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ORIGINAL ARTICLE

Calophyllum inophyllum methyl ester biodiesel blend as an alternate fuel for diesel engine applications

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Abstract Calophyllum inophyllum oil is non-edible in nature could be used as a source for biodiesel esterification in India and it is also available in abundant quantities in places such as Southern east and East Asia and Australia. The present research work examines the suitability of Calophyllum inophyllum as promising feedstock for biodiesel production and its employability in diesel engine operation. The Calophyllum trees are found in abundance in India and can reduce the dependency of petroleum imports to a certain extent. The biodiesel Calophyllum inophyllum Methyl Ester (CIME100) and its blends CIME30 and CIME60 are used in engine testing. The experimental parameters such as brake thermal efficiency, brake specific energy consumption, unburned hydrocarbon, carbon monoxide, and NOx emissions are evaluated with CIME100 biodiesel and the results are compared with conventional fuel. It is observed that the CIME biodiesel resulted in slight decrease in brake thermal efficiency. The hydrocarbon and carbon monoxide emissions are reduced with the use of biodiesel with significant penalty in oxides of nitrogen emissions. In addition, the combustion parameters such as cylinder gas pressure, ignition delay period, and heat release rate of CIME100 are discussed in detailed and compared to conventional diesel fuel under various loading conditions.

1. Introduction

The inadequacy of accessible energy resources because of its expanding utilization has driven us to hunt down dependable roots for making alternative fuels. Also, the need to meet the requirements of stringent emission regulations of the government coupled with the need to overcome fuel crisis in the future has forced us to look for alternative sources of fuel [1–3]. Biodiesels are gaining worldwide acceptance because of the faster depleting petro-diesel fuels. Biodiesels are biodegradable, renewable and more environment friendly than petroleum based fuels. Biodiesel is a renewable and biodegradable fatty acid methyl ester extracted from any kind of vegetable oil and animal fats [4,5]. Nowadays, the usage of edible oil from food crops for the production of biodiesel is limited in countries like India, because of their abundant need for domestic purposes which made researchers to narrow down and sharpen

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their focus of extracting biodiesel from non-edible feedstock. Oil from non-edible resources is gaining overall consideration because they can be discovered easily in numerous parts of the world particularly in wastelands that are not appropriate for cultivating food crops which wipes out rivalry for food crops and are more efficiency and nature friendly and are more economical compared to edible oils [6–8].

Some of the non-edible oil widely used for the process of biodiesel production are Jatropacurcas, Calophyllum inophyllum, Pongaminapinnata, Ricinus Communis and Ceiba Pentantra. Calophyllum inophyllum fruit and seeds shown in Fig. 1 are considered as a suitable feedstock for the production of biodiesel. Some of its advantages over jatrophais that the Calophyllum tree has a high yield of oil of 4560 kg per hectare as compared to oil yield of 1560 per hectare for Jatropha [9–11]. The Calophyllum seed has a very high oil content of 65–75% but Jatropha seed has an oil content of only 55–60%. Fuels produced from non-edible oils are highly recommended than edible oils because it does not have any impact on the demand for food crops. One yet major limitation of Calophyllum inophyllum feedstock is that its rich content of free fatty acids, which should be properly removed during trans-esterification process. The normal trans-esterification process would result in higher viscous nature of the oil which would diminish the quality of the biodiesel that would be yielded. When Rudolf Diesel used biodiesel on engines it did not burn completely due to high viscosity and volatility of vegetable oils and it forms deposits on fuel injectors. Later biodiesel which meets the requirements of ASTM stands is produced which has fuel properties similar to that of petroleum diesel [12,13].

Low volumetric energy capacity, high kinematic viscosity, poor cold-flow properties, inferior oxidation stability and higher NOx emission are some disadvantages of using biodiesel which prevents its widespread usage. However, numerous research works have been carried on the evaluation of performance, combustion and emission characteristic of CI engine fuelled with biodiesel. Monirul et al. compared the performance, emission and combustion parameters of blends Palm, Jatropha and Calophyllum inophyllum biodiesel blends and concluded that Palm biodiesel blend (PB20) operated with maximum efficiency and less emissions [14]. S. Choudhury and Bose experimented with various blends of Jatropha biodiesel and diesel to find its potential to be used as a CI engine fuel [15]. Ankur et al. operated with dual biodiesel blends of palm and Jatropha to find the potential of hybrid biodiesel as an alternative to conventional diesel in the future [16]. Avinash and Atul used Jatropha oil blends in diesel engines and concluded that blends of less than 20% are operable in diesel engines without any modifications [17]. Harish and Avinash studied the combustion characteristics of Jatropha oil blends in a transportation engine and found that the heat release is less and combustion duration is high when vegetable oils are used [18]. Shehata et al. experimented with corn and soya bean fuel blends with a blending ratio of 20% of biodiesel. The tests are done for various engine speed and loads, and injection pressure of 180, 190 and 200 bar and reported that BTE and BSFC showed 15% improvement at an injection pressure of 200 bar from the original pressure of 180 bar [19]. Silitonga et al. produced biodiesel which meets the standards set by American Society of Testing and Materials (ASTM) using a two-step acid-alkali trans-esterification process for three non-edible oils including Calophyllum inophyllum oil with an optimum methyl ester yield of 98.53% which complies with ASTM D6751 and EN14214 standards [20].

Calophyllum inophyllum seed is one of the easily cultivable and widely available feedstock for biodiesel transesterification in developing countries like India. Only very few research works have been carried out in implementing 100% Calophyllum inophyllum methyl ester and blends as alternative fuel for diesel. The literatures have not arrived at systematic investigation for deploying 30%, 60% and 100% Calophyllum inophyllum with diesel in a CI engine. Hence, the present research work aims at focusing on the performance, emission and combustion characteristics of direct injection diesel engine fuelled with various blends of CIME such as 30% CIME, 60% CIME and 100% CIME. The experimental results have been compared with conventional diesel fuel. Certain important parameters such as brake specific energy consumption, brake thermal efficiency, heat release rate, in-cylinder pressure, unburned hydrocarbons, carbon monoxide, carbon dioxide, NOx emissions and smoke density are evaluated.

2. Biodiesel preparation

Most common method used to reduce the viscosity of vegetable oil to produce biodiesel is by trans-esterification. Triglyceride (TAG) is composed of three esters of fatty acid

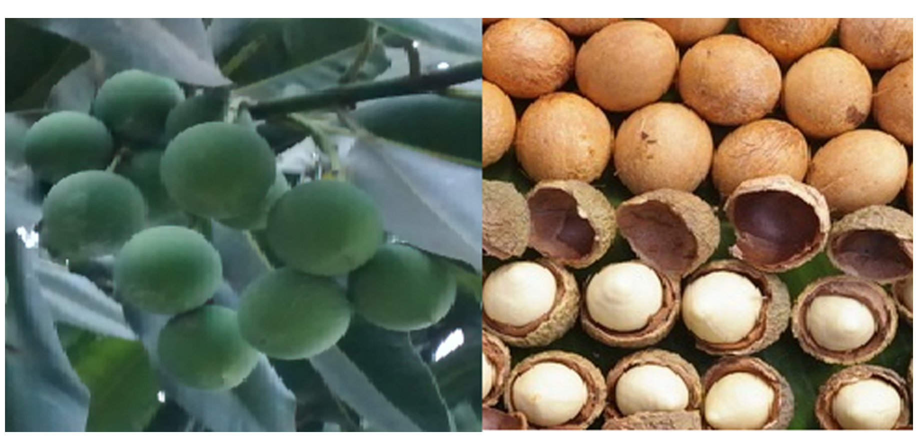

Figure 1 Calophyllum inophyllum fruit in tree and dried seeds.

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chain attached to glycerol backbone. Glycerol part of TAG contributes to the high viscosity of vegetable oil. Free Fatty Acid (FFA) part is 10 times less viscous than vegetable oil. TAG is a type of ester and the reaction that converts TAG into biodiesel is known as trans-esterification. The process of trans-esterification is shown in Fig. 2 for the biodiesel extraction.

It is critical that feedstock used in alkali-catalyzed transesterification should contain free fatty acids (FFA). Fatty acids in the feedstock can significantly affect the ester yield and glyceride conversion in alkali-catalyzed transesterification process. Higher the acidity of oil, lower the yield and conversion rate. If FFA content is more, extra alkali is needed to neutralize the FFA. Also it will cause soap formation.

Stage 1:-Esterification with acid catalyst to produce ester

In this stage FFA is esterified with methanol and acid catalyst to produce ester. Molar ratio of alcohol to oil is one of the main parameters which affects the conversion efficiency, biodiesel yield and production. In addition, it also increases the miscibility and improves the contact between alcohol and tri-glyceride. Moreover, the excess amount of alcohol enhances the biodiesel purity. The optimum conditions for the reactants were found to be 16:1 methanol to oil ratio, 10 ml of H_2SO_4 for 100 ml of oil, reaction temperature of 60 °C, and 45 min of reaction time along with a constant stirring rate on a magnetic stirrer.

Stage 2:-Trans esterification with alkali catalyst

Since FFA was converted to ester in the first step, we use alkali catalyst for trans-esterification process. The optimum conditions for the reactants were found to be 16:1 methanol to oil ratio, 0.5 g concentration of Sodium hydroxide for 100 ml of oil, reaction temperature of 60 °C, 30 min of reaction time along with a constant stirring rate.

Stage 3:-Purification

Purification is done by removing methanol while heating biodiesel at 75 °C for about 30 min to remove trapped methanol and the yield of biodiesel was found to be 85%. The various physical and chemical properties of CIME have been evaluated and compared with diesel which is presented in Table 1.

3. Experimental setup

A four-stroke single cylinder Kirloskar TAF-1 direct injection diesel engine with specification listed in Table 2 is used for the purpose of testing the biodiesel. The engine is connected to a SWINGFIELD electric dynamometer for the application of load which is varied by the controller in the dynamometer as shown in Fig. 3. The air flow rate is calculated by measuring the pressure difference of the U-tube manometer connected

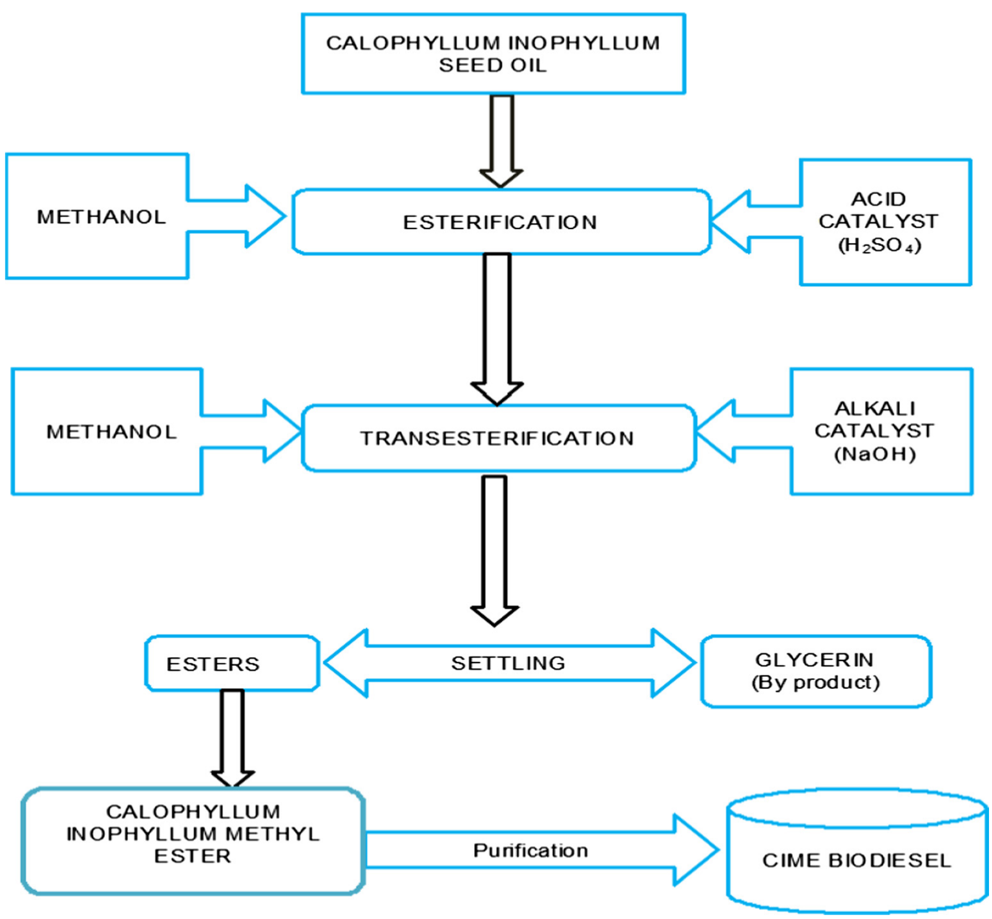

Figure 2 Transesterification process of Calophyllum inophyllum biodiesel.

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Table 1 Physical and chemical properties of fuels [11].

Fuel properties	Units	Diesel	CIME
Acid number	mg of KOH/g	–	0.39
Sulfated ash	wt.%	–	0.001
Methanol content	wt.%	–	0.02
Flash point	°C	53	170
Kinematic viscosity at 40 °C	mm^2/s	2.30	5.4
Density at 15 °C	kg/m^3	824	870
Calorific value	MJ/kg	42.5	37.9
Cetane index	–	39	59.5

to the path of airflow pipe in the engine and the time taken for 10 cc of fuel is also noted using stop watch and weighted fuel tank for calculating fuel flow rate. AVL digas 444 exhaust gas analyzer is used for measuring engine exhaust emission such as HC, CO, CO_2, and NO_X. However, all the engine emissions are estimated in g/kW h as per emission standard procedure for non-road application engines (stationary/genset and others). The AVL DIGAS 444 exhaust gas analyzer is used to measure the CO and CO2 emissions in terms of percentage (%) and HC and NOx emissions as ppm. The measured emissions of CO, HC and NOx are converted into ppm and further converted into g/kW h as per the standard emission testing procedure. The sample conversion of CO emission from ppm into g/kW h is given below. The brake specific emission concentrations of CO is obtained from their measured emission concentrations in ppm as,

$$\mathrm{CO(g/kW\ h)} = \frac{\mathrm{CO(ppm)} * 1e^{-6} * \dot{m}_{exh}\mathrm{(g/h)} * MW_{CO}\mathrm{(g/mol)}}{BP\mathrm{(kW)} * MW_{exh}\mathrm{(g/mol)}}$$

where CO is carbon monoxide, $\dot{m}_{exh}$ is the mass flow rate of exhaust gas (sum of mass flow rate of air and fuel), MW_{CO} is the molecular weight of carbon monoxide and MW_{exh} is the molecular weight of exhaust gas

The Exhaust Gas Temperature (EGT) is interpreted from the ChromelAlumel (K-Type) thermocouples which has a range of 200 °C to +1260 °C. AVL 437C Smoke meter that has a measurement range of 0–10 FSN is used to calculate the amount of smoke in the exhaust in FSN (Filter Smoke Number) which is measured by passing a specific amount of exhaust gas through a white filter paper. A microprocessor is used to evaluate the filter paper blackening which is detected by a photoelectric measuring head. An electro optical sensor is used to detect the TDC position by giving voltage signals which were fed to A/D converter and then send to data acquisition system for recording. The pressure signals are also recorded by the data acquisition system. A KISTLER transducer that has a sensitivity of about 79.5 pC/bar is used to measure the in cylinder pressure and is mounted flush on the cylinder head for avoiding passaging effects. The in-cylinder pressure of the engine was measured using an AVL Pressure transducer (GH14D/AH01). A high-speed computer based Digital Data Acquisition System is used for measuring the signals of in-cylinder pressure and TDC position. A 12-bit analog to digital converter is used to convert analog signals to digital form. The A-D converter had external and internal triggering facility with sixteen single ended channels. The combustion parameters such as peak pressure and maximum rate of pressure rise were obtained by processing the signals received by recording the data obtained from of 100 consecutive cycles. The uncertainty of engine parameters is estimated based on square root method and the results are presented in Table 3.

Table 2 Specifications of the engine used for testing.

Parameters	Specification
Ignition	Compression ignition
Stroke	Four stroke
Displaced volume	600 cc
Stroke	110 mm
Bore	87.5 mm
Connecting rod length	255 mm
Compression ratio	17.5:1
Speed	1500 rpm
Rated power	4.4 kW

4. Results and discussion

The engine is started and allowed to warm-up for some time. The experiments are carried out at injection timings of 23° CA bTDC and injection pressure of 200 bar. The performance, combustion and emission data are obtained at various loads of 0%, 25%, 50%, 75% and 100%.

4.1. Brake thermal efficiency

Performance parameters such as brake thermal efficiency, brake specific energy consumption and brake specific fuel consumptions are compared for the different blends of biodiesel. Brake thermal efficiency is the evaluation of an engine's capacity to convert the heat energy of a fuel into mechanical energy. The brake thermal efficiency of CIME biodiesel at different blends is presented in Fig. 4. The brake thermal efficiency of CI biodiesel is less than that of diesel because of the high density, high viscosity and less calorific value of biodiesel. The brake thermal efficiency of biodiesel decreases with increase in the percentage of biodiesel in the biodiesel-diesel blends because of the decrease in the calorific value with increasing concentration of biodiesel in the blends. This is due to the uneven combustion as a result of decrease in atomization and vaporization of blends due to increased viscosity and density [4].

4.2. Brake specific fuel consumption

The low calorific value of CIME biodiesel and the changes in combustion characteristics leads to a slightly increased BSFC than that of diesel fuel. More fuel needs to be supplied to the engine to maintain the same input energy. The amount of CIME biodiesel sprayed by the injector is more than that of diesel for the same volume on account of its high density. Fig. 5 shows the variation of BSFC for various percentages of biodiesel-diesel blends. BSFC of biodiesel blends increases with increase in the percentage of biodiesel in the biodiesel-diesel blend because of the decrease in calorific value of biodiesel with increase in the percentage of biodiesel. The reduced calorific value results in increased supply of fuel to the engine to produce the same amount of brake power which results in increased fuel consumption.

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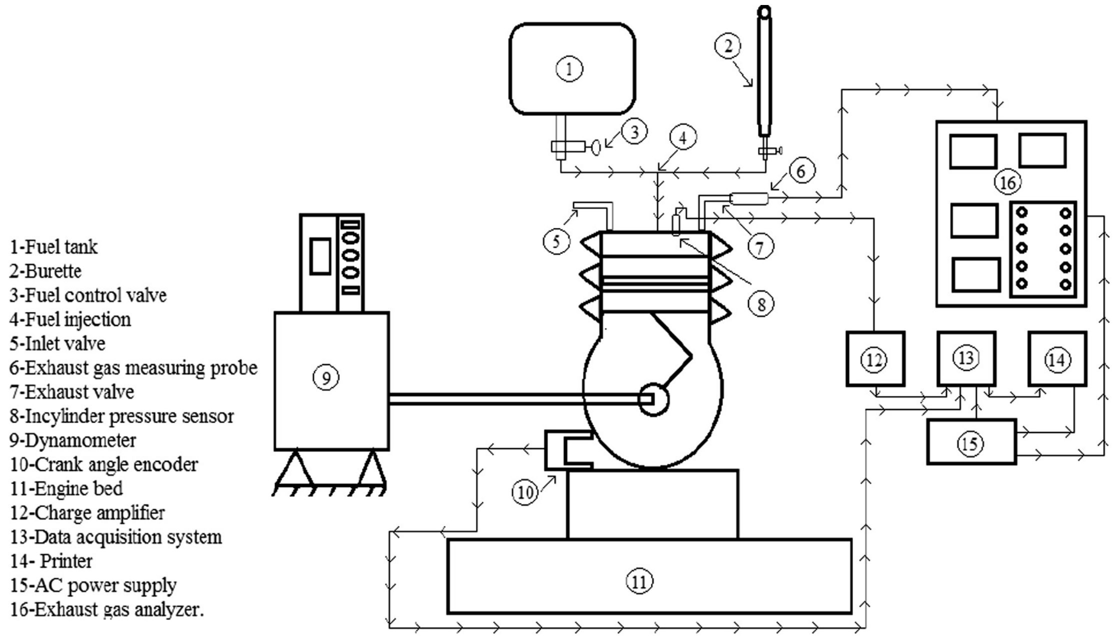

Figure 3 Experiment test setup used for testing the biodiesel.

Table 3 Uncertainty of computed parameters.

Parameter	Uncertainty (%)
Air flow rate, kg/s	0.6
Brake power, kW	0.7
Brake thermal efficiency, %	0.8
Brake specific fuel consumption, kg/kW h	1.3
Carbon monoxide, %	0.2
Unburned hydrocarbons, ppm	0.4
Oxides of nitrogen, ppm	0.3
Smoke opacity	0.3
Cylinder pressure, bar	1.0
Exhaust gas temperature, °C	0.6

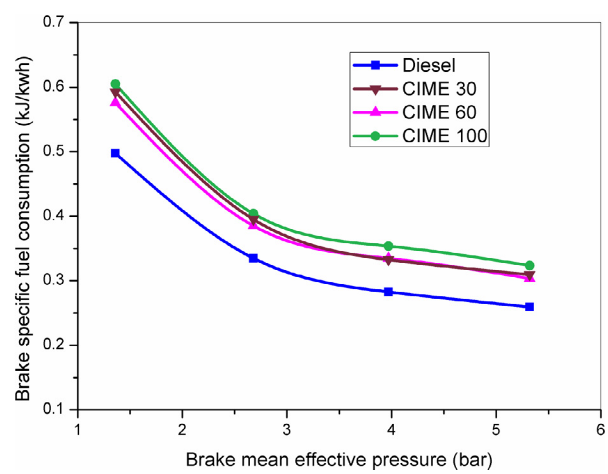

Figure 5 Brake specific fuel consumption vs BMEP.

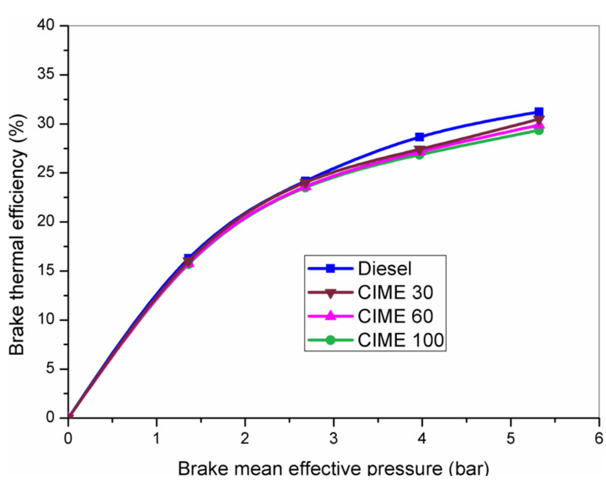

Figure 4 Brake thermal efficiency vs Brake mean effective pressure.

4.3. Brake specific energy consumption

BSEC is an indicative of efficiency of obtaining energy from the fuel to produce unit power. BSEC is the calorific value times BSFC and it is used to compare fuels with different calorific values. The specific energy consumption is a more exact measure than specific fuel consumption for comparing fuels with different calorific values. Fig. 6 depicts the variation in brake specific energy consumption for different injection timings. The BSEC of biodiesel is higher than that of diesel fuel. The low calorific value, high viscosity and boiling point may be a possible reason for this increased brake specific energy consumption. The brake specific energy consumption is a more exact parameter to compare fuels with different calorific values. The increase in the percentage of blends in the biodiesel leads to increase in the BSEC because of the

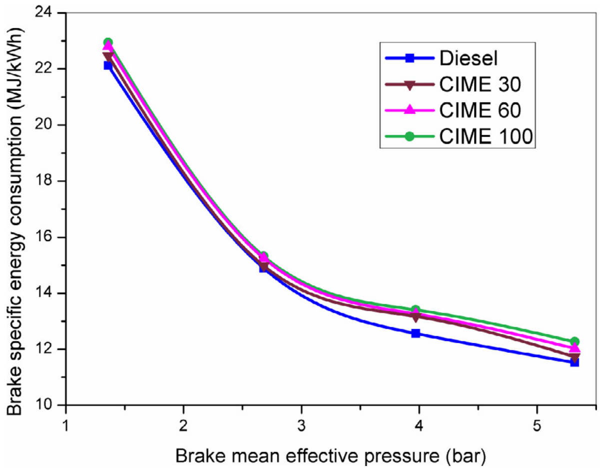

Figure 6 Brake specific energy consumption vs BMEP.

decrease in the calorific value of the fuel with increase in the blend percentage.

4.4. Unburned hydrocarbon emission

Various emissions such as HC, CO, NOx and smoke values are obtained for the diesel and CIME blends. The incomplete combustion of fuel is one of the main reasons behind the occurrence of hydrocarbon emissions. The UBHC emissions are lower for biodiesel because of better combustion as a result of high cetane index and increased gas temperature of the biodiesel which leads to shorter ignition delay. The UBHC emission of biodiesel decreases with increase in percentage of CIME in diesel blends is shown in Fig. 7. This is because of complete combustion of the fuel due to the presence of the increased molecular oxygen content and high cetane content of the biodiesel.

4.5. Carbon monoxide emission

Carbon monoxide is a highly toxic gas and the main cause for its formation is the partial oxidation of compounds containing carbon. CO plays a major role in formation of ground level ozone. The variation in CO emissions is depicted graphically in Fig. 8. The CO emissions of CIME biodiesel are less than those of diesel due to the presence of higher oxygen concentration in the biodiesel which promotes complete oxidation of CO [11]. The shorter ignition delay because of the high temperature and cylinder pressure and the inferior premixed combustion phase with respect to retarded injection timing leads to a slight increase in CO emissions. Lower temperature coupled with insufficient air supply during combustion is a major reason for the formation of CO emissions. The CO emission follows the same trend as the HC emission. The CO emission decreases with increase in the percentage of the biodiesel in the blends. This is because of the increase in the oxygen concentration of the biodiesel with increase in the percentage of biodiesel in the blends which aids complete combustion.

4.6. Oxides of nitrogen emission

The variation in NO_x emission is depicted in Fig. 9. The formation of NOx is favored in the presence of high oxygen content

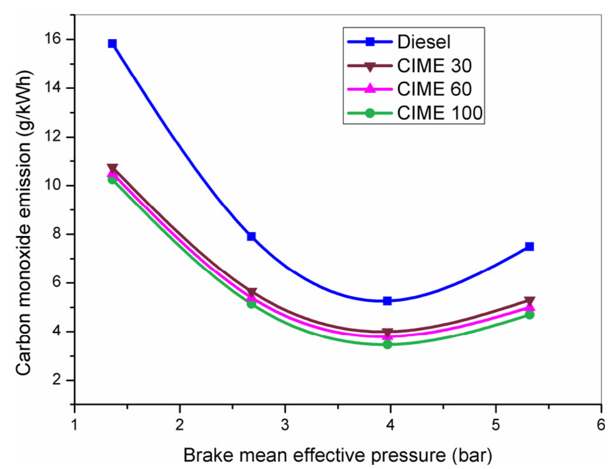

Figure 8 Comparison of carbon monoxide emission for various blends.

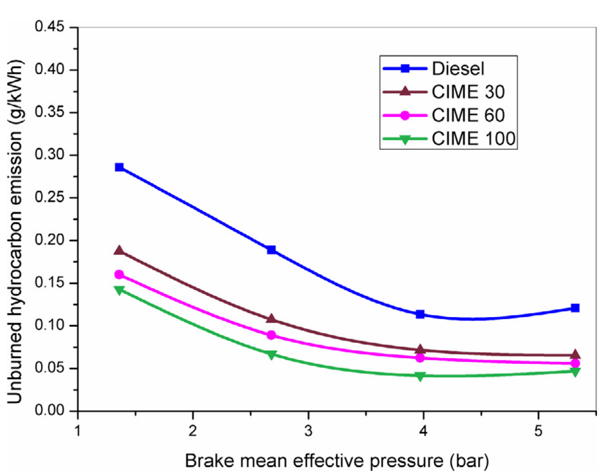

Figure 7 Comparison of unburned hydrocarbon emission for various blends.

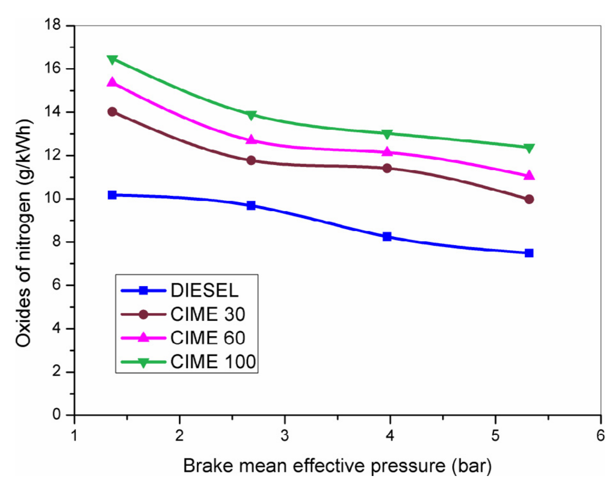

Figure 9 Comparison of nitrous oxide emission for various blends.

and high temperature. The NOx emission increases with the increase in the percentage of biodiesel in the blends which is due to the corresponding increase in oxygen content of the fuel. The high density of biodiesel also plays a role in the formation of NOx emissions [7]. The NOx emissions of CIME biodiesel are higher than those of diesel fuel because high combustion temperature as a result of better combustion due to the presence of high molecular oxygen in the biodiesel. There exists a slow burning rate and slow rise in pressure and temperature as a result of shorter mixing time with shorter ignition delay.

4.7. Smoke emission

The smoke emitted by biodiesel was comparatively lower than diesel expect at higher load due to higher oxygen content in biodiesel and higher BTE which means complete conversion of large sized carbon atoms into CO due to complete combustion resulting in reduced smoke emission. Fig. 10 portrays the variation of smoke for different concentrations of biodiesel blends. The smoke emission decreases with increase in the percentage of biodiesel in the biodiesel-diesel blend except for CIME100. The smoke emission of diesel is higher than that of biodiesel and its blends with diesel. The reduction in smoke opacity of biodiesel is due to the presence of aromatic compounds in the biodiesel and a lower carbon to hydrogen ratio compared to conventional diesel fuel.

4.8. In-cylinder pressure

Combustion parameters such as in-cylinder pressure, ignition delay and heat release rate are discussed in the following section. The smoother transfer of gas pressure forces to the crankshaft and smooth functioning of the engines are determined by the rate of pressure rise. The cylinder pressure of diesel is higher than that of biodiesel as shown in Fig. 11 and the cylinder pressure decreases with increase in the percentage of biodiesel in the biodiesel-diesel blend. The in-cylinder gas pressure depends on the calorific value of the fuel. In general the in-cylinder gas pressure for biodiesel would be lower than conventional diesel. As presented in Table 2, the calorific value of Calophyllum inophyllum methyl ester was lower than conventional diesel. These results were similar to the most of the research studies [21].

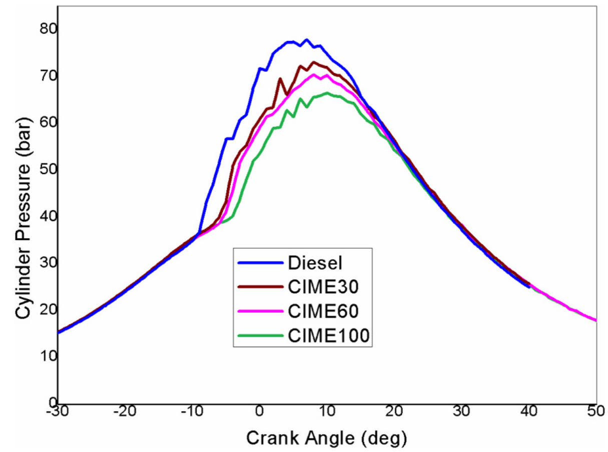

Figure 11 Comparison of in-cylinder pressure at full load condition.

4.9. Heat release rate

In addition, the heat release rate is calculated from the in-cylinder pressure as per the first law of thermodynamics. The peak heat release rate of CIME biodiesel is less than that of diesel fuel. This lower heat release rate is mainly because of the shorter ignition delay of biodiesel because of the higher cetane number [12]. Furthermore, the high viscosity, surface tension and poor spray atomization also play a role in lowering the heat release rate of biodiesel. Fig. 12 shows the variation of heat release rate with crank angle at 100% engine load. The heat release rate is an indicative of details of stages of combustion and events. The first and the second peak in the Fig. 12 denotes the pre-mixed combustion phase and mixed combustion phase [7]. The heat release rate of CIME 100 is very less and it increases with increase in percentage of diesel in the biodiesel-diesel blend with diesel recording the highest heat release rate.

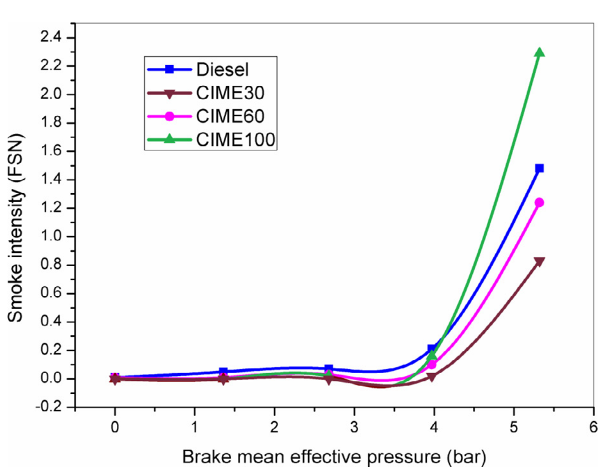

Figure 10 Variation of smoke for different blends of biodiesel.

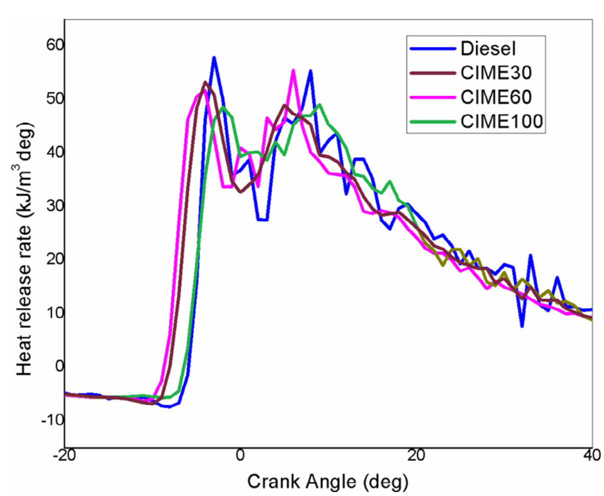

Figure 12 Comparison of heat release rate at full load condition.

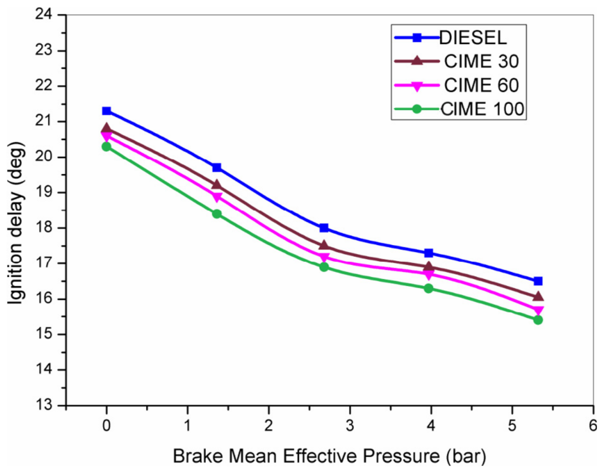

Figure 13 Variation in ignition delay for different blends.

4.10. Ignition delay

The ignition delay is defined as the difference in degree between the start of injection and start of combustion. The ignition delay of CIME biodiesel is less than that of diesel because of its high cetane number as shown in Fig. 13. There is a reduction in ignition delay with increase in load which is due to reduced exhaust gas dilution and increased in cylinder pressure and temperature at higher loads. The ignition delay decreased with increase in percentage of biodiesel in the blends because of the decrease in cetane number.

5. Conclusions

Calophyllum inophyllum methyl ester has been obtained from the feedstock and the obtained biodiesel is blended with diesel in the proportion of CIME30, CIME60 and CIME100 for engine testing. The performance, emission and combustion characteristics of different blends of CIME biodiesel are compared to those of the fossil fuel diesel and the results are summarized as follows:

1. As the property of CIME and diesel fuel is similar, it can be concluded that the blends of CIME can be used without any modifications in the diesel engine.
2. The BTE is higher for diesel compared to CIME biodiesel and it decreases with increase in percentage of biodiesel in the blends.
3. BSFC and BSEC increase with increase in percentage of CIME biodiesel in the blends.
4. The increase in percentage of CIME biodiesel in the blends leads to reduction in HC, CO and smoke emissions but at the cost of NOx emissions.
5. Combustion parameters such as in-cylinder pressure, ignition delay and heat release rate are obtained for CIME fuel and the results are acceptable in the range as compared to the diesel fuel.

Thus, it is found that CIME can serve as a suitable replacement for conventional diesel fuel. It is more environment friendly in nature. Further studies related various blends of biodiesel with diesel and various compression ratios can be a deciding factor to find the optimum conditions to utilize the biodiesel in a better way

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