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Performance, Emissions, and Combustion Evaluations of a Diesel Engine Fuelled with Biodiesel Produced from High FFA Crude Mahua (*Madhuca longifolia*) Oil

Aman Hira, Debasish Das and Ranjna Thakur

Abstract

Biodiesel is one of the environment-friendly alternative fuels need to be developed in order to meet the increasing demand for mineral fuels for transportation. In this study, nonedible crude Mahua oil has been used to extract biodiesel. Performance, emission and combustion characteristics of Mahua oil biodiesel blends with conventional diesel are compared on a single cylinder, natural aspirated, water-cooled direct injection (DI) diesel engine. Brake thermal efficiency of an engine fuelled with Mahua biodiesel blend B30 has been shown nearly same or insignificant lower compare to mineral diesel. The optimum engine operating condition based on lower brake specific fuel consumption and higher brake thermal efficiency was observed at 60% load for blend B30 of crude Mahua oil biodiesel. From an emissions point of view blend, B30 was found to be the best fuel as it showed lesser exhaust emission such as CO, HC, CO₂, and NO_x. Heat and pressure curve with respect to crank angle showed the details of combustion characteristics and revealed that combustion starts earlier for higher biodiesel blends. Results show that biodiesel obtained from nonedible Mahua oil gave better results and can be used as an excellent substitute for fossil fuels.

Keywords: High FFA crude Mahua oil, transesterification, esterification, diesel engine, performance, emissions, combustion

1. Introduction

Biomass sources, especially vegetable oils have received much more attention as an alternative source of energy [1]. But its higher viscosity rises some problems like filter clogging, carbon deposition on injector nozzle, compression ring groove piston lend etc. [2, 3]. To solve these problems following methods have been adopted to make it usable in the engine such as blending in small ratio with standard diesel fuel, emulsification, cracking and conversion into biodiesel through transesterification [4]. As per ASTM standard biodiesels are monoalkyl of long chain fatty acid [5].

Biodiesel is an alternative diesel fuel made from renewable biological sources such as vegetable oils and mineral oil [6, 7]. It is biodegradable, nontoxic, renewable and environment-friendly [8–10]. Biodiesel makes the environment fairly less hazardous compared to petroleum diesel, such as decrease acid rain and greenhouse effect caused by combustion. Renewability, biodegradability, sustainability, and environment-friendly properties make it an advantage to that of fossil fuel [8]. Besides this, it protects the global from the exponentially increasing emission, such as CO₂, SO_x and unburned hydrocarbon (HC) during the combustion process [11]. India is a seventh largest and developing country in the world needs a large amount of energy source to sustain their social and economic growth in 2010 India was the world fifth largest net importer of oil, imported more than 2.2 million bbl/d (Barrel per day), or about 70% of consumption [12]. It implies a dependency on petroleum imports. The supply of part of the demand with biodiesel can contribute to decreasing this dependency.

Many authors have reported that blends of vegetable oils (edible or non-edible) based biodiesel with diesel when used in a diesel engine, a reduction in emission and comparable performance were achieved [13, 14]. Nabi et al. [15] conducted an experiment with Neem oil biodiesel blend in the comparison of diesel fuel on four-stroke natural aspirated (NA) direct injection (DI) diesel engine. Blend showed lower carbon monoxide (CO) emission but higher NO_x emission compared to conventional diesel. Later in the second phase, NO_x emission was slightly reduced compared to diesel when the engine was applied Exhaust gas recirculation (EGR). Atul Dhar et al. [16] evaluated performance, emission and combustion characteristics of Neem oil biodiesel in a constant speed direct injection (DI) diesel engine. Brake thermal efficiency of all biodiesel blend was found to be increased compared to mineral diesel however specific fuel consumption for biodiesel and its blends were higher than mineral diesel. CO and HC emissions for biodiesel were lower than mineral diesel while NO_x emissions were higher for biodiesel blends. Combustion was started earlier for higher blends while for lower blends combustion was slightly delayed in comparison to standard diesel. All biodiesel blends were shown almost same heat release trend and shorter combustion duration in comparison of standard diesel.

In his study, the biodiesel from nonedible Mahua oil has been produced by two step acid-alkaline base catalyst transesterification. There has been substantial research on other non-edible oils like Jatropha, Pongamia, Karanja, and Sunflower for their suitability in Indian conditions and also to meet the automobile blending requirements. However, we are required to be focused on the Mahua oil. It is mainly a nonvolatile oil compressed from Mahua (*Madhuca longifolia*). Mahua is perhaps the widely grown tree in India after mango and almost all parts of Mahua tree are saleable.

2. Methodology

Mahua oil was purchased from a local general store in Uttar Pradesh market, chemical items which play an important role in converting fatty acid content of oil into ester like methanol (CH₃OH), (KOH) and H₂SO₄.

2.1 Biodiesel production and specifications

The biodiesel fuel used in this study was produced from the two-step acid-base catalyst transesterification of crude Mahua oil with methanol (CH₃OH) catalyzed by sulfuric acid in the first step called esterification process followed by the second

step called transesterification process in which esterifies crude oil Mahua with methanol was catalyzed by potassium hydroxide (KOH). In first step acid quantity and methanol to oil molar ratio both were varied but another reaction parameter as reaction time 1 h stirrer speed 300 rpm and reaction temperature 60°C were kept constant. Acid quantity 0.8% wt of oil and molar ratio of 18:1 was obtained as an optimized parameter at which maximum yield of esters was obtained. This oil had an initial acid value of 29 mg KOH/g, corresponding to a free fatty acid (FFA) level of 14.5%, which is far above the 1% limit for satisfactory transesterification reaction using an alkaline catalyst. The process of transesterification is complicated if oil contains large amounts of acid value that will form soap with an alkaline catalyst. The soap can rise difficulties or prevent separation of the biodiesel from the glycerol [17]. Therefore, free fatty acids were first converted to esters in a pretreatment process, an acid value of crude Mahua oil reduced to below 1 mg KOH/g approximate and completed transesterification with an alkaline catalyst to produce biodiesel [18, 19]. A titration was performed to determine the amount of KOH needed to neutralize the free fatty acids in esterified crude sunflower oil. The amount of KOH needed as a catalyst for every liter of crude Mahua oil was determined as 9.9 g. For transesterification, 250 ml CH₃OH (molar ratio 6:1) plus the required amount of KOH were added for every liter of esterified CNO, and the reactions were carried out at 60°C for 1 h. The mixture was stirred at a constant speed of 300 rpm continuously and then allowed to settle under gravity in a separating flask. Two separate layers form due to gravity settling after 24 h. The upper layer was of ester and the lower layer was of glycerol. The lower layer was separated out. The separated ester was mixed with some warm water at (40–42°C) around 30% volume of ester to remove the excess catalyst present in ester and allowed to settle under gravity for 4–6 h. At least three times this washing was done to ensure no catalyst present in esters. The catalyst got dissolved in water, which was separated and removed from the ester. After washing, a drying process was followed to make ester moisture free in which washed ester was allowed to heat at (100–120°C) for (1–1.5) h. The important properties of Mahua oil biodiesel are taken from references [20] and compared with those of diesel fuel [21] in **Table 1**. Some properties like density, viscosity acid values of Mahua oil biodiesel were found out at NIT-Hamirpur, Himachal Pradesh, India (177005). Then Mahua oil biodiesel was mixed with standard diesel in various concentrations such as B10, B20, B30, B40 and B50 for preparing biodiesel blends for conducting various engine tests.

Properties	Oil biodiesel
Density @ 21°C (cc/gm)	0.916
Viscosity (cSt) @40°C	3.58
Flash point (°C)	129
Fire point (°C)	–
Cloud point (°C)	1
Pour point (°C)	5
Calorific value (Mj/Kg)	42.8
Cetane number	51
Acid value (mg KOH/g)	0.532

Table 1.
Specification of biodiesel and diesel.

2.2 Experimental setup

The setup for the study consists of a single cylinder, four strokes naturally aspirated water cooled, and direct injection (DI) diesel engine connected to eddy current type dynamometer for loading (see **Figure 1**). The detailed specifications of the engine and uncertainty of some measured parameter are given in **Table 2**. Windows-based Engine Performance Analysis Software Package “Engine soft” was taken for online performance evaluation. Emission characteristics like CO, CO₂, unburned HC, smoke and NO_x by the combustion of biodiesel was measured by the online five-gas analyzer and smoke meter. The experiments were conducted under varying load condition at the rated speed of 1500 rpm in IC engine laboratory at NIT-Jalandhar, Punjab, India (144001). The engine was started with standard diesel fuel and warmed up. The warm-up period ends when cooling water temperature is stabilized. Then brake specific fuel consumption, brake power, brake thermal efficiency, and exhaust gas temperature were measured.

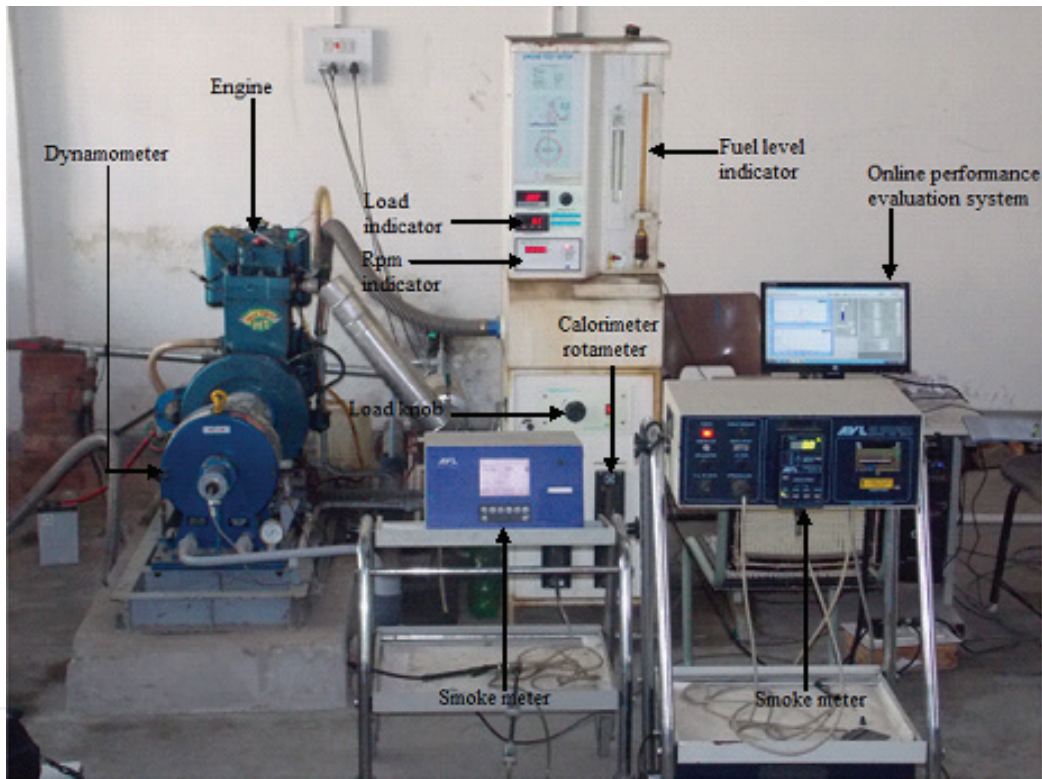


Figure 1.
Schematics of the test set-up.

Engine type	Single cylinder 4 stroke, DI
Bore	87.5 mm
Stroke	110 mm
Power	5.2 KW
Compression ratio	17.5:1
Speed	1500 rpm
Air box	MS fabricated with orifice meter and manometer
Fuel tank	Capacity 15 lit with glass fuel metering column

Table 2.
Specification of diesel engine.

3. Result and discussions

Performance, emissions and combustion characteristics of blends B10, B20, B30, B40 and B50 with conventional diesel are investigated on single cylinder computerized diesel engine and are discussed in the following subsections.

3.1 Brake thermal efficiency, brake-specific fuel consumption, and exhaust gas temperature

Figure 2a shows that the variation of brake thermal efficiency (BTE) with a load for different blends. It has been observed that the brake thermal efficiency for all test fuel is increasing with the increase in applied load. It happens due to a reduction in heat land increase in power developed with an increase in load [22]. Blend B30 and diesel has been shown the BTE of 33.75 and 34.57% respectively. Hence B20 gave the little difference in efficiency among all test fuel, which is about 0.82% less than the diesel. Initially, efficiency was found to be increased with increased blend ratios up to B30 and after that, it got a decrease as shown in **Figure 2a**. The decrease in brake thermal

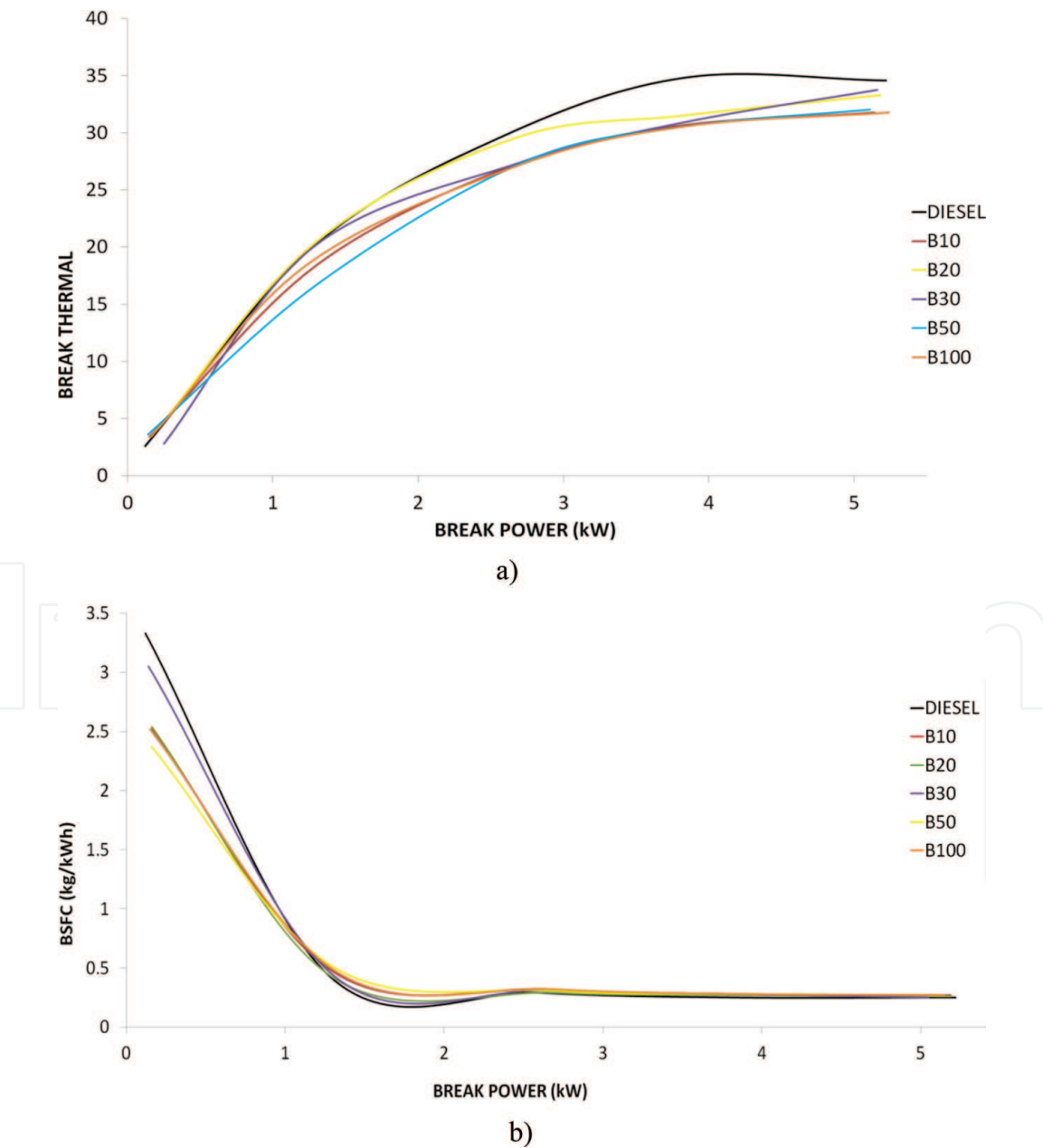


Figure 2.
Variation of brake power with (a) BT efficiency and (b) BSFC.

efficiency for higher blends may be due to the combined effect of its lower heating value and increase in fuel consumption [23]. In spite of this increasing viscosity may be the other reason for decreasing efficiency with higher blend ratio fuel, thereby, poor spray and poor atomization occurred due to which charge was not properly burned.

The variation of brake specific fuel consumption with regard to load is given in **Figure 2b**. It is obvious from the name that the BSFC of the engine gradually decreases with increasing load and then becomes constant up to full load condition. The same trend for brake specific fuel consumption (BSFC) can be viewed as it was seen in efficiency **Figure 2**; B30 has given lowest brake specific fuel consumption to all other blends and diesel at full load condition [24–28]. Diesel and B30 have been read 0.25 and 0.25 kg/kWh of BSFC respectively, at full load which is more or less same as diesel. For a higher percentage of biodiesel blends, BSFC is found to be increased. This may be due to high density, high viscosity and lower heating value of the fuels. B30 has a minimal value of fuel consumption among B10, B20, B50, and B100 at and above 100% load.

3.2 Results and discussion regarding the engine emission in term CO, CO₂, NO_x, and unburned HC are as follows

3.2.1 Carbon monoxide (CO) emission

The figure shows the variation of carbon monoxide emission of blends and diesel under various loads. The discharge of CO is found to be diminished with increasing load at the initial stage up to approximate 75% load after that it increases for B10 up to 0.2 (%Volume). But for B30 decrement of 0.2 (%Volume) of CO at the stage of 75–100% load. This is because of more fuel accumulates at a higher load to produce more power due to which higher temperature achieved in the fumes. This increased temperature helps in the oxidation of CO on account that its value decreases. Blend B10, B20, B50, and B100 have been given equal amount of CO to that of diesel at full load stage, because for B10 due to the inefficient inherited oxygen of biodiesel CO could not oxidize to CO₂, and for B50 increased viscosity and high non-volatility of biodiesel caused poor spray, atomization and burning of CO into CO₂ (**Figure 3**).

3.2.2 Hydrocarbon emission

Variation of unburned hydrocarbon can be seen in the figure. Significant reduction in HC emission has been found with decreasing the blend ratio of biodiesel in fuel. Blends B10, B20, B30, B50, B100 and diesel are given 36.5, 34.8, 30.2, 23, 23.2 and 27.4 ppm of HC emission on an intermediate basis. Hence B50 and B100 have been given the lowest HC compare to all test fuels due to the optimum level of oxygen and viscosity of the fuel. This decrease indicates that more complete combustion of fuels due to which low HC level was obtained (**Figure 4**).

3.2.3 NO_x emission

Variations of NO_x emission with loads for different blends are presented in the figure.

The NO_x emission is found to be increased with growth in shipment due to less heat rejection at higher load. That is the way all test fuels shows the highest value of discharge at full load condition. Blends B10, B20, B30, B50, B100 and diesel show 549, 743, 608, 704, 669, and 730 ppm respectively at full load condition. In initial blends, only B20 has been given higher. NO_x due to higher temperature compared to B10 and B20. In universal, vegetable-based fuel contains a low quantity of

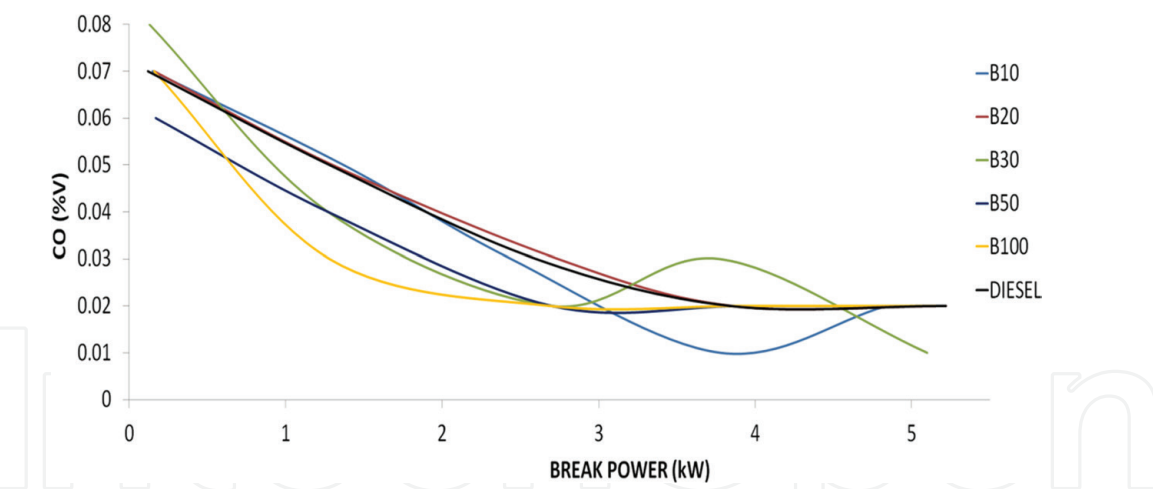


Figure 3.
CO vs. BP emission for Mahua oil BD blends and diesel.

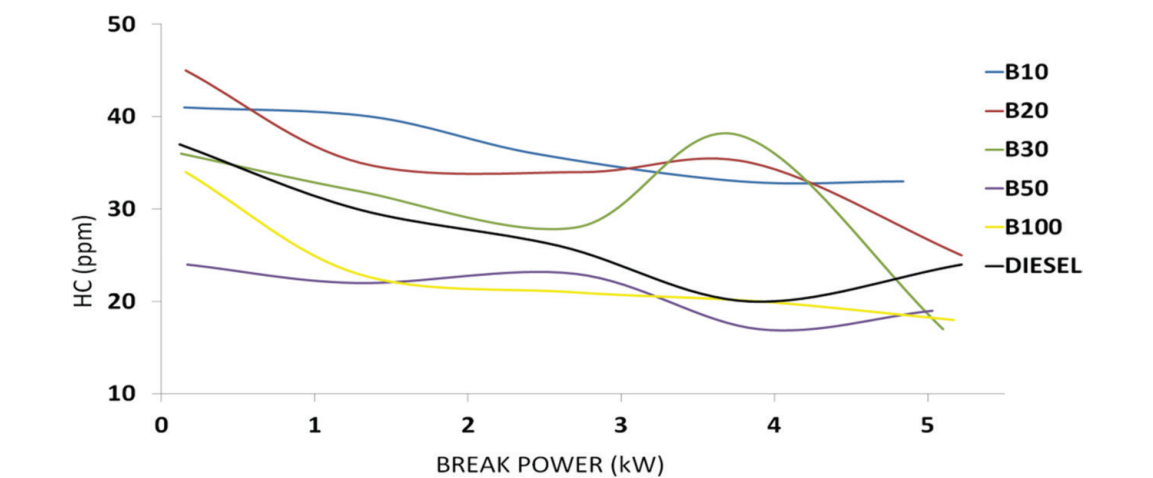


Figure 4.
BP vs. unburned HC for Mahua oil BD blends and diesel.

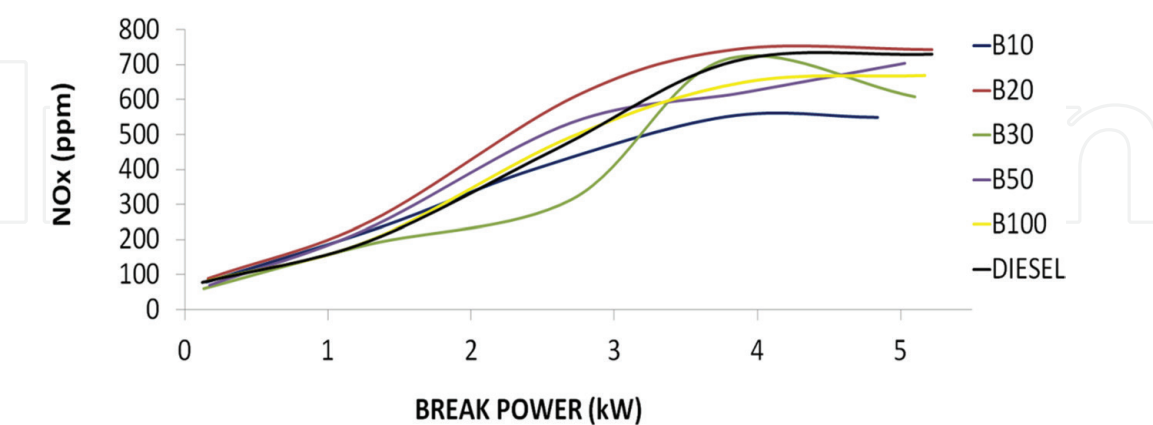


Figure 5.
BP vs. NOx for Mahua oil BD blends and diesel.

nitrogen that contributes towards NO_x production. In malice of this NO_x emission is the function of temperature also, more NO_x is emitted at high load because of the higher temperature of gas oxidized the nitrogen oxides into nitrogen and thus NO_x increase. From this figure, it can be concluded that B20 exhibiting proper complete combustion compare to others fuels (**Figure 5**).

3.2.4 CO₂ emission

Percent of CO₂ in the exhaust is the direct indication of complete combustion of fuel in the combustion chamber. The figure shows the variation of CO₂ under varying load for different biodiesel blends. All test fuels show increasing trends, CO₂ emission with an increase in shipment due to an increase in the accumulation of fuel. Blends B10, B20, B30, B50, B100 and diesel shows 3.6, 4, 3.7, 4.2, 3.7 and 4.5% of CO₂ respectively at full load condition. Only B50 has been shown higher CO₂ emission compare to diesel due to the significant issue of higher cetane number compare to other test fuel. Other blends have been presented the lower value of CO₂ than diesel. It can also be cleared from exhaust gas temperature vs. load curves in which B50 has been shown a higher temperature than other blends (**Figure 6**).

3.2.5 Combustion analysis

Combustion characteristics parameter like pressure-crank angle, rate of cylinder pressure rise, heat release rate and cumulative heat release are analyzed for different blends of Soybean oil biodiesel under varying load to compare the combustion characteristics of the engine with conventional diesel fuel.

3.2.5.1 In-cylinder pressure vs. crank angle

The figure shows the variation of in-cylinder pressure with a crank angle for blends B10, B20, B30, B50 and B100 in comparison of baseline data obtained from standard diesel. Pressure rise has been found to be comparable with diesel for higher biodiesel blends fuel. Moreover, low biodiesel blends such as B10 and B20 show delayed pressure rise with respect to standard diesel at full load due to longer physical ignition delay period because of the higher boiling point range of biodiesel compared to diesel. It can as well be visualized in the figure that all test fuel has shown decreases in ignition delay with an increase in shipment. This was passed due to an increase in gaseous state temperature at high load operation; therefore, a reduction in the physical ignition delay period was held (**Figure 7**).

I all cases higher biodiesel blends as B100 and B50 has been shown higher in-cylinder peak pressure compared to diesel and other low biodiesel blends. Two elements are mostly responsible for that first presence of inherited oxygen molecules

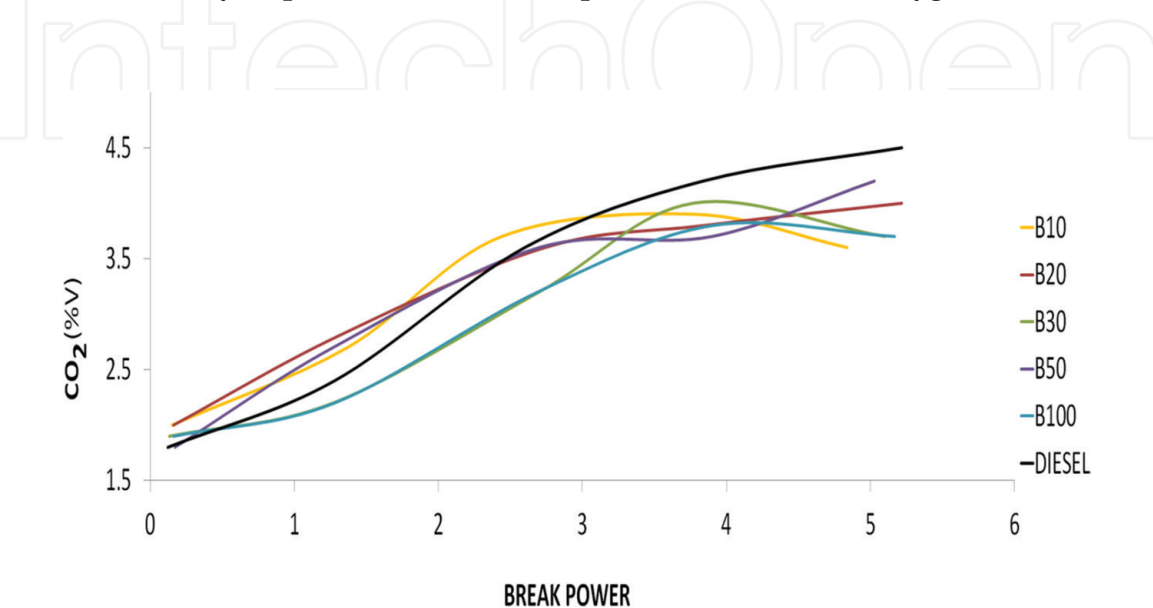


Figure 6.
BP vs. CO₂ for Mahua oil BD blends and diesel.

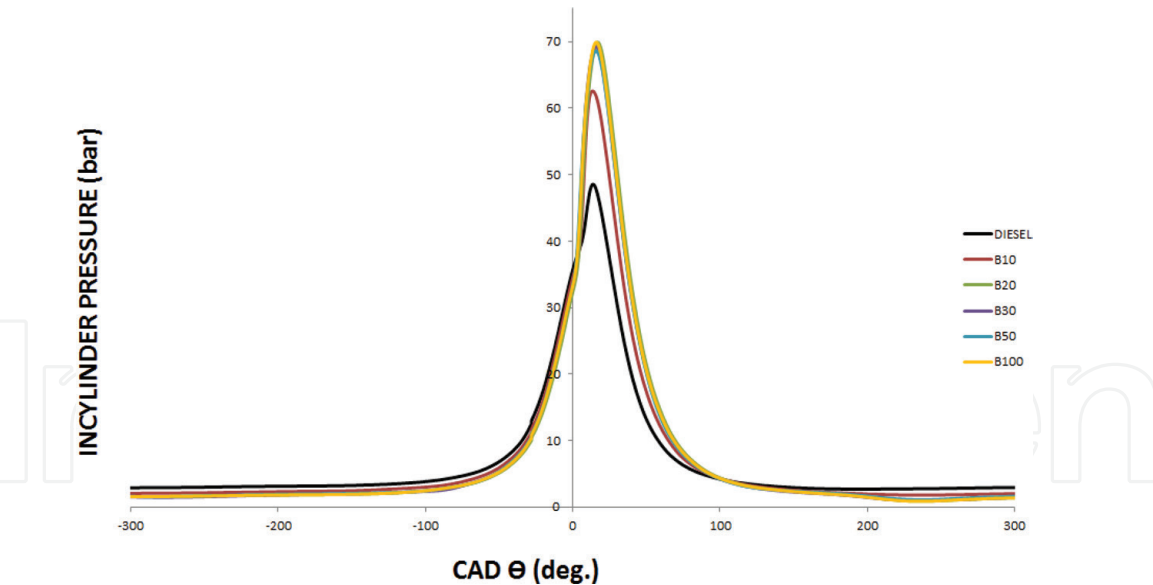


Figure 7.
In-cylinder pressure vs. crank angle.

in biodiesel helps in combustion and the second is the lower viscosity of mineral diesel which ensures adequate air-fuel blending.

3.2.5.2 Rate of cylinder pressure rise vs. crank angle

The figure shows the variation in the rate of pressure rise ($dP/d\theta$) with a crank angle (θ) under varying load for all test fuels. It can as well be visualized in the figure that the maximum rate of pressure rise is 4.55 bar/deg. for B30 blend and 4.51 bar/deg. for B20 blend, biodiesel blend B20 has been shown the highest rate of pressure rise compares to diesel. It can be due to higher accumulation of fuel during premixed combustion on account of that B20 biodiesel blends showed the earlier start of combustion with a consequence high rate of pressure rise (**Figure 8**).

3.2.5.3 Heat release rate vs. crank angle

The figure shows the heat release rate for biodiesel blends in comparison of standard diesel at different engine operating conditions. After burning of fuel, fluctuation of heat release rate occurs. However, at B100 shows the highest rate of heat release compare to diesel and other biodiesel blends are two other blends, because of the higher cetane number and higher oxygen capacity of biodiesel that improves

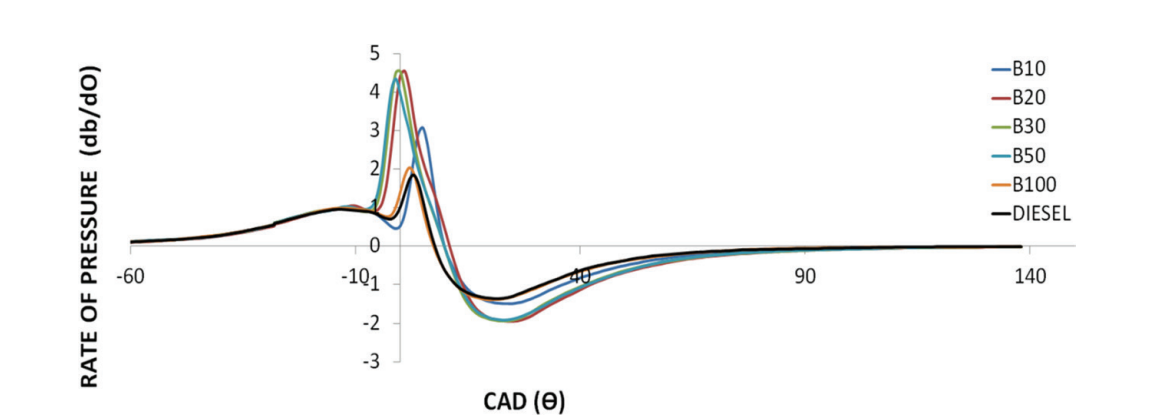


Figure 8.
Pressure rise rate vs. crank angle.

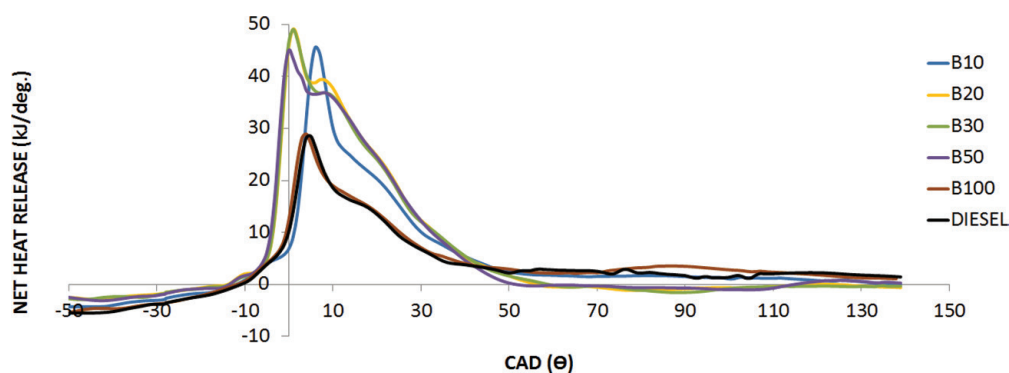


Figure 9.
Heat release rate vs. crank angle.

the burning quality of fuel and helps in firing at a higher charge per units. Moreover B10, B20 and B50 have been established a corresponding rate of heat release with diesel. This is because in low blends the concentration of biodiesel is low, that is way fuel does not cause a significant force on a certain number, but it touches the air-fuel mixture formation due to changes in viscosity and evaporation properties of the fuel. That is way lower blends showed a less charge per unit of heat release than B100 (**Figure 9**).

3.2.5.4 Cumulative heat release vs. crank angle

Cumulative heat release is the total heat energy that has been dropped for a given production. The figure shows the cumulative heat release for all blends at various engine loads in comparison of diesel. It can be pictured in figures that cumulative heat increases with increasing engine load for all test fail because the bulk of the fuel increases with a gain in shipment. It is also cleared from the diagram that up to 40% load all blends show low cumulative heat compare to diesel, but after that, blends have been shown gradually increase in cumulative heat than diesel in which B30, B50, and B100 show high cumulative heat.

4. Conclusions

High acid value Mahua oil was used to produce biodiesel by a two-step process of esterification followed by transesterification. In etherification, the molar ratio of methanol to oil and quantity of sulfuric acid was two main reaction parameters which were optimized to produce a low acid value of oil. Molar ratio 18:1 and 0.8% w/w to oil of sulfuric acid was observed optimum reaction parameters. While reaction temperature, reaction time and a stirrer speed of 60°C, 1 h and 300 rpm respectively were maintained during esterification. For transesterification, the molar ratio of alcohol to oil of 6:1, 9.9 g of catalyst (KOH), 60°C temperature, 1 h reaction time and stirring speed 1300 rpm were used.

The performance, emission and combustion characteristics of an engine fuelled with crude Mahua oil biodiesel and diesel blends were investigated and compared with that of standard diesel. The experimental results confirm that the BTE, BSFC, exhaust gas temperature is the function of biodiesel blend and load. For similar operating conditions, a particular blend gave better engine performance and reduced emissions compared to other blends in comparison of standard diesel. B30 of Mahua oil biodiesel blend gave the better overall performance among all other blends in comparison of diesel. However, Mahua oil gave 33.75% BTE for B30,

which is less compared to diesel, the increased value of BSFC reduced CO, HC, NO_x and CO₂ emissions with high-value smoke which indicates better combustion of fuel, which can be considered as acceptable results in overall performance with biodiesel without any modification of engine. In combustion characteristics, higher blends showed the earlier start of combustion and for lower blends start of combustion was slightly delayed in comparison of standard diesel. Almost identical trends were to be seen for all the biodiesel blends in heat release rate. The very negligible difference was seen in combustion duration for blends and diesel however under full load condition, blends showed insignificant shorter duration of combustion than diesel. Therefore, Mahua oil biodiesel blends, B30 can be used in unmodified CI engines.

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