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Combustion analysis of Jatropha, Karanja and Polanga based biodiesel as fuel in a diesel engine

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ABSTRACT

Non-edible filtered Jatropha (*Jatropha curcas*), Karanja (*Pongamia pinnata*) and Polanga *(Calophyllum inophyllum*) oil based mono esters (biodiesel) produced and blended with diesel were tested for their use as substitute fuels of diesel engines. The major objective of the present investigations was to experimentally access the practical applications of biodiesel in a single cylinder diesel engine used in generating sets and the agricultural applications in India. Diesel; neat biodiesel from Jatropha, Karanja and Polanga; and their blends (20 and 50 by v%) were used for conducting combustion tests at varying loads (0, 50 and 100%). The engine combustion parameters such as peak pressure, time of occurrence of peak pressure, heat release rate and ignition delay were computed. Combustion analysis revealed that neat Polanga biodiesel that results in maximum peak cylinder pressure was the optimum fuel blend as far as the peak cylinder pressure was concerned. The ignition delays were consistently shorter for neat Jatropha biodiesel, varying between 5.9° and 4.2° crank angles lower than diesel with the difference increasing with the load. Similarly, ignition delays were shorter for neat Karanja and Polanga biodiesel when compared with diesel.

1. Introduction

The concept of using biofuels in diesel engines was originated from the demonstration of the first diesel engine by the inventor of diesel engine "*Rudolf Diesel*" at the World Exhibition in Paris in 1900 by using peanut oil as a fuel. However, due to abundant supply of petro-diesel, R&D activities on vegetable oil were not seriously pursued. It received attention only recently when it was realized that petroleum fuels were dwindling fast, and environment-friendly renewable substitutes must be identified [1]. In the recent years, serious efforts have been made by several researchers to use different sources of energy as fuel in existing diesel engines. The use of straight vegetable oils is restricted by some unfavorable physical properties, particularly their viscosity. Due to higher viscosity, the straight vegetable oil causes poor fuel atomization, incomplete combustion and carbon deposition on the injector and valve seats resulting in serious engine fouling. It has been reported that when direct injection engines are run with neat vegetable oil as fuel, injectors get choked up after few hours and lead to poor fuel atomization, less efficient combustion and dilution of lubricating oil by partially burnt vegetable oil [2]. One possible method to overcome the problem of higher viscosity is blending of vegetable oil with diesel in proper proportion, and the other method is transesterification of oils to produce biodiesel.

It was [3] reported that the transesterification process has been proven worldwide as an effective means of biodiesel production and viscosity reduction of vegetable oil. Temperatures, catalyst type, concentration ratio of alcohol to fuel and stirring speed rate have been observed to influence the transesterification process to a greater extent. A brief study was conducted [4] on the use of biodiesel from coconut oil (50/50 blend), "B50" in motor coaches. This study revealed that it is a viable and a practical alternative fuel for older in-service engines. Particulate matter was almost negligible with the use of this fuel. Operators reported that the test vehicles had no noticeable drivability downsides. On the other hand, it was observed that the vehicles had some improved power performance while operating under city traffic conditions.

It was [5] also found that no significant engine problems were reported in tests with urban bus fleets running on B20. Fuel economy was comparable with diesel fuel and the fuel consumption of biodiesel blend being only 2–5% higher than that of conventional diesel. Ester blends have been reported to be stable, and did not separate at room temperature over a period of three months. One limitation to the use of biodiesel is its tendency to crystallize at low temperatures below 0° C. Such crystals can plug fuel lines and filters, causing problems in fuel pumping and engine operation. Wagner et al. [6] conducted 200 h engine tests with soybean oil ester fuel on John Deere (4239T Model) engine. It was reported that the engine performance with methyl, ethyl and butyl esters was nearly the same as that with diesel fuel. There was no difference in thermal efficiency resulting from the use of the various

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fuels to power the engine. The esters showed a slight power loss and an increased fuel consumption, which was attributed to the lower gross heating values. Engine wear was normal. There was, however, an increased carbon deposition on the pistons with the methyl and butyl esters. Emissions of oxides of nitrogen were significantly higher for the esters. They concluded that the esters could be used on a short-term basis, and that further testing to be done for determining long-term ester fuel effects.

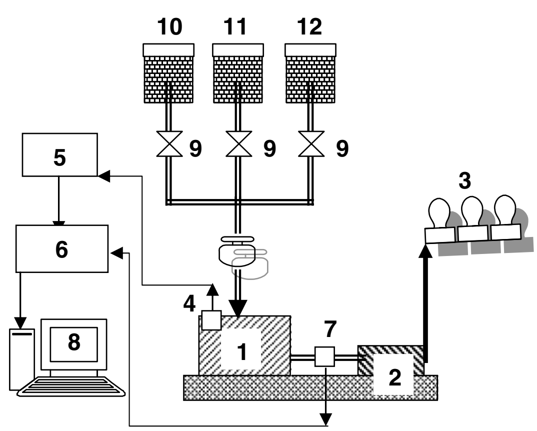
Experiences with diesel indicate that an increase in fuel viscosity typically results in an increase in spray penetration and a decrease in spray angle [7]. A study by Ryan and Bagby found that the vegetable oils (peanut, sunflower, cottonseed and soybean oils) exhibit characteristics opposite to those expected in most other fossil fuels [8]. They observed a lower penetration and a larger spray angle despite their higher viscosities. By using sampling collection method, they concluded that chemical reaction plays a significant role in increasing the atomization process of vegetable oil during the injection process, leading to shorter ignition delay. Apart from the problem of diesel scarcity and higher fuel costs, there is the growing menace of vehicular pollution. To compensate for the shortages of diesel fuel, the adaptation of a selected alternative fuel to suit the diesel engine is considered more economically attractive in the short-term than engine modification to suit the fuel. For this purpose, an alternative liquid fuel that will blend readily with diesel fuel is required. Such an alternative fuel should lend itself to local production in adequate and economic quantities. There should be little modifications to the existing engine. Engine performance and durability should not be affected significantly. Hence, there is a greater motivation to utilize biodiesel as a supplementary fuel for diesel in compression ignition engines. It is extremely relevant in this context to assess the combustion characteristics of biodiesel fueled engine. The specific objective of this study is to analyze the combustion characteristics of biodiesel from Jatropha, Karanja and Polanga oil and their blends with diesel; and to investigate its suitability as a fuel in diesel engines.

2. Biodiesel production for combustion study

Biodiesel from Jatropha, Karanja and Polanga was produced in a laboratory-scale setup, which consists of heating mantle, reaction flask and mechanical stirrer. The working capacity of reaction flask is 5 l. It consists of three necks for stirrer, condenser and an inlet of reactant as well as for placing the thermocouple to observe the reaction temperature. The flask has a stopcock at the bottom for collection of the final product. Process parameters such as mode of reaction condition, molar ratio of alcohol to oil, type of alcohol, type and amount of catalysts, reaction time and temperature, and purity of reactants were optimized. A two-step ‘acid–base’ process; acid-pretreatment followed by main base-transesterification reaction; using methanol as reagent and H_2SO_4 and KOH as catalysts for acid and base reactions, respectively, was followed to produce biodiesel from Polanga oil. Single stage base-catalyzed transesterification was adopted for Jatropha and Karanja oil. The physico-chemical properties of the Jatropha, Karanja and Polanga oil based biodiesel (B100) and their various blends with diesel were evaluated as per the ASTM standards. The fuel properties data of Jatropha, Karanja and Polanga oil methyl esters and their different blends with diesel are summarized in a tabular form as shown in Table 1.

3. Experimental technology for combustion study

The investigations on the combustion characteristics were conducted on a small size 6 kW air-cooled single cylinder four-stroke diesel engine (Kirloskar Oil Engines Ltd., India) fueled with pre-



1. Single cylinder 4-stroke diesel engine, 6 kW	7. Magnetic pickup (Encoder)
2. Alternator	8. Data acquisition computer
3. AC shunt lamp load	9. Control valve
4. Pressure transducer	10. Fuel tank for neat diesel
5. Charge amplifier	11. Fuel tank for blends of diesel and biodiesel
6. Cathode Ray Oscilloscope (CRO)	12. Fuel tank for neat biodiesel

Fig. 1. Schematic diagram of test setup for combustion study.

pared test fuels. The experimental setup (Fig. 1) equipped with experimental technologies to measure the combustion parameters such as peak pressure, time of occurrence of peak pressure, heat release rate and ignition delay was computed.

The experimental test rig consists of the engine coupled with alternator and various measuring systems. The engine (Table 4) was provided with a suitable arrangement, which permitted a wide variation of controlling parameters. The alternator was used for loading the engine. When the load bank was switched on, it consumed the electricity generated by alternator. The engine/alternator was loaded up to 100% load using these load banks. A variac was also connected in the load bank, so that load was controlled precisely by controlling the voltage in one of the coils of the load bank. Voltmeter and ammeter were used to measure the voltage and the current consumed by the load in the load bank. The product of voltage and current gives the actual load on engine–alternator system. The speed was also checked with an infrared-type digital tachometer.

Combustion diagnosis was carried out by means of a Kistler make quartz piezoelectric pressure transducer (Model - 701A) fitted on the cylinder head and an electro magnetic pickup (Model – 3010AMa) fixed on the output shaft of the engine. The pressure and crank angle signals were fed to a console for onward transmission to a Pentium personal computer through charge amplifier (Model - 3059 HICF) and cathode ray oscilloscope (CRO). These instruments were used for measuring the cylinder gas pressure. A two-channel HP 54645A/D oscilloscope digitizing system was used for monitoring different signals such as TDC, crank angle signals for calculation of injection duration and setting the start of injection. It was also used for monitoring cylinder versus pressure crank angle diagram signals from piezoelectric pressure transducer.

The pressure transducer was mounted on the cylinder head in the standard position. Piezoelectric pressure transducer has the advantage of good frequency response and linear operating range. A continuous circulation of water was maintained for cooling the transducer by using a small water pump to maintain the required temperature. Distilled water was circulated through the transducer to avoid corrosion of water passage. The charge amplifier and pressure transducer were calibrated by using a dead weight pressure gauge tester. The charge amplifier was used to amplify the output of pressure transducer into the desired voltage level, so that the output of the charge amplifier could be used for recording or display on the oscilloscope screen.

Combustion parameters such as peak pressure, time of occurrence of peak pressure, heat release rate and ignition delay were evaluated. All the tests were conducted by starting the engine with diesel fuel only. After the engine was warmed up, it was then switched to biodiesel and their blends. At the end of the test, the fuel was switched back to diesel and the engine was kept running for a while before shut-down to flush out the biodiesel from the fuel line and the injection system. A total of ten fuels were tested during the investigation keeping all the independent variables same (Table 2). The experiments were carried out by using diesel, Jatropha biodiesel (JB), Karanja biodiesel (KB), Polanga biodiesel (PB) and their various blends with diesel at different load conditions on the engine. The objective of such a study was to analyze and compare the suitability of each of these fuels for engine application from the point of view of normal combustion systems.

Table 2
Test matrix for combustion study on single cylinder diesel engine.

Sl.no.	Variables	Types of variables studied	Details of variables studied
1	Independent	1. Fuels used	Diesel, JB, KB, PB
		(a) Diesel	100% neat
		(b) Jatropha oil methyl ester (JB)–Diesel blends (v/v) (%)	JB20, JB50, JB100
		(c) Karanja oil methyl ester (KB)– iesel blends (v/v) (%)	KB20, KB50, KB100
		(d) Polanga oil methyl ester (PB)–Diesel blends (v/v) (%)	PB20, PB50, PB100
		2. Load, (%)	0 , 50, 100
2	Dependent	1. Brake mean effective pressure (BMEP)	At 0% , 50%, 100% load
		2. Heat release rate (HRR)	At 0% , 50%, 100% load
		3. Ignition delay	At 0% , 50%, 100% load

4. Theoretical consideration

The combustion characteristics and heat release rate based on the data of the recorded in-cylinder pressure were analyzed at the same load. The heat release rate $\frac{dQ_t}{d\theta}$ can be calculated by the following formula:

$$\frac{dQ_t}{d\theta} = \frac{\gamma}{\gamma - 1}P\frac{dV}{d\theta} + \frac{1}{\gamma - 1}V\frac{dP}{d\theta} + \frac{dQ_{ht}}{d\theta}$$

where $\gamma = \frac{C_p}{C_v}$ (for diesel, its value is from 1.3 to 1.35), $\frac{dQ_{ht}}{d\theta}$ = Heat transfer, Joule/Degree crank angle, P = Instantaneous cylinder pressure, (Pa), V = Instantaneous cylinder volume, (m^3).

Large surface area is exposed to gases in the later part of the combustion and hence for heat transfer. Therefore, the heat-transfer rate must be estimated accurately enough, while obtaining the heat release rate during this period, experimentally. Hohenberg's correlation [9] for the instantaneous heat transfer considers truly the conditions present in a DI diesel engine. This correlation is based on extensive experiments done on a DI diesel engine. The instantaneous heat transfer across the walls for the engine was estimated using the following equation:

$$h_c = \frac{130 p_c^{0.8}(v_p + 1.4)^{0.8}}{V^{0.06}.T_g^{0.4}}$$

Table 1
Properties of biodiesel from Jatropha (JB), Karanja (KB), Polanga (PB), Diesel and their blends.

S.no.	Fuel blend	Density (kg/m^3)	CV (kJ/kg)	Viscosity at 40 °C (cSt)	Flash point (°C)	Cloud point (°C)	Pour point (°C)
1	Diesel	850	44000	2.87	76	6.5	3.1
2	JB20	852	43759.5	3.02	88	6.9	3.3
3	JB50	857	43323	3.59	113	7.3	3.4
4	JB100	873	42673	4.23	148	10.2	4.2
5	KB20	851	43690	3.04	96	8.9	3.1
6	KB50	856	43307	3.62	106	11.2	4.2
7	KB100	883	42133	4.37	163	14.6	5.1
8	PB20	852	43109	2.98	86	7.8	2.9
9	PB50	857	42542	3.42	93	8.7	2.9
10	PB100	869	41397	3.99	140	13.2	4.3
Testing procedure		ASTM D4052	ASTM D240	ASTM D445	ASTM D93	ASTM D2500	ASTM D97

where h_c = Heat-transfer coefficient, W/m^2.K, υ_p = mean piston velocity, (m/s), V = instantaneous cylinder volume, (m^3), T_g = cylinder charge temperature, (K), P_c = instantaneous cylinder pressure, (bar).

The cyclic-averaged heat-transfer coefficient for individual surfaces can be used in the network of heat resistances to iteratively obtain different surface temperatures of the combustion chamber enabling precise estimation of the instantaneous heat transfer [10].

$$\frac{dQ_{ht}}{d\theta} = h_c A_g (T_g - T_w) \left\langle \frac{1}{6n} \right\rangle$$

where A_g = instantaneous surface area, (m^2), T_w = wall temperature, (K).

The ignition delay is the time interval from the start of nozzle valve lift to the start of rapid pressure rise. The rapid combustion duration is the time interval from the start of rapid pressure rising to the end of rapid pressure rise. The total combustion duration is the time interval from the start of heat release to the end of heat release. The in-cylinder pressures of the diesel engine fueled with diesel–biodiesel fuel at the same operating conditions are discussed under Section 5.2.

5. Results and discussion

5.1. Characterization of biodiesel from Jatropha, Karanja and Polanga oil

The fuel properties of JB, KB, PB and their blends in comparison with those of diesel are shown in Table 1. The experimental procedures and techniques adopted for the analysis of fuel properties are also given in Table 1. The properties of biodiesel and their blends are compared with those of ASTM biodiesel standards. Most of the fuel properties of JB, KB, PB and their blends are comparable to those of diesel. The present results obtained show that the transesterification process improved the fuel properties of the oil with respect to density (kg/m^3), calorific value (kJ/kg), viscosity (cSt), flash point (°C), cloud point (°C) and pour point (°C). The comparison of these properties with diesel shows that the methyl esters of Jatropha, Karanja and Polanga oil have relatively closer fuel property values to that of diesel (HSD). Hence, no hardware modifications are required for handling these fuels (biodiesel and their blends) in the existing engine.

The calorific values of all the biodiesel and their blends are lower than that of diesel because of their oxygen content [11–15]. The presence of oxygen in the biodiesel helps for complete combustion of fuel in the engine. The flash point of all the biodiesel and their blends is lowered by transesterification, but it is still higher than that of diesel. Addition of a small quantity of biodiesel with diesel increases the flash point of diesel. Hence, it is safer to store biodiesel–diesel blends as compared to diesel alone. It is observed that the typical combustion characteristics of Jatropha (JB), Karanja (KB) and Polanga biodiesel (PB) are in the close range of the requirement of the engine.

5.2. Combustion analysis

The significant features related to combustion aspects are summarized in Fig. 2 through Fig. 4. The peak pressure achieved using diesel, Jatropha, Karanja, Polanga biodiesel and their blends at full load condition is shown in Fig. 2. The heat release rate at selected operating points of different diesel–biodiesel blend fuels and neat diesel operation are also shown in Fig. 3. The peak pressure, heat release rate at no load and half load are also analyzed, which gives very significant information on the ignition delay in case of biodiesel, diesel and their blends.

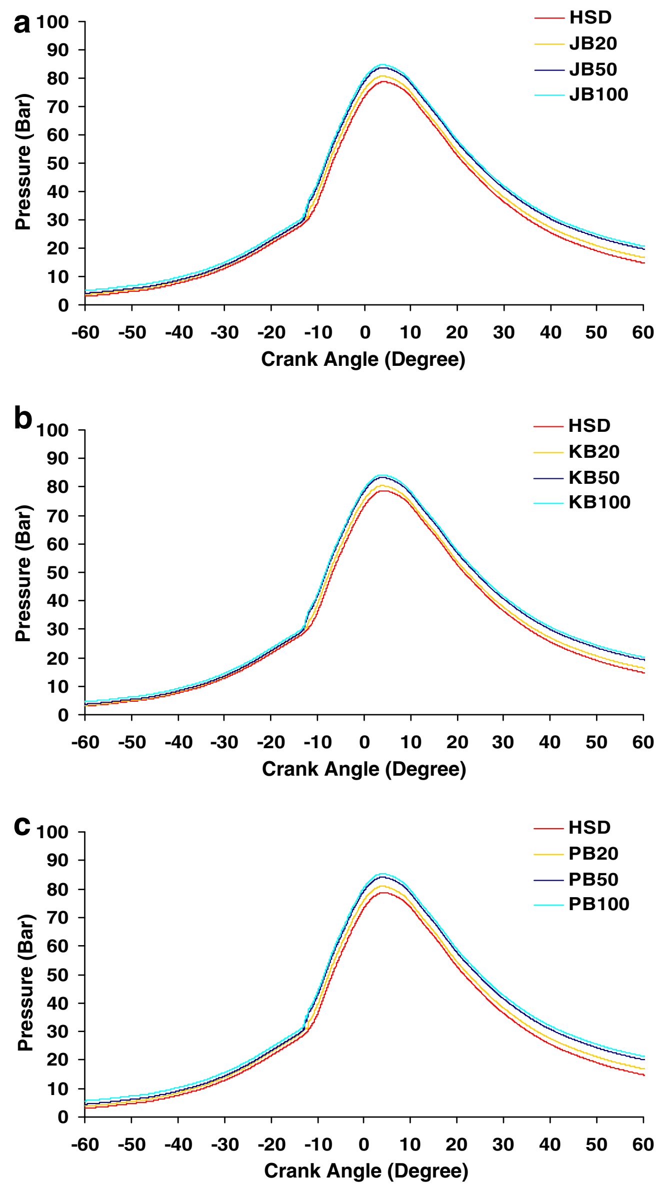


Fig. 2. (a) Pressure vs. crank angle for diesel, Jatropha biodiesel and blends at full load. (b) Pressure vs. crank angle for diesel, Karanja biodiesel and blends at full load. (c) Pressure vs. crank angle for diesel, Polanga biodiesel and blends at full load.

5.2.1. Effect of blends on cylinder pressure

It can be seen from Fig. 2a–c that Polanga biodiesel (PB100) had an 8.5% higher peak pressure than that of neat diesel followed by JB100 (7.6%) and KB100 (6.9%). The same trend is observed during the entire range of engine operation at no load and half load conditions for all the test fuels. It is clear from Fig. 2 and Table 3 that the peak pressure for JB100, JB50, JB20, KB100, KB50, KB20, PB100, PB50 and PB20 is 84.7 bar occurring at 4.8° CA after TDC, 83.71 bar occurring at 5° CA after TDC, 80.7 bar occurring at 5.3° CA after TDC, 84.2 bar occurring at 4.9° CA after TDC, 83.3 bar occurring at 5.2° CA after TDC, 80.4 bar occurring at 5.3° CA after TDC, 85.31 bar occurring at 5° CA after TDC, 84.1 bar occurring at 5.1° CA after TDC and 80.9 bar occurring at 5.2° CA after TDC, respectively, while in the case the peak pressure is 78.7 bar occurring at 5.8° CA after TDC. Therefore, the peak pressure for JB100, JB50, JB20, KB100, KB50, KB20, PB100, PB50 and PB20 is 6 bar, 4.09 bar, 2 bar, 5.5 bar, 4.6 bar, 1.7 bar, 6.61 bar, 5.4 bar and 2.2 bar higher than that of diesel, respectively.

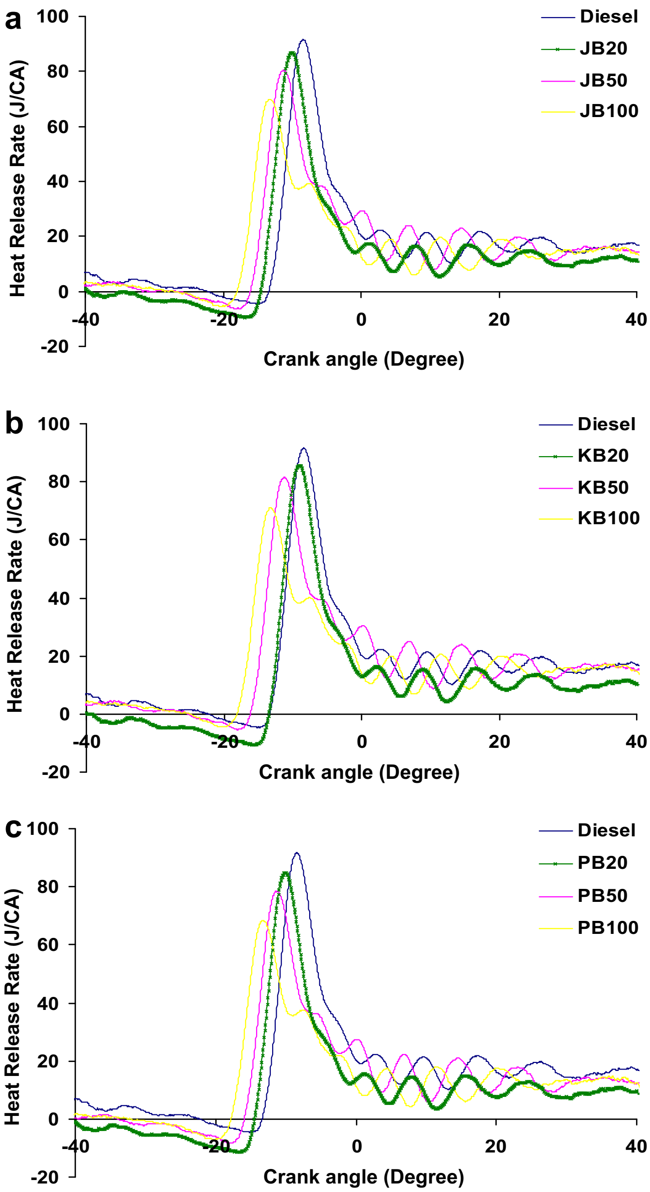


Fig. 3. (a) Heat release rate for diesel, Jatropha biodiesel and blends at full load. (b) Heat release rate for diesel, Karanja biodiesel and blends at full load. (c) Heat release rate for diesel, Polanga biodiesel and blends at full load.

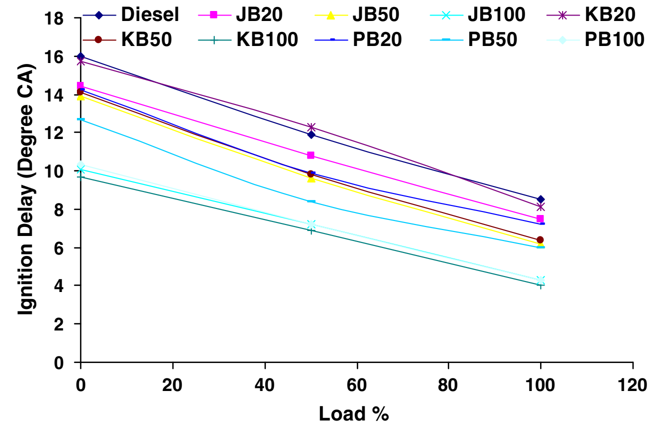


Fig. 4. Effect of load on the ignition delay for diesel, biodiesel and their blends.

Table 3
Combustion parameters of test fuels on diesel engine at peak load.

Fuel and parameters	Start of injection (°) BTDC	Start of combustion (°) BTDC	Ignition delay (°)	Peak pressure (Bar)	Peak HRR (Joule/CA)
Diesel	23	14.5	8.5	78.7	90.96
JB20	23	15.5	7.5	80.7	86.79
JB50	23	16.8	6.2	83.71	80.52
JB100	23	18.7	4.3	84.7	69.97
KB20	23	14.9	8.1	80.4	85.49
KB50	23	16.6	6.4	83.3	81.52
KB100	23	19	4	84.2	70.93
PB20	23	15.8	7.2	80.9	84.8
PB50	23	17	6	84.1	78.56
PB100	23	18.7	4.3	85.31	68.37

The early peaking characteristics warrant careful attention to ensure that, while running with biodiesel and their blends, the peak pressure takes place definitely after TDC for safe and efficient operation. Otherwise, a peak pressure occurring very close to TDC or before that causes severe engine knock, and thus affects engine durability. It is concluded from this discussion, PB100 which gives maximum peak cylinder pressure (6.61 bars higher than that of diesel) is the optimum fuel blends as far as the peak cylinder pressure is concerned. However, it is important to study the instantaneous work done by the piston, and it may give the most accurate analysis to find out the optimum fuel blend.

5.2.2. Effect of blends on heat release rate

Fig. 3a–c shows heat release rate indicating that the ignition delay for biodiesel and their blends was shorter than that for diesel. It can also be seen from the Table 3 that the maximum heat release rate of biodiesel and their blends is lower than that of diesel, specifically, 69.97 J/deg CA for JB100, 70.93 J/deg CA for KB100 and 68.37 J/deg CA for PB100 compared with 90.96 J/deg CA for diesel. This is because, as a consequence of the shorter ignition delay, the premix combustion phase for biodiesel and their blends is less intense. On the other hand, while running with diesel, increased accumulation of fuel during the relatively longer delay period resulted in higher rate of heat release. Because of the shorter delay, maximum heat release rate occurs earlier for biodiesel and their blends in comparison with neat diesel. However, the heat release during the late combustion phase for biodiesel and their blends is marginally lower than that of diesel. This is because the constituents with higher oxygen content are adequate to ensure complete combustion of the fuel that is left over during the main combustion phase and continue to burn in the late combustion phase.

5.2.3. Effect of blends on ignition delay

The increase in fuel viscosity, particularly for petroleum-derived fuels, results in poor atomization, slower mixing, increased penetration and reduced cone angle. These result in longer ignition delay. But biodiesel is not derived from crude petroleum, and the opposite trend is seen in the case of biodiesel and their blends. Fig. 4 compares the delays between neat diesel, neat biodiesel and their blends at various loads. The delays are consistently shorter for JB100, varying between 5.9° and 4.2° CA lower than diesel with the difference increasing the load. Similarly, delays are shorter for KB100 (varying between 6.3° and 4.5° CA) and PB100 (varying between 5.7° and 4.2° CA) lower than diesel. Biodiesel usually includes a small percentage of diglycerides having higher boiling points than diesel. However, the chemical reactions during the injection of biodiesel at high temperature resulted in the break-

Table 4
Specifications of Kirloskar single cylinder diesel engine.

S.no.	Particulars	Specifications
1	Make	Kirloskar oil engines Ltd.
2	Model	DAF 8
3	Rated brake power (bhp/kW)	8/6
4	Rated speed (rpm)	1500
5	Number of cylinder	One
6	Bore x Stroke (mm)	95×110
7	Displacement volume (cc)	779.704
8	Compression ratio	17.5:1
9	Cooling system	Air-cooled
10	Lubrication system	Forced feed
11	Cubic capacity	0.78 Lit
12	Inlet valve open (°)	4.5° BTDC
13	Inlet valve closed (°)	35.5° ABDC
14	Exhaust valve open (°)	35.5° BBDC
15	Exhaust valve closed (°)	4.5° ATDC
16	Fuel injection timing (°)	26° BTDC
17	Injector opening pressure (bar)	200

down of the high-molecular weight esters. These complex chemical reactions led to the formation of gases of low-molecular weight. Rapid gasification of this lighter oil in the fringe of the spray spreads out the jet, and thus volatile combustion compounds ignited earlier and reduced the delay period. Biodiesel derived from Jatropha, Karanja and Polanga oil having higher molecular weight is likely to react identically.

6. Conclusion

The appropriate blend necessary to ensure optimum performance, low-emission and best combustion characteristics depends upon the particular feedstock and the subsequent biodiesel formulation. The present analysis reveals that biodiesel from unrefined Jatropha, Karanja and Polanga seed oil is quite suitable as an alternative to diesel. It is concluded that neat Polanga biodiesel (PB100) which results in maximum peak cylinder pressure (6.61 bars higher than that of diesel) is the optimum fuel blend as far as the peak cylinder pressure is concerned. The ignition delays are consistently shorter for JB100, varying between 5.9° and 4.2° crank angle lower than diesel with the difference increasing with the load. Similarly, ignition delays are shorter for KB100 (varying between 6.3° and 4.5° crank angle) and PB100 (varying between 5.7° and 4.2° crank angle) lower than diesel. However, further research and development on the additional fuel property measures, long-term run and wear analysis of biodiesel fueled engine is also necessary along with injection timing and duration for better combustion of biodiesel in diesel engines.

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