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Biodiesel production, characterization, engine performance, and emission characteristics of Malaysian Alexandrian laurel oil

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Abstract

Biodiesel is a green fuel produced from renewable resources. It is a clean-burning alternative fuel, which has drawn attention of the energy researchers for last two decades. This paper presents an experimental investigation on Alexandrian laurel oil-a potential feedstock for biodiesel development. Biodiesel was produced using two step esterification-transesterification process. Analysis of physicochemical properties of diesel-biodiesel blends precedes the performance and emission study using 10% and 20% blends (ALB10 and ALB20). A 55 kW, 2.5 L, four-cylinder indirect injection diesel engine was used to carry out tests under conditions of constant load and varying speed. Brake power reduced 0.36-0.76% and brake specific fuel consumption (BSFC) increased 2.42-3.20% for these blends. In general exhaust emission profile was much better compared to diesel except NOx emission. NOx emission was increased by 2.12-8.32% compared to diesel. Thus, from overall performance and emission characteristics, both of the blends are prospective fuels for diesel engines.

Keywords: Alexandrian laurel biodiesel; Biodiesel blends; Performance; Emission.

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1. Introduction

The energy consumption is increasing throughout the world due to progress in lifestyle and substantial growth of population. The transportation sector is one of the top consumers of energy. Earlier the increasing need for energy in this sector was catered with fossil resources like coal, gasoline, diesel etc. alone. On the contrary, burning of fossil fuels in transport vehicles results in serious ecological changes which include increase in global surface temperature (global warming), changes in rainfall patterns, and changes in the frequency of extreme weather events. Hence, the increasing scarcity of conventional fossil fuel and negative effect on climate has driven scientists worldwide to look for new alternatives.[1] During the last few decades, researchers have discovered many renewable sources of harnessing energy. Biodiesel is one of the renewable sources of energy which can partially replace the fossil fuel i.e. diesel which is the main driving force the vehicles of the present world.[2] Nowadays, diesel engine is used in power generators, construction vehicle and industrial activities other than automobiles. Increasing fossil fuel prices, their limited reserve and environmental concerns have boost up the research on biodiesel fuels.

Biodiesel, which refers to the fatty acid alkyl esters (FAAEs), are derived from lipid substances originated from vegetable oil, animal fats, waste greases, recycled cooking oils etc..[3, 4] To produce biodiesel, vegetable oils of edible source were treated as one of the potential feedstocks. However, due to criticism on edible-based oil use for fuel production, other sources e.g. non-edible oils of plant origin, waste fats with high free fatty acid (FFA) content etc. are now being used for biodiesel production. Researchers are also in the quest for newer feedstock of biodiesel production.[5, 6] Advantages of biodiesel over petroleum diesel fuel include derivation from renewable feedstocks, superior lubricity and biodegradability, lower toxicity, higher flash point and cetane number (CN), ability to blend with petro-diesel in any proportion, adaptability in an engine without major modification, positive energy balance and reduced emissions of carbon monoxide (CO), total hydrocarbon (THC), particulate matter (PM) and polyaromatic hydrocarbons (PAH).[7, 8] Disadvantages include limited feedstock availability, inferior oxidative and storage stability, lower volumetric energy content; inferior cold flow properties, higher specific fuel consumption, and higher nitrogen oxide exhaust emissions.[9, 10]

Alexandrian laurel (*Calophyllum inophyllum*) is a member of Clusiaceae or Guttiferae (mangosteen) family. It is commonly known as Penaga Laut in Malaysia.[11] It is also known as Kamani, Honne, Polanga, Tamanu, Pinnai etc. in other parts of the world. It is medium-sized to large ornamental evergreen tree that averages 8–20 m in height with a broad spreading crown of irregular branches.[12] It grows along coastal areas and adjacent lowland forests, although it occasionally occurs inland at higher elevations. The fruit is a round, green drupe reaching 2 to 4 cm in diameter and having a single large seed. The kernels have very high oil content (75%). The oil is non-edible in nature and obtained by cold expression which results in dark green oil with an aromatic odor and an insipid taste. The seeds yield thick, dark green non-edible oil for mainly medicinal use. The annual yield of a mature tree is about 100 kg of seeds, which produces approximately 18 kg of oil.[13] It is native to East Africa, South, Southeast and East Asia, Australia, and the South Pacific. However, it has been widely planted throughout the tropics now. Due to growing interest on non-edible oils with high free fatty acid content for biodiesel production, AL oil has drawn attention of the researchers during the last decade.

Very few studies are available on AL biodiesel in the published articles so far. Among them, most of the articles deal with biodiesel production and its process optimization. Sahoo et al. [14] developed biodiesel from polanga oil (acid value 44 mg KOH/g) using three stage transesterification process form this oil. The first stage removes the organic materials and other impurities where the extracted oil reacts with 35% (v/v) methanol and 5% (v/v) toluene. Second stage transesterification reduces the acid value below 2 mg KOH/g in order to make the oil suitable for experiencing base catalyzed transesterification. An optimized quantity of methanol with molar ratio of 6:1 and 0.65% (v/v) of anhydrous sulphuric acid (98.4%) was used in this stage with reaction time of 4 h. The product of the second stage was reacted with methanol (molar ratio of 9:1) and 1.5% potassium hydroxide (KOH) (w/w oil) with a reaction duration of 4 h that yielded a maximum amount of esters from this stage. To study its suitability in diesel engine authors then employed different percentage of blends with diesel in a single cylinder diesel engine and found that pure biodiesel was the best fuel for diesel engine operation as it provided lower BSFC, higher BTE, lower HC and NOx emission compared to diesel operation. Later, Sahoo and Das [15] experimentally optimized the reaction parameters of CI biodiesel production by measuring the acid values of the product. The optimized reaction parameters of the first stage are 35% (v/v) methanol, 0.5% (v/v) toluene, 0.5% (v/v) *ortho* phosphoric acid, 66°C reaction temperature and 2 h time. For the second stage, these are 12% (v/v) methanol, 0.65% (v/v) sulfuric acid (H_2SO_4), 55°C reaction temperature and 4 h time. For the third stage, these are 7.5% (v/v) methanol, 9% (w/w) KOH, 66°C reaction temperature and 4 h time.

In their study, for producing biodiesel Venkanna and Venkataramana Reddy [16] employed one step acid catalyzed esterification, one step alkali catalyzed transesterification and post treatment. Post treatment stage employed here was washing of methyl esters. The acid value of their oil was very low (only 4.76 mg KOH/g) compared to other studies. To obtain maximum conversion efficiency they run each process at different reaction parameters with one hundred grams of moisture free CI oil (acid value 44). The optimum conversion attained for first stage with 4:1 molar ratio of methanol, 0.5 ml anhydrous H_2SO_4 with reaction time of 120 minutes at 60°C.

Optimal parameters for transesterification were 8:1 molar ratio of methanol, 1.25% KOH (w/w) with a reaction time of 120 minutes at 60°C. In their study, SathyaSelvabala et al. [17] employed one step esterification using phosphoric acid modified β-zeolite as catalyst and one step transesterification process using 1% KOH as catalyst for biodiesel production. They optimized the reaction parameters of the esterification step using Central Composite Design and Response Surface Methodology. The global solution for the optimization was the oil methanol ratio of 0.33 (wt. %) and a catalyst amount of 1% and temperature of 60°C. They run experiments using these values and found that the acid value dropped to 1.9 mg KOH/g from 44 mg KOH/g with 93% conversion efficiency. Venkanna and Reddy [18] studied the effect of different blends of honne oil with diesel on a single cylinder diesel engine. They concluded that up to 20% blend with diesel could be used in diesel engines without any adverse effect. In their study Belagur and Chitimi [19] presented different fuel properties of 10% to 90% blends of AL oil which are related to combustion in diesel engines. They concluded, up to 50% blend with diesel meets the fuel specification limits set by ASTM D6751-08 and can be used as a substitute of neat diesel for short-term application. Rahman et al. [20] studied the effect of AL biodiesel blends on high idling conditions of a four cylinder diesel engine. They found lowest CO and HC emission for 20% blend with diesel in this range of operation. In another study Venkanna and Venkataramana Reddy [21] studied the effect of injector opening pressure of a single cylinder diesel engine on engine performance and found that at 100% load, increase in BSFC was 16.18% and decrease in BTE was 4.11%. However, with increase in pressure at 100% load emission is reduced. For CO it was 65%-80% and for smoke opacity (SO) it was 45% to 60%. However, the opposite trend was observed in case of NOx. With increasing load as well as pressure NOx emission was generally slightly higher in case of biodiesel. Belagur and Chitimini [22] studied the effect of variation of static injection timing (SIT) of a single cylinder diesel engine on engine performance and emission and found that at 28 crank angle bTDC (original 23 crank angle bTDC) and 100% load condition BSFC decreases and BTE increases. However, BSFC is still about 16% higher and BTE is 4% lower compared to original diesel operation. It is observed from the literature review that, most of the studies on engine performance and emission were carried out in single cylinder diesel engines, necessitating an investigation of AL biodiesel (ALBD) and its blends on a turbocharged heavy-duty diesel engine.

The present study is an endeavor to produce biodiesel from AL oil of Malaysian origin using one stage esterification and one stage transesterification process and characterization of produced biodiesel and its blends with diesel. ASTM D7467 allows blending of biodiesel with diesel from 6% up to 20% (B6-B20). B20 represents a good balance of cost, emissions, materials compatibility, and cold weather performance.[23] Thus, applicability of ALBD blends e.g. ALB10 and ALB20, in an unmodified IDI diesel engine is experimentally investigated and then compared with diesel here.

2. Materials and method

2.1 Material

In this study, crude AL oil was purchased from local markets. Other chemicals such as methanol, potassium hydroxide (KOH) and anhydrous sodium sulfate (Na_2SO_4) were of Friendemann Schmidt Chemicals, USA. All purchased chemicals i.e. methanol, sulfuric acid (H_2SO_4) etc. were of analytical grade and catalysts and antioxidants were of 99.5% purity.

2.2 Biodiesel production

Crude AL oil had a high free fatty acid content of 20%, i.e. acid value of 40 mg KOH/g. Canakci and Van Garpen [24] mentioned that if the oil contains more than 1% free fatty acids (FFA) which corresponds to an acid value of 2 mg KOH/g; then it cannot undergo alkaline-catalyzed transesterification reaction. If the FFA level exceeds this amount, the formation of soap will inhibit the separation of the ester from the glycerin and reduce the ester conversion rate. However, Ramadhas et al. showed that, if the acid value of oil is less than 4 then it can undergo transesterification.[25] As free fatty acid content was very high, biodiesel conversion using one-step alkaline transestarification was not possible and needs pretreatment. Among the available pretreatment methods, including steam distillation, extraction of alcohol and esterification by acid catalysts, the last one i.e. esterification of FFA with methanol in the presence of acidic catalysts is the most commonly used method because of its simplicity and utilization of acid catalysts to convert FFAs' into biodiesel.[26] Thus for producing biodiesel acid catalyzed pretreatment process was carried out at first.

2.2.1 Pre-treatment process (acid catalyzed esterification)

In this process, crude AL oil was placed with 12:1 molar ratio of methanol and 1.5% v/v (of oil) of H_2SO_4 in a "FAVORIT jacket reactor". The temperature was maintained at 60°C using circulating water bath for 3 h and the mixture was stirred at 1000 rpm using "IKA Eurostar motor stirrer". Afterwards, a separation time of 1 h was given to this mixture to separate out esterified product and catalyst layer. After separation, the lower layer is taken out to remove excess methanol and water using "IKA RV10 Control" rotary evaporator. The yield of this step is about 98%.

2.2.2 Alkali catalyzed transesterification process

Product of pretreatment was heated to 60°C and placed for transesterification with 6:1 molar ratio of methanol and 1% w/w (of oil) KOH in the same setup. The temperature was maintained for 2 h and the mixture was stirred at 1200 rpm. Afterwards, a separation time of 12h was given to this mixture to separate out glycerin from methyl ester. The lower layer containing impurities and glycerin was discarded.

2.2.3 Post treatment process

The methyl ester was washed with distilled water to remove the entrained impurities and glycerin. In this process, 50% (v/v) of distilled water at 60°C was sprayed over the esters and shaken gently. This process was repeated several times until the methyl ester becomes neutral. The opaque lower layer containing water and impurities was taken out. Then, methyl ester was distilled under vacuum distillation at 65°C for 30 minutes using "IKA RV10 Control" rotary evaporator to remove water and methanol. Finally, methyl ester was dried using anhydrous Na_2SO_4 for 3 h and filtered using qualitative filter papers. **Table 1** provides the list of equipment and their accuracies for crude oil and biodiesel characterization. The characteristics of crude oil and ALBD are given in **Table 2**. Saponification Number (SN), Iodine Value (IV) and Cetane Number (CN) of the produced biodiesel was calculated using the Eqns. (1), (2) and (3) [27]:

$$SN = \sum\left(\frac{560 * A_i}{MW_i}\right) \qquad (1)$$

$$IV = \sum\left(\frac{254 * D * A_i}{MW_i}\right) \qquad (2)$$

$$CN = \left(46.3 + \left(\frac{5458}{SN}\right) - (0.225 * IV)\right) \qquad (3)$$

where A_i is the percentage of each component, D is the number of double bonds and MW_i is the mass of each component. The molecular mass of each component is given in **Table 4**. To analyze the effect of blending of ALBD with diesel (B10 to B90) on different fuel properties such as kinematic viscosity, density, flash point and calorific value etc. was examined and presented in **Fig. 1 (a-d)**.

Table 1. List of equipment used in the characterization of fuels

Property	Equipment	Manufacturer	Standard Method	ASTM D6751 limit	Accuracy
Kinematic viscosity at 40°C	SVM 3000- automatic	Anton Paar, UK	D 445	1.9-6.0	±0.35%
Dynamic viscosity at 40°C	SVM 3000- automatic	Anton Paar, UK	D 7042	n.s.	±0.35%
Density at 40°C	SVM 3000- automatic	Anton Paar, UK	D 7042	n.s.	±0.1 kg/m^3
Viscosity Index	SVM 3000- automatic	Anton Paar, UK		n.s.	
Lower Heating Value	C2000 basic calorimeter - automatic	IKA, UK	D 240	n.s.	±0.1%
Flash Point	Pensky-martens flash point - automatic NPM 440	Normalab, France	D 93	130 (min)	±0.1 °C
Oxidation stability	873 Rancimat - automatic	Metrohm, Switzerland	EN 14112	3h (min)	±0.01 h
Cloud Point	Cloud and Pour point tester - automatic NTE 450	Normalab, France	D 2500	Report	±0.1°C
Pour Point	Cloud and Pour point tester - automatic NTE 450	Normalab, France	D 97		±0.1°C
CFPP	Cold filter plugging point – automatic NTL 450	Normalab, France	D 6371	n.s.	
Acid Value	G-20 Rondolino Automated Titration System	Mettler Toledo, Switzerland	D 664	0.5 max	± 0.001 mg KOH/g

n.s. ≡ not specified in ASTM standard

Table 2. Physicochemical properties of crude oil, produced biodiesel and tested fuels

Property	Unit	Crude AL oil	ALBD	PBD[a]	JBD[b]	ALB10	ALB20	ASTM D7467[c]	Diesel
Kinematic viscosity at 40°C	mm^2/s	53.136	4.7128	4.6889	4.9476	3.1969	3.3538	1.9-4.1	3.0738
Dynamic viscosity at 40°C	m Pa s	48.973	4.1470	4.0284	4.2758	2.7098	2.8695	n.s.	2.5501
Density at 40°C	kg/m^3	921.6	868.6	859.1	864.2	833.4	837.1	n.s	829.6
Viscosity Index		159.2	174.7	203.6	194.6	132.7	133	n.s.	152.6
Lower Heating Value	MJ/kg	38.511	39.389	40.009	39.738	44.656	44.111	n.s	45.238
Flash Point	°C	218.5	141.5	214.5	186.5	71.5	77.5	52 (min)	69.5
Oxidation stability at 110°C	h	3.28	6.01	23.56	4.84	25.65	18.73	6 (min)	59.10
Cloud Point	°C	8	10	12	10	8	8	Report	8
Pour Point	°C	8	8	15	10	4	4	n.s.	7
Cold Filter Plugging Point	°C	27	8	12	10	8	8	n.s.	8
Acid value	mg KOH/g	40	0.3	-	-	0.14	0.17	0.3 (max)	
Saponification Number (SN)			191.6					n.s.	-
Iodine Value (IV)	g I$_2$/ 100g		82.1						-
Cetane Number (CN)			56.3					40 (min)	48

n.s. ≡ not specified; PBD: Palm Biodiesel; JBD: Jatropha Biodiesel

[a,b] Data obtained from [28]

[c] Data obtained from [23]

2.3 Fatty acid composition

Biodiesel sample was injected into a gas chromatograph (Agilent 7890 Series, USA) equipped with a flame ionization detector. **Table 3** shows the GC operating conditions for fatty acid composition. Total ester content and methyl linolenate content was measured as per EN14103 standard. Monoglyceride content, diglyceride content, triglyceride content, free and total glycerin was measured as per EN 14105 standard. **Table 4** shows the composition of produced biodiesel. It is found that ALBD contains 29.3% saturated methyl esters and 40.5% monounsaturated methyl esters and 25.8% polyunsaturated methyl ester.

Table 3. GC conditions for determination of fatty acid composition

Column	0.32 mm x 30 m, 0.25 µm
Injection volume	(1 µL
Carrier gas	Helium, 83 kPa
Injector	Split/splitless 1177, full EFC control
Temperature	250 °C
Split flow	100 mL/min
Column 2 flow	Helium at 1 mL/min constant flow
Oven	210 °C isothermal
Column temperature	60 °C for 2 min
	10 °C/min to 200 °C
	5 °C/min to 240 °C
	Hold 240 °C for 7 min
Detector	250 °C, FID, full EFC control

Table 4. Fatty acid composition of ALBD

Fatty acid ester	Structure	Molecular mass	Formula	ALBD (% m/m)
Methyl Palmitate	16:0	270.45	$CH_3(CH_2)_{14}CO_2CH_3$	13.9
Methyl Palmitoleate	16:1	268.43	$CH_3(CH_2)_5CH{=}CH(CH_2)_7COOCH_3$	0.2
Methyl Stearate	18:0	298.50	$CH_3(CH_2)_{16}CO_2CH_3$	15.1
Methyl Oleate	18:1	296.49	$CH_3(CH_2)_7CH{=}CH(CH_2)_7CO_2CH_3$	40.3
Methyl Linoleate	18:2	294.47	$CH_3(CH_2)_3(CH_2CH{=}CH)_2(CH_2)_7CO_2CH_3$	25.6
Methyl Linolenate	18:3	292.46	$CH_3(CH_2CH{=}CH)_3(CH_2)_7COOCH_3$	0.2
Methyl Arachidate	20:0	326.56	$CH_3(CH_2)_{18}COOCH_3$	0.3
Total ester content				95.6
Monoglyceride content				0.32
Diglyceride content				0.08
Triglyceride content				0.12
Total glycerin				0.109
Free glycerin				0.003

2.4 Engine test

The experimental investigation was carried out in the Heat Engine Laboratory of the Mechanical Engineering Department, University of Malaya, on a turbocharged IDI four-cylinder diesel engine. The detail of the engine is described in **Table 5**. The test engine was directly coupled to the Froude Hofman AG250 eddy current dynamometer. Fuel flow was measured using a Kobold ZOD positive-displacement type flow meter. Engine oil, cooling water, exhaust gas, and inlet air temperatures were measured using a K-type thermocouple. A REO-dCA Data Acquisition System collected the data. The engine fuel system was modified by adding separate tanks with two-way valves, which allowed the rapid switching of fuels. The exhaust gas composition CO, HC, and NOx emissions were measured by gas analyzer (AVL DiCom4000). In this equipment, the CO and HC measuring instrument uses the non-dispersive infrared (NDIR) detectors and the NOx analyzer uses electrochemical method. Smoke opacity was measured by a continuous flow smoke meter (AVL DiSmoke 4000) working on Hartridge principle.

To carry out tests using biodiesel blends, the engine was run with diesel until a steady operating condition was achieved. Then the fuel was changed to biodiesel blend. After consumption of sufficient blend fuel, the data acquisition was started to ensure the removal of residual diesel in the fuel line. After each test, the engine was again run with diesel to drain all of the blend out of the fuel line. This procedure was followed for all blends. The test fuels were fossil diesel, 10% and 20% biodiesel in diesel (ALB10 and ALB20). The fuels were blended using a homogenizer device at a speed of 3000 rpm for ten minutes. **Table 2** shows some important characteristics of the tested fuels. The engine was operated between 1000 and 4500 rpm with a step of 500 rpm at 100% load condition. The performance and emission measurements were triplicated. The results of each test were highly repeatable within that test series.

Table 5. Detailed engine specification

Description	Specification
No. and arrangement of cylinders	4 in-line, longitudinal
Rated Power	55 kW at 4200 rpm
Combustion chamber	Swirl chamber
Total displacement	2477 cc
Cylinder bore x stroke	91.1 x 95 mm
Valve mechanism	SOHC
Compression ratio	21:1
Valve timing	IVO: 20°BTDC IVC: 49°ABDC EVO: 55°BBDC EVC: 22°ATDC
Lubrication system	Pressure feed, full flow filtration
Fuel system	Distributor type injection pump
Air flow	Turbocharged
Fuel Injection Pressure	157 bar
Lift of Plunger	7°ATDC

2.5 Accuracies and Uncertainties

Uncertainties in the experiments can arise from instrument selection, experimental condition, equipment calibration, ambient environment, observation, reading and test preparation. Uncertainty analysis is needed to establish the accuracy of the experiments. Uncertainty of measured quantities like torque, CO, HC, NOx and smoke were calculated using the uncertainties of various instruments used in the experiment. The relative uncertainty of calculated BSFC was determined using the linearized approximation method of uncertainty. [29] **Table 6** shows the accuracies and uncertainties of the measured and calculated parameters.

Table 6. The accuracies and uncertainties of the quantities

Measured Qty.	Measuring range	Accuracy	Uncertainty
Torque	0-1200 Nm	± 3 Nm	
Fuel flow measurement	0.5 – 36 l/h	± 0.089 l/hr	

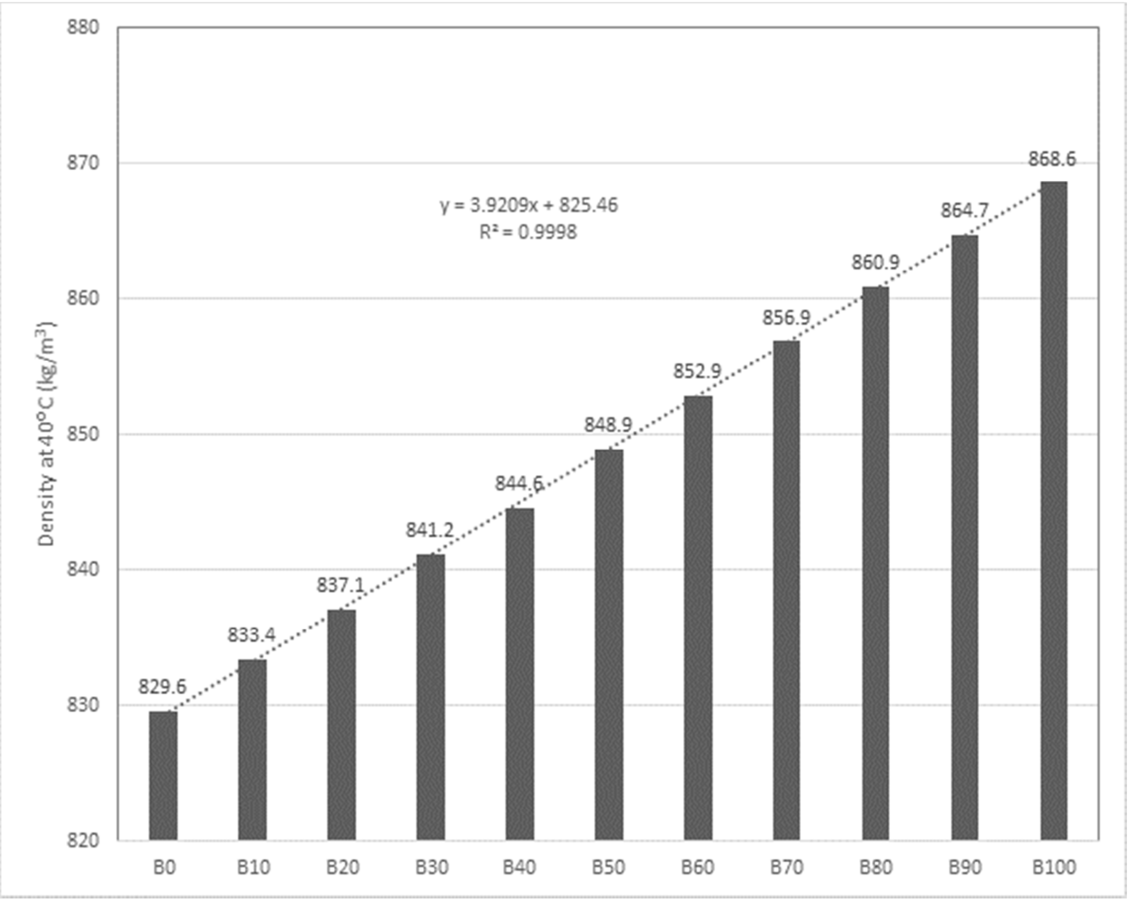
Speed	0-6000 rpm	± 1 rpm	
Smoke opacity	0-100%	0.1%	± 0.5 %
CO	0-10%vol	0.01 %vol	± 0.01 %vol
HC	0-20000 ppm vol	1 ppm vol	± 1 ppm
NOx	0-5000 ppm vol	1 ppm vol	± 5 ppm
Calculated Results			
Power			± 0.1 kW
BSFC			± 0.35 g/kWh

3. Results & discussions

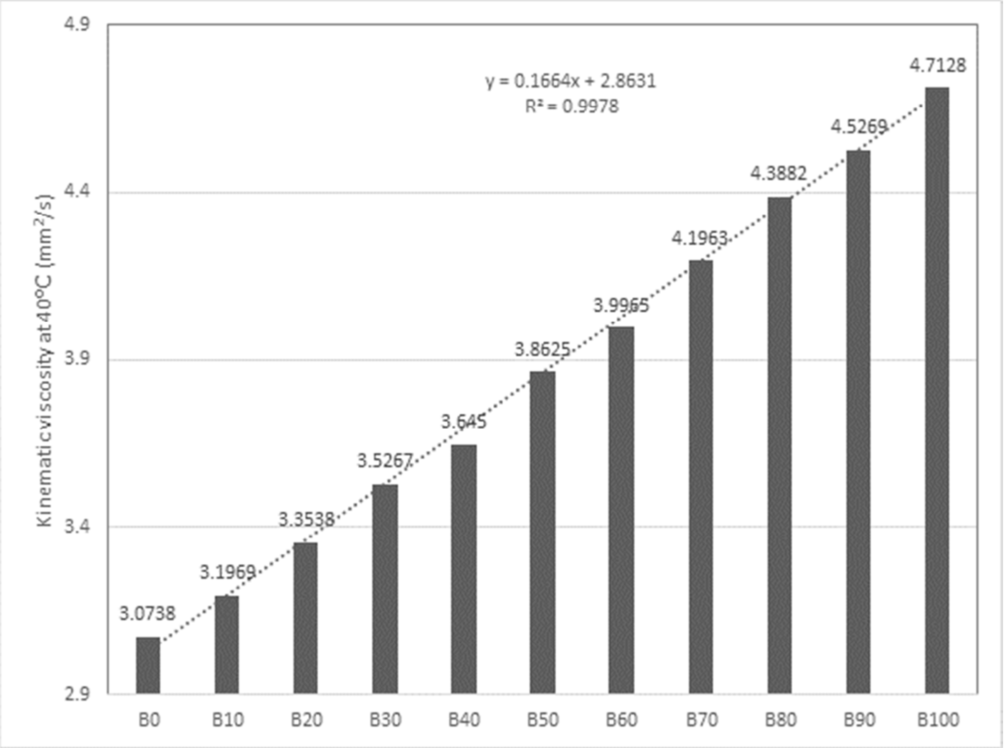
3.1 Physicochemical properties of oil, biodiesel and its blends

The characteristic property of crude AL oil is its high free fatty acid content of 20%, i.e. acid value of 40 mg KOH/g which necessitates a pretreatment step before transesterification step for biodiesel production. The crude oil has a very high kinematic viscosity (53.136 mm^2/s) compared to other feedstocks like palm (41.932 mm^2/s), soybean oil (31.739 mm^2/s), canola oil (35.706 mm^2/s) etc.[30] The kinematic viscosity of produced ALBD is 4.7128 mm^2/s, which is 53.32% higher compared to diesel (3.0738 mm^2/s). Mass energy content or Lower Heating Value (LHV) of ALBD (39.389 MJ/kg) is much less compared to fossil diesel (45.238 MJ/kg) due to its high oxygen content. Flash point is inversely related to fuel volatility. As ALBD contains mostly heavy constituents like methyl oleate and methyl linoleate (**Table 4**), its flash point is higher and meets the ASTM D6751 specification of 130°C. Cetane number (CN) is a measure of a fuel's autoignition quality characteristic. Since ALBD has mostly unsaturated fatty acid esters (68.4%) it has CN of 56.3 which meets the ASTM D6751 specification of ≥ 47. The oxidation stability improved after conversion of crude oil to biodiesel and meets the ASTM D6751 specification. However, since its unsaturated ester content is high it can quickly degrade and lose its oxidative stability.

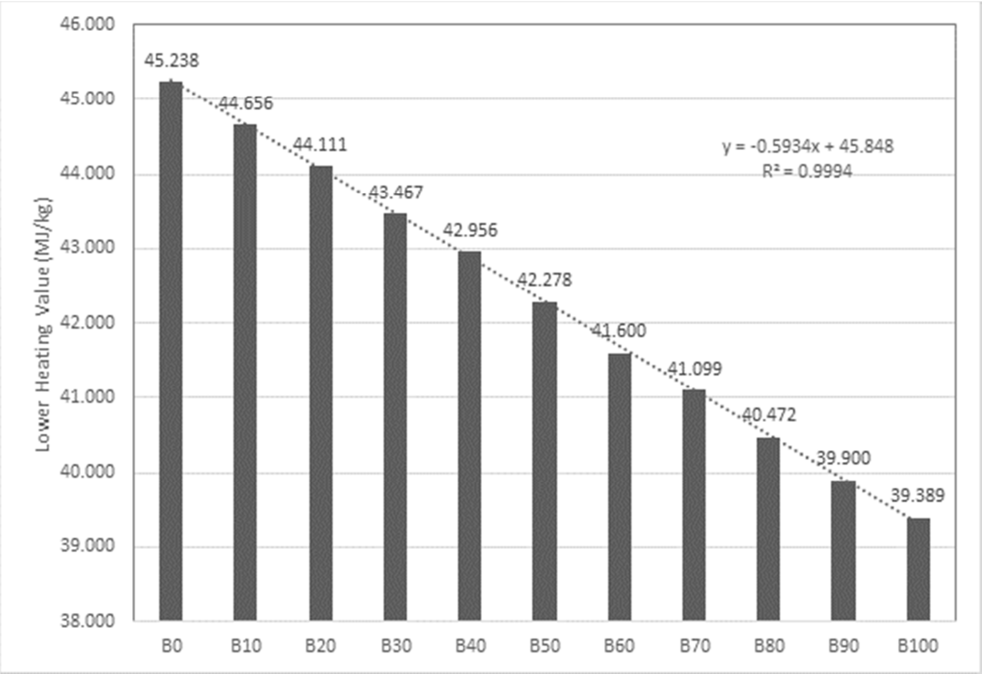
Addition of biodiesel in diesel forms a non-separable liquid phase which signifies biodiesel is dissolved in diesel at any proportion. As shown in **Fig. 1(a)** and **Fig. 1(b)** with increasing percentage of biodiesel density and kinematic viscosity increases linearly with coefficients of determination (R^2) of 0.9998 and 0.9978 respectively, LHV decreases linearly with an R^2 of 0.9994 and flash point increases in second degree polynomial nature with an R^2 of 0.9965. From the graph it is observed that ALB10 and ALB20 possess physicochemical properties close to diesel fuel. Densities and kinematic viscosities of ALB10 are 833.4 and 3.1969 mm^2/s and that of B20 837.1 kg/m^3 and 3.3538 mm^2/s that are 4% and 9.1% higher than that of diesel. The LHV of ALB10 and ALB20 are 44.656 and 44.111 MJ/kg which are slightly less compared to diesel **(Fig. 1(c))**. Increasing percentage of biodiesel results in an increasing percentage of oxygen in the fuel that reduces the no. of carbon and hydrogen atoms present in the fuel. The flash point of the ALB10 and ALB20 blends are 71.5 °C and 77.5 °C respectively **(Fig. 1(d))**. Thus, they meet the ASTM D7467 limits of 40°C, which makes them safe storing fuels.


880
870
860
850
840
830
820
Density at 40°C (kg/m^3)
y = 3.9209x + 825.46
R² = 0.9998
829.6
833.4
837.1
841.2
844.6
848.9
852.9
856.9
860.9
864.7
868.6
B0
B10
B20
B30
B40
B50
B60
B70
B80
B90
B100

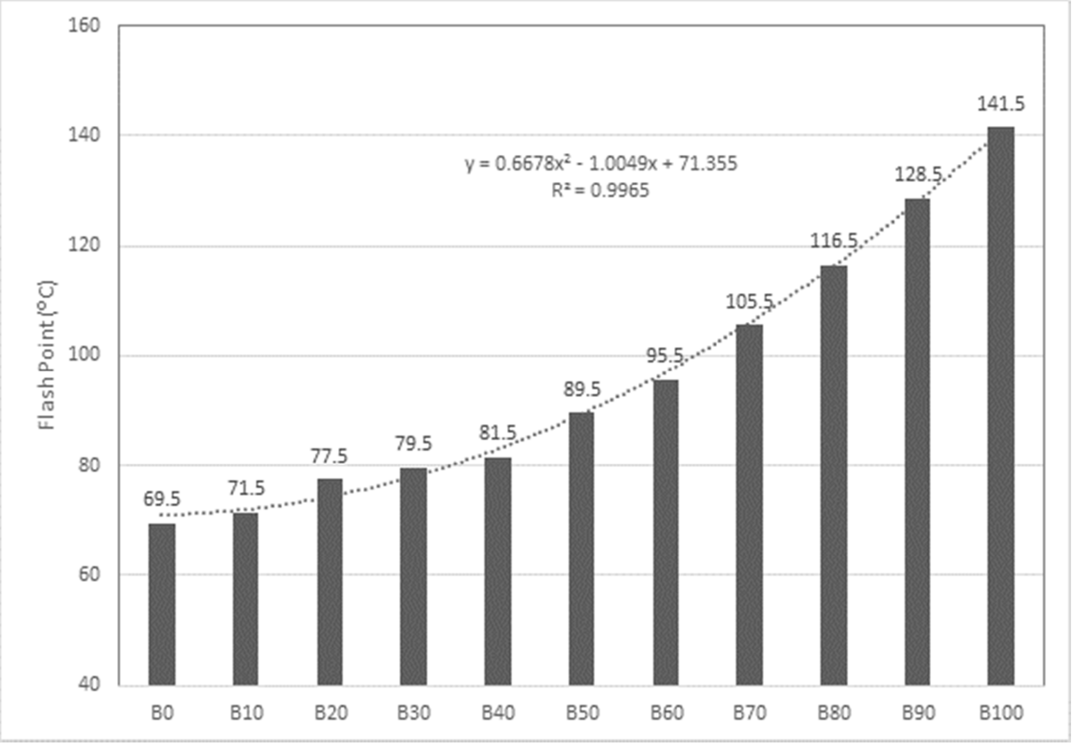
(a)


Kinematic viscosity at 40ºC (mm²/s)
4.9
4.4
3.9
3.4
2.9
y = 0.1664x + 2.8631
R² = 0.9978
3.0738
3.1969
3.3538
3.5267
3.645
3.8625
3.9965
4.1963
4.3882
4.5269
4.7128
B0
B10
B20
B30
B40
B50
B60
B70
B80
B90
B100

(b)


Lower Heating Value (MJ/kg)
46.000
45.000
44.000
43.000
42.000
41.000
40.000
39.000
38.000
y = -0.5934x + 45.848
R² = 0.9994
45.238
44.656
44.111
43.467
42.956
42.278
41.600
41.099
40.472
39.900
39.389
B0
B10
B20
B30
B40
B50
B60
B70
B80
B90
B100

(c)



(d)

Fig. 1 (a-d). Effect of biodiesel blending with diesel on physicochemical properties

3.2 Engine performance characteristics

3.2.1 Brake power

The brake power output from the engine with different tested fuels are shown in **Fig. 2**. The maximum brake powers recorded at 4000 rpm for diesel, ALB10 and ALB20 were 48.5 kW, 48.3 kW and 48.2 kW respectively. Thus, ALB10 and ALB20 showed 0.41 and 0.62% lower maximum power compared to diesel, respectively. This reduction can be attributed to its lower LHV and higher viscosity compared to diesel fuel.[31] Higher kinematic viscosity results in higher resistance in the fuel line for pump line nozzle system as in the tested engine, which results in a higher delay in start of injection.[32] This also leads to poorer fuel atomization.[33] Together with higher volumetric fuel consumption, these effects results in lower power output. Mofijur et al.

reported about 4.67% and 8.86% average reduction of power with 10% and 20% of jatropha biodiesel blends respectively.[34] Furthermore, the average brake power reduction for ALB10 and ALB20 compared to diesel were 0.36% and 0.76%, respectively.

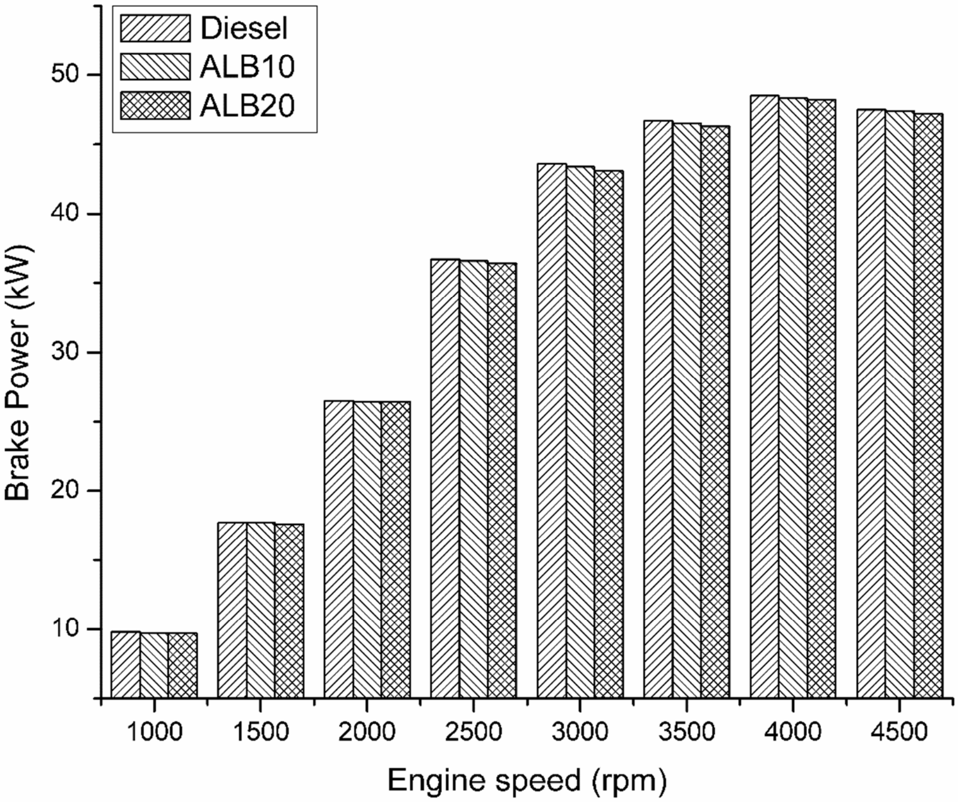


Fig. 2. Variation of brake power for the test fuels with engine speed

3.2.2 Brake specific fuel consumption

Fig. 3 shows the variation of BSFC with engine speed for the test fuels. It is obvious from the figure that the BSFC of the engine was lowest at 2500 rpm and then increased with increases in speed. The average values of BSFC for diesel, ALB10 and ALB20 were 300.49, 307.76 and 310.11 g/kWh respectively. Thus, ALB10 and ALB20 produced about 2.42% and 3.20% higher

BSFC, respectively. Higher fuel consumption can be attributed to the volumetric effect of constant fuel injection rate together with higher viscosity and lower calorific value of biodiesel and its blends.[35] The lower heating value is compensated through higher volumetric consumption of fuel to obtain the same power, higher viscosity which reduces the back flow across the piston clearance of the injection pump and higher lubricity of fuel which also acts for friction loss reduction.[36] With the increase in biodiesel content in the fuel, BSFC generally increases due to higher volumetric fuel is consumed due to the higher density of the fuel.

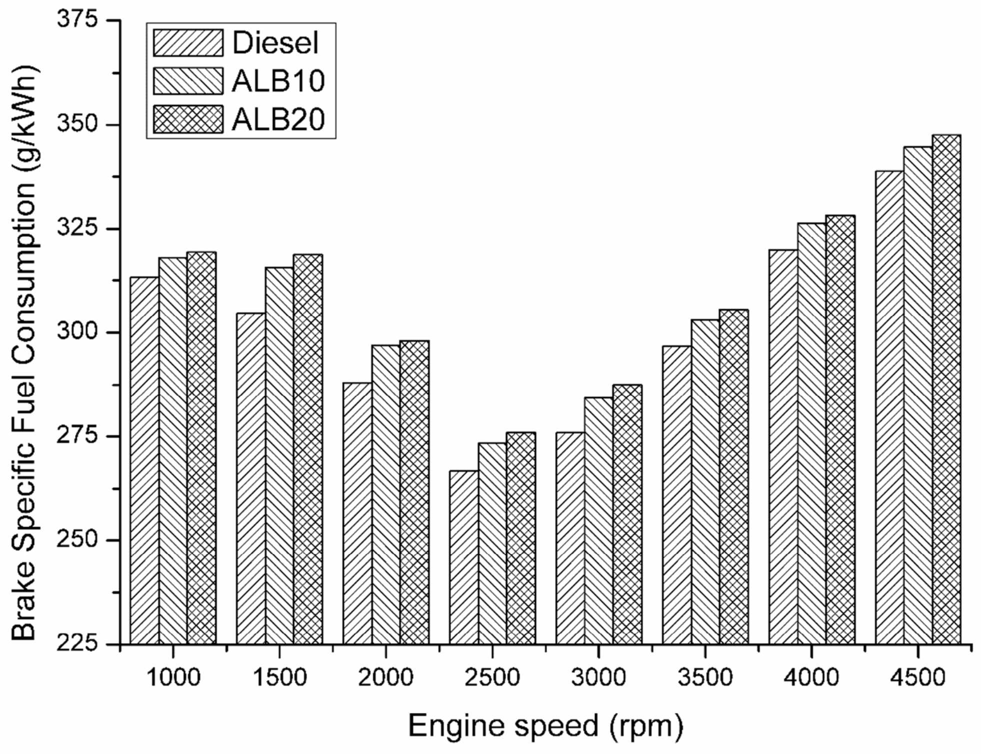


Fig. 3. Variation of brake specific fuel consumption (BSFC) for the test fuels with engine speed

3.2.3 Brake thermal efficiency

The brake thermal efficiency is defined as the actual brake work per cycle divided by the amount of fuel chemical energy. The chemical energy input is the product of the injected fuel mass flow rate and the heating value. The comparison of brake thermal efficiency (BTE) with engine speed for different fuels is shown in **Fig. 4**. Thermal efficiency varies inversely with the product of BSFC and calorific value of the fuel. BTE is calculated using the following equation:

$$BTE = \frac{3600}{BSFC * LHV} * 100\%$$

The maximum BTE calculated at 2500 rpm for diesel, ALB10 and ALB20 were 29.83%, 29.49% and 29.57% respectively. Thus, ALB10 and ALB20 showed 1.14% and 0.87% lower maximum BTE compared to diesel, respectively. Lower efficiency can be attributed to higher BSFC with lower power output. This may be related to the atomization of the blends during injection and/or with the stability of the mixtures of fuels during storage, pumping and injection.[37] The maximum BTE was observed at 2500 rpm.

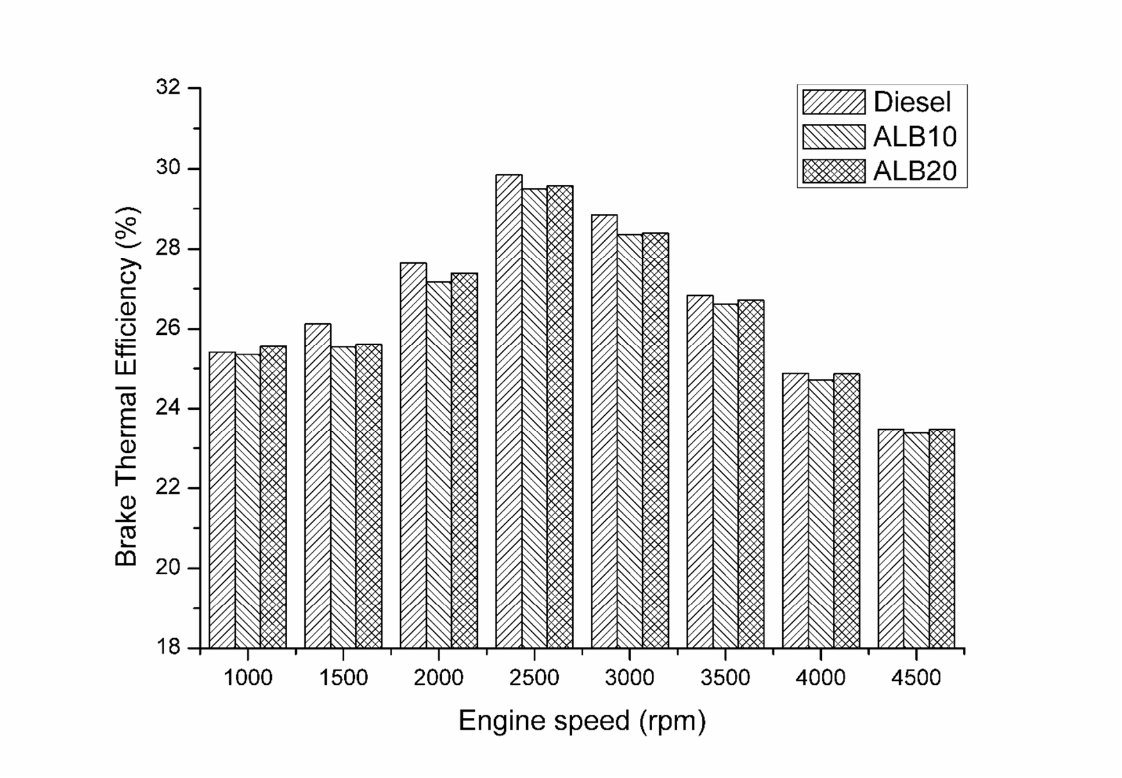


Fig. 4. Variation of brake thermal efficiency (BTE) for the test fuels with engine speed

3.3 Engine emission analysis

3.3.1 Oxides of nitrogen emission

Fig. 5 illustrates the NOx emission from the test diesel engine for different test fuels. The thermal (Zeldovich), prompt (Fenimore), N_2O pathway, fuel-bound nitrogen and the NNH mechanism are the most common mechanisms for NOx formation in diesel combustion. NOx is the most deleterious pollutant that should be controlled at the combustion stage. It is well documented that higher combustion temperature and longer combustion duration inside the combustion chamber, ample local oxygen concentration, and so on are the major factors in NOx formation.[38] ALBD consists of higher molecular weight species which burns in late combustion phases due to poor atomization in premixed region. Late phase combustion resulting in higher temperature together with oxygen content in the fuel resulted in the formation of higher amount of NOx.[39] The average NOx emission for diesel, ALB10 and ALB20 were 10.778 g/kWh, 11.007 g/kWh and 11.675 g/kWh respectively. Thus, ALB10 and ALB20 results in 2.12% and 8.32% higher average NOx emission compared to diesel. Higher NOx emission compared to diesel can be validated from the literature.[40, 41]

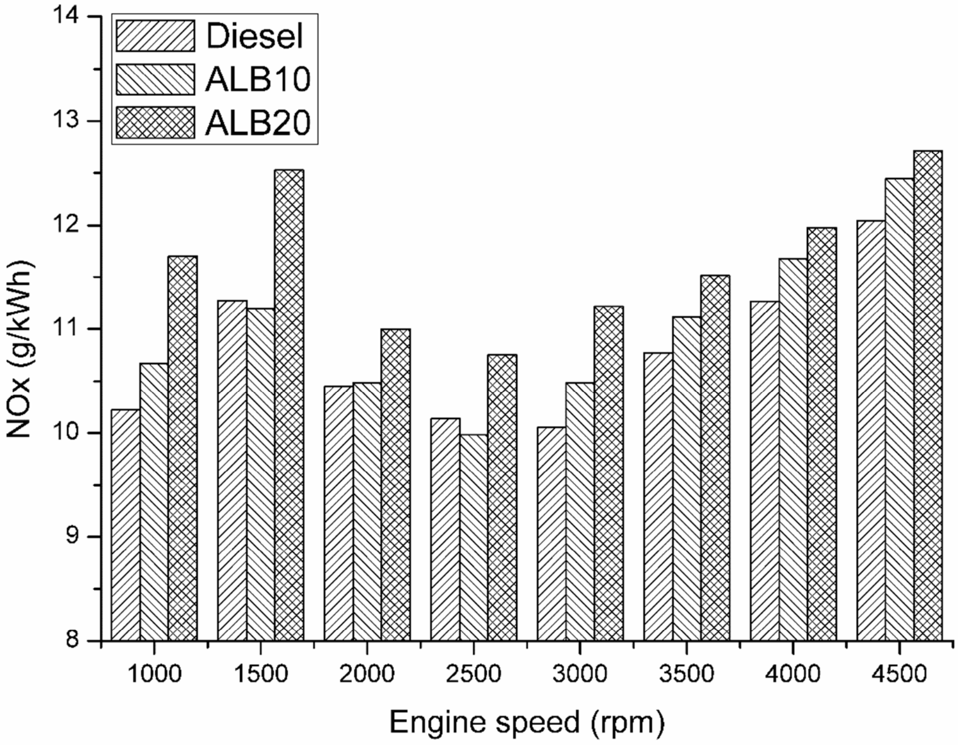


Fig. 5. Variation of NOx emission for different test fuels with speed

3.3.2 Carbon monoxide emission

CO is formed during combustion whenever charge is burned with an insufficient air supply with low flame temperature. The variation of CO emission as a function of engine speed with diesel, ALB10 and ALB20 is shown in **Fig. 6**. The average CO emission for diesel, ALB10 and ALB20 for the entire speed range are 17.888 g/kWh, 15.184 g/kWh and 13.086 g/kWh respectively.

Thus, average CO emission is reduced by 15.12% and 26.84% for ALB10 and ALB20 respectively. With increasing biodiesel percentage in the blend, CO emission level decreases as the amount of oxygen content of biodiesel helps to achieve more complete combustion.[42] Moreover, biodiesel possesses slightly lower carbon/hydrogen (C/H) ratio than that of diesel fuel, which as assists in decreased CO emissions.[43]

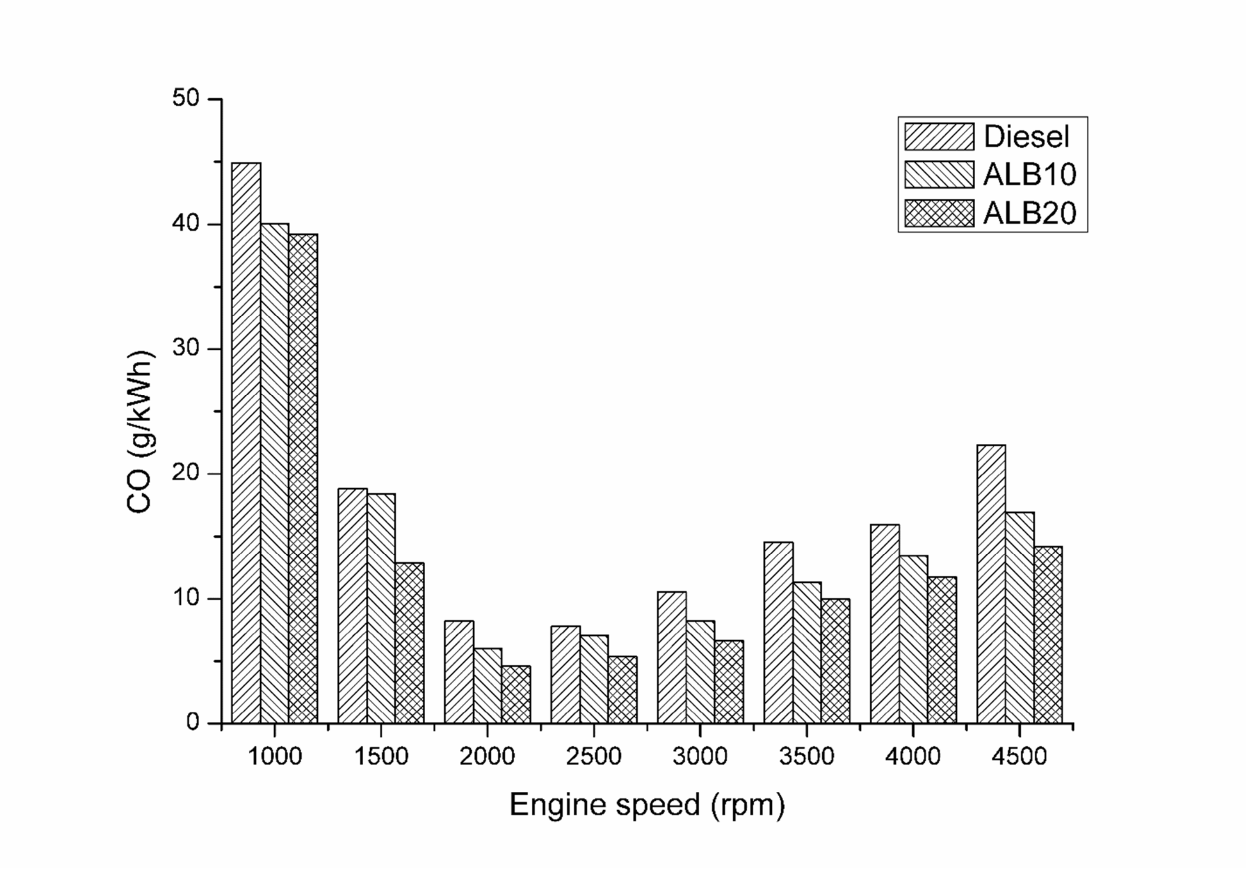


Fig. 6. Variation of CO emission of different test fuels with speed

3.3.3 Hydrocarbon emission

Two major causes for HC emission in diesel engine are: (1) fuel mixed to leaner than the lean combustion limit during the delay period; (2) under mixing of fuel which leaves the fuel injector nozzle late in the combustion process at low velocity. **Fig. 7** shows the variation of HC emission at various speeds. The average HC emission for diesel, ALB10 and ALB20 for the entire speed range are 0.270 g/kWh, 0.245 g/kWh and 0.224 g/kWh respectively. Thus, average HC emission is reduced by 9.26% and 17.04% for ALB10 and ALB20 respectively. The oxygen content of biodiesel might have provided some advantageous conditions (post flame oxidation, higher flame speed, etc.) during air–fuel interactions, particularly in the fuel-rich regions, which enhanced the oxidation of unburned HC, thus reducing HC significantly.[44]

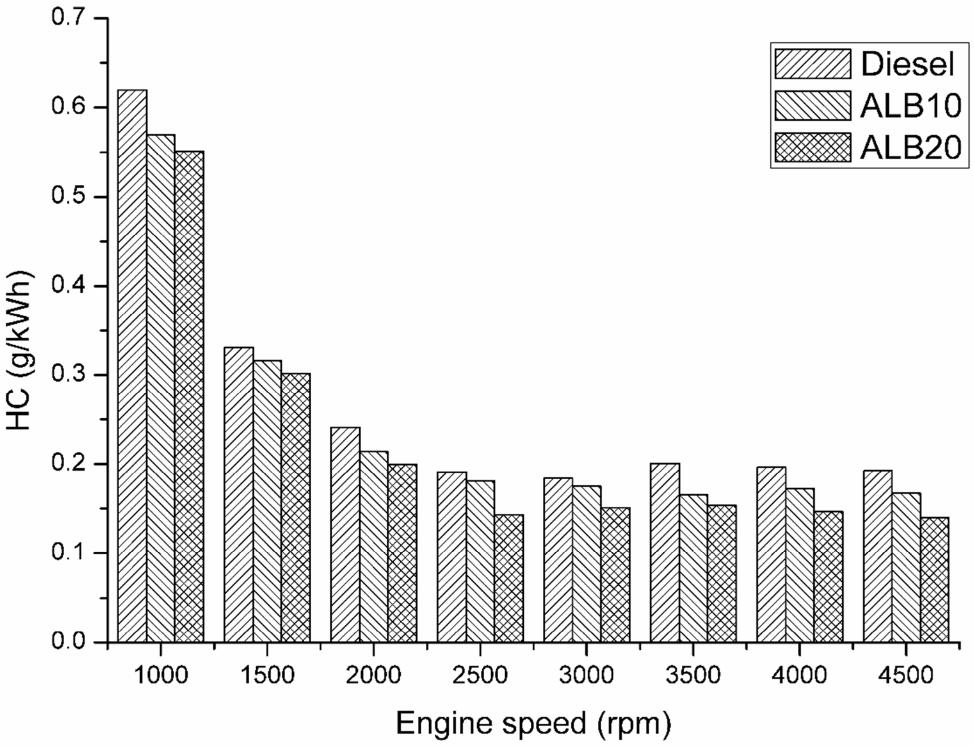


Fig. 7. Variation of HC emission for different test fuels with speed

3.3.4 Smoke opacity

Smoke opacity is indicative of dry soot emissions which is one of the main components of particulate matter. [45] **Fig. 8** shows the exhaust smoke opacity of tested fuels. The average smoke opacity for diesel, ALB10 and ALB20 were 27.25%, 25.13% and 23.63%, respectively. Thus, an average reduction of smoke for ALB10 and ALB20 were 7.78% and 13.28% compared to diesel, respectively. The smoke opacity is all blends are well below the level of diesel. The lower smoke opacity can be explained with the reduction of probability of rich zone formation (high local fuel–air ratio) in presence of fuel borne oxygen and oxidation of soot nuclei during fuel combustion.[46] This also explains why ALB20 has a lower smoke opacity compared to ALB10.

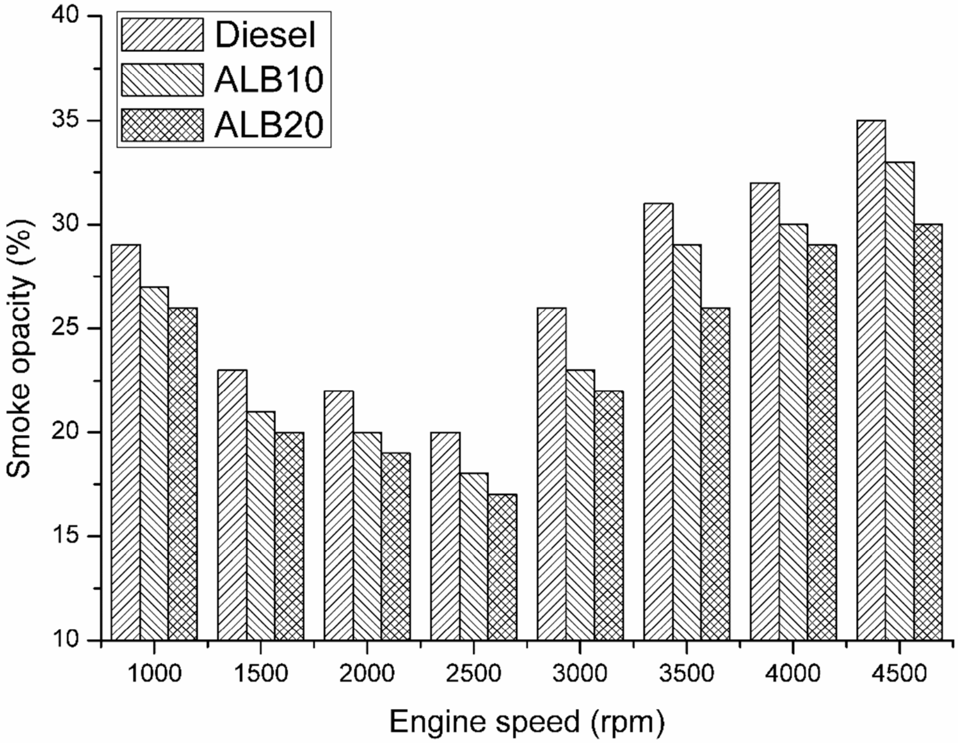


Fig. 8. Variation of Smoke opacity of different test fuels with speed

4. Conclusions

Non edible high acid value Alexandrian laurel oil is a potential source of biodiesel production. In this study biodiesel was obtained through one step acid catalyzed esterification and one step alkali catalyzed transesterification step. Based on experimental observation the following conclusions can be made:

- With an increase in the biodiesel content of the blend density and kinematic viscosity increases linearly, calorific value decreases linearly and flash point increases in second degree polynomial nature.
- The average brake power reduction for ALB10 and ALB20 compared to diesel were 0.36% and 0.76%, respectively, due to their lower LHV and higher viscosity.
- ALB10 and ALB20 produced about 2.42% and 3.20% higher BSFC due to the volumetric effect of constant fuel injection rate together with higher viscosity and lower calorific value.
- Both ALB10 and ALB20 results in higher NOx emission (2.12-8.32%) due to combustion mainly occurring in late combustion stage. Higher viscosity results in poor atomization which hampers the fuel atomization and mixing in premixed combustion stage.
- CO and HC emission were reduced by 15.12-26.84% and 9.26-17.04% compared to diesel operation.
- Average smoke opacity reduction of smoke for ALB10 and ALB20 were 7.78% and 13.28% lower compared to diesel respectively, due to the oxidation of soot nuclei by fuel borne oxygen.

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Novelty: Articles studies production and characterization of Malaysian Alexandrian Laurel oil and effect of common blends on engine performance and emission.