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Performance, emissions and combustion characteristics of Karanja biodiesel in a transportation engine

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HIGHLIGHTS

- Performance, emissions and combustion characteristics of Karanja biodiesel blends.
- Lower biodiesel blends produced higher maximum torque than diesel.
- At higher loads, higher biodiesel blends produce higher BSNOx emissions.
- BSHC, BSCO and smoke emissions of KOME blends were lower than diesel.
- Combustion duration of lower biodiesel blends was shorter than diesel.

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ABSTRACT

Effect of Karanja biodiesel (Karanja oil methyl ester; KOME) and its blends on engine performance, emissions and combustion characteristics in a direct injection compression ignition (DICI) engine of a medium size utility vehicle with varying engine speed and load has been investigated. Maximum torque attained by 10% and 20% KOME blends were higher than mineral diesel, while higher biodiesel blends produced slightly lower torque. BSFC for lower KOME blends was comparable to mineral diesel however BSFC increased for higher biodiesel blends. BSCO, BSHC and smoke emissions of Karanja biodiesel blends were lower than mineral diesel but BSNOx emissions were slightly higher. Comparative investigation of performance, emissions and combustion characteristics of Karanja biodiesel blends and mineral diesel showed that up to 20% Karanja biodiesel blend can be utilized in an unmodified DICI engine.

1. Introduction

Petroleum based fossil fuels have been dominant transport fuels since the very beginning of mechanized mobility in nineteenth century. Predicted exhaustion of fossil fuels in foreseeable future and environmental pollution concerns provide motivation for search of renewable alternative fuel for the transport sector, which would have relatively lesser harmful impact on the environment. Fatty acid alkyl esters derived from transesterification of triglycerides, which are commonly known as biodiesel, are well accepted renewable alternatives of petroleum diesel. In last two decades, several studies from across the globe have reported successful operation of compression ignition (CI) engines with biodiesel derived from a host of feedstocks and their blends with mineral diesel.

Xiaoming et al. reported that torque of B50 fueled engine decreased by up to 2.6% in the engine speed range of 1000–2400 rpm at full load and brake specific fuel consumption (BSFC) increased by 3.6–8.3% [1]. Sinha et al. observed that maximum torque was either equal or slightly higher for the lower biodiesel blends (B05, B10, and B20) of rice-bran biodiesel and decreased slightly for higher blends vis-à-vis mineral diesel at lower engine speeds in a direct injection (DI) diesel engine. At higher engine speeds, torque output was almost similar for all test fuels [2]. Mahanta et al. reported higher BSFC for 20% Karanja biodiesel blend as well as higher brake thermal efficiency (BTE) than mineral diesel at all engine loads [3]. Qi et al. reported higher BSFC for soybean biodiesel vis-à-vis mineral diesel, which was due to difference in heating values of biodiesel and mineral diesel [4]. Corgard et al. observed same level of BSFC with biodiesel and diesel [5]. Prabhahar et al. reported higher BSFC for Karanja biodiesel and blends in comparison to mineral diesel [6]. Grimaldi et al. obtained slightly higher BTE, when the engine was fueled with biodiesel, particularly at high loads in comparison to mineral diesel fueled engine [7]. Sinha et al. reported improvement of 1.5–3% in BTE for rice-bran biodiesel blends in comparison to mineral diesel [2]. Suryawanshi et al. found significant reduction in HC and CO

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emissions for Pongamia methyl ester blends in comparison to mineral diesel at part loads as well as full load [8]. Spessert et al. reported that CO emissions were quite similar for rapeseed methyl ester (RME) and diesel. CO emissions for RME increased marginally at low loads and decreased at high loads [9]. Generally biodiesel and biodiesel blend fueled engines lead to reduction in CO and HC emissions in comparison to mineral diesel [9–18]. Studies investigating effect of biodiesel on NOx emissions report mixed responses, ranging from increased NOx emissions for biodiesel fueling at all operating points to decreased NOx emissions at all operating points [19]. But majority of papers on biodiesel emission characteristics report increase in NOx emissions with biodiesel [19,20]. Advancing the combustion phasing [8,11], higher combustion temperatures [21], oxygen content of biodiesel [21–23] and differences in the chemical composition of diesel and biodiesel [24–27] are thought be possible causes of these effects of biodiesel on NOx emissions. Reduction of particulate emissions with utilization of biodiesel is a general trend reported in the published literature [19,28] however few studies have also reported identical or increased levels of PM emissions [15,17]. Reduction in particulate emissions with biodiesel fueled engine operation is attributed to higher oxygen content of biodiesel [25,29,30].

Literature review shows that exact change in performance and emission characteristics of engine with respect to conventional diesel varies considerably depending upon biodiesel properties, blend concentration and engine technology used. Karanja oil is a promising feedstock for producing biodiesel in India on large scale because it is well adapted to local climatic conditions and is available in surplus quantities throughout the length and breadth of the country [31,32]. Earlier investigations on Karanja biodiesel and blends [3,6,8,33–35] have been carried out on constant speed CI engines. Anand et al. [36] compared the performance, emissions and combustion characteristics of 100% Karanja biodiesel and mineral diesel at different engine speeds. In an attempt to search suitable feedstock for production of biodiesel for Indian transportation sector, effect of Karanja biodiesel and its blends on engine performance, emissions and combustion characteristics of CI engine with varying engine speeds and loads have been investigated.

2. Experimental setup and procedure

Performance, emissions and combustion characteristics of Karanja biodiesel blends were evaluated in a typical medium-duty transportation direct injection compression ignition (DICI) engine (Mahindra and Mahindra; MDI 3000) used in a medium size utility vehicle. Test engine was a four-cylinder, four-stroke, variable-speed, transportation engine with direct injection of fuel. The technical specifications of the test engine are given in Table 1.

Table 1
Technical specifications of the test engine.

Manufacturer/model	Mahindra & Mahindra Ltd., India/MDI 3000
Engine type	Four stroke in-line, Naturally aspirated, Water cooled diesel engine
Number of cylinders	4
Compression ratio	18:1
Combustion system	Direct injection, Re-entrant bowl
Bore/stroke	88.9/101.6 mm
Swept volume	2520 cc
Liner type	Cast iron replaceable wet liners
Fuel injection timing	(SOI) 17 ± 1° BTDC
Injector opening pressure	194 bar
No. of injection holes	4
Rated power	41 kW @ 3000 rpm
Max. torque	152 Nm @ 1800 rpm
Firing order	1-3-4-2

The test engine was coupled with an eddy-current dynamometer (Schenck-Avery; ASE-70) for controlling the engine speed and load (Fig. 1). For evaluating the performance, emissions and combustion characteristics of different Karanja biodiesel blends, test engine was suitably instrumented. A laminar flow element (Meriam; 50MC2-2F) was used for intake air flow rate measurement. Volumetric fuel consumption was measured by gravimetric fuel flow meter. The mass of fuel consumed was determined by multiplying volumetric fuel consumption to the density of the test fuel. Concentrations of CO, HC and NOx, in the engine exhaust were measured using raw exhaust gas emission analyzer (Horiba; EXSA-1500). This equipment consists of CO/CO_2 analyzer (NDIR detector: MCA-220UA), HC analyzer (Hot flame ionization detector: FIA-225UA) and NOx analyzer (Chemiluminescence detector: CLA-220UA). The opacity of the exhaust was measured by smoke opacimeter (AVL; 437). Detailed combustion analysis of various test fuels was performed by measuring cylinder pressure-crank angle history and fuel line pressure. Cylinder pressure was measured using a piezoelectric pressure transducer (AVL; GU21C) and a charge amplifier (AVL; 3066A02). For measuring fuel line pressure, a fuel line pressure sensor (Kistler; 4067BC) was installed in the high pressure fuel line using a pressure sensor adapter. For synchronizing the cylinder pressure and fuel line pressure signals with the crank shaft rotation, a high precision crank angle encoder (AVL; 333) and a TDC sensor were installed on to the engine crank-shaft.

Performance, emissions and combustion characteristics of 5%, 10%, 20%, 50% biodiesel blends with mineral diesel, 100% biodiesel along with baseline data of mineral diesel were experimentally evaluated. Table 2 shows the viscosity, density and calorific value of mineral diesel, Karanja biodiesel (KOME100) and test blends of biodiesel and mineral diesel. Viscosity and density of test fuels increased with increasing concentration of Karanja biodiesel in the test blends. Calorific value of test fuels decreased with increasing concentration of biodiesel in the test blend. Cetane number (CN) of KOME100 and mineral diesel used in this study were 50.8 and 51.2 respectively.

3. Results and discussion

Effect of speed and load on engine performance, emissions and combustion characteristics of Karanja biodiesel (KOME100), and blends of Karanja biodiesel with mineral diesel (KOME50, KOME20, KOME10 and KOME05) vis-à-vis baseline mineral diesel were investigated in the test engine. Experiments were conducted at 1200, 1500, 1800, 2100, 2400 and 2600 rpm engine speeds with varying loads (up to 6.8 bar BMEP). Detailed results of performance, emissions and combustion characterization for various test fuels are shown at 1800 rpm (rated speed, at which maximum torque is obtained) as well as 2600 rpm (maximum speed, at which experiments were conducted).

3.1. Engine performance characteristics

Speed-torque characteristics of all test fuels are similar, typically showing maximum torque in the speed range of 1700–1800 rpm (Fig. 2). Maximum torque produced by KOME10 and KOME20 were higher than mineral diesel. Roughly 0.7% and 0.3% higher torque were obtained for KOME10 and KOME20 respectively in comparison to baseline mineral diesel. Maximum torque for KOME05 was almost similar to baseline mineral diesel.

However reduction in torque by 1.4% and 2.1% was observed for higher biodiesel blend (KOME50) and pure biodiesel (KOME100) respectively in comparison to baseline mineral diesel. Sinha et al. also reported slightly higher peak torque for rice-bran biodiesel blends up to B20 and lower torque for B30 and B50 in comparison

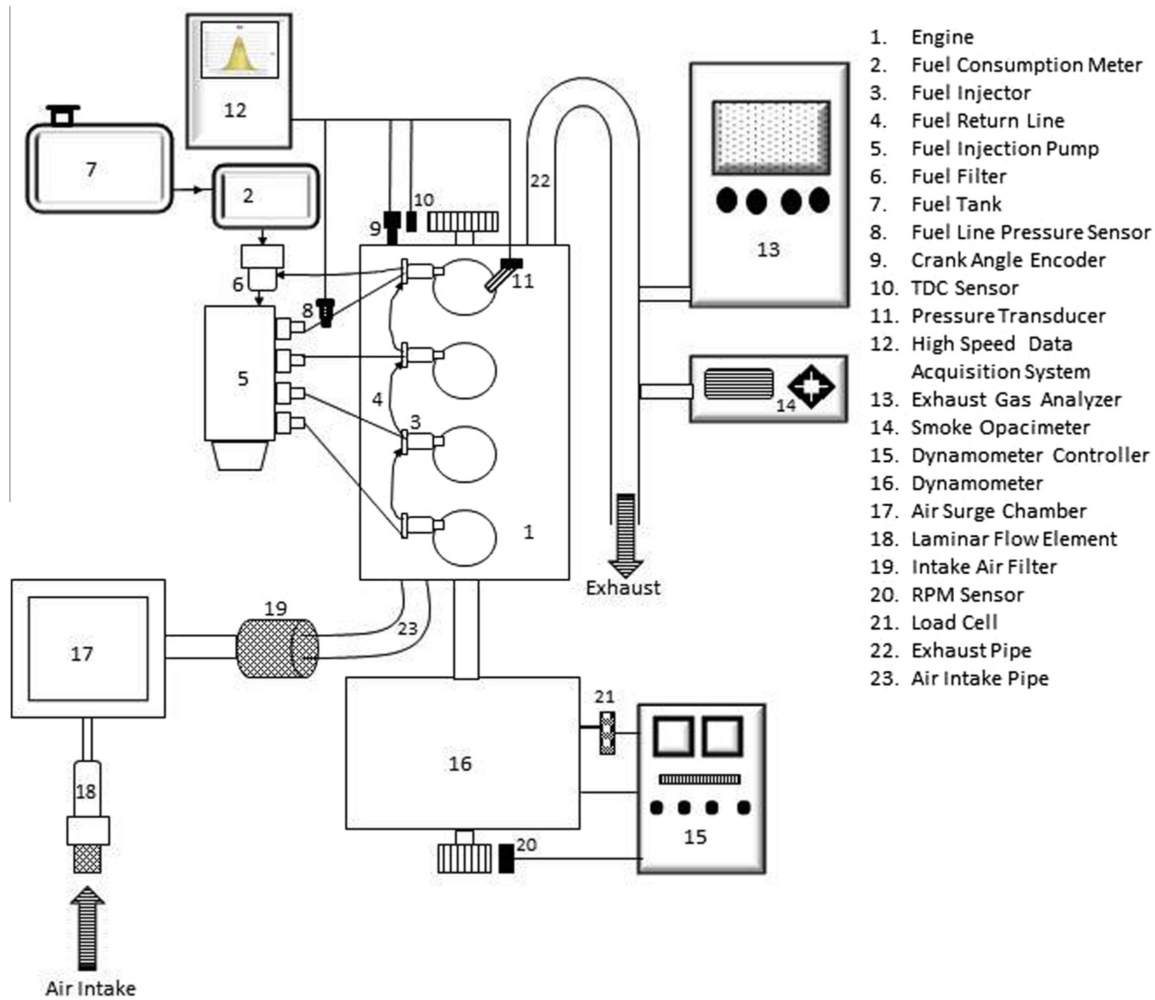

Fig. 1. Schematic of the experimental setup.

Table 2
Important physical properties of test fuels.

Test fuel	Viscosity @ 40 °C (cSt)	Density (g/cm^3)	LHV (MJ/kg)
Diesel	2.78	0.831	43.79
KOME 05	2.91	0.833	43.48
KOME 10	3.04	0.836	43.18
KOME 20	3.11	0.841	42.57
KOME 50	3.51	0.856	40.8
KOME 100	4.42	0.881	37.98

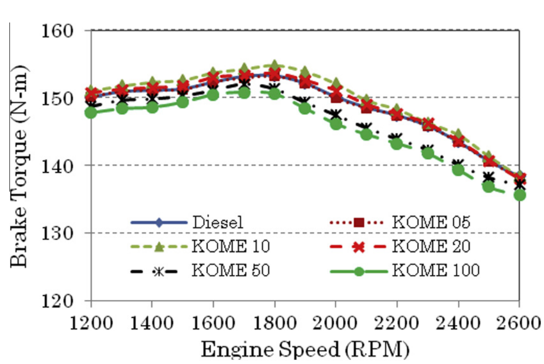

Fig. 2. Speed–torque characteristics for different test fuels.

to baseline mineral diesel [2]. Lin et al. reported 3.5% and 1% power reduction for palm biodiesel and B20 at rated load respectively in comparison to baseline mineral diesel [37]. For producing the same engine torque, higher quantity of biodiesel blends than mineral diesel were required because biodiesel blends have lower energy content (calorific value) in comparison to baseline mineral diesel. Therefore reduction in maximum torque is also observed for higher blends of Karanja biodiesel (KOME50 and KOME100) in these tests. Lower blends show improved combustion of fuels due to presence of oxygen in biodiesel molecules, which results in superior combustion and higher torque for these lower blends.

Fig. 3 shows the variation of BSFC for different Karanja biodiesel blends with varying engine loads at two different engine speeds (1800 and 2600 rpm) vis-à-vis baseline mineral diesel. BSFC for higher biodiesel blends was always higher than mineral diesel due to their lower calorific value. BSFC of all these fuels first decreased and became lowest at 1800 rpm and then it increased with increasing engine speed. Engine was optimized for this speed because 1800 rpm is also the rated speed of the engine. Sinha et al. reported lower BSFC for B05, B10 and B20 and higher BSFC with further increase in biodiesel proportion in the blends in comparison to mineral diesel [2]. Differences in the BSFC of higher biodiesel blends and mineral diesel were higher at lower BMEPs and they reduced at higher engine loads. Xioming et al. reported higher BSFC for B20 and B50 in comparison to mineral diesel and differences in the BSFC of biodiesel and diesel were lower at higher BMEP [1]. At 2600 rpm, difference in the BSFC of biodiesel and mineral diesel

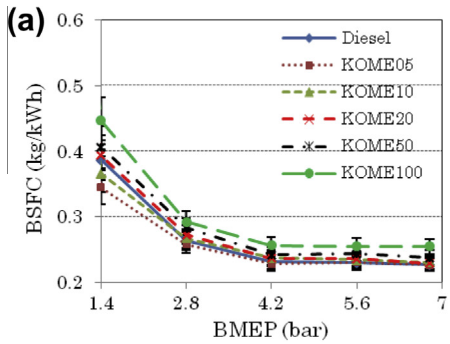

Fig. 3. Brake specific fuel consumption of Karanja biodiesel and blends vis-à-vis baseline mineral diesel at (a) 1800 and (b) 2600 rpm.

widened because of the lower time availability for completing one engine cycle, which deteriorates the combustion of biodiesel due to relatively inferior volatility and larger droplet size distribution of biodiesel blends (due to its higher viscosity). This adverse effect of inferior volatility characteristics on combustion was more significant at higher engine speed and load conditions. At such engine operating conditions, the contribution of mixing controlled combustion is relatively higher in comparison to premixed combustion. In such operating conditions, time scales for fuel spray/fuel-cylinder gas interactions differ by an order of magnitude from the time scales of the branching reactions [38].

Fig. 4 shows the variation of BTE for different Karanja biodiesel blends at varying engine loads and speeds vis-à-vis baseline mineral diesel. The thermal efficiency generally increased with increasing engine load for all fuels at the two test speeds (Fig. 4). At higher engine loads, BTE of all the fuels is almost identical. Sinha et al. reported higher BTE for biodiesel and its blends at rated load and maximum improvement in BTE was observed for B10 and B20 [2]. At lower engine loads, higher blends of biodiesel have lower BTE than mineral diesel due to higher fuel viscosity and higher latent heat of vaporization required for these blends due to higher biodiesel content. High viscosity, density and evaporation energy of biodiesel causes formation of larger droplets during atomization of fuel, which results in inadequate mixing of air and fuel [33,39]. Presence of oxygen in the fuel molecule however improves the combustion efficiency. Higher temperature of the air at high engine loads also helps in evaporation and mixing of biodiesel therefore BTE of higher biodiesel blends improves at higher engine loads.

3.2. Engine emission characteristics

Fig. 5 shows the variation of BSCO emissions from different test fuels at varying engine loads at two engine speeds (1800 rpm and 2600 rpm).

At higher engine speeds and loads (Fig. 5(b)), biodiesel blends produced lower CO emissions in comparison to mineral diesel. But at lower engine loads, CO emissions of higher biodiesel blends were found to be higher than mineral diesel. Cecrle et al. reported

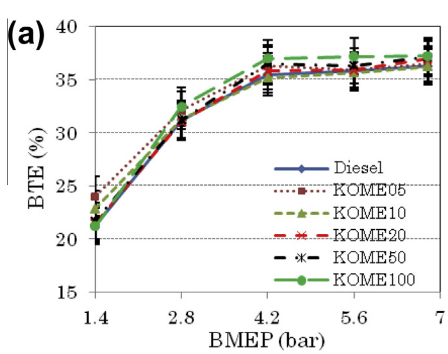

Fig. 4. Brake thermal efficiency of Karanja biodiesel and blends vis-à-vis baseline mineral diesel at (a) 1800 and (b) 2600 rpm.

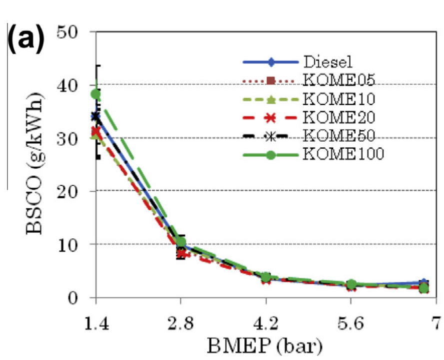

Fig. 5. BSCO emissions of Karanja biodiesel and blends vis-à-vis baseline mineral diesel at (a) 1800 and (b) 2600 rpm.

lower BSCO emissions for biodiesels of different feedstocks in comparison to mineral diesel at higher engine loads but mixed results at lower engine loads [40]. Sinha et al. reported lower BSCO emissions at rated engine load for biodiesel blends up to B50 [2]. CO emissions reduced with adequate fuel–air mixing. Higher viscosity, density and evaporation energy of biodiesel results in inadequate fuel–air mixing, especially at lower engine speeds and loads. This effect becomes less significant at higher engine speeds and loads, when the cylinder temperature rises. Oxygen content of biodiesel also helps in reduction of CO emissions. Trend of CO mass emission was governed by two contradictory effects (i) relatively inferior air–fuel mixing of biodiesels, which increases CO formation and (ii) superior combustion of biodiesel due to presence of oxygen, which reduces CO formation.

Fig. 6 shows the variation of BSHC emissions for different test fuels at varying engine loads at engine speeds of 1800 and 2600 rpm. It was observed that total hydrocarbon emissions of Karanja biodiesel blends were lower than mineral diesel. BSHC emissions for all test fuels were higher at lower engine loads and quantity of HC emissions decreased with increasing engine load. Over-leaning of air–fuel mixture (mixing becomes lean beyond the ignition limit) and fuel over-rich zones are the two sources of HC emissions in heterogeneous combustion environment of CI engines.

Over-leaning is a dominant mechanism at lower engine loads and over-rich mixing is a dominant mechanism at higher engine loads [41]. Sinha et al. reported that at lower engine speeds, higher BSHC emissions are observed for lower biodiesel blends and at higher engine speeds, BSHC emissions of B20 and B50 were comparable to mineral diesel [2]. Anand et al. reported lower BSHC emissions for Karanja biodiesel in comparison to mineral diesel [36]. At lower engine speeds and loads, HC emissions from higher biodiesel blends were found to be comparable to mineral diesel due to relatively higher fuel quantity injected and poor volatility of biodiesel, which widens the fuel rich zones. The reduced HC emissions observed with biodiesel operation are attributed to the combined effect of (a) reduction in over-mixing at lower engine loads due to poor biodiesel volatility, and (b) reduction in stoichiometric air requirement owing to fuel-bound oxygen in biodiesel, which enhances diffusion combustion and also increases heat release/gas temperature as compared to mineral diesel [36,42]. At higher engine loads, oxygen present in biodiesel molecules helps in reduction of HC emissions, when the HC emissions are mainly caused by deficiency of oxygen in the fuel-rich zones.

Fig. 7 shows the variation of BSNOx emissions for different test fuels at varying engine loads at engine speeds of 1800 and 2600 rpm. It was observed that NOx emissions were higher for biodiesel blends in comparison to mineral diesel. At lower engine loads and engine speeds, higher biodiesel blends showed comparatively higher increase in BSNOx emissions in comparison to mineral diesel. However, at higher engine speeds and loads, magnitude of increase in BSNOx emissions for Karanja biodiesel blends in comparison to diesel diminished with reduction in BSNOx emissions. This is because an increase in NOx concentration in exhaust was smaller than increase in engine brake power under these engine operating conditions. At lower engine loads and speeds, NOx emissions for lower biodiesel blends were lower than baseline mineral diesel however higher NOx emissions were observed at higher engine loads. BSNOx depend upon oxygen concentration and maximum cylinder temperatures [41]. Many studies proposed that fuel bound oxygen of biodiesel also contributes to higher NOx emissions for biodiesel fueled engines [21,22].

Lapuerta et al. however refuted the influence of fuel bound oxygen on NOx emissions, citing that a balance on oxygen availability shows the oxygen/fuel mass ratio is lower than conventional fuel [19]. Sinha et al. reported higher NOx emissions from biodiesel blend fueled engine at rated load, and highest increase in NOx emissions was shown by B10 and B20, while further increase of

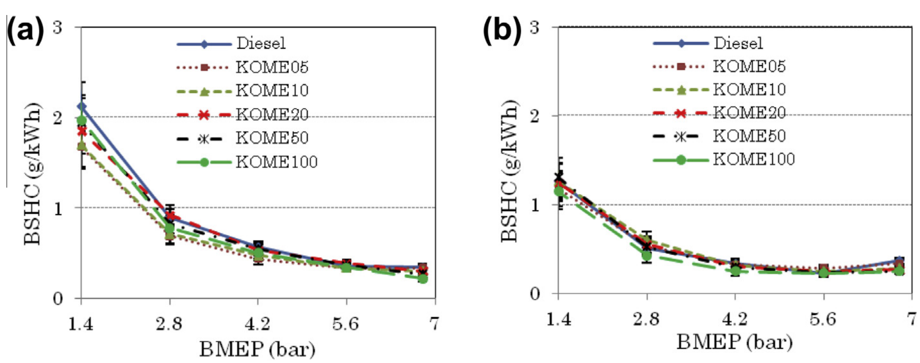

Fig. 6. BSHC emissions of Karanja biodiesel and blends vis-à-vis baseline mineral diesel at (a) 1800 and (b) 2600 rpm.

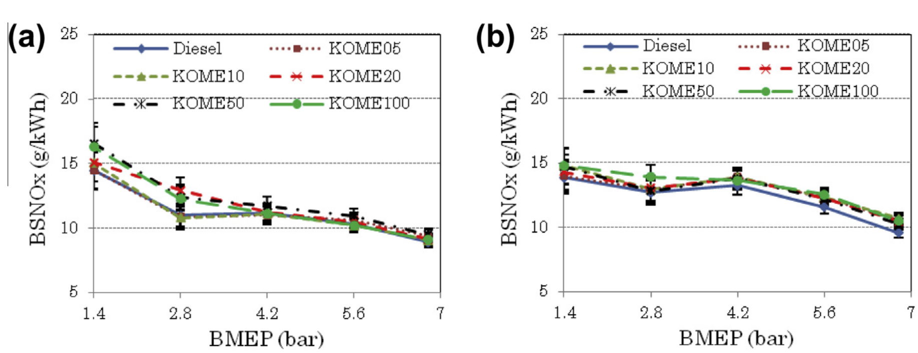

Fig. 7. BSNOx emissions of Karanja biodiesel and blends vis-à-vis mineral diesel at (a) 1800 and (b) 2600 rpm.

biodiesel proportion in the test fuel resulted in reduction of BSNOx emissions [2]. Salvi et al. reported increase in BSNOx emissions with increasing biodiesel concentration in the test fuel at all engine loads [43]. At lower engine speeds and load operating points, inadequate mixing of fuel and air results in lower in-cylinder temperatures for biodiesel fueled engines, which finally results in lower NOx emissions at these operating points in comparison to mineral diesel. In the literature, some studies have also attributed increase in NOx emissions from biodiesel fueled engine to prompt NOx formation [43–46]. Higher viscosities and surface tension, together with lower biodiesel volatility leads to richer biodiesel sprays, which provide additional opportunities for formation of intermediate species, possibly contributing to prompt NOx formation. Szybist et al. reported that final NOx concentration in the exhaust is more sensitive to the timings of maximum in-cylinder temperature and maximum heat release rate (HRR) [47,48]. In this study, due to almost same cetane numbers of Karanja biodiesel and mineral diesel, combustion phasing of fuels were almost identical. At higher BMEP, maximum HRR were higher for Karanja biodiesel in comparison to mineral diesel. These operating conditions also showed higher NOx emissions for biodiesel. Salvi et al. observed increase in NOx emissions for biodiesel with lower cetane number in comparison to mineral diesel [43]. In same study, they reported reduction in NOx emissions even with advanced combustion phasing, which exemplifies significance of fuel's chemical composition on NOx formation instead of its sole dependence on combustion profile [43]. Differences in chemical composition of Karanja biodiesel and mineral diesel may be also responsible for increase of BSNOx emissions.

Fig. 8 shows the variation in smoke opacity for different test fuels at varying engine loads and speeds. Exhaust smoke opacity is a qualitative indicator of number of larger diameter particulates, which are large enough to scatter the incident light falling onto the exhaust stream. It was observed that at lower engine loads for all test fuels, smoke opacity was almost identical at all speeds. At higher engine loads, smoke opacity decreased with concentration of Karanja biodiesel in the test fuel. Other studies also reported that smoke opacities for all biodiesel blends were lower than mineral diesel and smoke opacity decreased with increase in biodiesel concentrations in the test fuel at rated load [2,4,40,49,50]. Oxygen present in biodiesel led to superior combustion in the fuel-rich zones in the combustion chamber in comparison to mineral diesel, which is a non-oxygenated fuel. With increasing engine speed, smoke opacity first decreased due to increase in in-cylinder temperature, which facilitated oxidation of particulates, then increased it with further increase in engine speed due to lesser time available for oxidation of particulates. Anand et al. also reported reduction in smoke opacity with increasing engine speed from 1000 to 1400 rpm and then almost constant smoke opacity with further increase in engine speed for mineral diesel as well as Karanja biodiesel [36]. Salvi et al. reported higher smoke opacity at lower BMEP for B20 and B100 in comparison to mineral diesel [41]. At lower engine loads, reduction in smoke opacity was not significant since higher viscosity, surface tension, density and poor volatility of biodiesel caused inadequate fuel–air mixing at lower in-cylinder temperatures and pressures [43,45,46,51], which resulted in larger atomized fuel droplets during combustion, leading to increased partial oxidation of fuel and formation of larger number of particulates.

3.3. Engine combustion characteristics

Combustion characteristics of various Karanja biodiesel blends vis-a-vis baseline mineral diesel were analyzed by measuring in-cylinder pressure and fuel-line pressure with respect to crank angle degrees in a DICI engine. Measured pressure data of 100 consecutive engine cycles was averaged in order to eliminate cyclic variations and then analyzed to calculate heat release rate, mass burn fractions and combustion duration etc. COV of cycle to cycle variation of peak cylinder pressure, position of peak pressure and IMEP was within 0.6%, 6.5% and 1.5% respectively for all the engine operating conditions and fuels. From pressure data, heat release rate $\left(\frac{dQ(\theta)}{d\theta}\right)$ was calculated by first law of thermodynamics according to Eq. (1) [52]. In this calculation, combustion products were assumed to behave as ideal gas; and dissociation of combustion products and wall heat transfer were neglected. $P(\theta)$ and $V(\theta)$ were cylinder pressure and cylinder volume at θ degrees rotation of the engine crank shaft.

$$\frac{dQ(\theta)}{d\theta} = \frac{1}{\gamma - 1}\left(V(\theta)\frac{dP(\theta)}{d\theta} + \gamma P(\theta)\frac{dV(\theta)}{d\theta}\right) \qquad (1)$$

Value of polytrophic coefficient (γ) was taken to be 1.37 for the compression stroke and 1.30 for the expansion stroke. Heat release rate was integrated to obtain cumulative heat release till θ degrees rotation of crank shaft. Value of cumulative heat release was normalized by assuming completion of combustion till 120° CA (value of cumulative heat release at 120° CA is assumed 100% combustion energy). Crank angle at which 10% and 90% of this heat release was obtained were considered 10% and 90% mass burn fraction (MBF) crank angles respectively. Difference between crank angle positions of 10% and 90% MBF was used to characterize the combustion duration.

3.3.1. Cylinder pressure

Fig. 9 shows the variation in cylinder pressure with crank angle degrees at various engine loads and speeds for different test fuels. It can be observed from Fig. 9 that peak cylinder pressure rises with increasing engine load for all test fuels because more fuel quantity is injected and burnt at higher engine loads.

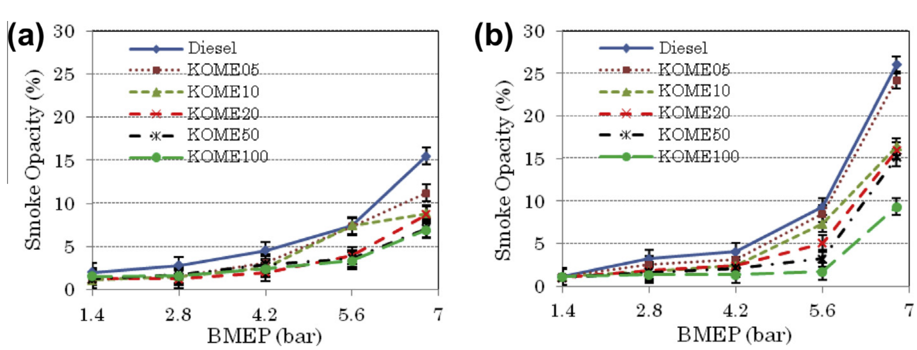

Fig. 8. Smoke opacity of Karanja biodiesel and blends vis-à-vis baseline mineral diesel at (a) 1800 and (b) 2600 rpm.

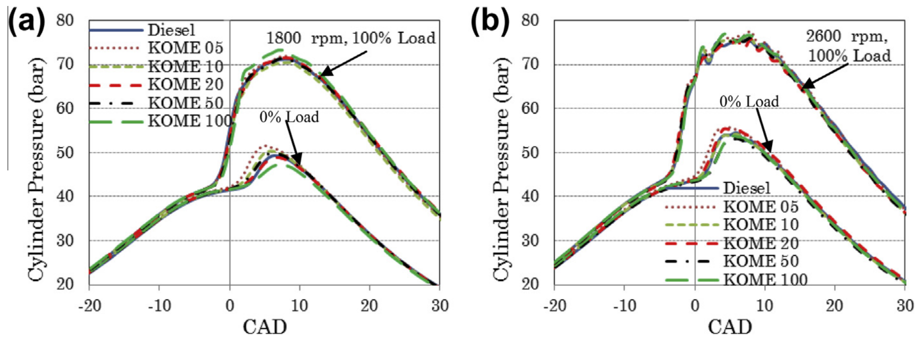

Fig. 9. Variation of cylinder pressure with load (a) 1800 rpm at 0% and 100 load and (b) 2600 rpm at 0% and 100% load for Karanja biodiesel blends vis-à-vis baseline mineral diesel.

At lower engine loads, lower biodiesel blends show relatively earlier start of pressure rise however the start of pressure rise was delayed for KOME100 in comparison to mineral diesel (Fig. 9(a)). At higher engine loads, cylinder pressure rise timings for all test fuels were almost similar. At higher engine loads, maximum cylinder pressure for KOME100 was higher than other fuels. Maximum cylinder pressure for KOME100 was lowest among all test fuels at lower engine loads. Gautam et al. also observed lower maximum cylinder pressure for 100% cottonseed biodiesel at lower engine loads and higher maximum pressure at higher engine loads in comparison to mineral diesel [38]. Gumus et al. reported reduction in maximum cylinder pressure with increasing concentration of hazelnut biodiesel in the fuel at lower as well as higher engine loads however the difference among various test fuels was lower at higher engine loads [53]. Sinha et al. reported advanced start of pressure rise for rice-bran oil biodiesel and its blends in comparison to mineral diesel at lower as well as higher engine loads [54]. Cetane number of rice-bran oil was 64, while cetane number of Karanja biodiesel used in this study was 51 only. Higher cetane number of biodiesel was responsible for advanced cylinder pressure rise. This shows that combustion characteristics of biodiesel improve when cylinder pressures and temperatures are high during fuel injection and at the point of "start of combustion". At higher engine loads, residual gas and cylinder wall temperatures are relatively higher, which lead to higher charge temperatures during fuel injection, which improve the fuel–air mixing characteristics of lower volatility fuel [39,54]. Due to this reason, maximum cylinder pressure of KOME100 becomes higher than mineral diesel and other lower biodiesel blends at higher engine loads.

Fig. 10 shows the variation in maximum cylinder pressure for Karanja biodiesel blends vis-avis baseline mineral diesel for varying engine loads at engine speeds of 1800 and 2600 rpm. At lower engine loads for all speeds, maximum cylinder pressure for KOME100 was lowest and lower biodiesel blends showed relatively higher maximum cylinder pressures. Maximum cylinder pressure is high, when substantial fuel combustion is completed at a time, when piston is closer to TDC. This trend is also evident in Fig. 11, which shows that maximum cylinder pressure for lower Karanja biodiesel blends was attained earlier (closer to TDC), whereas the position of maximum cylinder pressure for KOME100 was comparatively farther away from TDC. Maximum cylinder pressure for KOME100 was highest at higher loads. Xiaoming et al. also observed that maximum cylinder pressures for B100 and B20 were higher than mineral diesel at high engine loads, and low engine speed operating points [1].

At higher engine loads, occurrence of maximum cylinder pressure for KOME100 was advanced in comparison to other test fuels. Effect of inferior fuel–air mixing due to higher evaporation energy required for biodiesel is more significant in deteriorating the combustion at lower engine loads, where the cylinder temperature are normally rather low. At higher engine loads, cylinder temperatures increase, which help in evaporation and mixing of biodiesel with air, leading to improved combustion of higher Karanja biodiesel blends. Improved combustion of higher biodiesel blends at higher engine loads result in higher cylinder pressures.

Fig. 12 shows the variation of maximum rate of pressure rise ($(dP/d\theta)_{max}$) with varying engine loads for different Karanja biodiesel blends. Maximum rate of pressure rise is an indicator of harshness of combustion. Maximum pressure rise rate increases with increasing engine load at all speeds for all test fuels. It also increases with increasing engine speed. Rate of pressure rise varies from 2 bar/CAD at lower engine loads to 14 bar/CAD at higher engine loads. Higher blends of biodiesel show lower maximum cylinder pressure rise rate at lower engine loads and higher pressure rise rate at higher engine loads. Smaller pressure rise rate for KOME100 indicates less noisy combustion at lower BMEP. Maximum pressure rise rate is higher for lower biodiesel blends. $(dP/d\theta)_{max}$ decreases as the biodiesel concentration increases in the

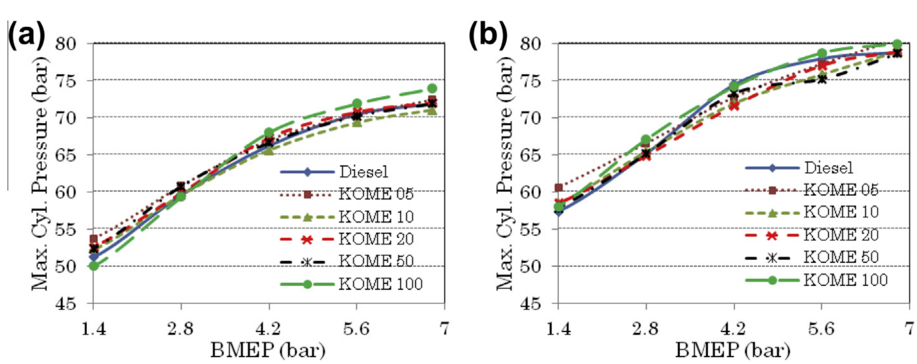

Fig. 10. Variation of maximum cylinder pressure for Karanja biodiesel blends vis-à-vis baseline mineral diesel with load at (a) 1800 and (b) 2600 rpm.

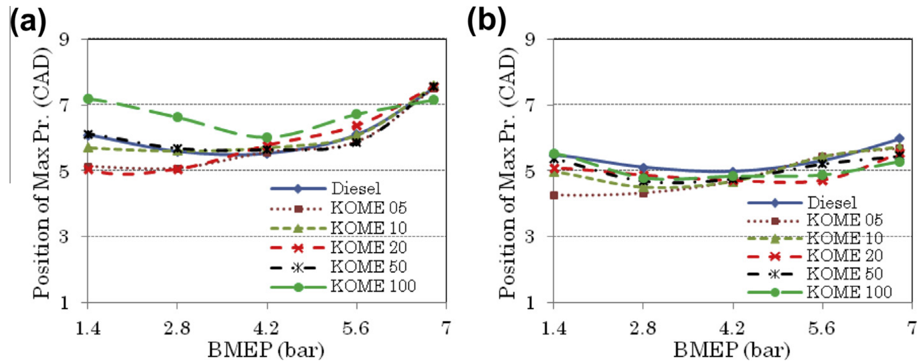

Fig. 11. Position of peak cylinder pressure for Karanja biodiesel blends vis-à-vis baseline mineral diesel with varying engine loads at engine speeds of (a) 1800 and (b) 2600 rpm.

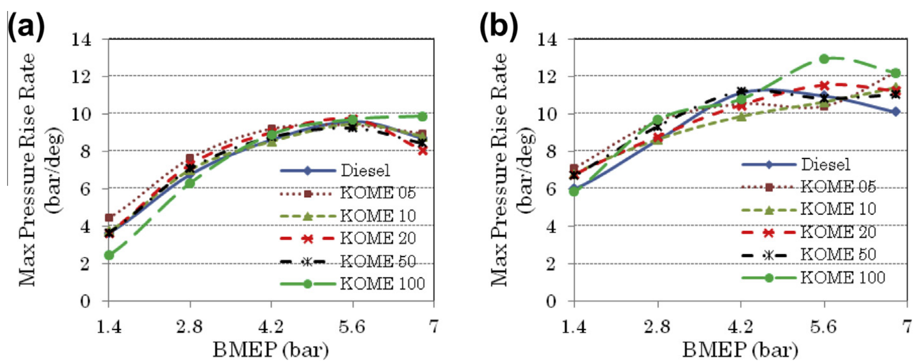

Fig. 12. Variation of peak pressure rise rate for Karanja biodiesel blends vis-à-vis mineral diesel with load at (a) 1800 rpm and (b) 2600 rpm speed.

test fuel at lower engine loads. This is possibly because biodiesel contains longer carbon-chain length molecules having higher boiling point and lower volatility. At higher engine speeds and loads, very high cylinder temperature exists and these low volatility components of the fuel are therefore able to evaporate and mix properly with air hence maximum pressure rise rate for KOME100 becomes higher at higher engine loads.

3.3.2. Fuel line pressure

Fig. 13 shows the variation of fuel-line pressure for various Karanja biodiesel blends with varying engine load and speed.

It can be observed that fuel-line pressure increases with increasing engine load. Anand et al. also reported increase in fuel-line pressure with increasing engine load for Karanja biodiesel and methanol-Karanja biodiesel blends because higher amount of fuel flows through the fuel line at higher engine loads [34]. Maximum fuel-line pressure is always higher for higher biodiesel blends and this difference increases with increasing engine load due to higher bulk modulus of compressibility of Karanja biodiesel in comparison to mineral diesel. Canacki also reported advanced injection timings for soybean oil biodiesel and its 20% blend in comparison to mineral diesel because fuel's physical properties were different and different fuel quantities were injected [55]. Anand et al. reported slightly retarded fuel injection timings for Karanja biodiesel-methanol (90:10) blend in comparison to biodiesel due to lower bulk modulus of compressibility for methanol [34]. Salvi et al. reported larger relative difference in injection timing as engine speed and load increases which corresponds to a roughly constant real-time injection event for fuels with different bulk modulus of compressibility [43].

Fuel-line pressure also increased with increasing engine speed for all test fuels at fixed engine load. With increasing engine speed at fixed load, fuel injection timing was advanced for all test fuels. Fuel-line pressure for higher biodiesel blends was higher than min-

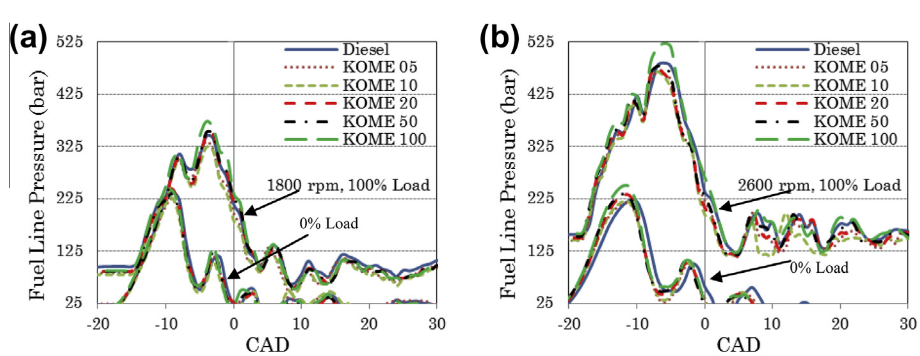

Fig. 13. Variation of fuel line pressure with load (a) 1800 rpm at 0% and 100 load and (b) 2600 rpm at 0% and 100% load for Karanja biodiesel blends vis-à-vis baseline mineral diesel.

eral diesel and this difference increased with increasing engine speed due to relatively higher bulk modulus of compressibility, higher viscosity and higher sonic velocity for biodiesel. Higher bulk modulus leads to rapid pressure wave propagation from the pump to the injector needle [56]. Higher viscosity of biodiesel reduces fuel loss during the injection process, which leads to faster evolution of pressure leading to advanced fuel injection. Furthermore, lower vapor content in high pressure injection system due to poor volatility of biodiesel could also be a reason for advanced injection timings [56].

3.3.3. Heat release rate analysis

Fig. 14 shows the variation of HRR for various test fuels at varying engine loads and speeds. All Karanja biodiesel blends showed identical combustion stages, similar to baseline mineral diesel. After the ignition delay period, premixed fuel–air mixture burns rapidly, leading to very high HRR. This stage was followed by diffusion combustion, where the burn rate was relatively slower because of the air–fuel mixing process. In the beginning, a negative heat release was observed due to vaporization of fuel accumulated during ignition delay, which becomes positive after the start of combustion (SOC).

At lower engine loads, heat release profile showed primarily premixed combustion, which changed to combination of premixed and diffusion combustion at higher engine loads. At lower engine loads, maximum HRR was highest for KOME05 and lowest for KOME100. Gautam et al. also reported higher peak premixed heat release for biodiesel blends at lower engine loads and higher peak premixed heat release for 100% cottonseed biodiesel at higher engine loads [38]. Magnitude of maximum HRR increased with increasing engine loads for all fuels. At lower engine loads, combustion started earlier for lower biodiesel blends (KOME05, KOME10 and KOME20). This indicated that these lower biodiesel blends had optimum conditions for mixture formation and improved combustibility of mixture due to presence of oxygen in the fuel, which resulted in reduced ignition delay and improved combustion.

Amount of heat released during mixing controlled combustion phase also increased with increasing engine load. At higher engine loads, peak of premixed heat release for KOME100 was most prominent. Increased cylinder temperature during fuel injection at higher engine loads due to higher residual gas temperatures supported the evaporation of lower volatility biodiesel, which resulted in higher premixed heat release peak. Timing of start of heat release was almost same for all test fuels at rated engine load. At rated engine load, magnitude of maximum HRR during premixed combustion was highest for KOME100 in the entire speed range. Magnitude of premixed heat release increased with increasing fuel quantity accumulated during ignition delay [35,43]. Sinha et al. reported advanced start of heat release and lower peak of premixed heat release for rice-bran biodiesel in comparison to mineral diesel. Cetane number of rice-bran biodiesel was 64, which was higher than the cetane number of Karanja biodiesel (CN 51) used in this study [54]. Salvi et al. [43] reported delayed start of heat release for B100 (CN 48.6) and B50 (CN 49.6) in comparison to mineral diesel (CN 51.4).

3.3.4. Mass burn fraction

Position of 10% MBF was used to represent the 'SOC'. At higher engine loads, SOC was almost same for all test fuels. Combustion started earliest for KOME05. At lower engine loads, SOC for lower biodiesel blends was advanced compared to mineral diesel however SOC was delayed for KOME100. Higher latent heat of vaporization, viscosity and density of Karanja biodiesel reduces the rate of air–fuel mixing for higher Karanja biodiesel blends hence SOC was delayed for these fuels. Mixing of 5% Karanja biodiesel did not cause any significant deterioration in spray formation and air–fuel mixing however such a small concentration of biodiesel can significantly change the chemical properties of air–fuel mixture, which results in reduction in ignition delay.

Burning of 50% fuel mass at lower engine loads is completed in 8–12 crank angle degrees. This however reduces to 8–10 crank angle degree (CAD) at 2600 rpm. Position of completion of 50% MBF is seen to be earliest for 2.8 bar BMEP. For the two engine speeds, though the completion of 50% MBF for KOME100 is delayed in comparison to mineral diesel at lower loads, it is relatively advanced at higher engine loads. Salvi et al. [43] also observed earlier 50% MBF for mineral diesel at lower engine loads, and at higher engine loads, the combustion phasing difference of B100 and B50 was negligible compared to mineral diesel. Evaporation and mixing of fuel and air for KOME100 was seen to be significantly slower at lower temperature (this condition prevailed at lower engine loads), however at higher engine loads, when the cylinder temperatures are relatively higher, this effect of lower volatility of biodiesel is not very prominent. After the formation of air–fuel mixture, rate of heat release of biodiesel was faster than mineral diesel, most likely due to higher oxygen content of the fuel.

90% MBF crank angle position is used to characterize the 'end of combustion (EOC)'. At higher engine speeds, 90% MBF position was advanced for lower Karanja biodiesel blends and this difference was significant at lower BMEPs. At higher engine speeds and loads, 90% MBF crank angle position for KOME100 came in the same range as that of other lower biodiesel blends.

3.3.5. Combustion duration

Difference in crank angle position for 90% MBF and 10% MBF is used to characterize the 'combustion duration'. Fig. 15 shows the combustion duration for various Karanja biodiesel blends and mineral diesel.

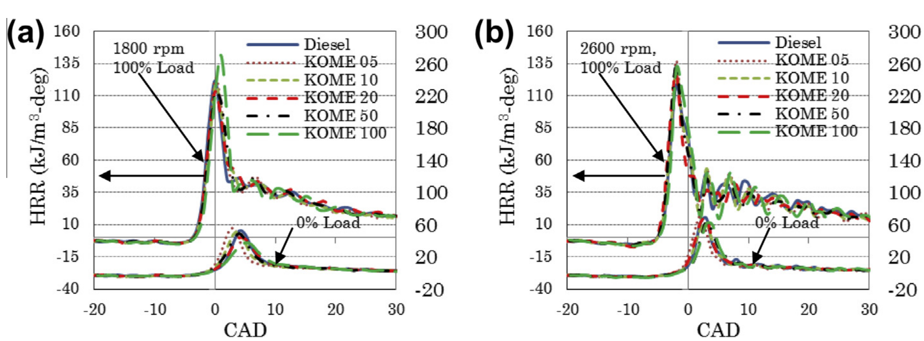

Fig. 14. Variation of heat release rate at (a) 1800 rpm at 0% and 100 load, and (b) 2600 rpm at 0% and 100% load for Karanja biodiesel blends vis-à-vis baseline mineral diesel.

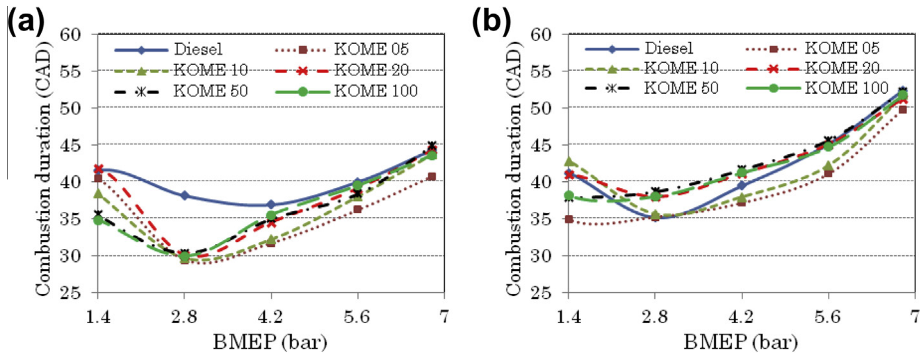

Fig. 15. Variation of combustion duration at (a) 1800 rpm, and (b) 2600 rpm.

All biodiesel blends showed shorter combustion duration for 1.4 or 2.8 bar BMEP at both engine speeds. With increasing engine loads, cylinder temperature also increases, which increases the air–fuel mixing as well as vaporization of fuel. Quantity of fuel injected into the cylinder also increases with increasing engine load, which tends to increase the time required for completion of combustion of higher injected fuel quantity. Due to resultant effect of these two causes, combustion duration was found to be shortest at intermediate engine loads for all test fuels. Combustion duration for lower Karanja biodiesel blends was found to be lower compared to mineral diesel for all operating points. For higher biodiesel blends, combustion duration was shorter than mineral diesel at higher engine loads however longer at lower engine loads. Anand et al. also reported shorter combustion duration of Karanja biodiesel at higher BMEP and longer combustion duration at lower engine speeds and lower loads in comparison to mineral diesel [40]. At lower engine loads, longer combustion duration of biodiesel can be attributed to its slower evaporation characteristics because of its inferior fuel sprays having larger droplet sizes.

4. Conclusions

Detailed comparative performance, emissions and combustion characterization of Karanja biodiesel and its blends vis-à-vis baseline mineral diesel was performed at different engine speeds and loads. Important findings are:

- Speed-torque characteristics indicated that maximum torque attained by KOME10 and KOME20 were higher than baseline mineral diesel, while higher blends (KOME50 & KOME100) produced slightly lower torque.
- BSFC for lower KOME blends was comparable to baseline mineral diesel however BSFC increased for higher biodiesel blends. At lower engine loads, higher biodiesel blends have lower BTE than mineral diesel. At higher engine loads, BTE of all KOME blends was almost same as mineral diesel.
- At higher engine speeds and loads, biodiesel blends produced lower CO emissions in comparison to mineral diesel. However at lower engine loads, BSCO emissions of higher biodiesel blends were higher than mineral diesel.
- BSHC emissions of KOME blends were lower than mineral diesel.
- Relatively higher BSNOx emissions were seen for higher biodiesel blends, particularly at higher engine loads.
- Smoke opacity of KOME blends was lower than mineral diesel.
- Lower cylinder pressures were observed for higher biodiesel blends at lower engine speeds.
- Fuel-line pressure of higher KOME blends was slightly higher than baseline mineral diesel due to higher bulk modulus of compressibility of biodiesel.
- Combustion started earlier for lower KOME blends but 'start of combustion' was slightly delayed for higher KOME blends.
- Combustion duration of lower KOME blends was shorter than baseline mineral diesel and amongst them, higher KOME blends showed longer combustion duration.

Detailed comparative investigation of performance, emissions and combustion characteristics of Karanja biodiesel blends showed that up to 20% blend of Karanja biodiesel can be utilized in an unmodified CI engine without any noticeable performance, combustion and emission issues.

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References

[1] Xiaoming L, Yunshan G, Sijin W, Xiukun H. An experimental investigation on combustion and emissions characteristics of turbocharged DI engines fueled with blends of biodiesel. SAE Paper 2005. 2005-01-2199.
[2] Sinha S, Agarwal AK. Performance evaluation of a biodiesel (rice bran oil methyl ester) fuelled transport diesel engine. SAE Paper 2005. 2005-01-1730.
[3] Mahanta P, Mishra SC, Kushwah YS. An experimental study of Pongamia pinnata L. oil as a diesel substitute. Proc Inst Mech Eng Part A J Power Energy 2006;220:803–8.
[4] Qi DH, Geng LM, Chen H, Bian YZH, Liu J, Ren XC. Combustion and performance evaluation of a diesel engine fueled with biodiesel produced from soybean crude oil. Renew Energy 2009;34:2706–13.
[5] Corgard DD, Reitz RD. Effects of alternative fuels and intake port geometry on HSDI diesel engine performance and emissions. SAE Paper 2001. 2001-01-0647.
[6] Prabhahar M, Muralimanohar R, Sendilvelan S. Performance, emission and combustion characteristics of a direct injection diesel engine with pongamia methyl ester and diesel blends. Eur J Sci Res 2012;73(4):504–11.
[7] Grimaldi CN, Postrioti L, Battistoni M, Millo F. Common rail HSDI diesel engine combustion and emissions with fossil/bio-derived fuel blends. SAE Paper 2002. 2002-01-0865.
[8] Suryawanshi JG, Deshpande NV. Effect of injection timing retard on emissions and performance of a pongamia oil methyl ester fuelled ci engine. SAE Paper 2005. 2005-01-3677.
[9] Spessert BM, Arendt I, Schleicher A. Influence of RME and vegetable oils on exhaust gas and noise emissions of small industrial diesel engines. SAE Paper 2004. 2004-32-0070.
[10] Kawano D, Ishii H, Goto Y, Noda A, Aoyagi Y. Application of biodiesel fuel to modern diesel engine. SAE Paper 2006. 2006-01-0233.
[11] Alam M, Song J, Acharya R, Boehman A, Miller K. Combustion and emissions performance of low sulfur, ultra low sulfur and biodiesel blends in a DI diesel engine. SAE Paper 2004. 2004-01-3024.
[12] Canakci M, Gerpen JHV. Comparison of engine performance and emissions for petroleum diesel fuel, yellow grease biodiesel, and soybean oil biodiesel. ASAE annual international meeting, Sacramento Convention Center Sacramento, California, USA July 30–August 1, 2001. Paper No. 016050.

[13] Sinha S, Agarwal AK. Combustion characteristics of rice bran oil derived biodiesel in a transportation diesel engine. ASME Conf. Proc; 2006. Paper no. ICES2006-1375: 333–340.
[14] Krahl J, Munack A, Schröder O, Stein H, Herbst L, Kaufmann A, et al. The Influence of fuel design on the exhaust gas emissions and health effects. SAE Paper 2005. 2005-01-3772.
[15] Baldassarri LT, Battistelli CL, Conti L, Crebelli R, Berardis BD, Iamiceli AL, et al. Emission comparison of urban bus engine fueled with diesel oil and 'biodiesel' blend. Sci Total Environ 2004;327:147–62.
[16] Wang WG, Lyons DW, Clark NN, Gautam M. Emissions from nine heavy trucks fueled by diesel and biodiesel blend without engine modification. Environ Sci Technol 2000;34(6):933–9.
[17] Lin Y, Wu YG, Chang CT. Combustion characteristics of waste-oil produced biodiesel/diesel fuel blends. Fuel 2007;86:1772–80.
[18] Agarwal AK, Dhar A. Comparative performance, emission and combustion characteristics of rice-bran oil and its biodiesel in a transportation diesel engine. J Eng Gas Turbines Power Trans ASME 2010:132. 064503-1-4.
[19] Lapuerta M, Armas O, Fernàndez JR. Effect of biodiesel fuels on diesel engine emissions. Prog Energy Combust Sci 2008;34:198–223.
[20] Sun J, Caton JA, Jacobs TJ. Oxides of nitrogen emissions from biodiesel-fuelled diesel engines. Prog Energy Combust Sci 2010;36:677–95.
[21] Usta N. An experimental study on performance and exhaust emissions of a diesel engine fuelled with tobacco seed oil methyl ester. Energy Convers Manage 2005;46:2373–86.
[22] Nabi MN, Shahadat MMZ, Rahman MS, Beg MRA. Behavior of diesel combustion and exhaust emission with neat diesel fuel and diesel-biodiesel blends. SAE Paper 2004. 2004-01-3034.
[23] Dhar A, Kevin R, Agarwal AK. Production of biodiesel from high-FFAneem oil and its performance, emission and combustion characterization in a single cylinder DICI engine. Fuel Process Technol 2012;97:118–29.
[24] Lin CY, Lin HA. Diesel engine performance and emission characteristics of biodiesel produced by the peroxidation process. Fuel 2006;85:298–305.
[25] Sharp CA, Ryan III TW, Knothe G. Heavy-duty diesel engine emissions tests using special biodiesel fuels. SAE Paper 2005. 2005-01-3671.
[26] AL-Shemmeri TT, Oberweis S. Correlation of the NOx emission and exhaust gas temperature for biodiesel. Appl Therm Eng 2011. 31: 1682-8.
[27] Assessment and Standards Division (Office of Transportation and Air Quality of the US Environmental Protection Agency). The effect of cetane number increase due to additives on NOx emissions from heavy-duty highway engines, EPA-420-R-03-002; 2003.
[28] Assessment and Standards Division (Office of Transportation and Air Quality of the US Environmental Protection Agency). A comprehensive analysis of biodiesel impacts on exhaust emissions; 2002. EPA420-P-02-001.
[29] McGill R, Storey J, Wagner R, Irick D, Aakko P, Westerholm M, et al. Emission performance of selected biodiesel fuels. SAE Paper 2003. 2003-01-1866.
[30] Yoon SH, Hwang JW, Lee CS. Effect of injection strategy on the combustion and exhaust emission characteristics of biodiesel-ethanol blend in a DI diesel engine. J Eng Gas Turbines Power 2010:132. 094503-1-3.
[31] Agarwal AK, Dhar A. Experimental investigations of performance, emission and combustion characteristics of Karanja oil blends fuelled DICI engine. Renew Energy 2013;52:283–91.
[32] Dhar A, Agarwal AK. Effect of multiple injections on particulate size-number distributions in a common rail direct injection engine fueled with Karanja biodiesel blends. SAE Paper 2013, 2013-01-1554.
[33] Banapurmatha NR, Tewari PG, Hosmath RS. Performance and emission characteristics of a DI compression ignition engine operated on honge, jatropha and sesame oil methyl esters. Renew Energy 2008;33(9):1982–8.
[34] Anand K, Sharma RP, Mehta PS. Experimental investigations on combustion, performance and emissions characteristics of neat karanji biodiesel and its methanol blend in a diesel engine. Biomass Bioenergy 2011;35:533–41.
[35] Sahoo PK, Das LM. Combustion analysis of Jatropha, Karanja and Polanga based biodiesel as fuel in a diesel engine. Fuel 2009;88:994–9.
[36] Anand K, Sharma RP, Mehta PS. Experimental investigations on combustion, performance, and emissions characteristics of a neat biodiesel-fuelled, turbocharged, direct injection diesel engine. Proc Inst Mech Eng Part D J Auto Eng 2010;224:661–79.
[37] Lin YC, Lee WJ, Wu TS, Wang CT. Comparison of PAH and regulated harmful matter emissions from biodiesel blends and paraffinic fuel blends on engine accumulated mileage test. Fuel 2006;85:2516–23.
[38] Gautam A, Agarwal AK. Experimental investigations of comparative performance, emission and combustion characteristics of a cottonseed biodiesel-fueled four-stroke locomotive diesel engine. Int J Eng Res. 2013;14(4):354–72.
[39] Qi DH, Chen H, Geng LM, Bian YZH. Experimental studies on the combustion characteristics and performance of a direct injection engine fueled with biodiesel/diesel blends. Energy Convers Manage 2010;51: 2985–92.
[40] Cecrle E, Depcik C, Duncan A, Guo J, Mangus M, Peltier E, et al. Investigation of the effects of biodiesel feedstock on the performance and emissions of a single-cylinder diesel engine. Energy Fuels 2012;26(4):2331–41.
[41] Heywood JB. Internal combustion engine fundamentals. New York: McGraw-Hill International Edition; 1998.
[42] Monyem A, Van Gerpen JH. The effect of biodiesel oxidation on engine performance and emissions. Biomass Bioenergy 2001;20:317–25.
[43] Salvi AA, Assanis D, Filipi Z. Impact of physical and chemical properties of alternative fuels on combustion, gaseous emissions, and particulate matter during steady and transient engine operation. Energy Fuels 2012;26(7):4231–41.
[44] Knothe G, Sharp CA, Ryan III TW. Exhaust emissions of biodiesel, petrodiesel, neat methyl esters, and alkanes in a new technology engine. Energy Fuels 2006;20(1):403–8.
[45] Suh HK, Roh HG, Lee CS. Spray and combustion characteristics of biodiesel/diesel blended fuel in a direct injection common-rail diesel engine. J Eng Gas Turbines Power 2008;130(3):1–9.
[46] Yoon SH, Suh HK, Lee CS. Effect of spray and EGR rate on the combustion and emission characteristics of biodiesel fuel in a compression ignition engine. Energy Fuels 2009;23(3):1486–93.
[47] Szybist JP, Song J, Alam M, Boehman AL. Biodiesel combustion, emissions and emission control. Fuel Process Technol 2007;88(7):679–91.
[48] Szybist JP, Boehman AL, Taylor JD, McCormick RL. Evaluation of formulation strategies to eliminate the biodiesel NOx effect. Fuel Process Technol 2005;86(10):1109–26.
[49] Enweremadu CC, Rutto HL. Combustion, emission and engine performance characteristics of used cooking oil biodiesel—A review. Renew Sustain Energy Rev 2010;14:2863–73.
[50] Bakeas E, Karavalakis G, Stournas S. Biodiesel emissions profile in modern diesel vehicles. Part 1: effect of biodiesel origin on the criteria emissions. Sci Total Environ 2011;409:1670–6.
[51] Lee CS, Park SW, Kwon SI. An experimental study on the atomization and combustion characteristics of biodiesel-blended fuels. Energy Fuels 2005;19(5):2201–8.
[52] Product Guide. Indicom Light Version 2.1. AVL List GmbH, Graz, Austria; 2009.
[53] Gumus M. A comprehensive experimental investigation of combustion and heat release characteristics of a biodiesel (hazelnut kernel oil methyl ester) fueled direct injection compression ignition engine. Fuel 2010;89: 2802–14.
[54] Sinha S, Agarwal AK. Experimental investigation of the combustion characteristics of a biodiesel (rice-bran oil methyl ester)-fuelled direct-injection transportation diesel engine. Proc Inst Mech Eng Part D J Auto Eng 2007;221:921–32.
[55] Canakci M. Combustion characteristics of a turbocharged DI compression ignition engine fueled with petroleum diesel fuels and biodiesel. Bioresour Technol 2007;98:1167–75.
[56] Kegl B. Influence of biodiesel on engine combustion and emission characteristics. Appl Energy 2011;88:1803–12.