Experimental Investigation of the Emission and Performance Characteristics of a DI Diesel Engine Fueled with the Vachellia nilotica Seed Oil Methyl Ester and Diesel Blends

Chandra Sekhar Sriharikota,* Karuppasamy Karuppasamy, Vedaraman Nagarajan, Ravishankar Sathyamurthy,* Bharathwaaj Ramani, Venkatesan Muthu, and Sathiyamoorthy Karuppiah

1. INTRODUCTION

Fossil fuels are largely used in industries, transportation, power plants, and automobiles. Industries and power plants use fossil fuels for power generation. Agricultural equipment such as pesticide sprayers and water pumps use compact engines, which are normally run by fossil fuels. Due to the rapid growth in the agricultural, industrial, and automobile sectors, the consumption of these fuels is increased. The demand for biofuels is rapidly increasing in view of depleting natural resources. These fossil fuels, especially diesel and petroleum, are extensively used for energy production. However, the emissions from the combustion of fuels are the principal causes of global warming and many environmental consequences. Various bio-oils are produced from biological resources, crops, byproducts from the forest, and feedstocks. The trans-esterification process or alcoholysis was the available best method to treat the oil to reduce the viscosity and remove the free fatty methyl ester acid and glycerol contents.1−8

Biodiesel is produced from various feedstocks of plants, including karanja, jatropha, soya bean, lemon seed, pumpkin seed, neem, pongamia, rape seed oils, etc. Oil obtained from conventional and nonconventional sources is also used to produce biodiesel.9−25 Ong et al.26 optimized the production of Calophyllum inophyllum biodiesel and studied the feasibility of its utilization in an internal combustion engine. The biodiesel production was optimized using RSM, and the operating parameters that include catalyst concentration, molar ratio, reaction time, and reaction temperature on yield were analyzed. The composition of biodiesel in diesel fuel varied from 10 to 50%. The results showed that, using 10% Calophyllum inophyllum in diesel fuel, BSFC and EGT were lower than those in diesel fuel, whereas NOx was higher than that in diesel fuel. The characterization and optimization of Calophyllum inophyllum−Ceiba pentandra oil were investigated

Received: January 24, 2021
Accepted: May 13, 2021
Published: May 21, 2021

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https://doi.org/10.1021/acsomega.1c00437
ACS Omega 2021, 6, 14068−14077
by Ong et al.27 ANN and ACO techniques were used to optimize the process variables such as the methanol–oil ratio, catalyst concentration, and reaction time on biodiesel yield. The recent challenges and opportunities in the production of biodiesel derived from agricultural products and microalgae using ionic liquids were reviewed by Ong et al.28 Trans-esterification using microwave irradiation on the synthesis of biodiesel produced from Ceiba pentandra oil was optimized by Silitonga et al.29 The performance and emission characteristics of biodiesel–bioethanol and diesel blends in diesel engines using the K-Extreme learning method were studied by Silitonga et al.30

The influential effect of different Minusops elangi methyl ester (MEME) fuel blends on the performance, emission, and combustion parameters of a DI diesel engine was studied by Krupakaran et al.31 In their study, the MEME was synthesized by the process of transesterification, and the test fuel blends were prepared with diesel in the volume of 10% (90% diesel–10% MEME), 20% (80% diesel–20% MEME), 30% (70% diesel–30% MEME), 40% (60% diesel–40% MEME), and 100% MEME. The fuel properties were evaluated and validated with the limits of ASTM standards. Engine test results revealed that, on operating the engine in the full load with 20MEME, the engine exhibited 5.12 and 4.18% higher BSEC and BTE, respectively, when correlated with base fuel (diesel). Results also indicated that the inside cylinder pressure developed and rate of heat release were superior while using 20MEME biodiesel blend at the full load condition. A significant reduction of HC (5.26%), CO (16.6%), and smoke (6.2%) resulted in juxtaposition with base fuel despite marginally higher CO2 (5.26%) and NOx (4.8%) at the maximum load of the engine operation.

The impact of oil derived from Cymbopogon martinii (Palmarosa methyl ester (PMO)) as an alternative fuel for a diesel engine was experimentally carried out by Sathiyamoorthy et al.32 The performance analysis showed that, compared to diesel, an extensive augmentation in BSFC was exhibited for 20MEME, the engine exhibited 5.12 and 4.18% higher BSEC and BTE, respectively, when correlated with base fuel (diesel). Results also indicated that the inside cylinder pressure developed and rate of heat release were superior while using 20MEME biodiesel blend at the full load condition. A significant reduction of HC (5.26%), CO (16.6%), and smoke (6.2%) resulted in juxtaposition with base fuel despite marginally higher CO2 (5.26%) and NOx (4.8%) at the maximum load of the engine operation.

The impact of using Pithecellobium dulce biodiesel (PBDB) in lower concentrations blended with diesel fuel on the engine performance and emission characteristics was experimentally investigated by Sekhar et al.33 On a volume basis, three fuel blends, namely, PBDB5, PBDB10, and PBDB20, were prepared and fueled in an unmodified diesel engine. On comparing the test results of PBDB blends over diesel fuel, it was revealed that the PBDB20 fuel blend produced lower HC (17.64%), CO (19.64%), and NOx (6.73%). Finally, it was contemplated that the PBDB20 diesel blend could be a successful fuel for use in an unmodified engine.

The extraction of biodiesel from Oenothera lamarckiana oil (OLO) in a diesel engine with an engine power of 9 kW was experimentally carried out by Hoseini et al.34 to assess its performance and emissions. Two blends, namely, B10 and B20, along with diesel fuel, were tested with various engine loads. Results showed that, using the B20 blend, the SFC was lower than that in diesel fuel by about 6.8%. Similarly, by operating the engine at the full load condition, the HC and CO are lower compared to those of diesel by about 37.28 and 10.13%, respectively. However, with the engine operating at the peak load, the other emissions emitted, such as CO2 and NOx, were improved by about 7.9 and 4.6%, respectively.

Performance analysis on a diesel engine fueled with sand-apple-based biodiesel blends was experimentally carried out by Ogunkunle and Ahmed.35 Sand apple oil was blended in the volume concentration of 5, 10, 15, and 20 along with diesel fuel. The engine tests were implemented by changing the load of the engine from 0 to 100%. Results on performance revealed that increased BSFC and lower BTE were observed using the biodiesel blend.

The biodiesel synthesized from juliflora seed oil was exploited as an additional source of fuel in a DI diesel engine by Asokan et al.36 In their study, the experiments were conducted with four different blends (B20, B30, B40, and B100) along with pure diesel. The test engine outcomes detected that the B20 fuel exhibits marginally higher BSFC (3.7%) and lower BTE (6.7%) at 100% load than those of diesel. In regard to emission, the B20 fuel generates minimum HC, CO, and smoke and slightly higher NOx than diesel fuel at 100% loading condition. From the conclusion, they recommended that the B20 fuel be utilized as a substitute for traditional diesel fuel.

Lalambari (LA) oil-based biodiesel and their blends (LA20, LA40, LA60, LA80, and LA100) were tested on a CI engine to study the effect on performance, combustion, and exhaust emissions. Test outcomes revealed that there are a devaluation in BTE (by 4.4%) and an increase in BSFC (by 2.5%) for LA20 than diesel fuel while the engine is operated at the peak load (3.7 kW). Also, pressure and heat release during the combustion were lesser for all the LA blends at 100% load. Furthermore, a reduction in smoke emission of about 16.6% and marginal increase in CO2 of 3.5% were recorded for LA20 at 3.7 kW compared to diesel fuel. Finally, the test results proved that LA100 and their blends could be incorporated as an additional fuel source for CI engines.37

Vachellia nilotica belongs to a member of the Leguminosae family, which grows to around 15–18 and 2–3 m in height and diameter, respectively. Its color commonly determines the age of the bark. The slaty green color of the bark indicates that the tree is immature, while the black color indicates that the tree is mature. In a matured tree, longitudinal gaps uncovering the inward gray-pinkish slash, radiating a ruddy low-quality gum, were observed. The tree leaves are bi-pinnate, 3–10 sets and 1.3–3.8 cm long, leaflets of 10–20 sets and 2–5 mm in length. Flowers of the tree are in globulous heads with sparkling golden yellow shading and have a diameter of 1.2–1.5 cm. When the tree is immature, the pods are green and tomatoes, while the mature tree pods are dark greenish. Pods are indehiscent, profoundly choked between the seed and offering a necklace view and a length of 7–15 cm. The pod consists of 8–12 seeds, packed, elliptical, and misty brown colored with strong tests. The Vachellia nilotica can bloom and fruit in a few years (2–3 years) after the period of germination. After the high-precipitation years, the rapid growth of fruits occurs. Normally, blooming starts during the months of March and June, while the shaping of the pods happens between July and December. During the periods of June and November, the leaf falls after it is completely dry. The seed pods can drop from the tree between October and January.38,39
From the review of various literature, researchers are majorly focusing on various new-generation feedstocks to produce biodiesel. Researchers are also focusing on the various techniques to produce biodiesel along with the traditional method. The main objective of the study is to determine the physiochemical properties of *Vachellia nilotica* biodiesel and the feasibility of using the prepared fuel on performance and emission characteristics of diesel engine. This study mainly focuses on the extraction of biodiesel produced from *Vachellia nilotica* seed oil and the suitability of *Vachellia nilotica* seed oil methyl ester (VNSOME) in different concentrations blended into diesel fuel to assess the engine performance and emission produced during the combustion. A competitive study is carried out in the engine fueled with diesel, VNSOME5, VNSOME10, VNSOME15, and VNSOME20. As per the ASTM standards, the properties of biodiesel were estimated. It is also noted that the produced biodiesel is suggested as a novel feedstock as an alternative source for a diesel engine without any engine modification.

2. MATERIALS AND METHODS

2.1. Extraction of *Vachellia nilotica* Seed Oil (VNSO). The *Vachellia nilotica* seeds utilized in this study are collected from the agriculture fields of rural villages nearby Tirunelveli District, Tamil Nadu, India. Initially, screening is done to remove the dust particles and undersized particles, and the seeds are thoroughly washed with water. The washed seeds are heated at an air temperature of 50 °C to remove the moisture content using an air blower. Then, the seeds are fed into a mechanical expeller to extract the *Vachellia nilotica* seed oil (VNSO). Further, the VNSO is refined by evacuating sticky substances and then neutralized for the betterment of its purity.

2.2. Preparation of VNSOME through a Biodiesel Production Plant. The VNSOME is produced through a small-scale biodiesel plant at CSIR-CLRI, Chennai, India. The detailed procedure is discussed below:

- The VNSOME is produced from the VNSO by a single-stage transesterification process due to the lower free fatty acid (2%) content.
- Sodium hydroxide (NaOH) is used as a catalyst and methanol is used as a solvent for the synthesis of VNSO into VNSOME.
- In the initial stages of the experimentation, the methoxide (CH₃OH and NaOH) solution is prepared based on the free fatty acid in the VNSO.
- Then, 5 L of VNSO is fed into the reaction heater 1 (RH1), as shown in Figure 1. Then, it is heated up to 60 °C. After reaching 60 °C, the methoxide solution is fed into the RH1 (Figure 1).
- The mixture (VNSO and methoxide solution) is then maintained in the temperature range of 60–65 °C.
- The process is carried out until the formation of glycerol. The glycerol formation can be identified by the appearance of brownish color during circulation.
- After glycerol evolution, the admixture is allowed to settle for 3–5 h.
- The VNSOME produced is at the top of the RH1, and the glycerol is settled at the bottom, and it is drained out.
- Then, the VNSOME is fed into the water heater tank 1 (WH1), in which water is available at a temperature of 50 °C. Water washing of the product is performed in WH1, and then the VNSOME is fed into the drying heater tank 1 (DH1). In DH1, the VNSOME is heated up to 110 °C to remove the moisture content. Finally, the VNSOME is collected from the plant and stored in containers.

2.3. Characterization of VNSOME. The chemical characterization of VNSOME has been performed to quantify the methyl esters present in the product. The characterization of VNSOME is analytically studied using Fourier transform infrared (FT-IR) spectrometry (test method: ASTM E1252) and gas chromatography–mass spectrometry (GC–MS) (test method: ASTM E2997-16).

2.3.1. GC–MS of VNSOME. Gas chromatography analysis of VNSOME is carried out to evaluate the composition of methyl esters in VNSOME. The working conditions of GC–MS are shown in Table 1.

Table 2 shows the saturated and unsaturated methyl esters present in the VNSOME. From Table 2, it is clear that the VNSOME contains higher unsaturated fatty acid methyl esters.

![Figure 1. Biodiesel plant.](https://doi.org/10.1021/acsomega.1c00437)

Table 1. GC–MS Operating Conditions

| property       | specification                      |
|----------------|------------------------------------|
| injection      | split ratio of 1:10 at 280 °C       |
| column         | capillary column Elite-5           |
| column dimension | 30 m × 0.25 mm i.d. × 250 μm film thickness |
| carrier gas    | helium                             |
| column flow rate | 1 mL/min                           |
| detector       | electron ionization                |
| electron energy | 70 eV                              |
| mass range     | 40–450 amu                         |
| oven temperature | initial temperature of 60 °C increased to 150 °C (hold for 2 min). Further, temperature is raised to 4 °C/min up to 280 °C and kept constant for 5 min with a total run time of 54.5 min. |
(around 77.57%). Hence, the VNSOME is suitable for cold weather conditions.

2.3.2. FT-IR Spectrometry of VNSOME. The FT-IR spectrometry results of Vachellia nilotica seed oil and the functional group with peak are tabulated in Table 3, and Figure 2 shows the FT-IR spectrum of VNSOME. The Perkin Elmer RXI-FT-IR spectrometer was used to develop the VNSOME spectrum.33

It can be observed that the peak detected at 3400 cm$^{-1}$ clearly states the presence of −OH, −NH, and water impurities. Similarly, a stretch in −CH$_3$ and CH$_2$ is found between the wavelength of 3000 and 2854 cm$^{-1}$ suggesting the existence of CH$_3$ and CH$_2$. The presence of >C=O is found in the wavelength between 1750 and 1600 cm$^{-1}$ as a peak is observed. The peak ranging from 1500 to 1400 cm$^{-1}$ classifies the C−C stretching vibrations. Also, the C−O vibrations can be noticed between the wavelengths of 1300 and 1400 cm$^{-1}$. The peaks of phenols of aromatic group vibration can be noticed with wavelength ranging from 850 to 650 cm$^{-1}$.

2.4. Properties of VNSO and VNSOME. The VNSOME is mixed with diesel fuel on volume basis of 5, 10, 15, and 20% by using a lab stirrer (Remi RQ-121/D) at 750 rpm for 2 h. The physiochemical properties of the diesel fuel, VNSO, and VNSOME are analyzed based upon the ASTM D6751-02 standards, and they are represented in Table 4. The calorific value (lower heating value) of VNSO and VNSOME is lower than that of the diesel fuel due to the existence of oxygen particles in the structure. The flash point of VNSO and VNSOME is detected to be 237 and 185 °C, respectively, making the products secure for transportation. Copper strip corrosion shows the value of class 1a for VNSO and VNSOME and is responsible for lower corrosiveness on the engine parts. Finally, it was found that the reaming fuel properties of VNSO and VNSOME are within the standard limits of ASTM D6751-02.

2.5. Test Engine and Experimentation. An experimental investigation is conducted on a stationary direct injection (DI) multifuel engine [single cylinder, four strokes, and compres-

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Table 2. Fatty Acid Methyl Ester Composition of VNSOME

| fatty acid methyl ester compound | molecular formula | composition (%) |
|---------------------------------|-------------------|----------------|
| linoleic acid methyl ester      | C$_{18}$H$_{34}$O$_2$ | 67.35 |
| elaidic acid methyl ester       | C$_{18}$H$_{36}$O$_2$ | 10.22 |
| total unsaturated fatty acid methyl esters | | 77.57 |
| palmitic acid methyl ester      | C$_{16}$H$_{32}$O$_2$ | 15.10 |
| isostearic acid methyl ester    | C$_{18}$H$_{36}$O$_2$ | 0.95 |
| arachidic acid methyl ester     | C$_{20}$H$_{40}$O$_2$ | 0.66 |
| behenic acid methyl ester       | C$_{22}$H$_{44}$O$_2$ | 0.54 |
| lignoceric acid methyl ester    | C$_{24}$H$_{48}$O$_2$ | 22.43 |

Table 3. Functional Group and Peak Identification

| wave number | functional group                        |
|-------------|-----------------------------------------|
| 850−650     | phenols of aromatic group               |
| 1300−1400   | C−O alcohols                            |
| 1500−1400   | C−C                                     |
| 1750−1600   | C=O                                     |
| 3000−2800   | CH stretching of CH$_3$ and CH$_2$      |
| 3400        | OH, NH, and water impurities            |

Figure 2. FT-IR spectra for VNSOME.
sion ratio (CR) of 17.5:1. It is loaded with an electrical dynamometer (eddy current type), and the engine is operated at 1500 rpm (constant speed). The details of the experimental test rig used in the present study are tabulated in Table 5, and Figure 3 shows the schematic diagram. On various engine loads, a series of experiments are carried out on the diesel engine using diesel fuel and biodiesel blends (VNSOME5, VNSOME10, VNSOME15, and VNSOME20). Exhaust gas temperature is measured using a K-type thermocouple attached to the tailpipe of the engine. The exhaust gas analyzer (AVL Digas 444) is connected to the tailpipe to determine the emissions (CO₂, NOₓ, HC, and CO) produced during combustion of the test engine. The smoke emissions are assessed by the smoke meter (AVL 437). The range and accuracy of the instruments to measure the emissions produced (exhaust gas analyzer and smoke meter) are tabulated in Table 6.

3. RESULTS AND DISCUSSIONS

3.1. Performance Analysis of VNSOME Blends. The performance analysis on a diesel engine operated at various loads using VNSOME blends and diesel fuel has been conducted, and the test results are discussed below:

Figure 3 shows the schematic diagram. On various engine loads, a series of experiments are carried out on the diesel engine using diesel fuel and biodiesel blends (VNSOME5, VNSOME10, VNSOME15, and VNSOME20). Exhaust gas temperature is measured using a K-type thermocouple attached to the tailpipe of the engine. The exhaust gas analyzer (AVL Digas 444) is connected to the tailpipe to determine the emissions (CO₂, NOₓ, HC, and CO) produced during combustion of the test engine. The smoke emissions are assessed by the smoke meter (AVL 437). The range and accuracy of the instruments to measure the emissions produced (exhaust gas analyzer and smoke meter) are tabulated in Table 6.

![Schematic diagram of the test engine setup.](https://pubs.acs.org/journal/acsofa)
The product of volume flow rate and calorific value of the fuel). At a particular load of operation, the BP remains constant; hence, the BTE of the test fuels strongly depends on the calorific value. It is found that the increase in the blend concentration of VNSOME with diesel fuel decreases the calorific value and it is less compared to that of diesel fuel. Therefore, the BTE is lower than the diesel for all the VNSOME blends. At the BP of 3.5 kW, BTEs of VNSOME5, VNSOME10, VNSOME15, and VNSOME20 are 1.97, 5.49, 6.37, and 7.34%, respectively, lower than the diesel.

The exhaust gas temperature (EGT) of using VNSOME fuel blends and diesel for different loads of engine operation is shown in Figure 6. With increased loading condition, the EGT of test fuels increases. Similarly, with the increase in the blend of VNSOME with diesel, the EGT significantly increases at all load conditions. The enriched oxygen content available in the VNSOME blends improves the process of combustion, which resulted in greater EGT. At the maximum loading condition (3.5 kW), the EGTs of VNSOME5, VNSOME10, VNSOME15, and VNSOME20 are 3.22, 6.25, 9.63, and 14.28% higher than the EGT of the diesel fuel, respectively.

3.2. Exhaust Emission Analysis of VNSOME Blends.

The engine exhausts emitted from the diesel engine such as hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NOx), smoke, and carbon dioxide (CO2) are analyzed for the VNSOME5, VNSOME10, VNSOME15, and VNSOME20 fuel blends in comparison with neat diesel, and the obtained results are discussed below:

The variation in carbon monoxide (CO) emission in regard to BP is outlined in Figure 7. CO emission is higher at lower loads and is increased gradually at higher loads for all the test fuels. The possible increase in the CO emission at high loads is due to the rich fuel mixture present in the cylinder during combustion. The test outcomes revealed that the CO emission formed during the combustion with VNSOME fuel blends is lower than that with diesel fuel. At 3.5 kW, the VNSOME5, VNSOME10, VNSOME15, and VNSOME20 generates 5.55, 11.11, 16.66, and 22.22% lower CO emission when correlated to diesel fuel operation. The inbuilt oxygen composition in the VNSOME fuel blends improves the poststoichiometric combustion and thus lessens the CO emission.

The hydrocarbon (HC) deviation using VNSOME fuel blends and diesel for different loads of engine operation is displayed in Figure 8. From the pictorial view, it is very clear that the VNSOME fuel blends produce lower HC emission.

3.2. Exhaust Emission Analysis of VNSOME Blends.
than diesel fuel. At the maximum load (3.5 kW), a reduction of 4.25, 8.51, 14.90, and 19.14% HC emission was depicted, respectively, for VNSOME5, VNSOME10, VNSOME15, and VNSOME20 in contrast with diesel. The oxygen composition in the VNSOME blends leads to enhance the combustion process, and it is responsible for the lower HC emission.50−52

The formation of oxides of nitrogen (NO\textsubscript{x}) emitted after combustion using VNSOME fuel blends and diesel for different loads of engine operation is plotted in Figure 9.

From Figure 9, it can be detected that the formation of oxides of nitrogen (NO\textsubscript{x}) is higher with VNSOME biodiesel blends with increased engine load. Also, it is found that the formation of NO\textsubscript{x} using diesel fuel is lower than that using VNSOME fuel blends. The oxygen content already available in the VNSOME fuel blend is the main cause of the increased formation of NO\textsubscript{x}. The availability of oxygen content present in the biodiesel blend leads to complete and enhanced combustion that simultaneously increased the combustion temperature.53−55 At 3.5 kW load, when compared to diesel fuel, the formation of NO\textsubscript{x} emission is found to be higher by about 1.94, 3.80, 5.60, and 7.34% for VNSOME5, VNSOME10, VNSOME15, and VNSOME20, respectively.

The fluctuation in smoke emission for the VNSOME fuel blends and diesel for different loads of engine operation is displayed in Figure 10. With the possible increase in the engine load, the smoke is also increased for all the test fuels since the smoke opacity strongly depends on engine load. In general, the smoke and NO\textsubscript{x} are trade-offs. The smoke emission was reduced by 4.42, 7.37, 9.30, and 11.20% for VNSOME5, VNSOME10, VNSOME15, and VNSOME20, respectively, in contrast with the pure diesel fuel at the maximum load (3.5 kW). The reduction in C–H ratio, superfluous oxygen composition, and absence of sulfur content in the VNSOME blends are the important causes of the effective reduction in smoke emissions.49,56,57

The disparity of carbon dioxide (CO\textsubscript{2}) emission of the test fuels (VNSOME5, VNSOME10, VNSOME15, VNSOME20, and diesel fuel) at different BPs is exhibited in Figure 11. When the load increases in the test, the engine emits higher CO\textsubscript{2} emissions for all the test fuels. At the full load (3.5 kW) condition, the VNSOME5, VNSOME10, VNSOME15, and VNSOME20 blends produce 2.34, 4.58, 6.01, and 7.40% higher CO\textsubscript{2} emission compared to diesel fuel. This may be due...
to the improved combustion of VNSOME blends than diesel fuel.  

4. CONCLUSIONS

In this study, an attempt was made to prepare the new biodiesel (VNSOME) fueled in a DI diesel engine for assessing the emission and performance characteristics. Based on the experimental results from the engine analysis, the conclusions are as follows:

- The blends of VNSOME in diesel fuel exhibited lower BTEs using VNSOME in different volume concentrations on diesel compared to neat diesel fuel. For VNSOME20, 7.34% marginally lower BTE is detected at 3.5 kW. Similarly, higher BSFC and EGT were found for all the VNSOME blends.
- The CO emissions produced from the engine tested with VNSOME in different volume concentrations are lower than that with neat diesel. At 3.5 kW, VNSOME20 emits 22.22% lower CO than that of diesel fuel.
- The formation of HC from the engine with different blends of VNSOME fuel is significantly lower than that with neat diesel. The VNSOME20 fuel blend generates 19.14% lower HC compared to diesel fuel at the maximum load of the engine.
- NOx emissions are marginally increased for VNSOME fuel blends. When compared to neat diesel, the NOx formed is higher by about 7.34% than the VNSOME20 blend with the engine operated at the peak load.
- Using VNSOME fuel blends in the engine, the smoke emission is considerably reduced. There is an 11.20% reduction of smoke identified for VNSOME20 compared to diesel fuel at the full load of the engine.
- CO2 emissions are slightly higher for all VNSOME fuel blends. At the full load (3.5 kW), VNSOME20 develops 7.40% higher CO2 than diesel fuel.

4.1. Future recommendations. It can be concluded that the biodiesel fuel blend (VNSOME20) was found to be an alternative source for diesel fuel and the diesel engine can be fueled with this blend without making any modification.

AUTHOR INFORMATION

Corresponding Authors
Chandra Sekhar Sriharikota — Department of Mechanical Engineering, N.B.K.R Institute of Science & Technology (Autonomous), Vidyanagar 524 413, Andhra Pradesh, India; Email: chandruthermal@gmail.com
Ravishankar Sathyamurthy — Department of Mechanical Engineering, KPR Institute of Engineering and Technology, Coimbatore 641 407, Tamil Nadu, India; orcid.org/0000-0002-2881-3455; Email: raviannauniv23@gmail.com

Authors
Karuppusamy Karuppusamy — Department of Mechanical Engineering, Anna University Regional Campus, Tirunelveli 627 007, Tamil Nadu, India
Vedaraman Nagarajan — Chemical Engineering Department, CSIR-CLRI, Chennai 600 020, Tamil Nadu, India
Bharathwaj Ramani — Department of Mechanical Engineering, KPR Institute of Engineering and Technology, Coimbatore 641 407, Tamil Nadu, India

Veikatesan Muthu — Department of Mechanical Engineering, University College of Engineering, Nagercoil 629 004, Tamil Nadu, India
Sathiyamoorthy Karuppi — Department of Mechanical Engineering, SRM Institute of Science and Technology, Kattankulathur 603203, Tamil Nadu, India

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.1c00437

Author Contributions
The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Notes
The authors declare no competing financial interest.

REFERENCES
(1) Knothe, G. Biodiesel and renewable diesel: a comparison. Prog. Energy Combust. Sci. 2010, 36, 364–373.
(2) Ma, F.; Hanna, M. A. Biodiesel production: a review. Bioresour. Technol. 1999, 70, 1–15.
(3) Hoekman, S. K.; Broch, A.; Robbins, C.; Ceniceros, E.; Natarajan, M. Review of biodiesel composition, properties, and specifications. Renewable Sustainable Energy Rev. 2012, 16, 143–169.
(4) Leung, D. Y. C.; Wu, X.; Leung, M. K. H. A review on biodiesel production using catalyzed transesterification. Appl. Energy 2010, 87, 1083–1095.
(5) Mata, T. M.; Martins, A. A.; Caetano, N. S. Microalgae for biodiesel production and other applications: a review. Renewable Sustainable Energy Rev. 2010, 14, 217–232.
(6) Meher, L. C.; Sagar, D. V.; Naik, S. N. Technical aspects of biodiesel production by transesterification—a review. Renewable Sustainable Energy Rev. 2006, 10, 248–268.
(7) Tan, T.; Lu, J.; Nie, K.; Deng, L.; Wang, F. Biodiesel production with immobilized lipase: a review. Biotechnol. Adv. 2010, 28, 628–634.
(8) Atabani, A. E.; Silitonga, A. S.; Badruddin, I. A.; Mahlia, T. M. I.; Masjuki, H. H.; Mekhilaf, S. A comprehensive review on biodiesel as an alternative energy resource and its characteristics. Renewable Sustainable Energy Rev. 2012, 16, 2070–2093.
(9) Haseeb, A. S. M. A.; Fazal, M. A.; Jahirul, M. I.; Masjuki, H. H. Compatibility of automotive materials in biodiesel: a review. Fuel 2011, 90, 922–931.
(10) Basha, S. A.; Gopal, K. R.; Jehar, S. A review on biodiesel production, combustion, emissions and performance. Renewable Sustainable Energy Rev. 2009, 13, 1628–1634.
(11) Atabani, A. E.; Silitonga, A. S.; Badruddin, I. A.; Mahlia, T. M. I.; Masjuki, H. H.; Mekhilaf, S. A comprehensive review on biodiesel as an alternative energy resource and its characteristics. Renewable Sustainable Energy Rev. 2012, 16, 2070–2093.
(18) Fadhil, A. B.; Ahmed, A. I. Ethanolysis of fish oil via optimized protocol and purification by dry washing of crude ethyl esters. J. Taiwan Inst. Chem. Eng. 2016, 56, 71–83.
(19) Ayooob, A. K.; Fadhil, A. B. Valorization of waste tires in the synthesis of an effective carbon based catalyst for biodiesel production from a mixture of non-edible oils. Fuel 2020, 264, 116754.
(20) Ayooob, A. K.; Fadhil, A. B. Biodiesel production through transesterification of a mixture of non-edible oils over lithium supported on activated carbon derived from scrap tires. Energy Convers. Manage. 2019, 201, 112149.
(21) Altikriti, E. T.; Fadhil, A. B.; Dheyab, M. M. Two-step base catalyzed transesterification of chicken fat: Optimization of parameters. Energy Sources, Part A 2015, 37, 1861–1866.
(22) Fadhil, A. B.; Saeed, I. K.; Saeed, L. I.; Altamer, M. H. Co-solvent ethanolysis of chicken waste: Optimization of parameters and characterization of biodiesel. Energy Sources, Part A 2016, 38, 2883–2890.
(23) Fadhil, A. B.; Aziz, A. M.; Altamer, M. H. Optimization of methyl esters production from non-edible oils using activated carbon supported potassium hydroxide as a solid base catalyst. Arab. J. Basic Appl. Sci. 2018, 25, 56–65.
(24) Fadhil, A. B.; Saeed, L. I. Sulfonated tea waste: A low-cost adsorbent for purification of biodiesel. Int. J. Green Energy 2016, 13, 110–118.
(25) Fadhil, A. B.; Ahmed, A. I. Production of mixed methyl/ethyl esters from waste fish oil through transesterification with mixed methanol/ethanol system. Chem. Eng. Commun. 2018, 205, 1157–1166.
(26) Ong, H. C.; Masjuki, H. H.; Mahlia, T. M. I.; Silitonga, A. S.; Chong, W. T.; Leong, K. Y. Optimization of biodiesel production and engine performance from high free fatty acid Calophyllum inophyllum oil in CI diesel engine. Energy Convers. Manage. 2014, 81, 30–40.
(27) Ong, H. C.; Milano, J.; Silitonga, A. S.; Hassan, M. H.; Shamsuddin, A. H.; Wang, C.-T.; Mahlia, T. M. I.; Siswanto, J.; Kusumo, F.; Sutrino, J. Biodiesel production from Calophyllum inophyllum-Ceiba pentandra oil mixture: Optimization and characterization. J. Cleaner Prod. 2019, 219, 183–198.
(28) Ong, H. C.; Tiong, Y. W.; Goh, B. H. H.; Gan, Y. Y.; Mohijur, M.; Pattah, I. M. R.; Chong, C. T.; Alam, A. M.; Lee, H. H.; Silitonga, A. S.; Mahlia, T. M. I. Recent advances in biodiesel production from agricultural products and microalgae using liquid iodics: Opportunities and challenges. Energy Convers. Manage. 2020, 228, 113647.
(29) Silitonga, A. S.; Shamsuddin, A. H.; Mahlia, T. M. I.; Milano, J.; Kusumo, F.; Siswanton, J.; Dharma, S.; Sebayang, A. H.; Masjuki, H. H.; Ong, H. C. Biodiesel synthesis from Ceiba pentandra oil by microwave irradiation-assisted transesterification: ELM modeling and optimization. Renewable Energy 2020, 146, 1278–1291.
(30) Silitonga, A. S.; Masjuki, H. H.; Ong, H. C.; Sebayang, A. H.; Dharma, S.; Kusumo, F.; Siswanton, J.; Milano, J.; Daud, K.; Mahlia, T. M. I.; Chen, W.-H.; Sugiyanto, B. Evaluation of the engine performance and exhaust emissions of biodiesel-bioethanol-diesel blends using kernel-based extreme learning machine. Energy 2018, 159, 1075–1087.
(31) Krupakaran, R. L.; Hariprasad, T.; Gopalakrishna, A. Impact of various blends of Minusops elengi methyl esters on performance and emission characteristics of a diesel engine. Int. J. Green Energy 2018, 15, 415–426.
(32) Sathiyamoorthy, R.; Sankaranarayanan, G.; kumaar, S. B. A.; Chiranjeevi, T.; Kumar, D. D. Experimental investigation on performance, combustion and emission characteristics of a single cylinder diesel engine fuelled by biodiesel derived from Cymbopogon Martini. Renewable Energy 2019, 132, 394–415.
(33) Sekhar, S. C.; Karuppayasamy, K.; Sathyamoorthy, R.; Elkelawy, M.; Bastawissi, H. A. E. D.; Paramasivan, P.; Sathyamoorthy, K.; Edison, P. Emission analysis on compression ignition engine fueled with lower concentrations of Pittosporum dulce biodiesel-diesel blends. Heat Transfer - Asian Res. 2019, 48, 254–269.
(34) Hoseini, S. S.; Najafi, G.; Ghobadian, B.; Mamat, R.; Ebadi, M. T.; Yusaf, T. Characterization of biodiesel production (ultrasonic-assisted) from evening-primroses (Oenothera lamarckiana) as novel feedstock and its effect on CI engine parameters. Renewable Energy 2019, 130, 50–60.
(35) Ogunkunle, O.; Ahmed, N. A. Performance evaluation of a diesel engine using blends of optimized yields of sand apple (Parinari polygona) oil biodiesel. Renewable Energy 2019, 134, 1320–1331.
(36) Asokan, M. A.; Prabu, S. B.; Bade, P. K. K.; Nekkanti, V. M.; Gatta, S. S. G. Performance, combustion and emission characteristics of jullflora biodiesel fuelled DI diesel engine. Energy 2019, 173, 883–892.
(37) Shrivastava, P.; Verma, T. N. An experimental investigation into engine characteristics fueled with Lal ambhari biodiesel and its blends. Therm. Sci. Prog. Prog. 2020, 17, 100356.
(38) Irani, R.; Khaled, K. L. Acacia nilotica gum: An Underutilized Food Commodity. Int. J. Curr. Res. 2015, 7, 14280–14288.
(39) Bargali, K.; Bargali, S. S. Acacia nilotica: a multipurpose leguminous plant. Nat. Sci. 2009, 7, 11–19.
(40) Bhuiya, M. M. K.; Rasul, M. G.; Khan, M. M. K.; Ashwath, N. Biofuel production and characterization of poppy (Papaver somniferum L.) seed oil methyl ester as a source of 2nd generation biodiesel feedstock. Ind. Crops Prod. 2020, 152, 112493.
(41) Chattopadhyay, S.; Sen, R. Fuel properties, engine performance and environmental benefits of biodiesel produced by a green process. Appl. Energy 2013, 105, 319–326.
(42) Kumar, T. S.; Kumar, P. S.; Annamalai, K. Experimental study on the performance and emission measures of direct injection diesel engine with Kapok methyl ester and its blends. Renewable Energy 2015, 74, 903–909.
(43) Khiai, K.; Awad, S.; Loubar, K.; Tarabot, L.; Mahmoud, R.; Tazrouw, M. Experimental investigation of pistacia lentiscus biodiesel as a fuel for direct injection diesel engine. Energy Convers. Manage. 2016, 108, 392–399.
(44) Nautyal, P.; Subramanian, K. A.; Dastidar, M. G.; Kumar, A. Experimental assessment of performance, combustion and emissions of a compression ignition engine fuelled with Spirulina platensis biodiesel. Energy 2020, 193, 116861.
(45) Srihari, S.; Thirumalini, S.; Prashanth, K. An experimental study on the performance and emission characteristics of PCCI-DI engine fuelled with diethyl ether-biodiesel-diesel blends. Renewable Energy 2017, 107, 440–447.
(46) Raman, L. A.; Deepanraj, B.; Rajakumar, S.; Sivasubramanian, V. Experimental investigation on performance, combustion and emission analysis of a direct injection diesel engine fuelled with rapeseed oil biodiesel. Fuel 2019, 246, 69–74.
(47) Mishra, S. R.; Mohanty, M. K.; Panigrahi, N.; Pattanaik, A. K. Impact of Simarouba glauca biodiesel blends as a fuel on the performance and emission analysis in an unmodified DICI engine. Renewable Energy Focus 2018, 26, 11–16.
(48) Sivaramakrishnan, K. Investigation on performance and emission characteristics of a variable compression multi fuel engine fuelled with Karanja biodiesel–diesel blend. Egypt. J. Pet. 2018, 27, 177–186.
(49) Sayin, C.; Gumus, M. Impact of compression ratio and injection parameters on the performance and emissions of a DI diesel engine fueled with biodiesel-blended diesel fuel. Appl. Therm. Eng. 2011, 31, 3182–3188.
(50) Hasan, M. M.; Rahman, M. M. Performance and emission characteristics of biodiesel–diesel blend and environmental and economic impacts of biodiesel production: A review. Renewable Sustainable Energy Rev. 2017, 74, 938–948.
(51) Kumar, M. V.; Babu, A. V.; Kumar, P. R. The impacts on combustion, performance and emissions of biodiesel by using additives in direct injection diesel engine. Alexandria Eng. J. 2018, 57, 509–516.
(52) Rahman, S. M. A.; Van, T. C.; Hossain, F. M.; Jafari, M.; Dowell, A.; Islam, M. A.; Nabi, M. N.; Marchese, A. J.; Tryner, J.; Rainey, T.; Ristovski, Z. D. Fuel properties and emission characteristics of essential oil blends in a compression ignition engine. Fuel 2019, 238, 440–453.
53) Baskar, P.; Senthilkumar, A. Effects of oxygen enriched combustion on pollution and performance characteristics of a diesel engine. Eng. Sci. Technol., Int. J. 2016, 19, 438−443.
54) Shameer, P. M.; Ramesh, K. Experimental evaluation on performance, combustion behavior and influence of in-cylinder temperature on NOx emission in a D.I diesel engine using thermal imager for various alternate fuel blends. Energy 2017, 118, 1334−1344.
55) Di, Y.; Cheung, C. S.; Huang, Z. Experimental investigation on regulated and unregulated emissions of a diesel engine fueled with ultra-low sulfur diesel fuel blended with biodiesel from waste cooking oil. Sci. Total Environ. 2009, 407, 835−846.
56) Srinivas, K.; Naik, B. B.; Radha, K. K. Performance and emission characteristics of VCR CI engine fueled with methyl ester of palm kernel oil and eucalyptus oil blends. Perspect. Sci. 2016, 8, 195−197.
57) Kumar, R. S.; Sureshkumar, K.; Velraj, R. Combustion, performance and emission characteristics of an unmodified diesel engine fueled with Manilkara Zapota Methyl Ester and its diesel blends. Appl. Therm. Eng. 2018, 139, 196−202.