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Tamanu oil - an alternative fuel for variable compression ratio engine

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Abstract

Biodiesel can be produced from vegetable oils and also from waste fats. Biodiesel is a mono-alkyl-ester of long chain fatty acids derived from renewable feedstock such as vegetable oils by transesterification process. The esterified cotton seed oil, pungam oil, rice bran oil, and tamanu oil are chosen as the alternative fuels. Among these oils, tamanu oil is considered for the first time as an alternative fuel. An experiment is conducted to obtain the operating characteristics of the variable compression ratio (VCR) engine run by chosen esterified oils, and the results are compared with esterified tamanu oil. From the comparison of results, it is inferred that the engine performance is improved with significant reduction in emissions for the chosen oils without any engine modification. The effective compression ratio can be fixed based on the experimental results obtained in the engine since the findings of the present research work infer that the biodiesel obtained from tamanu oil is a promising alternative fuel for direct-injection four-stroke VCR engine.

Keywords: Biodiesel, Esterified tamanu oil, Compression ratio, VCR engine, Transesterification

Background

Vegetable oils have good ignition quality since they are not branched and have very long molecular chains. Certain functional groups and the poor volatility could be responsible for their low cetane numbers. The heating value of vegetable oils is somewhat lower due to oxygen content, and viscosity and carbon residue are higher than diesel due to their larger molecular mass and chemical structure [1]. The flash point of these oils is much higher than that of diesel, indicating that they are much safer to store than diesel oil. They are about 10% denser than diesel [2]. Their cold point is higher, indicating problems of thickening or even freezing at low ambient temperatures. It is evident that vegetable oils are much less volatile than diesel. This makes their slow evaporation when injected into the engine. Vegetable oils have cetane numbers of about 35 to 50 depending on their composition [3]. It is seen that the value is very close to diesel. The compression process effectively starts only after the intake valve closes and also depends on the momentum of the flow into the cylinder, and thus, the actual realized amount of compression ratio is known as the effective compression ratio (ECR). ECR is a more suitable indicator of the compression process, and it also influences the engine operation. One of the very promising and interesting fields of study involves the use of alternative fuels including biodiesel and diesel fuels to provide effective solutions [4]. The development of treatment devices has also mitigated the emission problem to a large extent while allowing the combustion process to be optimized for maximum fuel efficiency [5]. Lehman et al. [6] obtained high ester conversion with a 6:1 M ratio of methanol to vegetable oil. In the process of peanut oil esterification, the 6:1 M ratio liberated significantly more glycerol than the 3:1 M ratio. These investigators also found that glycerol yields increased from 77% to 95% as the sodium hydroxide catalyst increased from 0.2% to 0.8% at the 6:1 M ratio. Fatty ester is the major product, and glycerol is the by-product. Barsic and Humke [7] have found that transesterification is one of the methods by which viscosity could be drastically reduced and the fuel could be adopted for use in diesel engine. The transesterification process involves reacting vegetable oils with alcohols such as methanol or ethanol in the presence of a catalyst (usually sodium hydroxide) at about 70°C to give the ester and the by-product glycerin. This esterified vegetable oil is popularly known as biodiesel which is commercially

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available in developed countries due to its distinct advantage over the conventional diesel. Free fatty acids (FFAs) present in the pongamia oil have got the greater influence in the process of converting it into biodiesel. This has been observed during the biodiesel preparation process in the laboratory level. However, their high viscosity and poor volatility lead to reduced thermal efficiency and increased hydrocarbon, carbon monoxide, and smoke emissions. Vellguth [8] studied the performance of a direct-injection single-cylinder diesel engine on vegetable oil. He conducted a variable load test on the engine with rapeseed oil, peanut oil, and soybean oil. He found that vegetable oils which are results of performance are comparable to diesel values with slightly reduced thermal efficiency. He concluded that vegetable oils could be directly used as fuel in diesel engines on a short-term basis.

Ramesh et al. [9] investigated the performance of a glow plug-assisted hot surface ignition engine using methyl ester of rice bran oil as fuel. Normal and mnemonic crown pistons were used for their tests. They reported an improvement in brake thermal efficiency of about 1% when the glow plug is on. The percentage improvement in brake thermal efficiency was higher in the case of normal piston compared with that in the case of mnemonic piston. Larry Wagner et al. [10] studied the effect of soybean oil esters on the performance and emissions of a four-cylinder direct-injection turbocharged diesel engine. They found that the engine performance with soybean oil esters is the same with diesel. Clark et al. [11] studied the effect of methyl and ethyl esters of soybean oil on engine performance and durability in a direct-injection John Deere four-cylinder diesel engine. They observed that the engine fuelled with soybean esters produced less power output with an increase in fuel consumption. Emissions results were found to be similar to diesel. Panwar et al. [12] conducted an experiment in single-cylinder variable compression ratio diesel engine at different loads. The engine performance for castor methyl ester was investigated. The lower blends of biodiesel increased break thermal efficiency and reduced fuel consumption. The work done by Gumus et al. [13] deals with the performance and emissions of a compression-ignition diesel engine without any modification using neat apricot seed kernel oil methyl ester and its blends. They found that a lower concentration of apricot seed kernel oil methyl ester in blends gives better improvement in engine performance and exhaust emissions. The work done by Celikten et al. [14] tells about the performance and emissions of diesel fuel from rapeseed and soybean oil methyl esters injected at different pressures (250, 300, and 350 bar), and they were compared. It has been found that the torque and power of diesel fuel engine were reduced with increasing injection pressure. Smoke level and CO emission were also reduced, while NO_x emission was increased as the injection pressure was increased. Jindal et al. [15] studied about the comparison of performance and emission characteristics for different compression ratios along with injection pressure, and the best possible combination for operating engine with Jatropha methyl ester has been found. It is found that the combined increase in compression ratio and injection pressure results in an increased brake thermal efficiency and reduced brake specific fuel consumption while emissions were lowered. The combustion performance and exhaust emission characteristics of turpentine oil fuel blended with conventional diesel fuel in a diesel engine was evaluated [16]. The combustion characteristics of crude rice bran oil methyl ester blended in a direct-injection compression-ignition engine were analyzed, and it was found that cylinder pressure was comparable, whereas delay period and the maximum rate of pressure rise were lower than that of diesel. Masjuki et al. [17] analyzed exhaust emissions and lube oil deterioration of a diesel engine fuelled with Malaysian palm oil diesel (ester of palm oil) and ordinary diesel emulsions containing 5% to 10% of water by volume and compared with 100% palm oil diesel (POD) on 200-h endurance tests. They observed that the exhaust of POD and emulsified fuels was much cleaner, containing less CO, CO_2, HC, NO_x, SO_x, and smoke level, than that of neat vegetable oil. Power output was slightly reduced when using POD emulsified fuels.

Monyem and Van Gerpen [18] conducted experiments to characterize the effect of oxidized biodiesel on engine performance and emissions. They used methyl soyate for testing a John Deere turbocharged direct-injection diesel engine. Oxidization was done by heating the oil up to 60°C and by bubbling. The diesel blends with 20% biodiesel were tested at two different loads and three injection timings. They found that the performance of neat biodiesel and their blends was similar to that of diesel fuel with the same brake thermal efficiency but higher fuel consumption. Compared with non-oxidized biodiesel, oxidized biodiesel produced lower exhaust carbon monoxide and hydrocarbons of 16%. Statically, there was no significant difference on the oxides of nitrogen. They found significant reduction in the Bosch smoke number with neat biodiesel and blends with diesel. The highest reduction was found for the oxidized biodiesel. Jacobs et al. [19] demonstrated drastic reduction in NO_x with high amounts of exhaust gas recirculation (EGR) on a light-duty diesel engine with 5% reduction in fuel

Table 1 Percentages of FFA values for biodiesel

Sample number	Biodiesel	FFA (%)
1	Cotton seed oil	1.9
2	Pungam oil	2
3	Rice bran oil	2.1
4	Tamanu oil	1.8

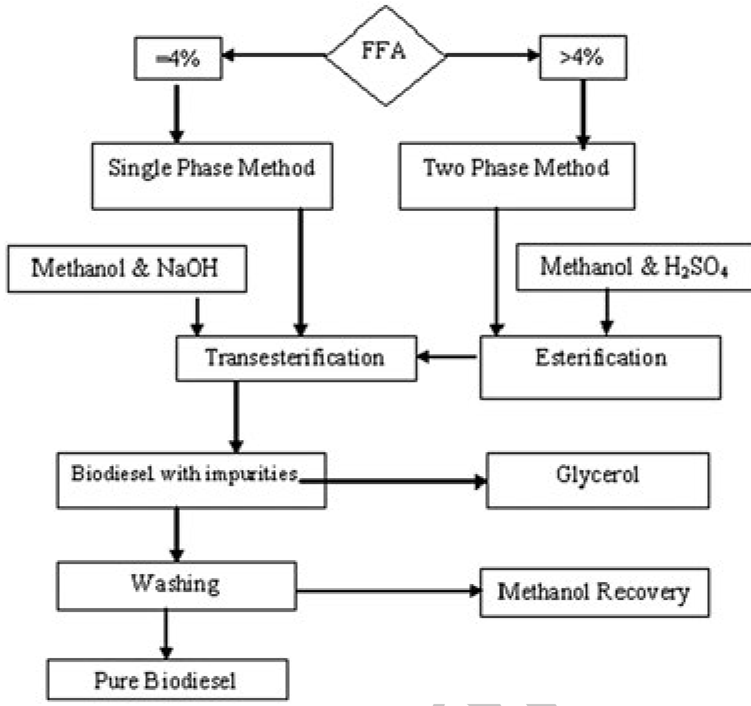

Figure 1 Schematic presentation of biodiesel production.

efficiency. Ishikawa et al. [20] performed early injection PCCI on an engine and a vehicle at low load operating conditions using high EGR rates. Using a low cetane number diesel fuel, their results showed about a 90% decrease in NO_x and an 85% reduction in particulate matter (PM) without any fuel efficiency drop. Murata et al. [21] reported a 60% reduction in both NO_x and PM with a very minute increase in fuel consumption in a single-cylinder engine. They used early fuel injection with high EGR rates and reduced ECR by intake valve closing (IVC) modulation. The model was validated against different operating points using engine data from Cummins. In addition, the model was also validated with data from a second engine of similar make at Purdue University's Herrick Laboratories. This model will be used here for the simulation study. Combustion homogenization is accomplished by early injection of fuel, allowing more time for the fuel to get thoroughly mixed with the charge inside the cylinder [22], resulting in a more uniform combustion. With early injection of fuel, combustion often occurs before it is desired, and one way to prevent this combustion is by reducing the ECR. This can be done by IVC modulation. The formation of uniform charge before the beginning of combustion enables reduction in particulate matter [23]. Also, the lower flame and post combustion temperature due to premixed combustion reduce NO_x formation. The early fuel injection with high EGR reduces the effective compression ratio by IVC modulation. It also outlined the various methods of achieving the desired burned gas fraction inside the cylinder by variable valve actuation. A very straightforward

Table 2 Comparison of biodiesel properties with diesel

Number	Properties	Esterified cotton seed oil	Esterified pungam seed oil	Esterified rice bran oil	Esterified tamanu oil	Diesel
1	Kinematic viscosity at 32°C (Cst)	11.1	17.84	18.7	9.0	6.0
2	Flash point (°C)	234	205	200	108	72
3	Density at 32°C (g/cm^3)	0.886	0.913	0.935	0.905	0.86
4	Lower calorific value (kJ/kg)	36,800	37,304	38,952	41,500	44,000
5	Pour point (°C)	15	13.2	15	11.3	12
6	Cetane number	45.5	55	53	50	45

Table 3 Variable compression ratio engine specifications

Number	Engine parts	Specification
1	Make and model	Kirloskar/PS 234
2	Number of cylinder	Single
3	Ignition system	Compression ignition
4	Bore and stroke	87.5 × 110 mm
5	Rated power	3.5 kW at 1,500 rpm
6	Cooling medium	Water-cooled
7	Combustion chamber	Open chamber (direct injection)
8	Compression ratio	12:1 to 18:1

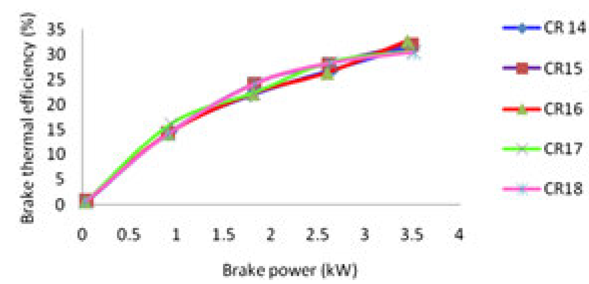

Figure 3 Variation of brake thermal efficiency with brake power.

method to compute the ECR is to take a ratio of the volume at IVC timing to the volume when the piston is at TDC. Although this method is generally good enough for initial system design, higher accuracy is expected for predicting performance and emissions [24]. Therefore, a pressure-based method is used to compute the effective compression ratio using the *P*-*θ* diagram of the process.

Methods

Preparation of biodiesel

Based on the percentage of FFA value, biodiesel can be prepared by either a single-phase or a two-phase method. The percentages of FFA values for biodiesel are given in Table 1.

Single-phase method

If the percentage of FFA present in the raw vegetable oil is less than 4%, the *transesterification* process by single-phase method has to be chosen. In this method, a measured amount of methanol (CH_3OH) and sodium hydroxide (NaOH) has to be mixed thoroughly with a measured amount of vegetable oil. The mixture is heated and maintained at 65°C for 2 h, and then, it undergoes natural cooling. Glycerol will deposit at the bottom of the flask, and it is separated out using a separating funnel. The remnants in the flask are the esterified vegetable oil. Another commercial name for esterified vegetable oil is biodiesel.

Two-phase method

If the percentage of FFA present in the raw vegetable oil is more than 4%, then we have to choose the two-phase method. In this method, the oil has to undergo esterification. Measured quantity of sulphuric acid and methanol has to be taken and mixed thoroughly and added with a measured amount of vegetable oil. The mixture is heated and maintained at 65°C for 2 h. The fatty ester is separated after natural cooling. At second level, the separated oil from the separating funnel has to undergo transesterification. Methoxide (methanol + sodium hydroxide) is added with the above ester and heated to 65°C. The same temperature is maintained for 2 h with continuous stirring, and then, it undergoes natural cooling for 8 h. Glycerol will deposit at the bottom of the flask, and it is separated out by a separating funnel. The remnants in the flask are the esterified vegetable oil (biodiesel).

The separated biodiesel from the above-mentioned method contains various impurities like traces of glycerol, unused methanol, soap particles, etc. Water washing is carried out to remove all impurities. *Air bubble wash* is one of the methods normally recommended in the laboratory level. In this method, the impure biodiesel is placed in a beaker initially. Water is added slowly through the side wall of the beaker (both are immiscible). It is ensured that the equal amount of water is added above the level of biodiesel. Air is made to pass through the biodiesel and the water from the bottom of

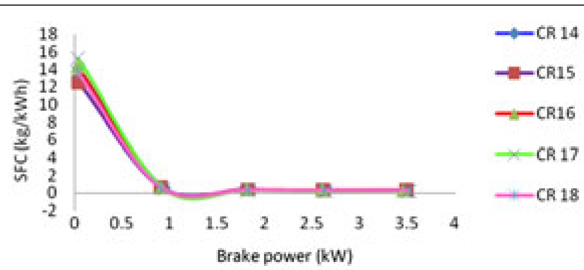

Figure 2 Variation of specific fuel consumption with brake power.

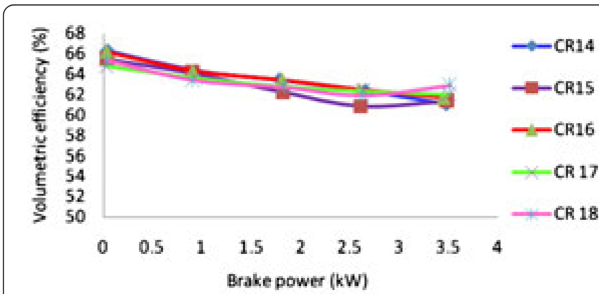

Figure 4 Variation of volumetric efficiency with brake power.

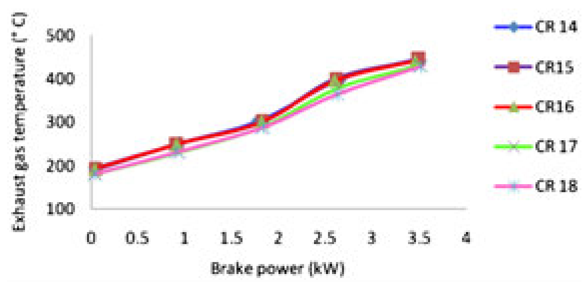

Figure 5 Variation of exhaust gas temperature with brake power.

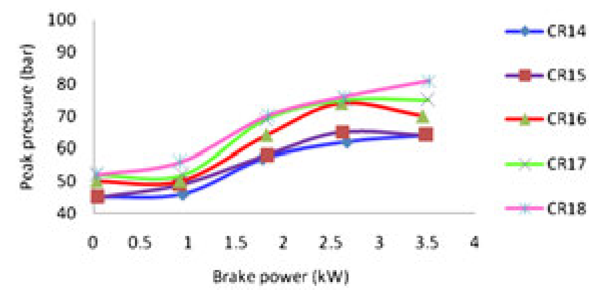

Figure 7 Variation of peak pressure with brake power.

the beaker with the help of a bubbler (electrically operated). The air will then take away all impurities from the biodiesel; they will move up as the bubbles move up, and they are added in the water. The unused methanol will be diluted in water. The traces of glycerol and soap particles make the water to become like soap water. Once the water becomes like soap water, the bubbler is stopped. After allowing some time for impurities to settle, the biodiesel is drained from the separating funnel, and pure biodiesel will be directly used, with or without blending, in the engine (Figure 1).

Properties of biofuel

The basic important properties of biodiesel like calorific value, flash point, viscosity, density, pour point, and cetane number are tested in the laboratory. The values are tabulated in Table 2 and compared with diesel.

Experimental setup

The specification of the engine is listed in Table 3. The engine performance analysis software package (Engine Soft) has been employed for online performance analysis. The setup consists of a single-cylinder four-stroke variable compression ratio (VCR) diesel engine coupled with an Eddy current dynamometer for loading. The compression ratio can be changed without stopping the engine and without altering the combustion chamber. A specially designed tilting cylinder block arrangement is used for varying the compression ratio. The setup is provided with necessary instruments for combustion pressure and crank-angle measurements. These signals are interfaced in a computer through an engine indicator for *Pθ-PV* diagrams. The setup has a stand-alone panel box consisting of transmitters for air and fuel flow measurements, process indicator, and engine indicator. Rotameters are provided for cooling water and calorimeter water flow measurement. The setup enables the VCR engine operating parameters such as brake power (BP), brake mean effective pressure (BMEP), indicated mean effective pressure, brake thermal efficiency, indicated thermal efficiency and mechanical efficiency, etc to be studied.

Experimental methodology

Using esterified tamanu oil in the variable compression ratio engine at a rated speed of 1,500 rpm, the performance analysis is carried out. In every test, volumetric efficiency specific fuel consumption and exhaust gas emissions such as carbon monoxide (CO), hydrocarbon (HC), nitrogen oxides (NO_x), carbon dioxide (CO_2), and oxygen (O_2) are measured. From the initial measurement, brake thermal efficiency, specific fuel consumption, BP, BMEP, mechanical efficiency, and exhaust gas temperature with respect to compression ratios 18:1 to 14:1 are calculated and recorded. At each operating conditions, the performance

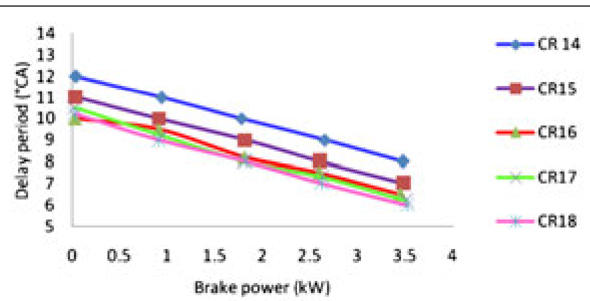

Figure 6 Variation of delay period with brake power.

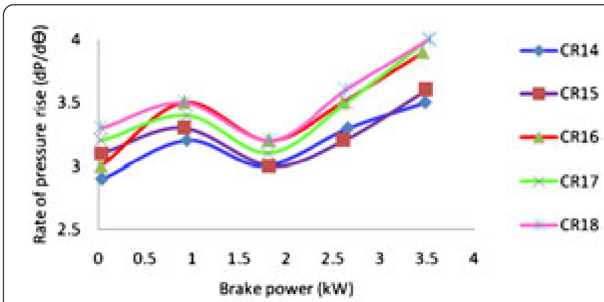

Figure 8 Variation of rate of pressure rise with brake power.

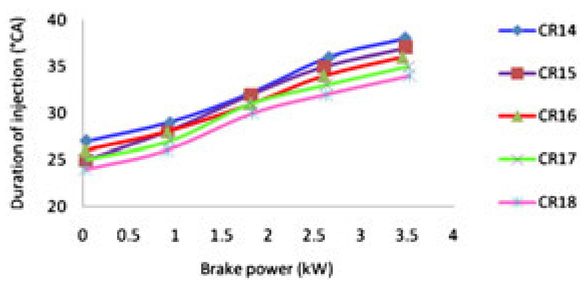

Figure 9 Variation of duration of injection with brake power.

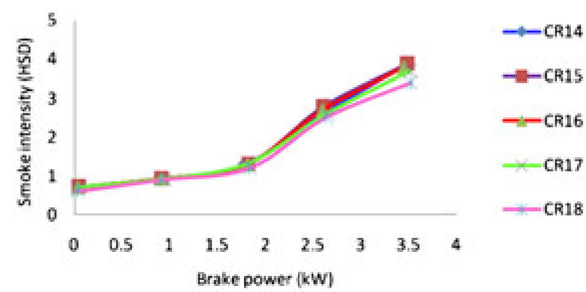

Figure 11 Variation of smoke intensity with brake power.

characteristics, combustion characteristics, and exhaust emission levels are performed and the same procedure is repeated for other loads also.

Results and discussion

The operating characteristics are analyzed by running the VCR engine with esterified tamanu oil at different compression ratios ranging from 14 to 18 at different load conditions.

Performance characteristics

The specific fuel consumption decreases with the increase in compression ratio. It is found to be lower at a compression ratio of 18. The specific fuel consumption of the esterified tamanu oil at the compression ratio of 18 is 0.24 kg/kWh, whereas at the compression ratio of 14, it is 0.29 kg/kWh for maximum load. It has been observed that the brake thermal efficiency of the biodiesel is slightly higher at the compression ratio of 16 and lower at the compression ratio of 18. The brake thermal efficiency of the esterified tamanu oil for the compression ratio of 18 is 30.4% at maximum load. By varying the compression ratio of the engine, the brake thermal efficiency also gets varied. The variation in the volumetric efficiency is comparably less for all range of compression ratios, and it is high at CR18. The reason for the increase in volumetric efficiency is due to increase in volume of incoming air to the engine. The volumetric efficiency of esterified tamanu oil for compression ratio of 18 is 62.91% at maximum load.

The result indicates that the variation in exhaust gas temperature is very minimal when the compression ratio is varied from 14 to 18. The highest temperature obtained is 446.35°C at the compression ratio of 14 and 430.5°C at the compression ratio of 18 at maximum load. These performance characteristic curves of the esterified tamanu oil have been compared by running the engine at various compression ratios, and it is shown in Figures 2, 3, 4, 5, and 6.

Combustion characteristics

The delay period is consistently low for esterified tamanu oil by increasing the compression ratio from 14 to 18. The delay period is 8° crank angle (CA) at the compression ratio of 14 and 6°CA at 18 for maximum load. The peak pressure increases linearly from 64 to 81 bar as the compression ratio increases from 14 to18 for maximum load. The rate of pressure rise is the derivative of peak pressure with respect to the crank angle degree. It varies from 3.3 to 4 bar per degree of CA for the compression ratio of 18 at maximum load. It decreases when the compression ratio is increased from 14 to 18. The duration of injection is 38°CA at the compression ratio 14 and 34°CA at 18 for maximum load. It increases with increase in compression ratios from 14 to 18. The combustion duration is 40°CA at the compression ratio of 14 and 43°CA at the

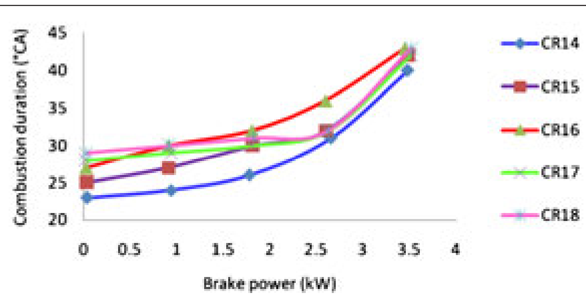

Figure 10 Variation of combustion duration with brake power.

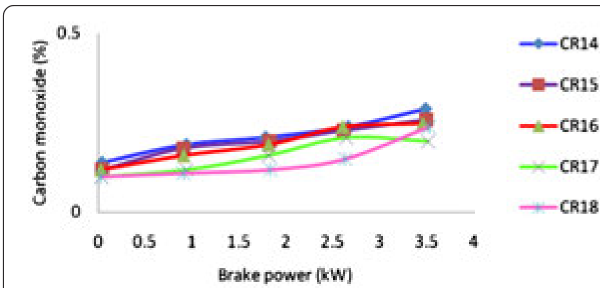

Figure 12 Variation of carbon monoxide emission with brake power.

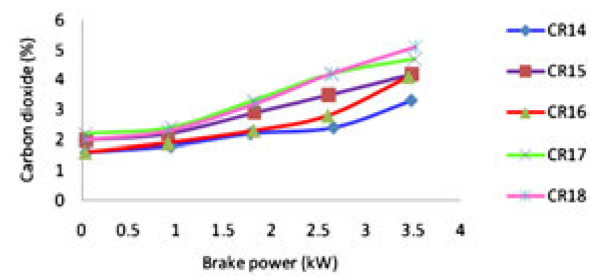

Figure 13 Variation of carbon dioxide emission with brake power.

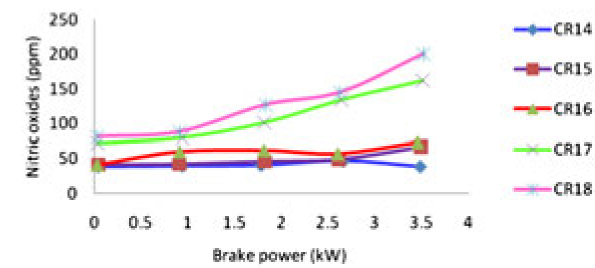

Figure 15 Variation of NO_x emission with brake power.

compression ratio of 18 for maximum load. It decreases with the increase in compression ratios from 14 to 18. The smoke intensity is 3.9 Hartridge smoke density (HSD) at the compression ratio of 14 and 3.4 HSD at the compression ratio of 18 for maximum load. These combustion characteristics are shown in Figures 7, 8, 9, 10, and 11.

Emission characteristics

These emission characteristics of the esterified tamanu oil have been compared, and they are shown in Figures 12, 13, 14, 15, and 16. The percentage of CO emission for low compression ratio increases due to the rising temperature in the combustion chamber. The CO emission of the esterified tamanu oil is found to be lower for high compression ratio of 18, and it is 0.18% at maximum load. The esterified tamanu oil emits higher percentage of CO_2 at high a compression ratio, less at lower compression ratios, and vice versa. More amount of CO_2 is an indication of complete combustion of fuel in the combustion chamber. The CO_2 emission is 3.3% at the compression ratio of 14 and 5.1% at the compression ratio of 18 for maximum load. In the case of esterified tamanu oil, the HC emission decreases with increase in compression ratio. This is due to the complete combustion of oil at a higher compression ratio. The HC emission is 152 ppm at the compression ratio of 14 and 125 ppm at the compression ratio of 18 for maximum load. From the figure, it is observed that the NO_x emission for esterified tamanu oil is higher with the increase in compression ratio. It is obvious that for higher compression ratio, NO_x emission is higher than that of low compression ratio. The reason for the higher NO_x emission for esterified tamanu oil is the higher peak temperature. The NO_x emission for esterified tamanu oil at the compression ratio of 18 is 201 ppm at maximum load. The particulate emission decreases with the increase of compression ratio from 14 to 18 for all loads. The particulate emission is 1,900 mg/m^3 at the compression ratio of 14 and 1,600 mg/m^3 at the compression ratio of 18 for maximum load.

Conclusions

The study aims to evaluate the suitability of using biodiesel as an alternative fuel in VCR engine. Experimental investigations were carried out on the operating characteristics of the engines. The following conclusions are drawn from the investigations:

- The brake thermal efficiency of the VCR engine slightly increases at higher loads when compared with that of standard engine.
- The specific fuel consumption is lower at all load conditions.
- The volumetric efficiency increases at higher loads.
- The exhaust gas temperature is the same and increases as the load increases.
- The delay period is consistently low when load increases.

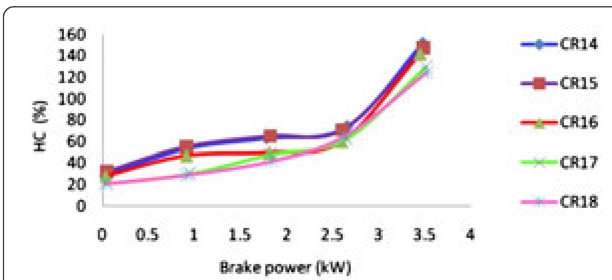

Figure 14 Variation of HC emission with brake power.

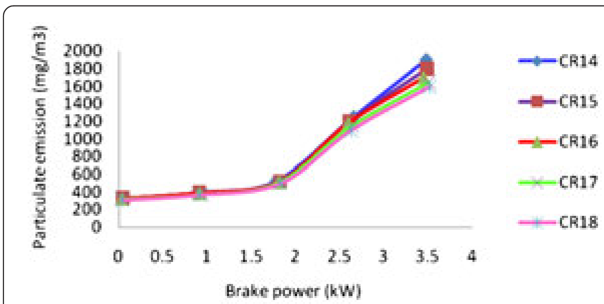

Figure 16 Variation of particulate emission with brake power.

- The peak pressure and the rate of pressure rise are higher and increase with increase in load.
- The duration of injection slightly decreases at all loads.
- Combustion duration is slightly higher at lower loads and lower at higher loads.
- There is not much variation in the HC, CO, CO_2, and NO_x emissions at all loads.
- Similarly, there is not much variation in the case of particulate matter emission and smoke intensity.

From the above conclusions, it is proved that the biodiesel could be used as an alternative fuel in VCR engine without any engine modifications.

Abbreviations
BMEP: brake mean effective pressure; CA: crank angle; CR: compression ratio; ECR: effective compression ratio; IVC: intake valve closing; PM: particulate matter; VCR: variable compression ratio.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
MTR participated in the preparation of biodiesel from cotton seed oil, pungam oil, rice bran oil, and tamanu oil and carried out the experimental investigation for these biodiesel. MKKK guided the preparation of biodiesel and helped carry out the experimental investigation. He also corrected the manuscript as per journal standards. All authors read and approved the final manuscript.

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MTR is an assistant professor at the Department of Mechanical Engineering in SASTRA University, Thanjavur, Tamilnadu, India. He completed his MT in Energy Engineering from the National Institute of Technology, Trichy. His research interests include the preparation of biodiesel from vegetable oils and the testing of these oils in diesel engine for performance characteristics. He is currently involved in the Research and Modernization project sanctioned by SASTRA UNIVERSITY at a cost of Rs 6.2 lakhs for variable compression ratio engine (VCR engine). MKKK is the principal of Paventhar Bharathidasan College of Engineering and Technology, Trichy. He received his ME in Automobile Engineering from Anna University, MIT Campus, Chennai and his PhD in Alternate Fuel for IC Engine from Bharathidasan University, Trichy. His research interests include the biodiesel in internal combustion engine with less pollution and recent trends in automobile technology. He is an active life member of the Society of Automotive Engineering.

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