Combustion, performance and emission characteristics of karanja blended biodiesel in CI engine: effect of CR

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Abstract. This research presents the Karanja biodiesel blends as fuel in a direct injection diesel engine. Combustion, performance and emission characteristics were carried out on a single cylinder with water cooled by four stroke diesel engine coupled with multigas analyzer. The suitability of biodiesel blends for combustion analysis were done by using fuel characterisation. Fuel properties such as density, calorific value kinematic viscosity, flash and fire points of the blends were evaluated according to ASTM standards. Based on fuel properties, Karanja biodiesel blends B20, B40 and B60 were selected for the study along with diesel fuel at different compression ratios 14, 16 and 18. From the observation, it shows that at 42% load, 1500rpm engine speed and CR-18, Karanja blended biodiesel B60 indicated shorter ignition delay, maximum cylinder pressure (\(P_{\text{max}}\)), higher CHRR, higher BTE and reduced CO, HC emissions compared with the diesel fuel.

Key words: Karanja biodiesel, Transesterification, Combustion, Ignition delay, Heat release rate.

1. Introduction
Increased population, urbanisation and high levels of standard of living especially after industrial revolution, has increased per-capita energy consumption exponentially across the world. In the present scenario, the major issues are energy crisis due to fast depletion of fossil fuel resources and the environmental degradation [1, 2]. The burning of fossil fuels leads to increase in pollution gases like particulate matter, CO, SOx and NOx. The pollutants SOx, CO, NOx and particulate matter in the atmosphere creates adverse effects results in global warming, acid rain, and health hazards due to burning of fossil fuels [3, 4]. In this context, lot of effort is being put on the development of alternative fuels, conservation of energy, efficiency improvement and preservation of environment. In the last decade, a great deal of attention has been given for development in biofuels as renewable, biodegradable, and non-toxic fuels. Literature revealed that usage of biofuels had less environmental impact compared to the fossil fuels [3, 5, 6]. Presently, vegetable oils gain importance as they contains up to 90 % of the heat content as that of diesel fuel. In present scenario, the cost of vegetable oils in the world are comparatively less than the cost of fossil fuels [2]. Different varieties of vegetable oils are available across the world. Some of the examples of non-edible oil seed crops available across the world are Karanja (Pongamia pinnata), Mahua (Madhuca indica), Jatropha ( Jatropha curcas), Neem (Azadirachta indica), Rubber seed (Hevea brasiliensis) etc [2], [7]–[9].
In the recent years, more focus is given on combustion characteristics of biodiesel from various feed stocks. The experimental results indicates that the biodiesel shows decrease in ignition delay period due to higher cetane number [10]. Some researchers believe that the biodiesel contains larger kinematic viscosity significantly affects the injection of fuel spray, evaporation and atomization process, results in slow propagation of flame and longer combustion duration [11][19]. Fuel spray characteristics considered as two phase flow complex processes occurred during fuel injection. Hence it is required to understand the fluid and thermodynamic processes clearly in order to adopt suitable engine designs to achieve better performance with lower emissions [12]. The combustion of biodiesel yields lower rate of heat release, reduced peak cylinder pressure and power due to the effect of both combustion duration and ignition delay [13]. Some studies observed an reduced brake specific fuel consumption and higher brake thermal efficiency due to combined effect of injection pressure and compression ratio leads to lower emissions [14].

It was evident that from the literature, the biodiesel blends from B10 to B100 can be used in the engine without any modifications after transesterification process. Several studies shows that the higher blends of biodiesel in the engine results in better performance and reduced emissions when compared with diesel fuel[17][18][20]. The diesel engine running for longer period with higher blends of biodiesel doesn’t create any engine problems. However, the study on the effect of variable compression ratio on combustion characteristics of biodiesel and its blends is inadequate and generally lacking. Hence a detailed study on biodiesel combustion characteristics and its blends in diesel engine is required with different compression ratios and loading conditions.

2. Experimental setup and methodology

2.1. Experimental setup
Figure 1 shows diesel engine test rig was used to determine the combustion, emissions, and performance characteristics of the fuels. This engine was able to develop power of 3.75 kW running at a rated speed of 1500 rpm, water cooled engine. The loading of the engine was done using eddy current dynamometer along with load cell, required instrumentation and data acquisition. The technical specifications of diesel engine test rig were given in the Table 1. Fuel injector and fuel pump (Make: Robert Bosch) were assembled to engine by the manufacturer. The injector had three orifice holes of dia 0.25 mm as measured using Tool Makers Microscope in our laboratory. The holes were equally spaced, injector injects fuel in to the engine cylinder at 200 bar injection pressure and injection of fuel starts at 23°BTDC as per engine manufacturer specifications. Tilting cylinder head method was adopted to vary the compression ratio in test engine. Pressure transducer (piezo electric) was connected on the engine top head and synchronization of the pressure data with crank angle were done using crank angle encoder when the piston is at TDC. Crank angle encoder resolution 1°, speed 5500 rpm with TDC pulse was connected to the output shaft. The engine speed was measured using non-contact proximity sensor, range from 0-9999 rev/min. Inlet and exhaust temperatures of the engine were measured using K-type thermocouple range from 0 -1500°C. Air flow and fuel flow measurements were done by using differential transducers, range 0-99 kg/h .All the data were captured using data acquisition system.
2.2. **Exhaust gas analyzer**

The emissions obtained from combustion fuels in an engine at the exhaust manifold were effectively measured with the help of exhaust gas analyzers. Analyzers are sensitive enough to find small traces of exhaust gases and even it is present in diluted form with any other gases. Non-Dispersive Infrared (NDI) technique is used in the exhaust gas analyzer to measure exhaust pollutants such as CO, HC, NOx, and CO2. Basically, gas analyser consists of HC, O2, CO, CO2, and NOx sensors. The calibration of these measurements were done using the option of zero calibration in the instrument. Normally, the analyser takes 10 min to capture the data. Before capturing the data it removes all the traces of gases from its path using zero calibration. The range, data resolution and accuracies of each measurements are given in the table 2.
Table 2. Range, resolution and accuracy of exhaust gas analyzer.

| Gas     | Range     | Data Resolution | Accuracy |
|---------|-----------|-----------------|----------|
| CO      | 0 to 15%  | 0.01%           | ± 0.1%   |
| CO₂     | 0 to 20%  | 0.01%           | ± 0.5%   |
| HC      | 0 to 30000ppm | 1ppm            | ± 3ppm   |
| NOₓ     | 0 to 5000ppm | 1ppm            | ± 1ppm   |
| O₂      | 0 to 25%  | 0.01%           | ± 0.2%   |

2.3. Fuel characterization

Karanja biodiesel was mixed with the commercially available diesel fuel on volume basis to get the various blends such as B20, B40 and B60. The biodiesel blends along with diesel fuel were characterized and determined by conducting the as per ASTM standard procedure. Hydrometer was used to measure the specific gravity of fuel at 15°C. The density of fuels were determined using specific gravity data. Redwood viscometer was used to find the kinematic viscosity fuels at the specified temperature. Calorific value of the diesel, and blended fuel was measured by using an isothermal bomb calorimeter. Pensky marten closed cup tester was used for measuring the flash and fire points of fuel samples. The Fuel properties of diesel and Karanja biodiesel blends were tabulated in table 3.

Table 3. Properties of diesel and Karanja biodiesel blends

| Property                  | Diesel | Karanja biodiesel blends | Procedure |
|---------------------------|--------|--------------------------|-----------|
| Calorific value (kJ/kg)   | 44500  | 43048 42534 39667        | ASTM D-420 |
| Kinematic viscosity (cSt)@40°C | 2.576  | 2.723 3.21 4.003         | ASTM D-445 |
| Flash point (°C)          | 46     | 55 68 80                  | ASTM D-93  |
| Fire point (°C)           | 54     | 61 74 89                  | ASTM D-93  |
| Density (kg/m³)           | 826    | 839 848 863               | ASTM 1298  |

2.4. Uncertainty Analysis

The experimental results may have some possible errors due to instrumental conditions, calibration, observation and environmental conditions. The accuracy of the experimental results was checked using uncertainty analysis. It involves systematic procedures adopted to calculate the error estimates for experimental values. Consider different parameters such as BSFC, BP, BTE, HC, CO, CO2 and NOx to check the uncertainty of various measuring instruments. The percentage of uncertainty of various parameters of trial values of experimental results can be calculated as follows:

\[
U_y = \sqrt{\left( \begin{array}{c} \frac{\mu_y}{x_1} \end{array} \right)^2 + \left( \begin{array}{c} \frac{\mu_y}{x_2} \end{array} \right)^2 + \left( \begin{array}{c} \frac{\mu_y}{x_3} \end{array} \right)^2 + \cdots + \left( \begin{array}{c} \frac{\mu_y}{x_n} \end{array} \right)^2}
\]

Where \( y \) and \( U_y \) represents testing and uncertainty value of various parameters \( x_1, x_2, x_3, \ldots, x_n \) respectively. In this method, measurement of experimental results was done by conducting initial trial with fuel in an engine. The values are expressed in percentage. The total uncertainty of experiment is calculated as follows:

\[
Total\ Uncertainty = \left[ (Uncertainty\ of\ BSFC)^2 + (Uncertainty\ of\ BTE)^2 + (Uncertainty\ of\ BP)^2 + (Uncertainty\ of\ HC)^2 + (Uncertainty\ of\ CO)^2 + (Uncertainty\ of\ NOx)^2 + (Uncertainty\ of\ CO_2)^2 \right]^{1/2}
\]
\[
= \left[ (2.19)^2 + (1.83)^2 + (2.4)^2 + (2.59)^2 + (0.4065)^2 + (0.9615)^2 + (0.1815)^2 \right]^{1/2} \\
= \pm 4.66\%
\]

3. Results and discussions

3.1. Combustion characteristics

3.1.1 Ignition delay (ID)

Here, effect of input engine variables such as compression ratio and blends on ignition delay are depicted in figure 2. Graph reveals that the ID reduces with increase in percentage of biodiesel content in the blend. Similar trend was observed in some works [15], [16]. Since the oxygen content of biodiesel is more, with the increase in percentage of biodiesel in the blend improves the ignitability as a result ID decreases [15]. ID of the Karanja biodiesel blends B20, B40 and B60 are 7.4%, 21.43% and 64.28% lower than the diesel fuel. Shorter ignition delay at higher CR is observed. Decrease in ignition delay at higher CR. All though the molecular weight of Karanja biodiesel is more, the breakdown of higher molecular weight esters takes place at higher CR due to high temperature of the cylinder results in earlier ignition and reduced ignition delay period.

![Figure 2. Ignition delay](image)

3.1.2 Cylinder Pressure (CP)

Higher CP was observed for the blends for Karanja blends B40 and B60, when compared with the diesel fuel indicated in figure 3 a. Rise in cylinder pressure was noticed with the increased biodiesel content in the blend, due to high oxygen content, higher bulk modulus and shorter ID leads to earlier combustion process. Increased trend of CP at higher compression ratios were observed in figure 3b. At higher compression ratio, cylinder temperatures and the presence of relatively more residual gases, which lead to increase in the temperature of the charges during injection of fuel and improve the air-fuel mixing of blend and volatile combustion compounds leads to earlier ignition. Hence, the cylinder pressure increases with increased compression ratio of the engine.
3.1.3 Heat release rate (HRR)
All Karanja biodiesel blends show earlier combustion than diesel fuel. After the ignition delay period, heat release rate will be more due to the rapid burning of premixed fuel–air mixture. In the starting stage of combustion, all the fuels exhibit heat release negative due to accumulated fuel vaporises during ignition lag period and becomes positive once the combustion process starts. Figure 4a indicates the maximum HRR decreases slightly with increase biodiesel content in the blend. As, the content of Karanja biodiesel in the blend increases, slight decrease in maximum HRR noticed mainly due to reduced ignition delay period. On the other hand, the fuel diesel (B0) show higher rate of heat release, due to the more collection of fuel during longer ignition delay period. However, Karanja blended biodiesel releases the heat even during late combustion phase. This is because higher content of oxygen available in the fuel helps in burning of the residual fuel in the mixed combustion phase to ensure the complete burning of the fuel.

Maximum HRR is noticed at higher CR-18 when compared with other compression ratios CR-16 and CR-14 shown in figure 4b. Along with this, mixed combustion phase is more for the biodiesel blend at higher CR, due to higher cylinder temperature, evaporation occurs at a faster rate results in improved combustion process.

3.1.4 Cumulative Heat Release Rate (CHRR)
Figure 5a shows cumulative heat release rate (CHRR) of various Karanja biodiesel blends. CHRR of blend B60 is more than other blends might be due to higher oxygen content of fuel, shorter ID which initiates earlier combustion and releases the heat in mixed combustion phase. The effect of CR on CHRR
shown in figure 5b. CHRR at higher CR is observed to be more, due to higher cylinder temperature results in more amount of heat release.

![Figure 5. Cumulative heat release rate](image)

3.2. Performance characteristics

3.2.1 Brake Specific Energy Consumption (BSEC)

BSEC of blends of Karanja biodiesel at different loads shown in figure 6a. When the engine running at higher compression ratio CR-18, low BSEC of Karanja blended biodiesel than the diesel fuel was observed. Even though the density and viscosity of the blended biodiesel is more, the presence of more oxygen content blend increases the rate of combustion and break down the molecular weight of the biodiesel at higher temperature results in earlier start of combustion and improved combustion process. This turn results in improved power out of the engine. Decrease in BSEC of the biodiesel blend at higher compression ratio was observed in Figure 6b, due to the better evaporation fuel in to the engine cylinder occurs due to high cylinder temperature, develops more power in turn reduces BSEC.

![Figure 6. Brake specific energy consumption](image)

3.2.2 Brake Thermal Efficiency (BTE)

Figure 7a shows the BTE of Karanja biodiesel blends at different loads. The curve indicates that the BTE of blended biodiesel is relatively higher than diesel fuel. This is because of higher cylinder pressure and presence of more oxygen content of the blend improves the efficiency of the combustion, in turn develops more power and heat release in the combustion process. BTE of biodiesel blends B20, B40 and B60 are 5.86%, 15.62% and 21.04% higher than diesel fuel at 42% loading condition. BTE of the biodiesel blends at CR-18 are found to be more compared with other compression ratios shown in figure
7b. BTE increases at higher CR and load, the evaporation of Karanja blends takes place completely due to hot combustion chamber and better mixing of biodiesel blends results in higher BTE [17][20].

![Graph](image1)

**Figure 7. Brake thermal efficiency**

3.3. Emission characteristics

3.3.1 CO emissions

CO emissions of Karanja biodiesel blends operating at various loads are shown in figure 8a. Karanja biodiesel blends B40 and B60 yields slightly lower emissions than the diesel fuel. Reduced CO emissions are observed for the biodiesel blends mainly due to presence of more oxygen content results in better combustion. The biodiesel blend B40 shows 15.59% and 8.49% reduced CO emissions compared with diesel fuel at 14% and 28% loading conditions. Whereas the blend B60 shows 3.6% at 28% load, 1.42% at 42% load and 20.40% at 70% load, reduced CO emissions than diesel fuel. At higher biodiesel in the blends, the CO emissions reduces significantly at higher loading conditions mainly due to more fuel burning results in high temperature of the engine cylinder and oxygen content of the biodiesel.

Large reduction in CO emissions at higher CR are indicated in figure 8b. CO emissions of blend B60 at CR-18 are found to be 10.38%, 11.82% and 27.73% lower when compared with the CR-16 at 28%, 42% and 70% load respectively. Reduced CO emissions at higher CR observed might be due to higher temperature of the engine cylinder and peak cylinder pressure leads to better combustion.

![Graph](image2)

**Figure 8. CO emissions**
3.3.2 HC emissions
HC emissions of the biodiesel blends and diesel fuel for various loads as shown in figure 9a. HC emissions of biodiesel blends are reduced at higher loads when compared with the diesel fuel. The reason for this may be due to the shorter ID, higher pressure of the cylinder, temperature results in better combustion process. The biodiesel blend B60 revealed 30%, 57.42%, 50.73% and 58.75% reduced HC emissions compared with diesel fuel at 14%, 28%, 42%, 56% and 70% load respectively.

Also, significant reduction in HC emissions are noticed at CR-18 when compared with other compression ratios shown in figure 9b. The decreased trend at higher CR, mainly due to higher cylinder pressure and temperature yields in the decomposition of higher molecular weight of the methyl ester makes the blend volatile and readily mixed with air leads to complete combustion. Karanja biodiesel blend B60 at CR-18 shows 23.63%, 44.06%, 39.84%, 17.35% and 45% reduced HC emissions compared with CR -16 at 14%, 28%, 42%, 56% and 70% load respectively.

![Figure 9. HC emissions](image)

3.3.3 NOx emissions
NOx emissions of Karanja biodiesel blends given in figure10a showed increased trend than the diesel fuel. The occurrence of this might be due to more oxygenated content of blend, higher cylinder temperature and peak cylinder pressure. The combustion of biodiesel blend B20 yields more NOx emissions than the blends B40 and B60 mainly due to longer delay in the ignition. Also, the NOx emissions of blend B60 is more at higher compression ratio shown in figure 10b.

![Figure 10. NOx emissions](image)

4. Conclusions
In this work, combustion, emission and performance characteristics of Karanja blended biodiesels in CI engine were carried out for different compression ratios and loads. The outcomes of the research findings are summarized as follows:

- Peak pressure of the Karanja blend B60 is 19.39% and B40 is 7.25% more than diesel fuel, due to reduced ignition delay, increased oxygen content and earlier combustion process. Karanja biodiesel blends indicates shorter ignition delay than the diesel fuel. As the biodiesel content in the blend increases improves the ignitability, and reduces ignition delay.

- Low peak HRR of Karanja blended biodiesel was noticed than the diesel fuel, due to decrease in ignition delay period and peak HRR is high at higher compression ratio was observed mainly due to higher temperature of the engine cylinder, evaporation occurs at a faster rate results in improved combustion process.

- Decrease in BSEC of the biodiesel blend at higher CR was observed, due to the injection of more fuel in to the engine cylinder, develops more power in turn reduces BSEC. Higher BTE was noticed in Karanja blended biodiesel than the diesel fuel at the 42% load.

- Reduced emissions of CO were observed for the blended biodiesel mainly due to presence of more oxygen in the biodiesel results in better combustion. Biodiesel blends combustion yields low HC emissions at higher loads than the diesel fuel. The reason for this may be owing to the shorter ID, higher cylinder pressure, temperature and better combustion process. But increased, NOx emissions of Karanja blended biodiesel were noticed at higher loads and compression ratios.

References

[1] O. S. S. Ivana B. Bankovi and V. B. Veljkovi 2012, “Biodiesel production from non-edible plant oils,” Renew. Sustain. Energy Rev., vol. 16, pp. 3621–3647.

[2] L. M. Das Agarwal A. K 2001, “Biodiesel development and characterization for use as a fuel in compression ignition engines,” ASME J. gas turbines power, vol. 123, no. April, pp. 441–447.

[3] N. R. Banapurmath, P. G. Tewari, and V. N. Gaitonde 2012, “Experimental investigations on performance and emission characteristics of Hoge oil biodiesel (HOME) operated compression ignition engine,” Renew. Energy, vol. 48, pp. 193–201.

[4] K. J. C. H. An, W. M. Yang, A. maghbouli, J. Li, S. K. Chou 2013, “Performance, combustion and emission characteristics of biodiesel derived from waste cooking oils,” Appl. Energy, vol. 112, pp. 493–499.

[5] E. Alptekin and M. Canakci 2008, “Determination of the density and the viscosities of biodiesel – diesel fuel blends,” Renew. Energy, vol. 33, pp. 2623–2630.

[6] Niraj kumar, Varun, S R Chaun 2013 “Performance and emission characteristics of biodiesel from different origins : A review,” Renew. Sustain. Energy Rev., vol. 21, pp. 633–658.

[7] A. S. Silitonga, H. H. Masjuki, T. M. I. Mahlia, H. C. Ong, A. E. Atabani, and W. T. Chong 2013, “A global comparative review of biodiesel production from jatropha curcas using different homogeneous acid and alkaline catalysts: Study of physical and chemical properties,” Renew. Sustain. Energy Rev., vol. 24, pp. 514–533.

[8] A. E. Atabani, A. S. Silitonga, H. C. Ong, T. M. I. Mahlia, H. H. Masjuki, I. A. Badruddin, and H. Fayaz 2013, “Non-edible vegetable oils: A critical evaluation of oil extraction, fatty acid compositions, biodiesel production, characteristics, engine performance and emissions production,” Renew. Sustain. Energy Rev., vol. 18, pp. 211–245.

[9] V. B. Borugadda and V. V Goud 2012, “Biodiesel production from renewable feedstocks: Status and opportunities,” Renew. Sustain. Energy Rev., vol. 16, no. 7, pp. 4763–4784.

[10] P. K. Devan and N. Va Mahalakshmi 2009, “Study of the performance, emission and combustion characteristics of a diesel engine using poon oil-based fuels,” Fuel Process. Technol., vol. 90, no. 4, pp. 513–519.
[11] D. H. Qi, C. F. Lee, C. C. Jia, P. P. Wang, and S. T. Wu 2014, “Experimental investigations of combustion and emission characteristics of rapeseed oil – diesel blends in a two cylinder agricultural diesel engine,” *Energy Convers. Manag.*, vol.77, pp. 227–232.

[12] A. K. Agarwal and V. H. Chaudhury 2012, “Spray characteristics of biodiesel / blends in a high pressure constant volume spray chamber,” *Exp. Therm. Fluid Sci.*, vol. 42, pp. 212–218.

[13] M. Gumus 2010, “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*, vol. 89, no. 10, pp. 2802–2814.

[14] K. Muralidharan, D. Vasudevan, and K. N. Sheeba 2011, “Performance, emission and combustion characteristics of biodiesel fuelled variable compression ratio engine,” *Energy*, vol. 36, no. 8, pp. 5385–5393.

[15] G. L. N. Rao, B. D. Prasad, and S. Sampath 2007, “Combustion analysis of diesel engine fueled with jatropha oil methyl ester - diesel blends,” *Int. J. Green Energy*, vol. 4, pp. 645–658.

[16] A. Dhar, R. Kevin, and A. Kumar 2012, “Production of biodiesel from high-FFA neem oil and its performance , emission and combustion characterization in a single cylinder DICI engine,” *Fuel Process. Technol.*, vol. 97, pp. 118–129.

[17] Atul Dhar, Avinash Kumar Agarwal 2014,” Performance, emissions and combustion characteristics of Karanja biodiesel in a transportation engine”, *Fuel*, Vol. 119, PP. 70–80.

[18] P. R. K Sivaramakrishnan 2014, “Optimization of operational parameters on performance and emissions of a diesel engine using biodiesel,” *Int.J.Environ.Sci.Technol, vol. 11*, pp. 949–958.

[19] Ezio Mancaruso, Carmela Perozziello, Luigi Sequino, Bianca Maria Vaglieco 2019, “Characterization of pure and blended biodiesel spray in a compression ignition engine by means of advanced diagnostics and 1D model”, *Fuel, vol.239*, pp.1102-1114.

[20] R. Balasubramanian and K. A. Subramanian 2019, “Experimental investigation on the effects of compression ratio on performance, emissions and combustion characteristics of a biodiesel-fueled automotive diesel engine”, biofuels, Taylor & Francis, doi.org/10.1080/17597269.2018.1558840, pp.1-12