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Characterization and prediction of blend properties and evaluation of engine performance and emission parameters of a CI engine operated with various biodiesel blends

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ABSTRACT

The present research is aimed to investigate the feasibility of using Palm (PB), Mustard (MB) and *Calophyllum biodiesel* (CB) as a renewable and alternative fuel. Biodiesels were produced from respective crude vegetable oils and physicochemical properties of biodiesel-diesel blends were graphically compared for all possible biodiesel blends at every 10% composition interval. By applying the curve-fitting method, equations are developed for predicting important properties, which show very close-fit to the experimental data. This will help future research, such as the optimization of blending percentage, engine combustion and performance and emission analysis. As up to 20% blends of biodiesels showed similar properties as diesel fuel, engine performance and emission of 10% and 20% biodiesel-diesel blends were studied for all three feedstock as well as diesel fuel to perform a comparative study. An average of 7-12% BSFC increment was observed for biodiesel blends compared to diesel fuel. The brake power was decreased on average 4.1-7.7% while operating on biodiesel blends. Nitric oxide (NO) emission increased 9-17% while hydrocarbon and carbon monoxide (CO) emission showed improved result for biodiesel blends. An average of 23-43% lower HC and 45-68% lower CO emission was resulted for biodiesel blends compared to diesel fuel.

Keywords: Production; prediction; performance; emission; biodiesel.

1. INTRODUCTION

In the recent decade, ever increasing trend of energy consumption due to industrialization and development has caused serious threat to the energy security and environment. Current reserve of liquid fuel has the capacity to meet only half of the global energy demand until 2023[1]. Besides, this tremendous drift of fossil fuel use, hazardously effecting world's environment, which includes global warming, deforestation, eutrophication, ozone depletion, photochemical smog and acidification[2]. The world is now moving towards green technology by encouraging the usage of cleaner, safer and renewable energy[3]. Greater energy security, pollution reduction, saving of foreign exchange and other socio-economic issues are stimulating rapid growth of biofuel industries over the next decade. Biodiesel is progressively gaining acceptance as an alternative and renewable energy source and market demand will rise intensely in near future[4, 5]. According to International Energy Agency (IEA), around 27% of total transport fuel will be replaced completely by biofuels within 2050 [6].

Biodiesel fuels are mono alkyl esters and generally derived from fatty ester of vegetable oil or animal fat. Trans-esterification is the most popular chemical treatment to reduce viscosity and improve other properties[7]. Trans-esterified vegetable oils are widely being used in diesel engines at present and meet standard specifications of ASTM and EN test method. Biodiesels and their blends have similar properties as diesel fuel and favoured due to lower exhaust emission.

Palm has been reported as the most productive plant among all biofuel feed stocks. At present more than 95% of world's biofuel production is produced from edible oils[8, 9]. Worlds total palm oil production is 45 million tonnes per year though maximum production is in South East Asia[5].

However, producing biofuel from edible oil source has received criticism from several non-governmental organisations worldwide[10]. Therefore, using non-edible vegetable oils as biofuel which are not suitable for human food can replace the current dependence on the edible oil source. *Calophyllum inophyllum* can be trans-esterified and is a very promising non edible source of biofuel. Production of *Calophyllum inophyllum* is still in nascent state compared to Palm biodiesel industry. Mustard oil is also a potential feedstock of biofuel. In most of the literatures reviewed, it was found that low-quality seeds which are unsuitable for food use, are adopted for fuel production[11]. Canola or rapeseed has gained widespread acceptance as biodiesel feedstock which is from the same plant family of mustard. But advantage of mustard oil is it contains high amount of erucic acid which makes it generally non edible (although mustard oil is used as condiment). Hence, mustard oil is suitable for industrial use and unlike canola using mustard as biodiesel feedstock would not interfere with the food supply[12]. Therefore, mustard is seemed to be a more feasible feedstock for biodiesel production[13].

This study was undertaken to investigate the possibilities and comparative evaluation of using palm, mustard and *Calophyllum inophyllum* biofuels in diesel engine. All three biodiesels were blended with diesel fuel from 10% to 90% biodiesel-diesel blend. Important physicochemical properties were measured for all these blends and presented graphically to understand the effect of blending clearly, which indicates their potentiality as biodiesel in future research. However, as 10% and 20% blends for all three biodiesels showed fuel properties very close to diesel fuel, they were further used in measuring engine performance and emission and compared with diesel fuel.

2. METHODOLOGY

2.1. Feedstock and chemicals

Palm and *Calophyllum inophyllum* oil were purchased from the Forest Research Institute of Malaysia (FRIM). FRIM usually collects the feedstock from local farms in Malaysia and Indonesia respectively. Mustard oil extracted from low quality inedible seeds was purchased from local farms in Bangladesh. All the chemicals needed for transesterification were purchased from LGC Scientific, Kuala Lumpur, Malaysia.

2.2 Production process of biodiesel

Crude oils were poured in a rotary evaporator and heated for 1hr at 95°C in order to eliminate moisture under vacuum condition.

To produce biodiesel from crude vegetable oil, transesterification was performed by two steps: (1) Acid esterification and (2) base transesterification process. Methanol was used as solvent with sulphuric acid (H_2SO_4) for acid esterification and potassium hydroxide (KOH) for base transesterification respectively. Acid esterification is needed if the acid value of crude oil is higher than 4 mg KOH/gm. Acid value was calculated by doing titration. For calophyllum oil both steps were needed as its acid value was high and for palm oil and mustard oil only base transesterification was needed.

Using acid catalyst, the first step reduced the free fatty acids (FFA) level of crude vegetable oil up to 1-2%. A favorite jacket reactor of 1 litre capacity was used with IKA Eurostar digital model stirrer and Wiscircu water bath arrangement. One litre of crude vegetable oil with 200 ml methanol and 0.5% v/v sulphuric acid were taken in the flask for acid catalysed esterification. The mixture was constantly stirred at 700 rpm and a temperature range of 50-60°C was maintained at atmospheric pressure by circulating hot water through the jacket. To determine the FFA level, 5 ml sample was taken from the flask at every 10 minutes interval and esterification process was carried out until FFA level was reduced up to 1-2%. After completing the acid esterification process the product is poured into a separating funnel where sulphuric acid and excess alcohol with impurities were moved to the top. Top layer was separated and lower layer was collected for base transesterification.

Same experimental setup was used for alkaline catalysed transesterification process. Meanwhile, 1% w/w of KOH (base catalyst) dissolved in 25% v/v of methanol was poured in the flux. Then the mixture was stirred at same speed and temperature was maintained at 70°C. The mixture was heated and stirred for 3 h and again poured into a separating funnel where it formed two layers. Lower layer contained glycerol and impurities and upper layer was methyl ester of vegetable oil. Lower layer was discarded and yellow upper layer was washed with hot distilled water (100% v/v) and stirred gently to remove remaining impurities and glycerol. Biodiesel was then taken in a IKA RV10 rotary evaporator to reduce the moisture content. Finally, moisture was absorbed by using sodium sulphate and final product was collected after filtration.

2.3 Characterization of fuel properties

The quality of oil is expressed in terms of the fuel properties such as viscosity, density, calorific value, flash point, pour point and cloud point etc. The important physical and chemical properties of the crude oils and their methyl esters were tested according to ASTM D6751 standard.

2.4 Biodiesel blending

Each test fuel blend was prepared prior to the properties test and engine test. Each test fuel blend was stirred at 2000RPM for 20 minutes in a homogenizer device. The homogenizer was fixed on a vertical stand by a clamp which allows its height to be changed. The engine test was carried out using 7 fuel samples including diesel fuel and 10% and 20% blend of each feedstock. These blends was chosen based on the reports by the researchers that up to 20% of biodiesel blend can be used in a diesel engine without any modification[8]. The blend compositions of all fuel samples are given in Table 1.

Table 1: Blend fuel compositions (%vol)

2.5 Engine Test

A 4-cylinder diesel engine was used in this experiment; its specifications were summarized in Table 2. Schematic diagram of the engine test bed is shown in Fig 1. At first the engine was warmed up for 5 minutes so that fluctuation of emissions can be avoided. Tests were carried out at different engine speed ranged from 1000 to 4000 rpm and full load condition. For engine performance and exhaust emission test, every fuel sample has been tested three times and their average results were reported in this study. The engine was connected with test bed and a computer data acquisition system. Therefore the test bed was connected to the data acquisition board, which collects signal, rectify, filter and convert the signal to the data to be read. The data acquisition board is connected to the laptop, where, user can monitor, control and analysis the data using software through REO-DCA controller. All the performance data was measured at step RPM test mode. At every 500 rpm increments, engine stabilizes for 20 seconds and acquires data for next 20 seconds.

Table 2: Test engine specification

Fig.1: Test engine set up

2.6 Apparatus for Engine Emission Studies

A BOSCH exhaust gas analyzer (model BEA-350) was used to measure the exhaust emission gases emission of NO and HC in ppm while CO in volume percent. The details of gas analyzer are shown in Table 3. In this research work exhaust emission was measured at various speeds range from 1000 rpm to 4000 rpm at an interval of 500 rpm at full load conditions by inserting probe into the tail pipe.

Table 3: Gas analyzer details

3. RESULTS AND DISCUSSION

3.1 Characterization of Palm, Mustard and *Calophyllum Inophyllum* oil

Biodiesel production process selection and duration depends on the physicochemical properties of feedstock. Acid value, FFA, density and kinematic viscosity influence the production steps and also the extra processing steps like filtration, heating, centrifuging and drying. Table 4 shows the measured physicochemical properties of crude vegetable oil feedstock used to produce biodiesel.

Table 4: Physicochemical properties of crude vegetable oils

From Table 4 it can be seen that *Calophyllum inophyllum* oil showed highest kinematic viscosity and density value followed by Mustard oil and Palm oil. Due to these higher values of viscosity and density, crude oil cannot be used in the diesel engine directly or without any modification. High viscosity values negatively affect the volume flow and spray characteristics in the injection manifold as well as leads to blockage and gum formation. Therefore, it is suggested that vegetable oil should be converted to biodiesel to reduce viscosity and density before using in diesel engines.

The flash point results showed that *Calophyllum inophyllum* oil possesses highest flash point followed by Mustard and Palm oil. All of these crude vegetable oils have very high flash points (>160ºC) which conclude that these feedstock are safe for storage, transportation and handling. Mustard oil showed the lowest cloud point and pour point among all tested feedstock. Analyzing the cloud point and pour point result it can be concluded that Mustard oil possesses better cold flow properties than Palm and *Calophyllum inophyllum.* Calorific value is an important fuel selection parameter. Again Mustard oil was found superior than other two biodiesel feedstock considering its highest calorific value followed by Palm and *Calophyllum inophyllum* oil. Oxidation stability results showed that Mustard oil has the highest oxidation stability followed by Palm and *Calophyllum inophyllum* feedstock. Thus, it would not get easily oxidized during storage and transportation.

3.2 Characterization of produced biodiesels and their blends

Physicochemical properties of biodiesel show variation depending upon the feedstock quality, chemical composition, production process, storage and handling process. Measured physicochemical properties of produced biodiesels are shown in Table 5. Kinematic viscosity, density, calorific value, oxidation Stability and flash point of 10 to 90% biodiesel-diesel blends of the produced biodiesel were also measured and shown in Table 6.

Table 5: Physicochemical properties of biodiesels

Table 6: Various properties of biodiesel-diesel blends (10-90% blend percentages)

All tested biodiesels showed higher kinematic viscosity and density values compared to diesel fuel. In percentage, kinematic viscosity of PB, MB and CB were found 87%, 53% and 30% higher than diesel fuel respectively. On contrast density values of PB, MB and CB were found 5%, 5.5% and 4% higher than diesel fuel respectively. CB showed lowest density and viscosity values than PB and MB. Thus, CB showed superior quality as biodiesel than PB and MB considering kinematic viscosity and density. Thus using CB would be more economical as it might cause lower fuel consumption than PB and MB. However, kinematic viscosity and density values for produced biodiesel were remained within ASTM specification for biodiesel standard. From Table 6 kinematic viscosities of biodiesel blends were varied from 3.47 mm^2/s to 5.46 mm^2/s, 3.10 mm^2/s to 3.95 mm^2/s and 3.37 mm^2/s to 4.63 mm^2/s for 10% to 90% mustard, *Calophyllum* and Palm biodiesel-diesel blends. From Table 6 densities of biodiesel blends were varied from 824.2 kg/m^3 to 859.2 kg/m^3, 822.4 kg/m^3 to 854.2 kg/m^3 and 823.1 kg/m^3 to 856.4 kg/m^3 for 10% to 90% mustard, *Calophyllum* and Palm biodiesel-diesel blends respectively. However, all biodiesel blends meet the ASTM standard for biodiesels viscosity and density range.

PB showed highest flash point among all tested fuels. Thus it provides advantage during storage, transport and handling compared to MB, CB or diesel fuel. In percentage, flash point values of PB, MB and CB were found 152%, 96% and 137% higher than diesel fuel respectively. Lower volatility of biodiesel than diesel fuel might be a reason behind the higher flash point value. Flash point values for all biodiesels were found within ASTM specification for biodiesel standard. From Table 6, Flash points of biodiesels were varied from, 77.5ºC to 149.5ºC, 82.5ºC to 172.5ºC and 87.5ºC to 182.5ºC for 10% to 90% mustard, *Calophyllum* and palm biodiesel-diesel blends respectively

MB showed promising cold flow properties than other tested biodiesels. Cloud point and pour point of MB was found much lower than PB and CB. Thus MB can be used in cold climate where PB or CB might suffer from freezing. However, diesel fuel was found still better than all biodiesels considering its use in cold climate.

In percentage, calorific values of PB, MB and CB were found 11.5%, 10% and 11.3% lower than diesel fuel. As biodiesels are oxygenated fuels and contain less carbon than diesel, decrease in calorific value is obvious. Calorific value of MB was found 40.41 MJ/kg. It might be considered as a unique finding for MB as this value is higher than most of the conventional biodiesel found in the market. Thus MB would provide advantage over CB and PB considering calorific value. From Table 6, calorific value of biodiesel blends were varied from 44.88 MJ/kg to 41.08 MJ/kg, 44.33 MJ/kg to 40.30 MJ/kg and 43.80 MJ/kg to 40.10 MJ/kg for 10% to 90% mustard, *Calophyllum* and palm biodiesel-diesel blends respectively.

As biodiesels are oxygenated fuel, oxidation stability is very important during long time storage. Oxidation stability results showed MB possessed the highest oxidation stability followed by PB and CB respectively. Thus MB provides advantage over PB and CB considering storage capability. Oxidation stability depends on the respective fatty acid composition of biodiesels. From Table 6 oxidation stability of biodiesel blends were varied from 69.66 h to 15.92 h, 40.2 h to 3.18 h and 58.2 h to 4.1 h for 10% to 90% mustard, *Calophyllum* and palm biodiesel-diesel blends respectively. All biodiesel blends meet the EN ISO 14112 standard for biodiesels oxidation stability range.

Cetane numbers of PB, MB and CB were found 6%, 58%, and 22% higher than diesel fuel respectively. Besides, MB showed highest iodine value and CB showed highest saponification number among three tested biodiesels. As cetane number, iodine value and saponification number were calculated from the fatty acid composition of respective biodiesels, these values are completely depends on their chemical composition. On the contrast, PB showed lowest acid value followed by MB and CB respectively. Thus, PB might cause less corrosion to the engine over MB or CB.

3.3 Prediction of blend properties

In this study, calorific value, oxidation stability, density and flash point are plotted against kinematic viscosity (Figure 2). Mathematical equations are formed using the polynomial regression analysis, the equations are shown in Table 7. The calorific value, oxidation stability, density and flash point can easily be calculated by these equations if kinematic viscosity is known.

Fig.2. (a) Calorific value, (b) Oxidation stability, (c) Density and (d) Flash point vs. Viscosity for Mustard, Palm and *Calophyllum* biodiesel-diesel blends

Polynomial regression is a form of linear regression in which the relationship between the independent variable x and the dependent variable y is modelled as an nth degree polynomial. Polynomial regression models are usually fit using the method of least squares. The least-squares method minimizes the variance of the unbiased estimators of the coefficients, under the conditions of the Gauss–Markov theorem.

Polymath can fit a polynomial of degree n with the general form:

$$P(x) = a_0 + a_1{*}x + a_2{*}x^2 + \ldots + a_n{*}x^n \qquad \text{Equation 1}$$

where a_0, a_1, ..., a_n are regression parameters to a set of N tabulated values of x (a single independent variable) versus y (a single dependent variable). The highest degree allowed for a polynomial is N - 1 (thus n >= N - 1)

Table 7: Derived mathematical equation and their validation for various properties of blended biodiesel

The equation developed using the polynomial curve fitting method for various biodiesel blend percentages are validated with the experimental data shown in Table 7. The variation of data is calculated using Equation 2.

$$Variation\ (\%) = \frac{100}{N}\sum_{1}^{N}\left|\frac{Data_{exp}-Data_{Calc}}{Data_{exp}}\right| \qquad \text{Equation 2}$$

N= number of data

For 20% blends Calorific value, density and flash point variation was found 0.36%, 0.27%, 1.58% maximum when the equation was use to derive the value, however, variation for oxidation stability value was as high as 20.89%.

3.4 Performance analysis

3.4.1 Brake specific fuel consumption

BSFC refers to the ratio between fuel mass flow rate and effective engine power. The BSFC of diesel engine depends on the relationship among volumetric fuel injection system, fuel density, viscosity and lower heating value[14]. Figure 3 shows the variation of BSFC for Palm, Mustard and Calophyllum inophyllum biodiesel blend with respect to engine speed. It was observed that BSFC of biodiesel is generally higher compared to diesel fuel. Due to higher density, viscosity and lower calorific value of biodiesel; increase in BSFC than diesel fuel is obvious[15, 16]. Average BSFC for PB10 and PB20 were found 7% and 11% higher than diesel fuel respectively. Similar results were also found by other researchers[17, 18]. Biodiesel fuel is delivered into the engine on a volumetric basis per stroke; thus, larger quantities of biodiesel are fed into the engine. As fuel is fed into the engine on a volumetric basis, to produce same amount of power, more biodiesel is needed than diesel fuel due to its higher density and lower calorific value. On contrast, average BSFC for MB10 and MB20 were found 9% and 12% higher than diesel fuel. Bannikov et al.[19] also found similar higher BSFC for mustard biodiesel over diesel fuel. This amount for CB10 and CB20 were found 6% and 10% higher than diesel fuel. Moreover, all tested fuels showed lowest BSFC at 1500-2000 rpm speed range.

Fig.3. BSFC versus engine speed for all tested fuels at full load condition

3.4.2 Brake specific energy consumption

Brake specific energy consumption (BSEC) is a more reliable criteria compared to BSFC for comparing fuels having different calorific values and densities. From Fig.4, it can be seen that, BSEC of pure diesel fuel at all tested speed were lower compared to biodiesel blends. Biodiesel blends exhibited higher BSEC.

Fig.4. BSEC versus engine speed for all tested fuels at full load condition

3.4.3 Brake thermal efficiency

The variation of brake thermal efficiency with speed for different biodiesel blends and diesel fuel can be seen in Fig.5. From the figure, it can be stated that, at all speeds, diesel fuel exhibited highest brake thermal efficiency. The reduction in brake thermal efficiency for the biodiesel blends is mainly due to poor combustion of the injected fuel as a result of high viscosity and density. The average reduction of BTE for CB10, CB20, PB10, PB20, MB10 and MB20 were 6.5%, 10.1%, 8.3%, 8.2%, 11.3% and 12.3% respectively.

Fig.5. BTE versus engine speed for all tested fuels at full load condition

3.4.4 Variation of power

The variation of engine power output with engine speed for all tested biodiesels and diesel fuel is presented in Fig. 6. Maximum power output for PB10 and PB 20 were 35.2 kW and 34.5 kW respectively at 3500 rpm engine revolution which means 4.1% and 5.8% reduction in power than diesel fuel for PB10 and PB20 respectively. Maximum power output for MB10 and MB 20 were 34.1 kW and 33.7 kW respectively at 3500 rpm engine revolution which resulted 6.9% and 8% reduction in power than diesel fuel for MB10 and MB20 respectively. On contrast, maximum power output for CB10 and CB20 were 34.5 kW and 33.8 kW respectively at 3500 rpm engine speed. Maximum power output of CB10 and CB20 were 5.8% and 7.7% less than diesel fuel respectively. Reduction of power for biodiesel may be explained due to higher density and viscosity value which resulted poor atomization and low combustion efficiency[20].

Fig.6. Power versus engine speed for all tested fuels at full load condition

3.5. Emission analysis

3.5.1 NO emission

NOx is produced during the combustion process when nitrogen and oxygen are present at elevated temperatures. The oxides of nitrogen in the exhaust emissions contain nitric oxide (NO) and nitrogen dioxide (NO_2). The formation of NOx is highly dependent on in-cylinder temperatures, the oxygen concentration, and residence time for the reaction to take place[21]. The increase in temperature and oxygen causes more NO_X to be produced. Variation in average NO emission for all biodiesel blends and diesel fuel at different engine speed is presented in Fig.7. PB10 and PB20 produced 14% and 17% higher NO than diesel fuel while MB10 and MB20 produced 9% and 12% higher NO than diesel fuel respectively. On the contrary, CB10 and CB20 produced 13% and 16% higher NO than diesel fuel respectively. Higher cetane number and shorter ignition delay of biodiesel increased NO emission[22]. Moreover, many researchers found that the higher oxygen content of biodiesel is responsible for increase in NO emission. Generally, higher oxygen content results in higher combustion temperature which leads to higher NO emission. Moreover, the reason of increasing NO/NOx can be explained in terms of adiabatic flame temperature. Biodiesel fuel contains higher percentages of unsaturated fatty acids that have higher adiabatic flame temperature which causes higher NO/NOx emission[23]. Higher cetane number and shorter ignition delay of biodiesel increased NO emission[22]. Many researchers found that the higher oxygen content of biodiesel is responsible for increase in NO emission[24].

Fig.7. Comparative variation in average NO emission for biodiesel blends at different engine speed

3.5.2 HC emission

Hydrocarbons present in the emission are either partially burned or completely unburned. HC emission is resulted from incomplete combustion of fuel due to flame quenching at cylinder lining and crevice region[20]. Variation in average HC emission for all biodiesel blends and diesel fuel at different engine speed is shown in Fig. 8. On an average, PB10 and PB20 produced 23% and 38% lower HC than diesel fuel while MB10 and MB20 produced 24% and 42% lower HC than diesel fuel respectively. For *Calophyllum* biodiesel blends, it was observed that CB10 and CB20 produced 31% and 43% lower HC than diesel fuel respectively. It can be seen that the HC emission values are lower when biodiesel blended fuel is being used, which is supported by the literature[25,26,27]. It was also observed that HC emission decreases with the increase in blending percentage in the blends. This can be attributed to the higher oxygen contents and higher cetane number of biodiesel fuel. Biodiesel contains higher oxygen and lower carbon and hydrogen than diesel fuel which trigger an improved and complete combustion process. Thus HC emission is reduced in case of using biodiesel blend in a diesel engine.

Fig.8. Comparative variation in average HC emission for biodiesel blends at different engine speed

3.5.3 CO emission

CO is produced when progression to CO_2 remains incomplete due to incomplete combustion. If the combustion is complete, CO is converted into CO_2. If the combustion is incomplete due to shortage of air or due to low gas temperature, CO will be formed. Mostly, some factors such as air-fuel ratio, engine speed, injection timing, injection pressure and type of fuels have an impact on CO emission[28].Variation in average CO emission for all biodiesel blends at different engine speed is shown in Figure 9. It was observed that PB10 and PB20 produced 45.4% and 63.6% lower CO than diesel fuel respectively. On contrast, MB10 and MB20 produced 48% and 64.8% lower CO and CB10 and CB20 produced 48.5% and 68.3% lower CO than diesel fuel respectively. CO is produced when progression to CO_2 remains incomplete due to incomplete combustion. Additional oxygen content of biodiesel aids more complete combustion than diesel fuel, hence results in lower CO emission. CO emission of mustard, palm and *Calophyllum* biodiesels showed similar variations and slight deviation in amount.

Fig.9. Comparative variation in average CO emission for biodiesel blends at different engine speed

4. CONCLUSION

In this study, biodiesels were produced from palm, mustard and *Calophyllum* oil. Then chief physicochemical properties were measured and using these measurement equations were evaluated in order to predict the key properties when only viscosity of the biodiesel is known. Then a compression ignition engine was operated using 10% and 20% palm, mustard and *Calophyllum* biodiesel-diesel blends at speeds ranging from 1000 RPM to 4000 RPM. Engine performance and emission parameters were evaluated. The following conclusions are drawn based on this experimental investigation:

1. The physicochemical properties of all the produced biodiesel blends were within the specified limit

2. By applying the curve-fitting method, equations are developed for predicting important properties, which show very close-fit to the experimental data. This will help future research, such as the optimization of blending percentage, engine combustion and performance and emission analysis. Calorific value, density and flash point variation was found 0.3621%, 0.2724%, 2.8512% maximum when the equation was use to derive the value. However, variation for oxidation stability value was as high as 20.889%.

3. An average of 7-11%, 9-12%, and 6-10% BSFC increments were observed for the addition of 10%, and 20% biodiesel of palm, mustard and *calophyllum* respectively. The palm blends provided an average of 14.4% lower BSFC compared to jatropha blends. The brake power was decreased on average 4.1-5.8%, 6.9-8.0% and 5.8-7.7% for 10% and 20% blends of palm, mustard and calophyllum biodiesel respectively. Therefore,

calophyllum biodiesel showed better engine performance compared to palm or mustard biodiesel blends.

4. BSEC of pure diesel fuel at all tested speed were lower compared to biodiesel blends. Biodiesel blends exhibited higher BSEC.
5. BTE was highest for diesel fuel at all speeds. The average reduction of BTE for CB10, CB20, PB10, PB20, MB10 and MB20 were 6.5%, 10.1%, 8.3%, 8.2%, 11.3% and 12.3% respectively.

6. PB10 and PB20 produced an average of 45.4% and 63.6% lower CO emission than the diesel fuel. An average of 48.0% and 64.8% CO emission reductions were observed for MB10 and MB20 respectively. On contrast, CB10 and CB20 produced 48.5% and 68.3% lower CO emission. Similarly, PB10 and PB20 produced an average of 23% and 38% lower HC emission than the diesel fuel. An average of 24% and 42% HC emission reductions were observed for MB10 and MB20 respectively. On contrast, CB10 and CB20 produced 31% and 43% lower HC emission. At higher engine speeds, these emissions were considerably lower.

7. The NO emission was increased by 14% and 17% for PB10 and PB20 respectively. On the contrary, MB10 and MB20 produced 9% and 12% higher NO while CB10 and CB20 produced 13% and 16% higher NO than diesel fuel respectively.

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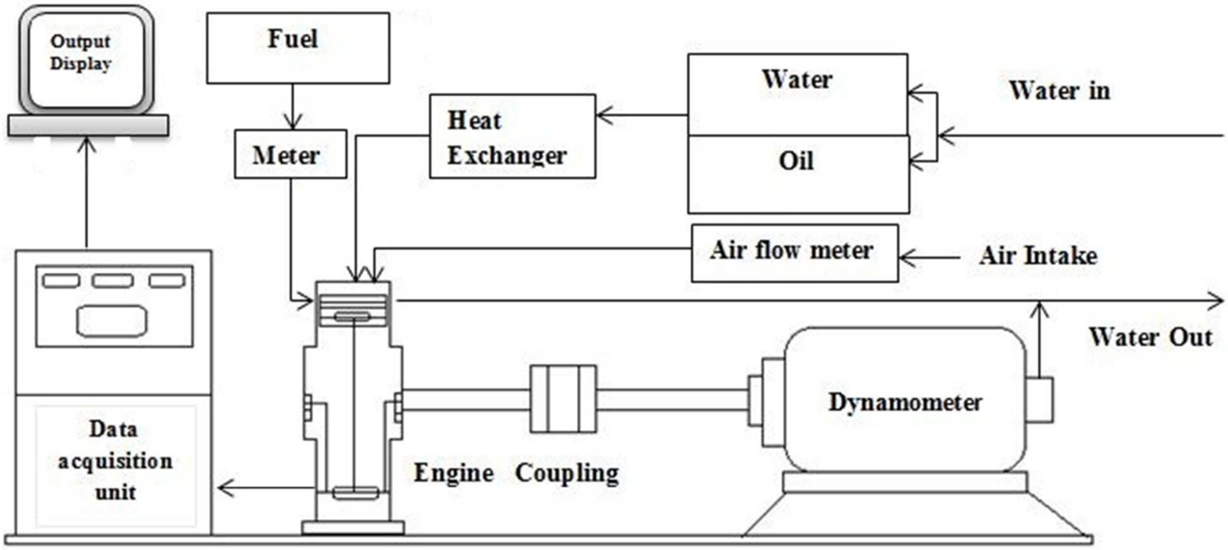
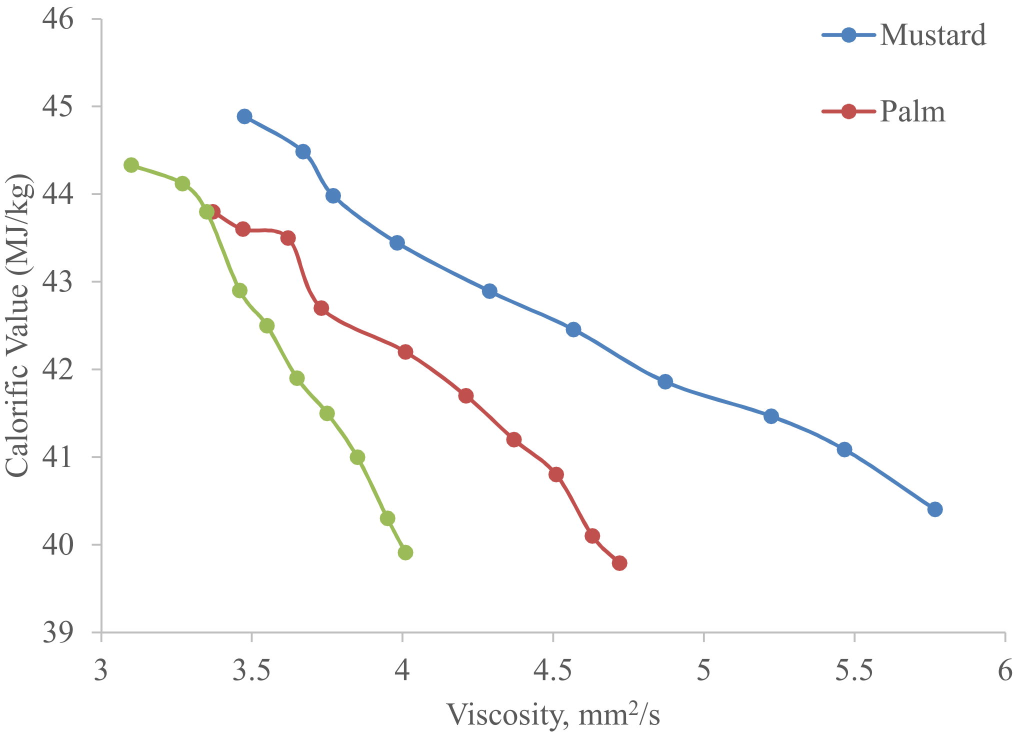
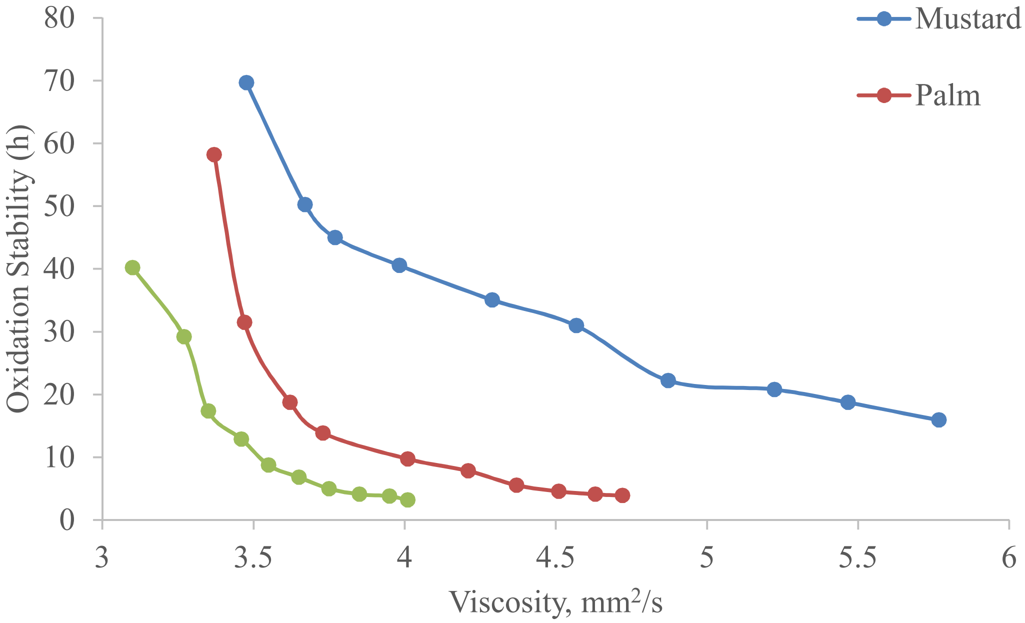


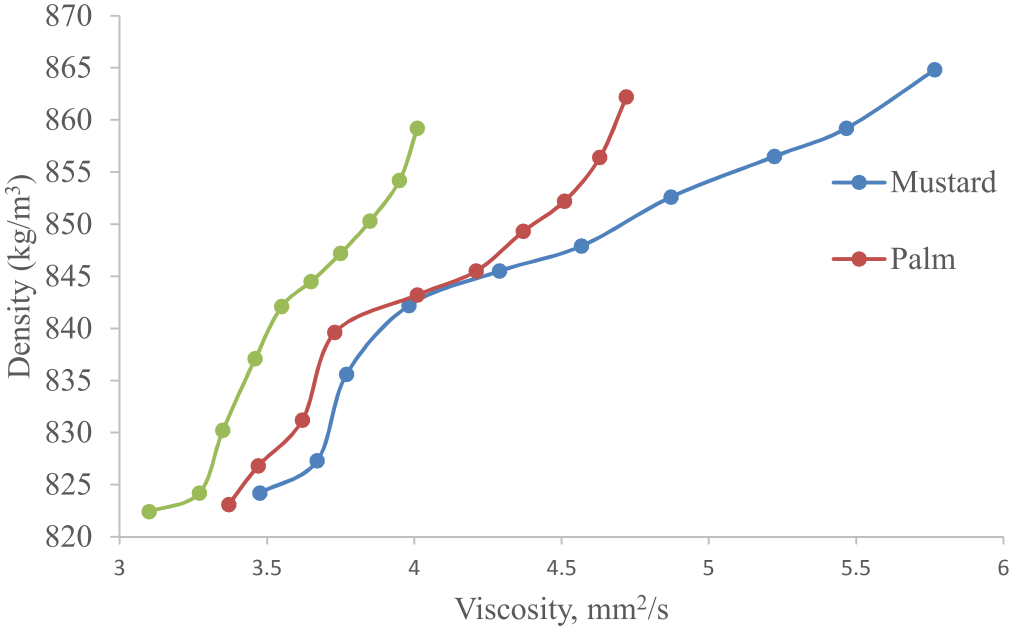
Fig.1: Test engine set up


Mustard
Palm
Calorific Value (MJ/kg)
46
45
44
43
42
41
40
39
3
3.5
4
4.5
5
5.5
6
Viscosity, mm²/s

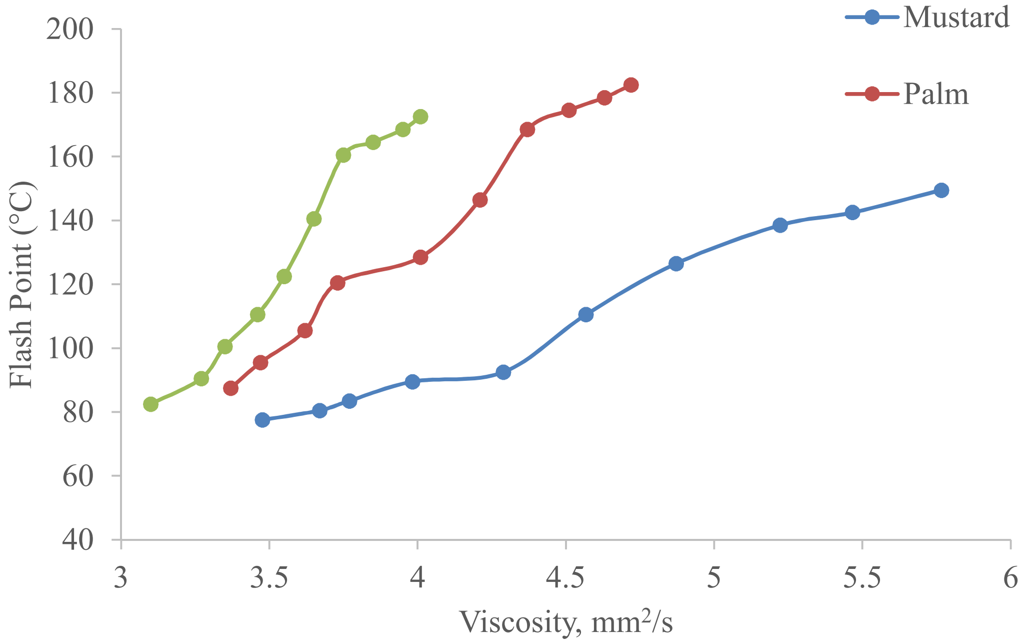
(a)


Mustard
Palm
Oxidation Stability (h)
80
70
60
50
40
30
20
10
0
3
3.5
4
4.5
5
5.5
6
Viscosity, mm²/s

(b)



(c)



(d)

Fig.2. (a) Calorific value, (b) Oxidation stability, (c) Density and (d) Flash point vs. Viscosity for Mustard, Palm and Calophyllum biodiesel-diesel blends

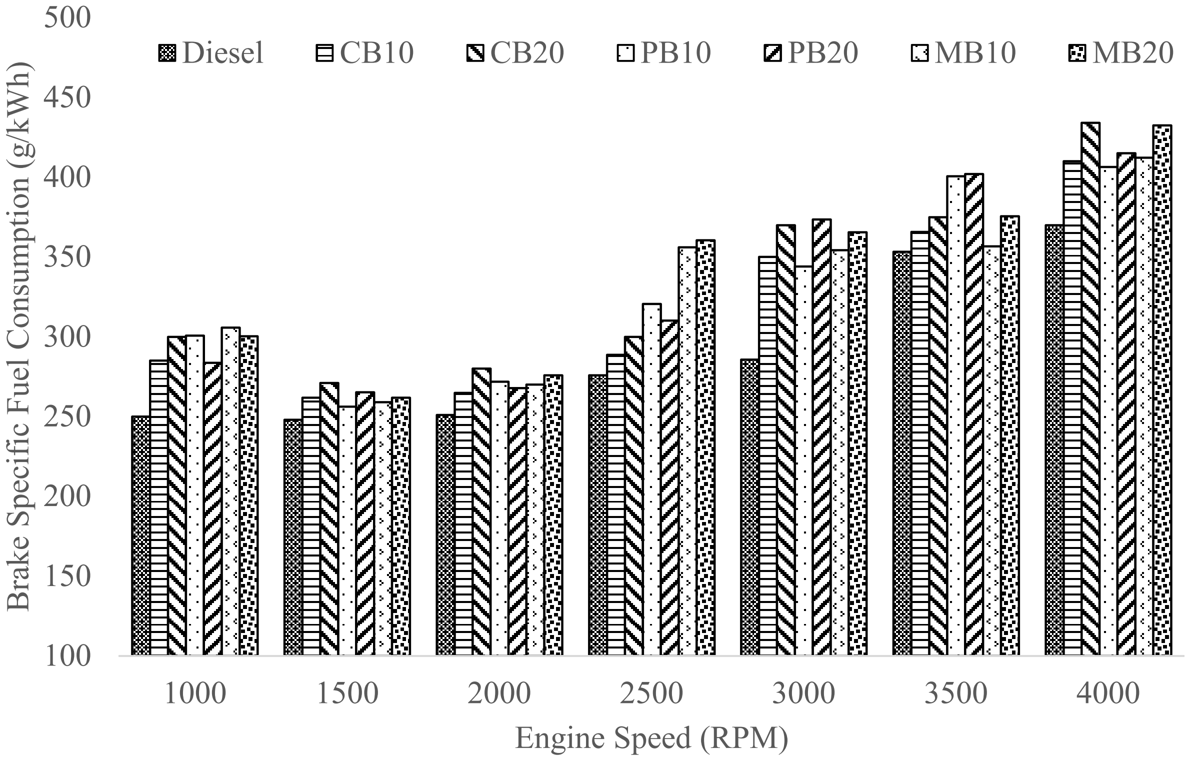


Fig.3. BSFC versus engine speed for all tested fuels at full load condition

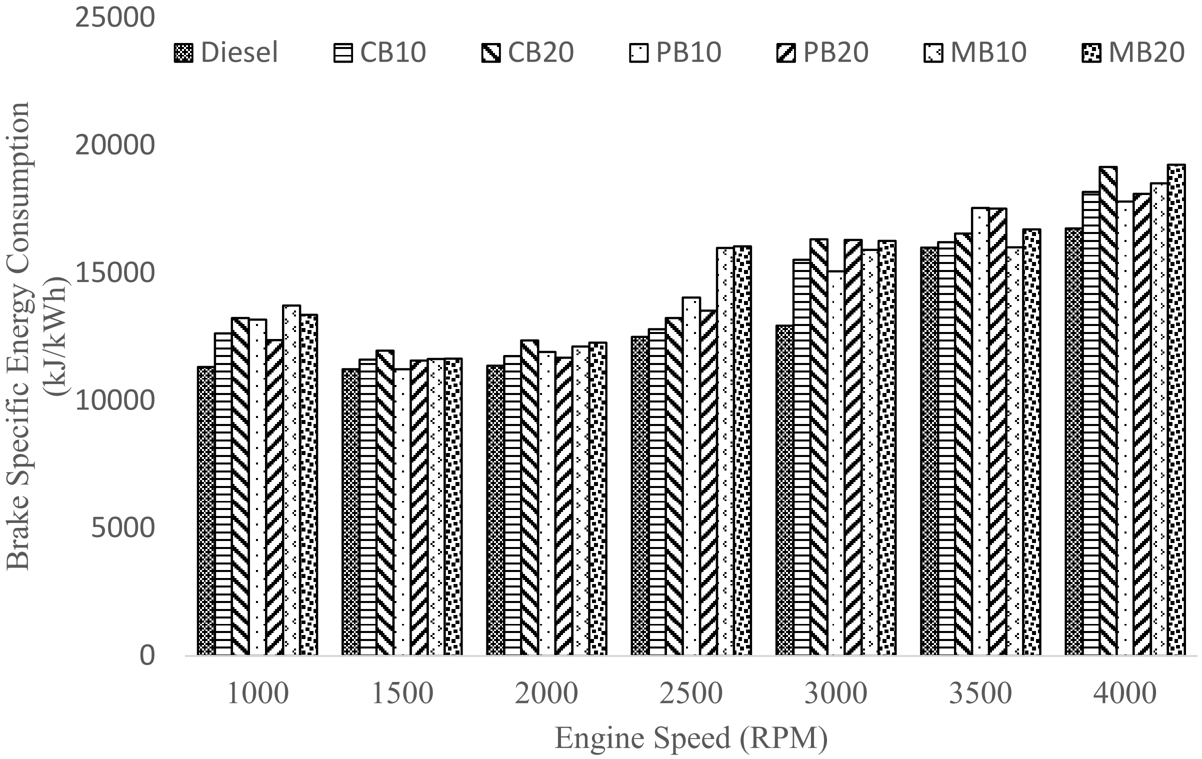


Fig.4. BSEC versus engine speed for all tested fuels at full load condition

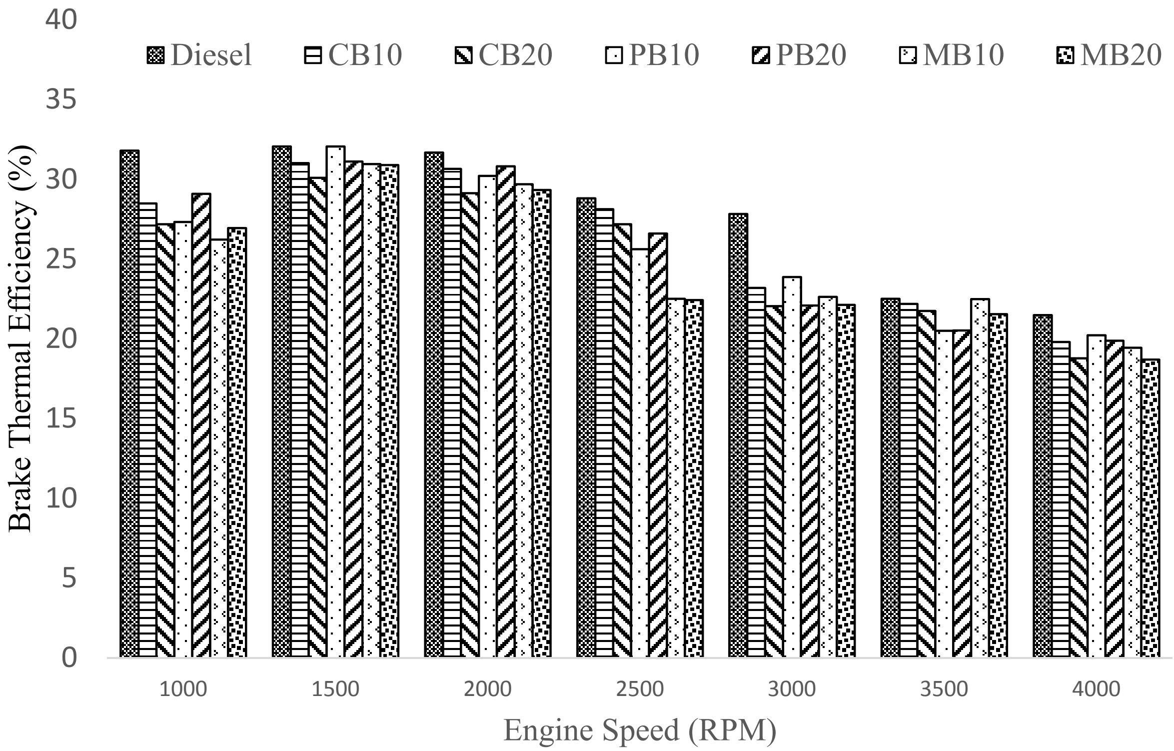


Fig.5. BTE versus engine speed for all tested fuels at full load condition

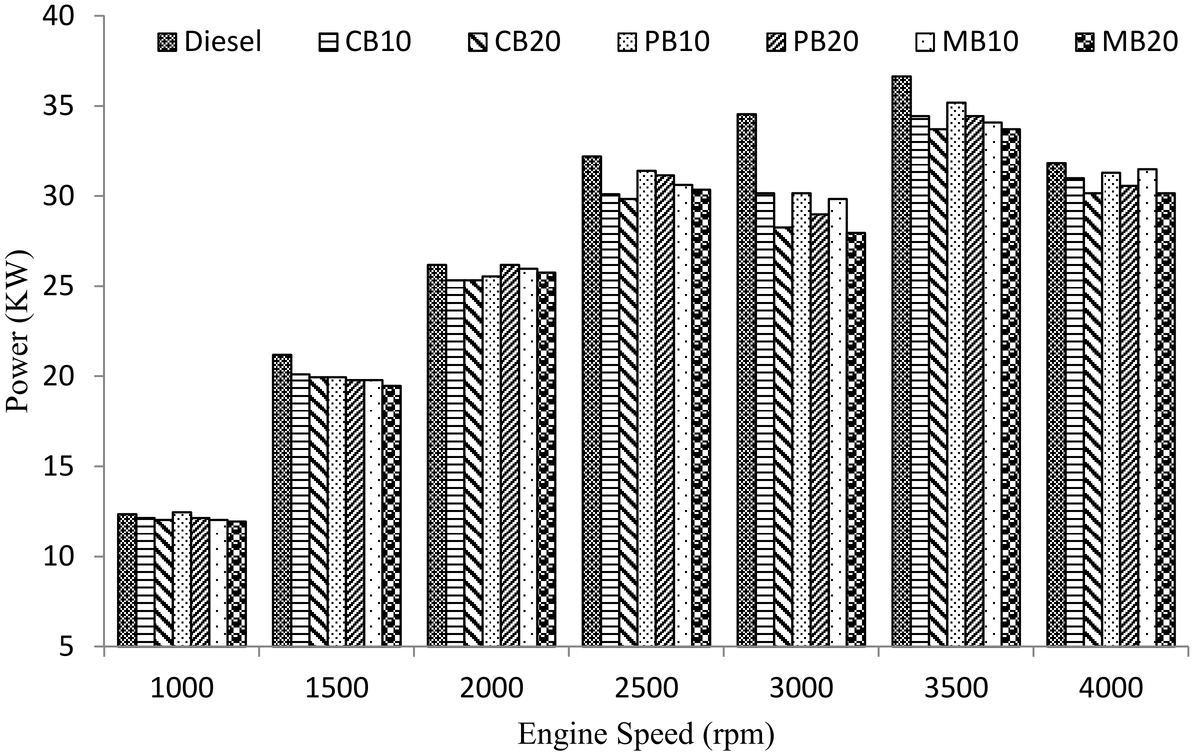


Fig.6. Power versus engine speed for all tested fuels at full load condition

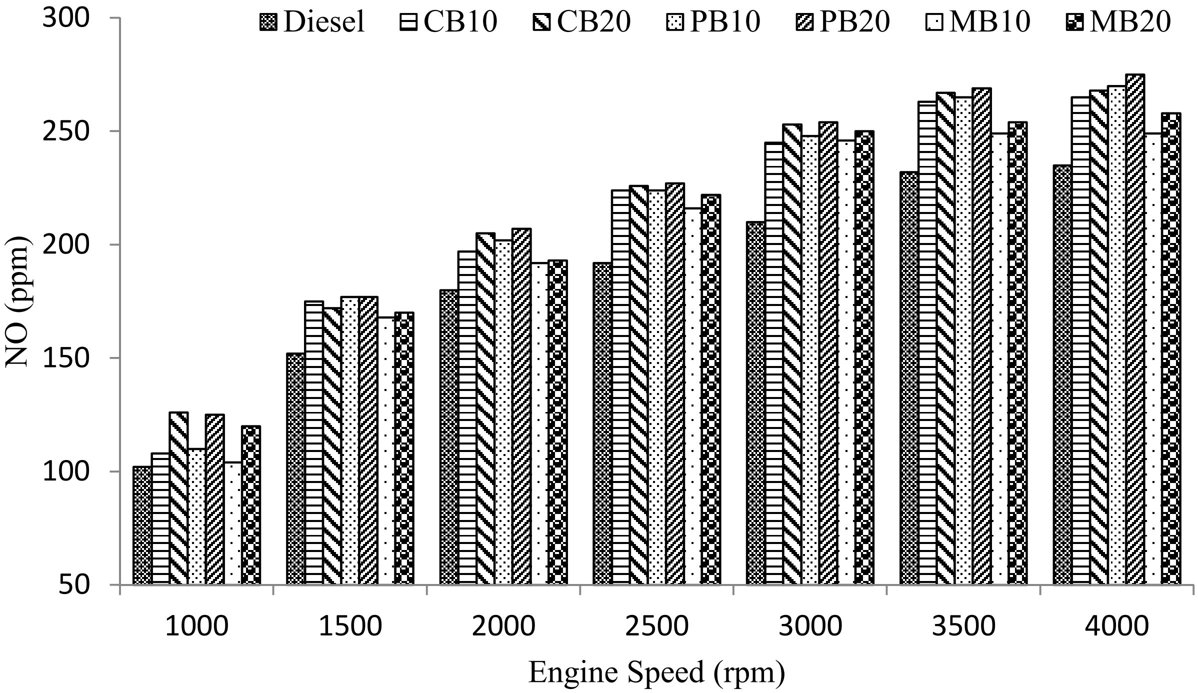


Fig.7. Comparative variation in average NO emission for biodiesel blends at different engine speed

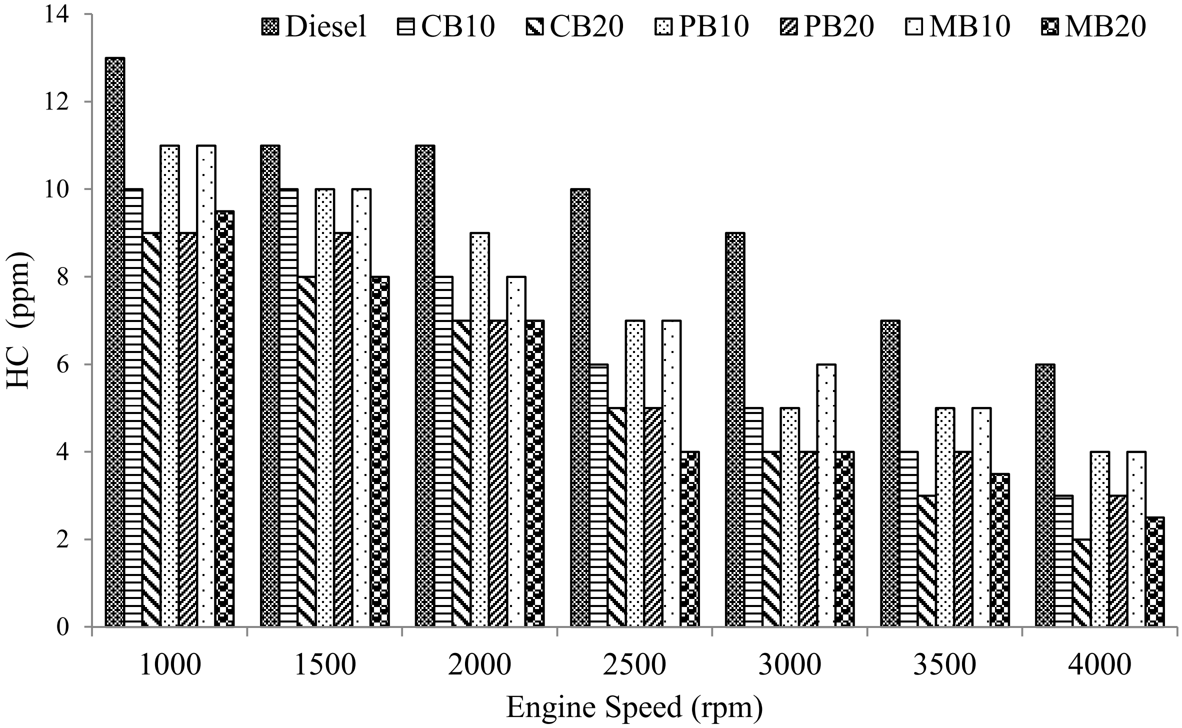


Fig.8. Comparative variation in average HC emission for biodiesel blends at different engine speed

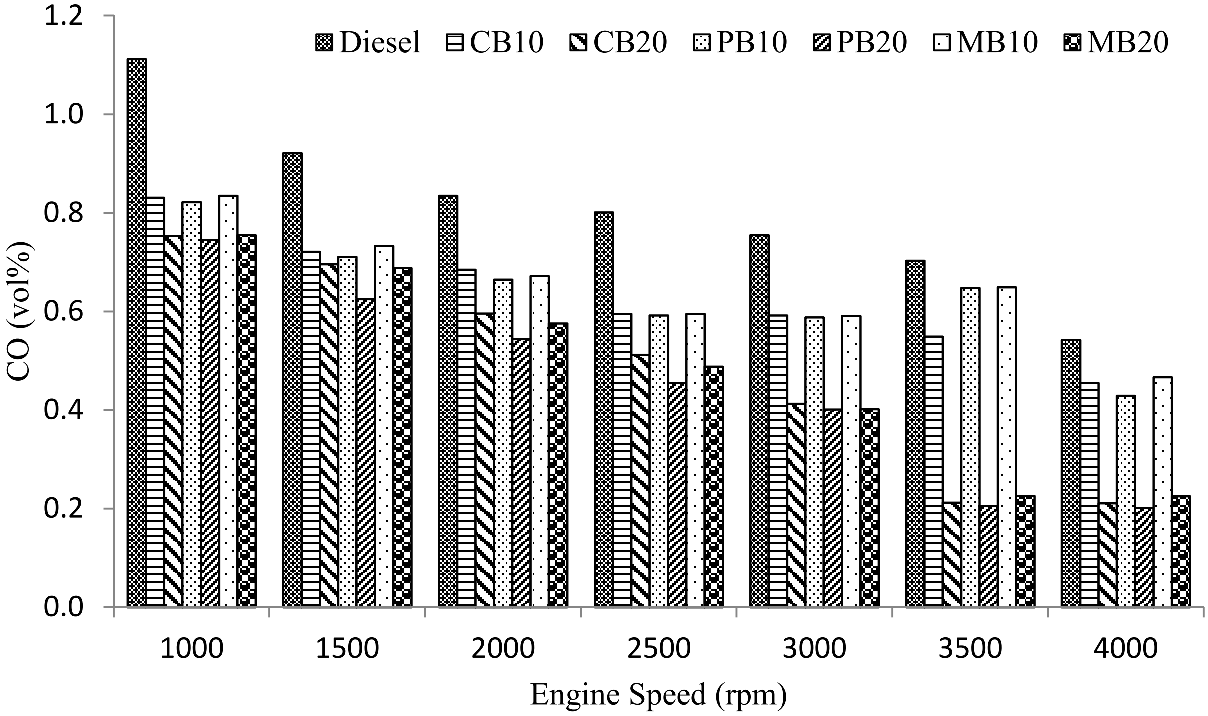


Fig.9. Comparative variation in average CO emission for biodiesel blends at different engine speed

Table 1: Blend fuel compositions (% vol)

No.	Fuel Samples	Samples description
01	Diesel	100% diesel fuel
02	PB10	10% Palm biodiesel + 90% diesel fuel
03	PB20	20% Palm biodiesel + 80% diesel fuel
04	CB10	10% Calophyllym biodiesel + 90% diesel fuel
05	CB20	20% Calophyllym biodiesel +80% diesel fuel
06	MB10	10% Mustard biodiesel + 90% diesel fuel
07	MB20	20% Mustard biodiesel + 80% diesel fuel

Table 2: Test engine specification

Engine type	4 cylinder inline
Displacement	2.5 L (2,476 cc)
Bore	91.1 mm
Stroke	95.0 mm
Torque	132 N.m , at 2000 rpm
Maximum engine speed	4200 rpm
Compression ratio	21:1
Cooling system	Water cooled
Combustion chamber	Swirl type
Lubrication system	Pressure feed

Table 3: Gas analyzer details

Equipment name	Model	Measuring element	Measuring method	Upper limit	Accuracy
BOSCH gas analyser	BEA-350	CO	Non-dispersive infrared	10.00 vol.%	±0.02 vol %
		HC	Flame ionization detector	9999 ppm	±1 ppm
		NO	Heated vacuum typechemiluminescence detector	5000 ppm	±1 ppm

Table 4: Physicochemical properties of crude vegetable oils

Properties	Units	Standards	Palm oil	Mustard oil	*Calophyllum Inophyllum* oil
Acid value	mg KOH/g oil	ASTM D664	3.47	3.64	10.72
Kinematic viscosity at 40 °C	mm^2/s	ASTM D445	38.10	45.52	48.82
Density at 15 °C	kg/m^3	ASTM D4052	890	898	921
Flash point	°C	ASTM D93	174.5	212.5	217.5
Pour point	°C	ASTM D97	5	-14	-3
Cloud point	°C	ASTM D2500	17	-13	-2
Calorific value	MJ/kg	ASTM D240	39.4	40.10	38.4
Oxidation stability	h	EN ISO 14112	3.42	11.30	2.72

Table 5: Physicochemical properties of biodiesels

Properties	Units	Standards	ASTM D6751	Mustard Biodiesel	Palm Biodiesel	Calophyllum Biodiesel	Diesel
Kinematic Viscosity at 40°C	mm^2/s	ASTM D445	1.9-6	4.967	4.723	4.017	3.0699
Density at 15°C	kg/m^3	ASTM D1298	860-900	864.8	862.2	859.2	821
Flash point	°C	ASTM D93	>130	149.5	182.5	172.5	72.5
Cloud point	°C	ASTM D2500	-	5	6	16	-8
Pour point	°C	ASTM D97	-	-18	3	15	-6
Calorific value	MJ/kg	ASTM D240	-	40.41	39.79	39.91	45.27
Oxidation stability	h	EN ISO 14112	3	15.92	3.92	3.18	-
Cetane number	-	ASTM D613	47 min	76	51	59	48

Table 6: Various properties of biodiesel-diesel blends (10-90% blend percentages)

Properties	Units	Biodiesel	Biodiesel-diesel blend %								
			10	20	30	40	50	60	70	80	90
Kinematic viscosity at 40 °C	mm^2/s	Mustard	3.4761	3.67	3.77	3.9823	4.2896	4.5676	4.8717	5.2231	5.4672
		Palm	3.37	3.47	3.62	3.73	4.01	4.21	4.37	4.51	4.63
		Calophyllum	3.1	3.27	3.35	3.46	3.55	3.65	3.75	3.85	3.95
Calorific value	MJ/kg	Mustard	44.886	44.486	43.983	43.445	42.892	42.455	41.86	41.467	41.085
		Palm	43.8	43.6	43.5	42.7	42.2	41.7	41.2	40.8	40.1
		Calophyllum	44.33	44.12	43.8	42.9	42.5	41.9	41.5	41	40.3
Flash point	°C	Mustard	77.5	80.5	83.5	89.5	92.5	110.5	126.5	138.5	142.5
		Palm	87.5	95.5	105.5	120.5	128.5	146.5	168.5	174.5	178.5
		Calophyllum	82.5	90.5	100.5	110.5	122.5	140.5	160.5	164.5	168.5
Density at 15 °C	kg/m^3	Mustard	824.2	827.3	835.6	842.2	845.5	847.9	852.6	856.5	859.2
		Palm	823.1	826.8	831.2	839.6	843.2	845.5	849.3	852.2	856.4
		Calophyllum	822.4	824.2	830.2	837.1	842.1	844.5	847.2	850.3	854.2
Oxidation Stability	h	Mustard	69.66	50.23	44.98	40.56	35.06	30.96	22.23	20.79	18.72
		Palm	58.2	31.5	18.75	13.84	9.74	7.82	5.55	4.55	4.1
		Calophyllum	40.2	29.2	17.35	12.88	8.74	6.82	4.98	4.12	3.8

Table 7: Derived mathematical equation and their validation for various properties of blended biodiesel

Property	Biodiesel blends	Mathematical equation	R^2	Variable, x	B20			B60		
					Exp value	Cal. value	Variation %	Exp value	Cal. value	Variation %
Calorific value vs kinematic viscosity at 40°C	Mustard-diesel	$y = -0.3442x^3 + 5.0526x^2 - 26.167x + 89.319$	0.9974	kinematic viscosity at 40°C	44.486	44.3249	**0.3621**	42.455	42.41076	**0.104**
	Palm-diesel	$y = -0.8766x^3 + 9.9172x^2 - 39.829x + 99.013$	0.9911		43.6	43.59	**0.02294**	41.7	41.6958	**0.01007**
	Calophyllum-diesel	$y = 4.4309x^3 - 49.011x^2 + 174.71x - 158.18$	0.9927		44.12	43.98	**0.31732**	41.9	42.024	**0.2959**
Oxidation stability vs kinematic viscosity at 40°C	Mustard-diesel	$y = -8.2615x^3 + 124.66x^2 - 634.2x + 1110.7$	0.9704		50.23	53.8459	**7.1986**	30.96	27.43698	**11.379**
	Palm-diesel	$y = -83.598x^3 + 1062.5x^2 - 4492.1x + 6325.1$	0.9616		31.5	38.08	**20.889**	7.82	7.26	**7.16113**
	Calophyllum-diesel	$y = -22.791x^3 + 306x^2 - 1347.9x + 1957.8$	0.9837		29.2	25.2892	**13.393**	6.82	6.389	**6.31965**
Density vs kinematic viscosity at 40°C	Mustard-diesel	$y = 5.9627x^3 - 87.141x^2 + 433.8x + 117.79$	0.9855		827.3	830.8839	**0.43**	847.9	849.402	**0.177**
	Palm-diesel	$y = 30.596x^3 - 374.72x^2 + 1544.9x - 1299.5$	0.989		826.8	827.697	**0.1084**	845.5	845.981	**0.0568**
	Calophyllum-diesel	$y = -20.447x^3 + 215.3x^2 - 711.45x + 1566.7$	0.978		824.2	826.446	**0.2724**	844.5	842.504	**0.23634**
Flash point vs kinematic viscosity at 40°C	Mustard-diesel	$y = -11.068x^3 + 154.41x^2 - 672.99x + 1017.3$	0.992		80.5	80.0587	**0.548**	110.5	110.09	**0.371**
	Palm-diesel	$y = -15.43x^3 + 183.91x^2 - 652.9x + 791.11$	0.9865		95.5	95.2938	**0.21587**	146.5	150.677	**2.8512**
	Calophyllum-diesel	$y = -276.65x^3 + 2952.6x^2 - 10350x + 12035$	0.9938		90.5	89.0727	**1.57716**	140.5	140.819	**0.2273**