

Where, A_i is the percentage of each component, D is the number of double bond and M_w is the molecular mass of each component.

Table 7
Characteristics peaks of JBD in FT-IR spectra.

Absorption bands (cm^{-1})	Functional group	Absorption intensity
2912	C–H stretching vibration	Strong
2853	CH_2 asymmetric and symmetric vibration	Strong
1741	C=O stretching vibration	Strong
1435–1462	CH_2 shear type vibration	Middling
1361	CH_3 bending vibration	Middling
1169–1195	C–O–C symmetric stretching vibration	Middling
1016	C–O–C anti-symmetric stretching vibration	Weak
844	Epoxy ring vibration	Middling
722	CH_2 plane rocking vibration	Weak

3.6. FT-IR analysis

Jatropha biodiesel was characterized by FT-IR, using a Perkin Elmer biodiesel FAME analyzer equipped with the MIR TGS detector in the range 4000–650 cm^{-1} and processed with the computer software program spectrum. Fig. 1 shows the Fourier transform infrared (FT-IR) spectrum of the *Jatropha* biodiesel. The resolution was 4 cm^{-1} and 8 scans. The characteristics peaks of the *Jatropha* biodiesel are shown in Table 7.

3.7. Blending of biodiesel

The test fuels are blended at various ratios by using a homogenizer device at a speed of 2000 rpm. The homogenizer was fixed

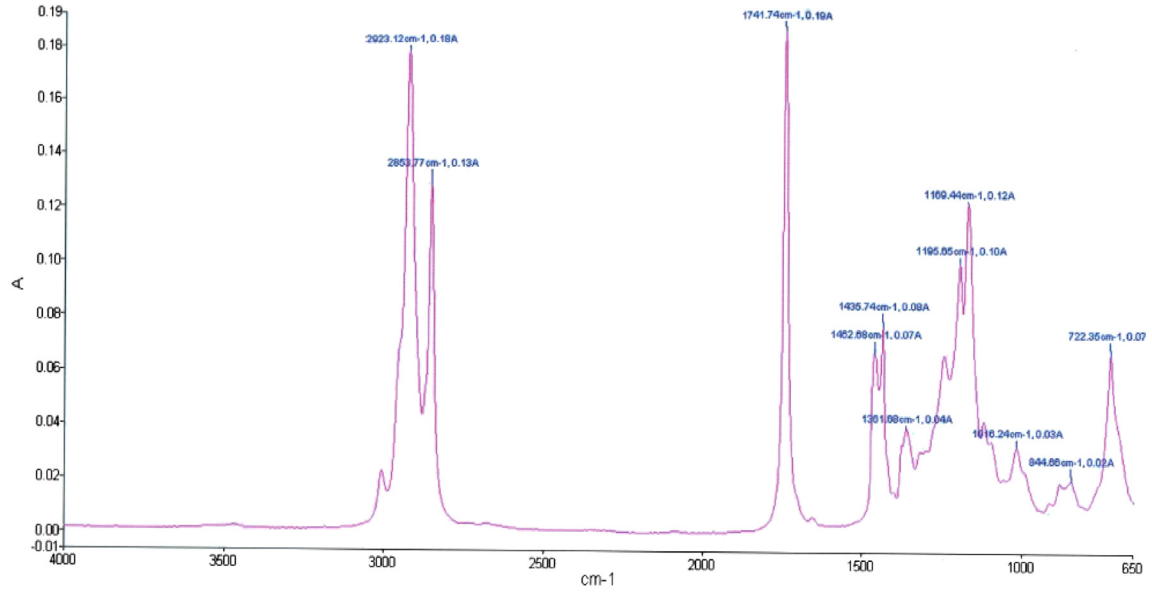


Fig. 1. Fourier transform infrared (FT-IR) spectrum of the JBD.

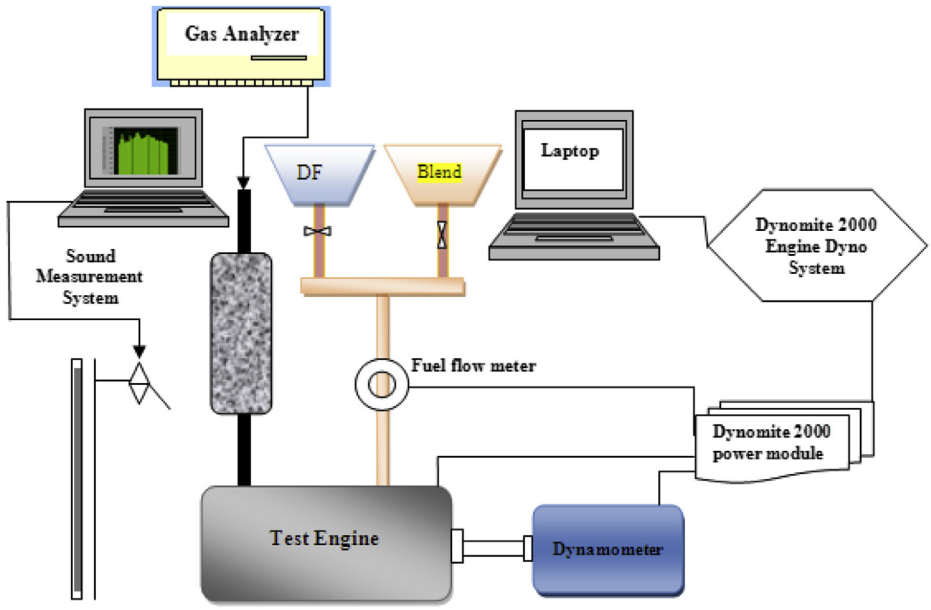


Fig. 2. Engine test set-up.

on a clamp on a vertical stand, which allows changing of the homogenizer's height. To mix the fuels by using the homogenizer, the plug is turned on and the appropriate speed is selected by using the selector which is located on top of the homogenizer.

3.8. Engine tests

The experimental investigation was carried out using diesel fuel, B_{10} (90% diesel and 10% *Jatropha* biodiesel) and B_{20} (20% *Jatropha* biodiesel and 80% diesel) blends. The engine used is a YANMAR TF 120-M diesel engine made by Yanmar Co. Ltd of Indonesia. Fig. 2 shows the test rig of the engine. The detailed specification of the engine is shown in Table 8.

Before running the engine with the biodiesel-blended fuels, the engine was first run with diesel fuel for a few minutes to warm up the engine. It was also run by diesel fuel before the engine was shutdown. The same procedure was maintained for each fuel. In order to carry out engine performance tests, the engine was first run at 100% load, keeping the throttle 100% wide open. The engine speeds were varied between 1200 and 2400 rpm, at an interval of 200 rpm. Engine test conditions were monitored by Dynomax-2000 software through a laptop connected to the engine test bed (Fig. 2). A BOSCH exhaust gas analyzer BEA-350 was used to measure the exhaust emission gases NOx/NO, HC and CO. The emissions analyses have been conducted only at maximum engine speed (2400 rpm). Details of gas analyzer are shown in Table 9. To get the average values, all tests were repeated three times.

Table 8
Details specification of the engine.

Engine type	4 Stroke DI diesel engine
Number of cylinders	One
Aspiration	Natural aspiration
Cylinder bore × stroke (mm)	92 × 96
Displacement (L)	0.638
Compression ratio	17.7
Maximum engine speed (rpm)	2400
Maximum power (kW)	7.7
Injection timing (deg.)	bTDC 17.0
Injection pressure (kg/cm^2)	200
Power take – off position	Flywheel side
Cooling system	Radiator cooling

4. Results and discussion

4.1. Characterization of Jatropha biodiesel–diesel blends

As was mentioned earlier in this paper, biodiesel can be blended with diesel fuel at different ratios [29]. In this study, biodiesel–diesel blends (B_{10}–B_{90}) were prepared and their influence on fuel properties (density, flash point, viscosity, calorific value, cloud and pour point, and oxidation stability) was examined and presented in Fig. 3a–e. It can be seen that the kinematic viscosities of all blends meet the ASTM D6751 specifications. Kinematic viscosity (KV) increases as the percentages of biodiesel in the blends increases (Fig. 3a). Moreover, the viscosities of B_{10} and B_{20} are almost closer to the diesel fuel (3.7135 mm^2/s and 3.7878 mm^2/s). Therefore, it can be noticed that B_{10} and B_{20} can be used in the diesel engine without any modifications.

Density increased as the percentage of *Jatropha* biodiesel increased in the blends (Fig. 3b). The densities of B_{10} and B_{20} are very close to the density of diesel fuel (836.1 kg/m^{3}and 839 kg/m^3).

Table 9
Details of the exhaust gas analyser.

Equipment	Method	Measurement	Upper limit	Accuracy	Percentage uncertainties
BOSCH gas analyser	Non-dispersive infrared	CO	10.00 vol.%	±0.02 vol.%	±0.2
	Non-dispersive infrared	CO_2	18.00 vol.%	±0.03 vol.%	±0.16
	Flame ionization detector (FID)	HC	9999 ppm	±1 ppm	±0.5
	Heated vacuum type chemiluminescence detector (CLD)	NOx/NO	5000 ppm	±1 ppm	±0.5

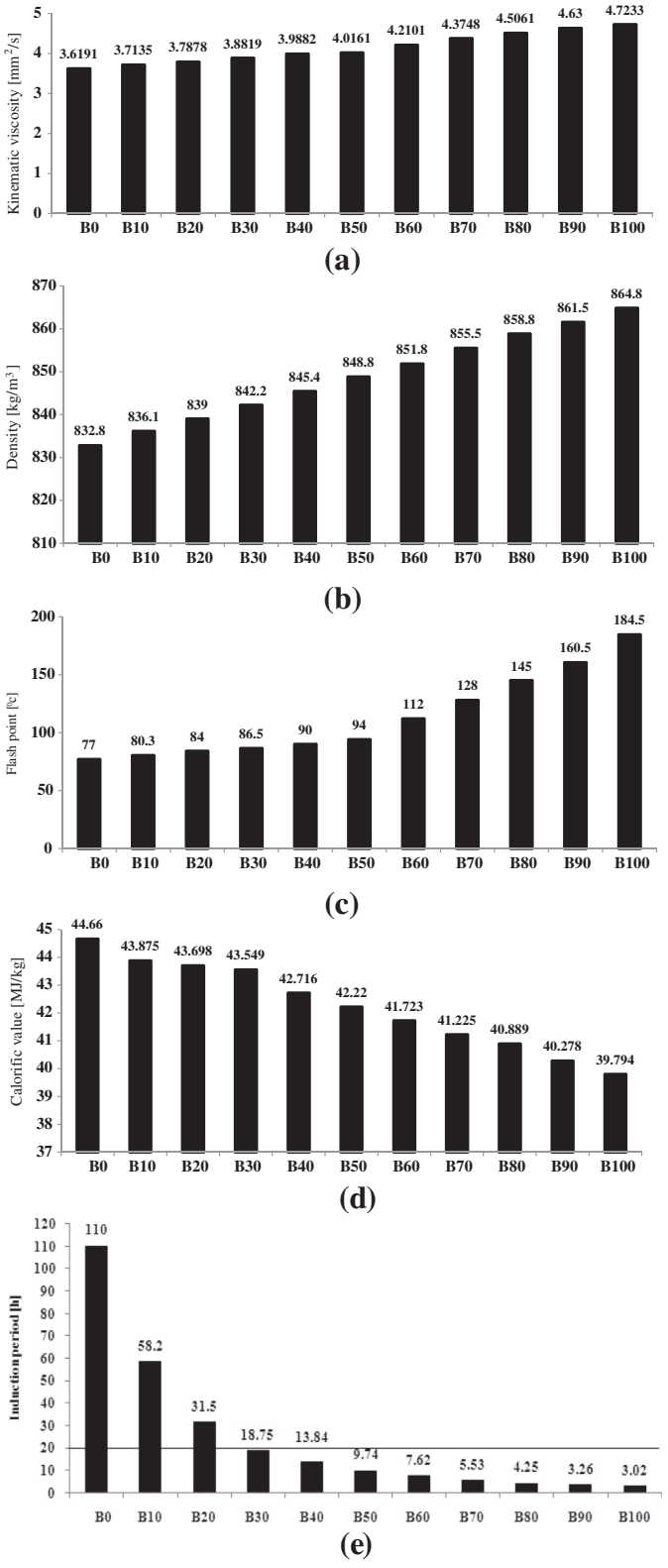


Fig. 3. Blending effect on (a) kinematic viscosity (b) density (c) flash point (d) calorific value (e) oxidation stability.

The flash point increases as the percentage of *Jatropha* biodiesel increases in the blends (Fig. 3c). Generally, fuel with the flash point more than 66 °C is considered as a safe fuel [30]. Therefore, the results of all biodiesel blends are considered to be safe to store and to use in the engine.

Calorific value decreases as the amount of *Jatropha* biodiesel increases in the blends (Fig. 3d). This is mainly due to the higher oxygen content of biodiesel than that of diesel (10% higher). Thus hydrogen and carbon contents in the blend decrease which is the source of thermal energy [14].

The oxidation stability of biodiesel is quantified by induction period (IP) [31]. It can be seen from (Fig. 3e) that (IP) decreases as the percentages of biodiesel increases in the blend. This is because of the increase in the percentage of unsaturated fatty acids in *Jatropha* biodiesel. It was observed that only B_{10} and B_{20} meet the European standard EN 590 specifications (20 h). The induction period for B_{10} and B_{20} is 58 h and 31.50 h respectively. The induction periods of remaining blends (B_{30}–B_{90}) do not meet the EN590 standard specification and all are below 20 h.

4.2. Engine performance

In this study, engine performance was evaluated in terms of torque, brake power (BP), and brake specific fuel consumption (BSFC). The following section will discuss the obtained results of these parameters.

4.2.1. Engine torque

Fig. 4a shows engine torque of all fuel samples with respect to the engine speed. It can be seen that torque increases steadily with speed up to a maximum value, and then falls with further increases in speed. This is mainly attributed to two main reasons. The first reason is the mechanical friction loss, and the second is lower volumetric efficiency of the engine due to increasing speed [32,33]. It can be seen that the engine torque of B_0 fuel is always higher than that of the B_{10} and B_{20} fuels. The maximum torque was recorded at 1800 rpm, and it was 21.1 Nm, 20.45 Nm, and 20.12 Nm for B_0, B_{10} and B_{20} respectively. The average torque reduction for B_{10} and B_{20} as compared to B_0 was 3.08% and 4.6%, respectively. The reason of reducing torque with the blended fuels is due to the higher viscosity and lower calorific value of the biodiesel fuel.

4.2.2. Brake power

Fig. 4b shows the engine brake power output at different engine speeds. It can be seen that brake power increased steadily with engine speed. The maximum brake power of the engine was recorded at 2400 rpm, and it was 4.06 kW, 3.87 kW, and 3.70 kW for B_0, B_{10} and B_{20} respectively. The reason for the lower brake power of biodiesels compared to diesel can be attributed to their lower calorific values and higher viscosities. Both the calorific value and viscosity have an effect on the combustion. Additionally, uneven combustion characteristics of biodiesel fuel decreased the engine brake power [34]. Furthermore, it is seen that the average brake power reduction for B_{10} and B_{20} in compared to B_0 fuel is 4.67% and 8.86%, respectively.

4.2.3. Brake specific fuel consumption

BSFC is the ratio between mass flow of the tested fuel and effective power. The BSFC of diesel engine depends on the relationship among volumetric fuel injection system, fuel density, viscosity and lower heating value [17]. Fig. 4c shows the variation of brake specific fuel consumption (BSFC) for all samples with respect to the engine speed. It is seen that the BSFC for biodiesel-blended fuels is higher compared to diesel. The average BSFC for B_0, B_{10}, and B_{20} is 273.5 g/kWh, 278.46 g/kWh, and 281.9 g/kWh, respectively. The reason for the higher BSFC of biodiesels can be attributed to the combined effects of the relative fuel density, viscosity and heating value of the blends [24]. Biodiesel fuel is delivered into the engine on a volumetric basis per stroke; thus, larger quantities of biodiesel are fed into the engine. Therefore, to produce the same

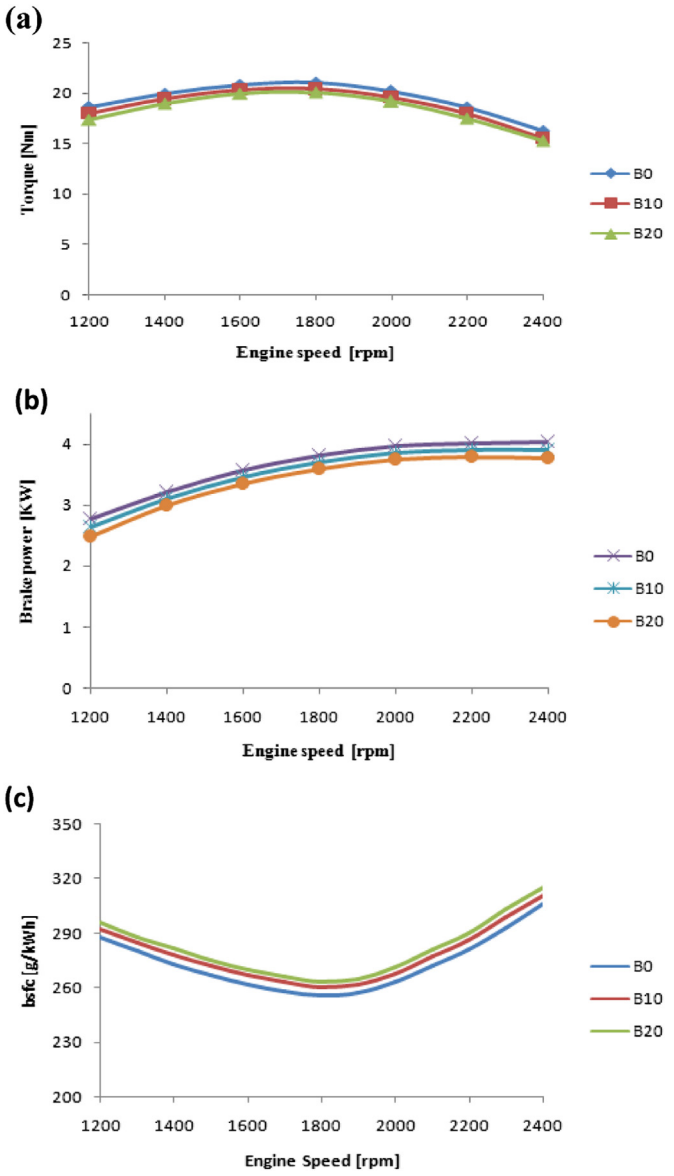


Fig. 4. (a) Torque-speed characteristics (b) brake power-speed characteristics (c) variation of BSFC with respect to speed.

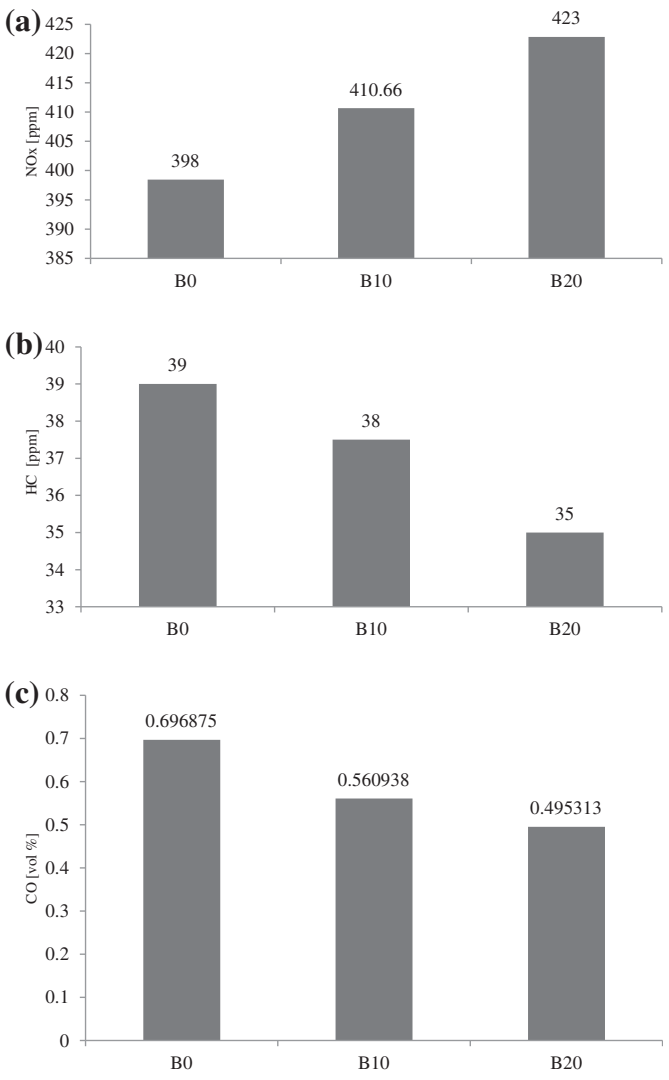


Fig. 5. (a) Average NO_x emission for all fuel samples at maximum engine speed, (b) average HC emission for all fuel samples at maximum engine speed (c) average CO emission for all fuel samples at maximum engine speed.

power, more biodiesel fuel is needed because biodiesel has a lower calorific value compared to diesel fuel [35,36].

4.3. Emissions analysis

The emissions analysis has been conducted only at maximum engine speed (2400 rpm). The variation of NO_x, HC and CO emissions for B_0, B_{10} and B_{20} are shown in Fig. 5a–c.

From Fig. 5a, it can be seen that the average NO_x emission for all fuel samples B_{20}, B_{10} and B_0 are 422 ppm, 411 ppm and 398 ppm respectively. It has been observed that B_{10} and B_{20} give 3% and 6% higher NO_x emission than that of diesel fuel. This can be attributed to the lean air/fuel ratio, as biodiesel contains 12% more oxygen in its molecular structure. Many researchers reported that oxygenate fuel blends can cause an increase in NO_x emission. Normally, complete combustion causes higher combustion temperature, which results in higher NO_x formation [37]. In addition, the higher viscosity of the blend of fuel leads to a bigger droplet size and shorter ignition delay. Hence NO_x emission is increased [38].

On the other hand, NO_x emission is strongly related to the higher peak combustion temperature. A fuel with a higher heat release rate in the premix combustion phase and lower heat release rate in the late combustion phase will increase NO_x emission [39].

Unburned HC results from the incomplete combustion of fuel and flame quenching [40]. Fig. 5b shows the results of unburned HC emissions at maximum speed. It can be seen that unburned HC for B_{10} and B_{20} are lower than that of diesel fuel. This is because of the higher oxygen content of biodiesel, which helps to complete the combustion and thus reduce HC emission [41]. The average reductions in HC emission for B_{10} and B_{20} compared to B_0 are 3.84% and 10.25% respectively. It can be also seen that HC emission are reduced as the percentage of biodiesel in the blends increases.

Carbon monoxide is formed during the combustion process with rich air-fuel mixtures regions and when there is insufficient oxygen to fully burn all the carbon in the fuel to CO_2 [42]. Fig. 5c shows the results of CO emission at maximum speed. The average reduction in CO emission for fuels B_{10} and B_{20} compared to B_0 are 16% and 25% respectively. It can be seen that CO emission is decreased with increasing biodiesel percentages in the blends. This is because biodiesel contains higher oxygen than diesel fuel which helps to complete the combustion [24].

5. Conclusions

Recently *Jatropha curcas* has drawn the attention of the Malaysian Government as a potential source for biodiesel production. Therefore, this paper aims to study the feasibility of biodiesel production from *Jatropha curcas* in Malaysia. Based on the experimental investigation, the following conclusions can be drawn:

- The viscosities of B_{10} and B_{20} (3.7135 mm^2/s and 3.7878 mm^2/s) are almost closer to the diesel fuel. Moreover, the oxidation stability of B_{10} and B_{20} (58 h and 31.50 h) only meet the European standard EN 590 specifications of (20 h).
- The flash point results of all blends are considered to be safe to store and to be used in diesel engines.
- Calorific value decreased as the amount of *Jatropha* biodiesel increased in the blends.
- Density increased as the percentage of *Jatropha* biodiesel increased in the blends
- An average reduction in brake power for B_{10} and B_{20} by 4.67% and 8.86% respectively was observed compared to B_0.
- The maximum torque was recorded at 1800 rpm, and it was 21.1 Nm, 20.45 Nm, and 20.12 Nm for B_0, B_{10} and B_{20} respectively
- The average BSFC for B_{10}, B_{20} (278.46 g/kWh, and 281.9 g/kWh) were found to be higher compared to B_0 (273.5 g/kWh).
- The use of B_{10} and B_{20} as a partial diesel fuel substitute produced lower HC (3.84% and 10.25%) and CO (16% and 25%) emissions but slightly higher NO_x (3% and 6%) emission compared to B_0.

These results show that *Jatropha* biodiesel–diesel blends (B_{10} and B_{20}) can be used in diesel engines without major modification. Therefore, it can be concluded that *Jatropha* crop can be considered as a promising source of biodiesel production in Malaysia.

Acknowledgment

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

References

[1] Agarwal AK, Rajamanoharan. Experimental investigations of performance and emissions of Karanja oil and its blends in a single cylinder agricultural diesel engine. Appl Energy 2009;86:106–12.
[2] Koh MY, Ghazi M, Idaty T. A review of biodiesel production from *Jatropha curcas* L. oil. Renew Sust Energy Rev 2011;15:2240–51.
[3] Tan P-Q, Hu Z-Y, Lou D-M, Li Z-J. Exhaust emissions from a light-duty diesel engine with Jatropha biodiesel fuel. Energy 2012;39:356–62.
[4] Mrad N, Varuvel EG, Tazerout M, Aloui F. Effects of biofuel from fish oil industrial residue – diesel blends in diesel engine. Energy 2012;44:955–63.
[5] Liaquat AM, Kalam MA, Masjuki HH, Jayed MH. Potential emissions reduction in road transport sector using biofuel in developing countries. Atmos Environ 2010;44:3869–77.
[6] Mofijur M, Masjuki HH, Kalam MA, Shahabuddin M. Experimental study of additive added palm biodiesel in a compression ignition engine. Energy Educ Sci Technol Part A: Energy Sci Res 2012;30:737–48.
[7] Silitonga AS, Atabani AE, Mahlia TMI, Masjuki HH, Badruddin IA, Mekhilef S. A review on prospect of Jatropha curcas for biodiesel in Indonesia. Renew Sust Energy Rev 2011;15:3733–56.
[8] Ng J-H, Ng HK, Gan S. Characterisation of engine-out responses from a light-duty diesel engine fuelled with palm methyl ester (PME). Appl Energy 2012;90:58–67.
[9] How HG, Teoh YH, Masjuki HH, Kalam MA. Impact of coconut oil blends on particulate-phase PAHs and regulated emissions from a light duty diesel engine. Energy 2012;48:500–9.
[10] Mofijur M, Masjuki HH, Kalam MA, Hazrat MA, Liaquat AM, Shahabuddin M, et al. Prospects of biodiesel from Jatropha in Malaysia. Renew Sust Energy Rev 2012;16:5007–20.
[11] Atabani AE, Silitonga AS, Badruddin IA, Mahlia TMI, Masjuki HH, Mekhilef S. A comprehensive review on biodiesel as an alternative energy resource and its characteristics. Renew Sust Energy Rev 2012;16:2070–93.
[12] Economic Research Institute for ASEAN and East Asia (ERIA). Current status of biodiesel fuel in East-Asia and ASEAN countries [cited 2012 28th November]; Available from: http://www.eria.org/CURRENT_STATUS_OF_BIODIESEL_FUEL_IN_EAST-ASIA_AND_ASEAN_COUNTRIES.pdf; 2012.
[13] Atabani AE, Silitonga AS, Ong HC, Mahlia TMI, Masjuki HH, Badruddina Irfan Anjum, et al. Non-edible vegetable oils: a critical evaluation of oil extraction, fatty acid compositions, biodiesel production, characteristics, engine performance and emissions production. Renew Sust Energy Rev 2013;18:211–45.
[14] Rao PV. Experimental investigations on the influence of properties of jatropha biodiesel on performance, combustion, and emission characteristics of a DI-CI engine. World academy of science. Eng Technol 2011;75:855–68.
[15] Rao GLN, Sampath S, Rajagopal K. Experimental studies on the combustion and emission characteristics of adiesel engine fuelled with used cooking oil methyl ester and its diesel blends. Int J Appl Sci Eng Technol 2008:64–70.
[16] Qi DH, Geng LM, Chen H, Bian YZ, Liu J, Ren XC. Combustion and performance evaluation of a diesel engine fueled with biodiesel produced from soybean crude oil. Renew Energy 2009;34:2706–13.
[17] Qi DH, Chen H, Geng LM, Bian YZ. Experimental studies on the combustion characteristics and performance of a direct injection engine fueled with biodiesel/diesel blends. Energy Convers Manag 2010;51:2985–92.
[18] Ozsezen AN, Canakci M, Turkcan A, Sayin C. Performance and combustion characteristics of a DI diesel engine fueled with waste palm oil and canola oil methyl esters. Fuel 2009;88:629–36.
[19] Ghorbani A, Bazooyar B, Shariati A, Jokar SM, Ajami H, Naderi A. A comparative study of combustion performance and emission of biodiesel blends and diesel in an experimental boiler. Appl Energy 2011;88:4725–32.
[20] Kannan GR, Karvembu R, Anand R. Effect of metal based additive on performance emission and combustion characteristics of diesel engine fuelled with biodiesel. Appl Energy 2011;88:3694–703.
[21] Haşimoğlu C, Ciniviz M, Özsert İ, İçingür Y, Parlak A, Sahir Salman M. Performance characteristics of a low heat rejection diesel engine operating with biodiesel. Renew Energy 2008;33:1709–15.
[22] Canakci M. Combustion characteristics of a turbocharged DI compression ignition engine fueled with petroleum diesel fuels and biodiesel. Bioresour Technol 2007;98:1167–75.
[23] Sahoo PK, Das LM. Combustion analysis of Jatropha, Karanja and Polanga based biodiesel as fuel in a diesel engine. Fuel 2009;88:994–9.
[24] Chauhan BS, Kumar N, Cho HM. A study on the performance and emission of a diesel engine fueled with Jatropha biodiesel oil and its blends. Energy 2012;37:616–22.
[25] Huang J, Wang Y, Qin J-B, Roskilly AP. Comparative study of performance and emissions of a diesel engine using Chinese pistache and jatropha biodiesel. Fuel Process Technol 2010;91:1761–7.
[26] Berchmans HJ, Hirata S. Biodiesel production from crude *Jatropha curcas* L. seed oil with a high content of free fatty acids. Bioresour Technol 2008;99:1716–21.
[27] Sarin R, Sharma M, Sinharay S, Malhotra RK. Jatropha–Palm biodiesel blends: an optimum mix for Asia. Fuel 2006;86:1365–71.
[28] Devan PK, Mahalakshmi NV. Study of the performance, emission and combustion characteristics of a diesel engine using poon oil-based fuels. Fuel Process Technol 2009;90:513–9.
[29] Jain S, Sharma MP. Stability of biodiesel and its blends: a review. Renew Sust Energy Rev 2010;14:667–78.
[30] Agarwal AK, Das LM. Biodiesel development and characterization for use as a fuel in compression ignition engines. J Eng Gas Turb Power 2001;123:440–7.
[31] Shahabuddin M, Kalam MA, Masjuki HH, Bhuiya MMK, Mofijur M. An experimental investigation into biodiesel stability by means of oxidation and property determination. Energy 2012;44:616–22.
[32] İlkılıç C, Aydın H. Fuel production from waste vehicle tires by catalytic pyrolysis and its application in a diesel engine. Fuel Process Technol 2011;92:1129–35.
[33] Liaquat AM, Masjuki HH, Kalam MA, Varman M, Hazrat MA, Shahabuddin M, et al. Application of blend fuels in a diesel engine. Energy Procedia 2012;14:1124–33.
[34] Muralidharan K, Vasudevan D, Sheeba KN. Performance, emission and combustion characteristics of biodiesel fuelled variable compression ratio engine. Energy 2011;36:5385–93.
[35] Lin B-F, Huang J-H, Huang D-Y. Experimental study of the effects of vegetable oil methyl ester on DI diesel engine performance characteristics and pollutant emissions. Fuel 2009;88:1779–85.
[36] Tsolakis A, Megaritis A, Wyszynski ML, Theinnoi K. Engine performance and emissions of a diesel engine operating on diesel-RME (rapeseed methyl ester) blends with EGR (exhaust gas recirculation). Energy 2007;32:2072–80.
[37] Devan PK, Mahalakshmi NV. A study of the performance, emission and combustion characteristics of a compression ignition engine using methyl ester of paradise oil–eucalyptus oil blends. Appl Energy 2009;86:675–80.
[38] Kalam MA, Masjuki HH, Jayed MH, Liaquat AM. Emission and performance characteristics of an indirect ignition diesel engine fuelled with waste cooking oil. Energy 2011;36:397–402.

[39] Masjuki HH, Kalam MA, Maleque MA. Combustion characteristics of biological fuel in diesel engine. SAE 2000 World Congress, Detroit, MI 2000; Paper no-2000-01-0689.
[40] Kalam MA, Masjuki HH. Emissions and deposit characteristics of a small diesel engine when operated on preheated crude palm oil. Biomass Bioenergy 2004;27:289–97.
[41] Lapuerta M, Armas O, Rodríguez-Fernández J. Effect of biodiesel fuels on diesel engine emissions. Prog Energy Combust Sci 2008;34:198–223.
[42] Kalam M, Masjuki H, Husnawan M, Yamane K. Performance improvement of a diesel engine using additive in palm oil methyl ester. Nippon Kikai Gakkai, Jidosha Gijutsukai Nainen Kikan Shinpojiumu Koen Ronbunshu 2005;18.