JOURNAL OF MECHANICAL ENGINEERING AND SCIENCES (JMES)
ISSN: 2289-4659 e-ISSN: 2231-8380
VOL. 14, ISSUE 4, 7551 – 7568
DOI: https://doi.org/10.15282/jmes.14.4.2020.21.0595

ORIGINAL ARTICLE

Performance and emission study of sesbania aculeate biodiesel in a VCR diesel engine

D. Mallesham[1], J. Krishnaraj[1] and CH. Ravi Kiran[1]

[1] Department of Mechanical Engineering, MLR Institute of Technology, Hyderabad 500 043, Telangana, India
Phone: +91 9949157224

ABSTRACT – The increasing energy demand and pollution due to fossil fuels influence the necessity of finding a appropriate alternative fuel for a cleaner environment and to sustain the usage of diesel engines in the automobile sector. This research focuses on such exploration of new alternative fuel (biodiesel) and to study its effect on emission and the performance parameters at a 1500 rpm constant speed on a 4-stroke, single-cylinder, variable compression ratio (VCR) diesel engine. The biodiesel from the sesbania aculeate seed oil is produced through the transesterification process. The blends of sesbania aculeate oil methyl ester (SAOME) with diesel mixture SAOME10, SAOME20, SAOME30, and SAOME40 are used as fuels at various engine loads (20% to 100%) and different compression ratios (CR) (16.5, 17.5 and 18.5). The emission and performance indicators of the proposed biodiesel are analyzed and an evaluation is made with diesel. The experimental outcomes demonstrate that for SAOME20, brake specific fuel consumption (BSFC) and brake thermal efficiency (BTE) are respectively 12.3% lesser and 8.21% higher than diesel under peak load at CR 18.5. Also the experimental investigation confirms a significant emission decrease in NO_X, HC, and CO when there is an increase in CR and load.

ARTICLE HISTORY
Received: 05th Aug 2019
Revised: 04th May 2020
Accepted: 20th May 2020

KEYWORDS
Biodiesel;
exhaust emissions;
sesbania aculeate oil methyl ester;
transesterification;
VCR diesel engine

INTRODUCTION

Exhaustion of non-renewable energy sources like fossil fuels is observed because of the increase in consumption and leads to severe environmental pollution which should be addressed immediately. Even today in major segments like automobile, agriculture, and various industries, diesel fuel is a main source of energy for power generation. There is a need to look for alternative fuels which reduces the dependency on conventional fuel. From this exploration, the Sesbania aculeate (sesbania bispinosa) seed oil can be considered as a favorable alternate fuel for diesel engines. It is because of their agricultural origin and lower exhaust emissions without altering the performance. The cost of Sesbania seeds per Kg is around 0.6 USD. The approximate cost per Kg of other seeds like Karanja, mustard (Rapeseed), Jatropha, and Sunflower is around 1.99 USD, 1.32 USD, 0.93 USD, and 0.79 USD respectively. Hence the low-cost sesbania seeds make this alternative more attractive to be used in biodiesel production when comparing with other seeds. The sesbania seeds are widely available in India, Eastern China, Pakistan, Thailand, and some parts of Taiwan. Also, note that the sesbania seeds can be used as green manure to mature the rice fields and its stem can be used in fiber board production. The biodiesel production from the sesbania seeds and its usage in engines help reduce the greenhouse gases, improve biodiversity, and rural economic development.

Diesel engines are the most effective prime movers. There is a need to develop some fuel with their properties and compare with the diesel to protect the global environment and energy security. Biodiesels are produced by synthetic processes like transesterification, pyrolysis, etc. from animal fats or vegetable oils and these are used to reduce the dependency of oil imports.

Over a few decades, many researchers are focusing on the emission and performance parameters investigation on various diesel engines operated with various biodiesels. Jindal et al. [1] studied the effects of CR and fuel injection on a diesel engine performance by using Jatropha methyl ester as fuel and reported the best combination as CR of 18 with an injection pressure of 25 N/mm^2. Nagaraja et al. [2] considered the effect of CR on the emission and performance parameters of a 4-stroke single-cylinder VCR diesel engine operated with pre-heated palm oil and conluded SFC of blend O20 is lesser than diesel fuel at larger CR of 20 and emissions like HC and CO decreases while CR and blending ratio increases. Sivaramakrishnan and Ravikumar [3] studied the effect of different CR (between 17.5 to 18.1) and reported CR of 17.9 as the optimum one. Several other investigators have also researched the impact of CR on a VCR diesel engine; notably, De and Panua [4] experimented with Jatropha and Jatropha oil blends; Eknath and Ramachandra [5] employed blends of Karanja and Jatropha oil with diesel; Ganesh and Chandrakishor [6] attempted with algae oil blends. Their experimental results show the lower BSFC, CO, and HC at CR of 18 (at 100% load) and higher NO_X emission.

Hariram and Vagesh Shangar [7] studied the impact of CR in a direct injection system diesel engine (DI-DE) and detected the reduction in peak cylinder pressure and increased ignition delay duration on reduced CR. The researchers, Shalem Raju and Ravi Kumar [8], Sivaramakrishnan [9], and Somasekar and Pandurangadu [10] were investigated with

*CORRESPONDING AUTHOR | D. Mallesham | dandumallesham14@gmail.com

biodiesels from neem oil, karanja oil, and mango seed oil respectively and their results are also reasonably closer to earlier researchers. Recently, many researchers attempted with Calophyllum inophyllum methyl ester oil and its combinations with diesel as fuel in VCR diesel engine to analyze the impact of compression ratio on combustion, emission and performance parameters (To cite a few, Nayak et al. [11], Mosarof et al. [12], Bridjesh et al. [13] and Deepika Nadipudi et al. [14]) to ensure their biodiesel usage without any engine modification.

Navaneethakrishnan et al. [15] investigated the emission and performance parameters of biodiesel from trash fish oil. They observed lesser CO and smoke emissions in contrast with diesel. Senthil et al. [16] tested the emission and performance indicators of a single-cylinder DI-DE by using eucalyptus and pongamia oil with diethyl ether as biodiesel and revealed lower HC, CO and smoke emissions for B20Eu70DEE10. Soukht Saraee et al. [17] used kolkhung as biodiesel and their results show the decrease in CO by 42%, HC by 36%, and smoke opacity by 45% than neat diesel because of complete combustion.

In the study of Wang and Ni [18], the fuel derived from waste lubrication oil was used on DI diesel engine and their test results demonstrate that at medium and low loads, the BSFC decreased by 3% at 3000 rpm and produces more NO_{X}, lower CO, and HC at heavy loads. Ravikiran et al. [19] tested the effects of jute blend combinations in diesel engine and reported that during increased load, the BTE of B30 (30% jute oil +70% Diesel) is around 16% more than neat diesel; also HC, CO and CO_2 are decreased and NO_X increased with load than neat diesel. In the study of Uyumaz [20], the biodiesel blends from mustard oil at different loads were tested in a DI-DE and presented the results such as indicated thermal efficiency decreased by 6.8% and BSFC increased to 4.8% at peak load for blend M10 (10% mustard oil+90% diesel) than neat diesel.

Other investigators like Ramarao et al. [21] and Nithya et al. [22] were attempted by adding nano additives like cerium oxide with diesel, cotton seed oil; and canola biodiesel with TiO_2. Their results show 1.72% betterment in SFC and a reasonable decrease in emissions of HC, CO, and NO_X in contrast to diesel. Very recently, Saravanan et al. [23] observed the effect of dual-fuel biodiesel (Rapeseed and Mahua) blend combinations on the emission and performance indicators in a VCR diesel engine. Their results show that blend BL20 performed nearer to diesel; and HC, CO, and smoke denseness were decreased by 8.56%, 20.66%, and 6.9% respectively than diesel. From the literature, it is identified that still there is a scope of further research in a VCR diesel engine to improvise the emission and performance parameters.

The key aim of the current study is to identify a suitable new plant source (sesbania aculeate oil seed) for the biodiesel production and to analyze the emission and performance parameters of VCR diesel engine with SAOME blends as fuel at various CR and 1500 rpm constant speed. The experiments are proposed to conduct under various loads ranging from 20% to 100% in steps of 20% and at different CRs (16.5, 17.5 & 18.5). Blends like SAOME10 (10% Sesbania aculeate oil + 90% diesel), SAOME20 (20% Sesbania aculeate oil + 80% diesel), SAOME30 (30% Sesbania aculeate oil + 70% diesel) and SAOME40 (40% Sesbania aculeate oil + 60% diesel) are to be prepared for the experimental study.

METHODS AND MATERIALS

Biodiesel Production

Figure 1 shows the setup for experimentation and various processes involved in biodiesel production. The Sesbania aculeate seeds are collected from its plant which is widely available in Vizag, Andhra Pradesh. The stainless steel reactor, burette, phenolphalein, indicator, thermometer, electric heater, stirrer, filter, glycerine, control valves, and glass beakers are used for the process of biodiesel production. It is also called transesterification which is the most commonly used method by many researchers [24]–[26]. Sesbania aculeate oil, Potassium hydroxide (KOH), and methanol (CH_3OH) is taken as raw materials in the SAOME biodiesel production. Note that Sujitha et al. [27] prepared methyl ester of sesbania seed oil (MESSO), an insulating fluid by transesterification process for transformers. They employed the transesterification process in which 1:6 ratios of sesbania oil and methanol, concentrated H_2SO_4 as catalysts are used to produce an insulating fluid with high thermal and oxidation stability. In this research, the biodiesel production through the transesterification process is carried out with 4:1 ratio of sesbania oil and methanol, 0.02Kg of KOH as catalyst. Also, note that the sesbania (sesbania grandiflora) seed used by Sujitha et al. [27] is different from the sesbania aculeate (sesbania bispinosa) seed which is used in this research for the biodiesel production.

In this process, the separated Sesbania aculeate oil is mixed with a catalyst (KOH) and CH_3OH in stainless steel reactor and it is stirred by stirrer at 60°C for 2 hours. The SAOME and glycerine are formed when the heated oil is kept for 12 hours. The glycerine settled in the bottom is then removed. The SAOME methyl esters produced were cleaned with distilled water to remove soaps, acids. If there are any water particles present in SAOME, the same should be removed by heating at 110°C. The procedure is repeated until the clear SAOME methyl ester is produced.

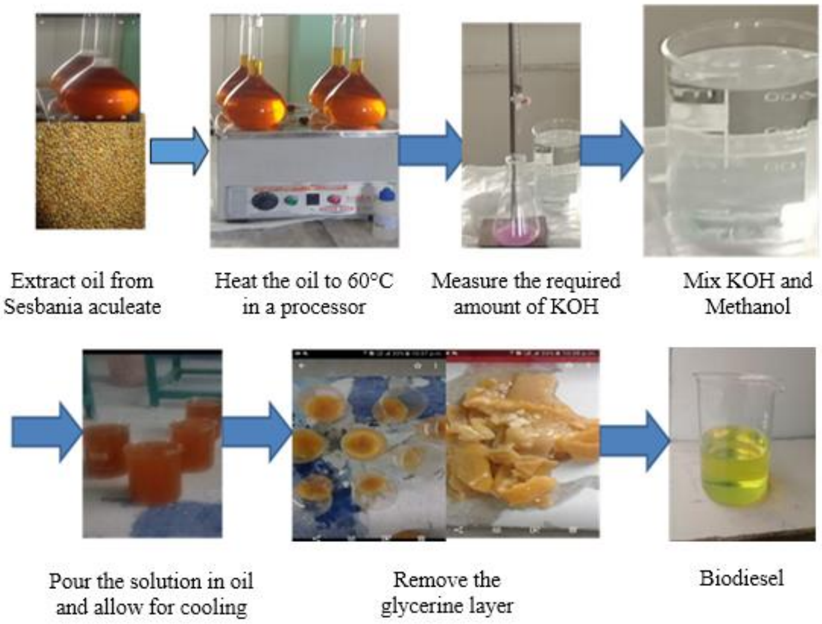


Figure 1. The process involved in the production of biodiesel

Biodiesel Properties

SAOME and its blends properties such as flash point by ASTM D 92 (employs Cleveland Open Cup Tester), viscosity by ASTM D 445 (Capillary Tube Viscometer Test Method), calorific value by ASTM D 5865 (employs Bomb Calorimeter), density by ASTM D 1298 (Hydrometer method), cetane number by ASTM D 613 (involves Cooperative Fuel Research (CFR) Cetane Engine) and Hydrogen, Carbon, Nitrogen, Oxygen and Sulphur by ASTM D 5291 (standard test methods for instrumental determination of H_2, C, and N_2 in petroleum products and lubricants) are determined in Petro Labs India Private Ltd, Chennai (refer Table 1). The flash point and viscosity of SAOME and its blends are higher as compared to diesel due to the higher Sesbania aculeate (seed) oil content. The cetane number and calorific value of SAOME and its blends are slightly lower than diesel. The density of SAOME is more in contrast with diesel but the density of SAOME blends is considerably lesser than the diesel fuel due to the reaction. Also note that % C and % H are lower than diesel nevertheless % N, % S and % O are considerably higher than that of diesel. The accurateness of instrument and their effectiveness may differ based on the environmental and operational conditions. Therefore the error and uncertainty occur due to observation, calibration, and unpredictable errors. The uncertainty in the parameters (measured) is calculated by analytical methods such as the root-sum-square method [3]. Table 2 shows the accuracy of measured parameters from uncertainty analysis.

Table 1. The Physio-chemical properties of fuels considered for the investigation

Properties	Diesel	SAOME	SAOME 10	SAOME 20	SAOME 30	SAOME 40	Test Method
Density in kg/m^3	849	878	833	839	835	837	ASTM D 1298
Viscosity in mm^2/sec	2.3	4.18	3.44	3.83	3.52	3.71	ASTM D 445
Calorific value in MJ/kg	43.35	38.50	41.18	41.56	40.93	40.68	ASTM D 5865
Flash point in °C	55	164	65	78	62	59	ASTM D 92
Cetane number	54.60	51	48	53	47	44	ASTM D 613
C (%)	84.71	81.71	83.3	82.9	82.63	82.31	ASTM D 5291
H (%)	13.67	10.73	12.11	11.97	11.13	11.02	ASTM D 5291
N (%)	1.149	2.48	1.62	1.83	1.983	2.135	ASTM D 5291
S (%)	0.443	0.49	0.46	0.462	0.46	0.469	ASTM D 5291
O (%)	0.03	4.32	2.94	3.23	2.76	2.53	ASTM D 5291

Table 2. Uncertainty analysis

Measurements	Accuracy
NO_X	± 5 ppm
CO	± 5% of the indicated value
CO_2	± 5% of the indicated value
HC	± 1 ppm
Smoke	± 1% of fuel scale reading
O_2	± 5% of the indicated value
Temperature	± 1%
Dynamic viscosity	± 1%
Calorific value	± 1%
Computed results	**Uncertainty**
Kinematic viscosity	± 1.3%
BSFC	± 1.5%
Total fuel flow	± 1%
BTE	± 1%
Speed	± 5 rpm

Experimental Setup and Procedure

Figure 2 and Figure 3 show the setup for experimentation which contains a 4-stroke single-cylinder VCR diesel engine, an electrical loading device (an eddy current dynamometer), and a data acquisition unit. Table 3 displays the standard specifications of a VCR diesel engine. The VCR diesel engine is started by a manual crank starting method. The engine load is applied when the engine meets the actual working state. The experimentation at 1500 rpm constant speed is carried out on the VCR engine with diesel, SAOME10, SAOME20, SAOME30, and SAOME40 as fuels at various engine load conditions (20% to 100%) and various CR (16.5, 17.5 and 18.5). The fuel flushing out process on the fuel line has to be carried out by using diesel after completion of each experiment. To determine the crank angle and pressure, the VCR diesel engine is provided with the required instruments. The signals are passed from the engine indicator and interfaced to the computer to draw a P-θ diagram. It is also provided with the fuel flow, air flow, load, and temperature measurement interfaces. This set up comprises air box, fuel estimating unit, air, and fuel transmitters for flow estimations. The measurement of cooling water flow rate and heat carried away are respectively found through a rotameter and calorimeter. This experimental setup can be used to study various performance parameters of the engine like BP, IMEP, BMEP, BTE, ME, ITE, BSFC, VE, A/F ratio, and heat balance. In this work, BTE and BSFC are considered for the analysis. Emissions like CO_2, CO, HC, NO_X, and smoke are determined by using a five gas analyzer made by MARS Technologies Inc. with serial number 585. The smoke denseness is noted from AVL 437 type Smoke meter. A Windows-based software “Engine Soft” was used for online performance evaluation.

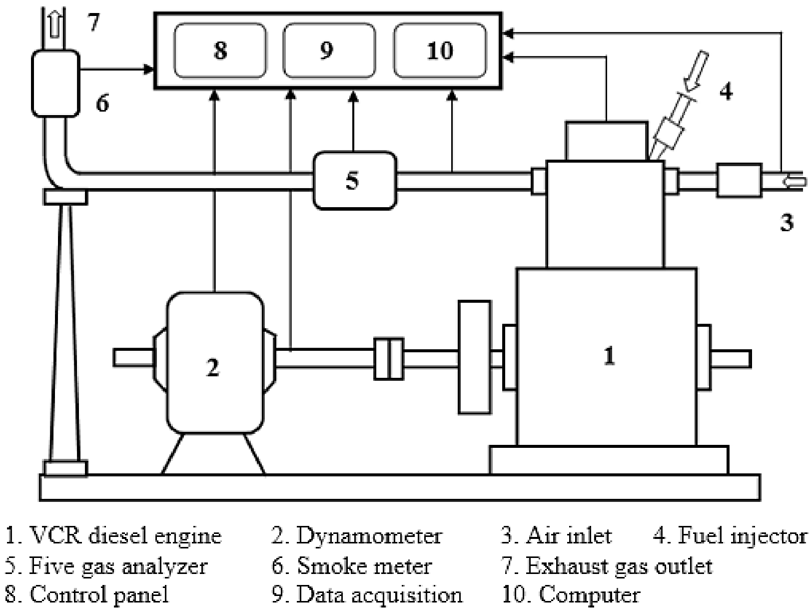


Figure 2. Line drawing of the VCR diesel engine test setup

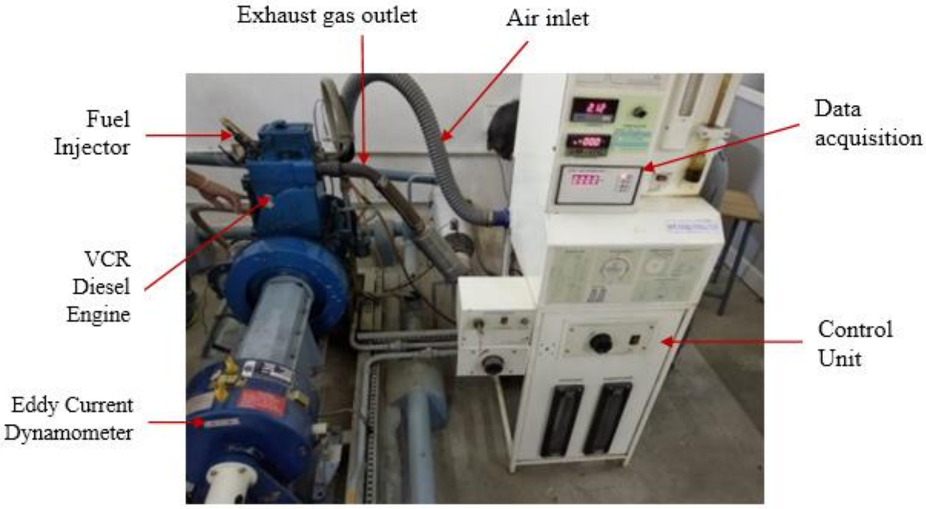


Figure 3. Photographic view of the test setup

Table 3. VCR diesel engine specifications

Description	Specification
Model and make	TV1, Kirloskar
Count of cylinders	1
Bore diameter	87.5 mm
Stroke	110 mm
Combustion chamber	Hemispherical
Piston bowl	Shallow bowl
CR	17.5;1
Power rating	5.2 kW
Speed rating	1500 rpm
Type of fuel injection	DI
Count of nozzle holes	3
Injection pressure of fuel	22 N/mm^2
Injection timing of fuel	23CA° b TDC
Loading device	7.5kW, 1500-3000 rpm, air-cooled with loading element (Eddy current type dynamometer)
Load measurement	Direct coupling, strain gauge

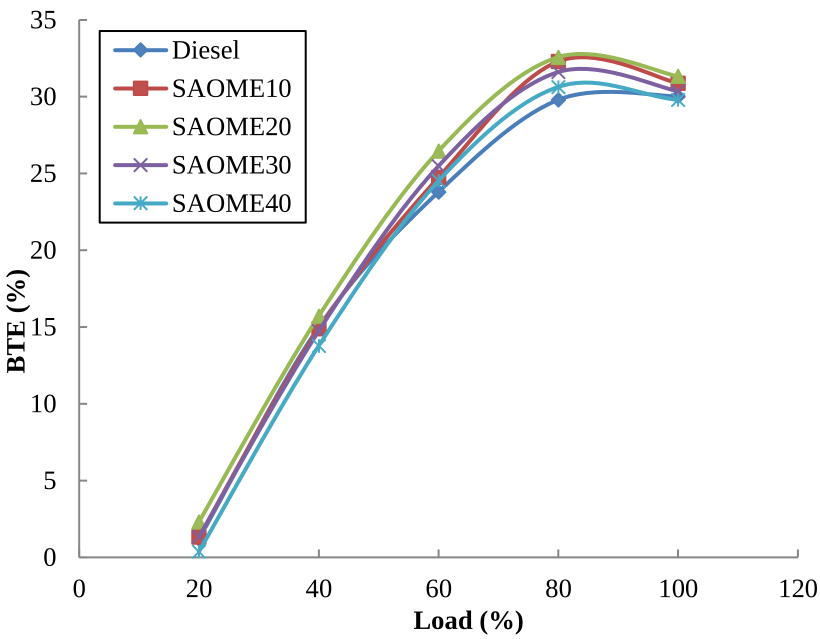
Experimental Investigation

Experiments are done on the VCR diesel engine using SAOME blends and diesel at 1500 rpm constant speed by using the standard operating procedures provided by the manufacturer. To ensure uniformity, the standard test procedure is performed which includes (i) the level of both lubricating oil and air flow is checked before staring of the VCR engine, (ii) the VCR engine is cranked with the use of decompression lever and the fuel pump kept in ON, the engine starts when disengaging the decompression lever and the engine speed increases to 1500 rpm and maintained, (iii) The VCR engine is permitted to run for 15 minutes to reach the optimum steady-state and then required load is applied, (iv) The time required for collecting 10 cubic centimeters of fuel at the stated compression ratio is noted, (v) Under each load and required compression ratio, the CO, CO2, O2, HC, and NOX are measured through the smoke meter. The experiments are conducted from 20% to 100% load conditions in steps of 20 and at different CR (16.5, 17.5 & 18.5) without any engine modification to investigate the emissions and performance parameters of the VCR engine. The biodiesel blend combinations are fuelled in the engine only after running the engine in diesel fuel for 15 to 20 minutes and test readings are taken after reaching the stable state of the engine. The quality of test readings is ensured by repeating the experiment three times and by taking the average values. A Windows-based software "Engine soft" is employed for the operational performance assessment and analysis. Also, note that the statistical analysis carried out in this research work was published as a research paper. In which, the Analytical Hierarchy Process (AHP) method is employed to determine the best combination of VCR diesel engine performance indicators and the best blend of Sesbania aculeate biodiesel. The readers may refer to the published article by Mallesham and Krishnaraj [28].

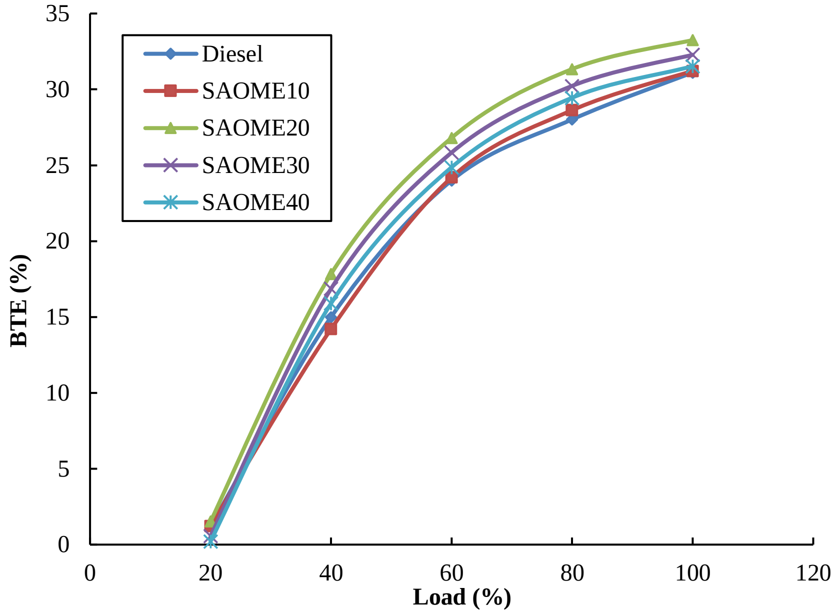
RESULTS AND DISCUSSION

Brake Thermal Efficiency

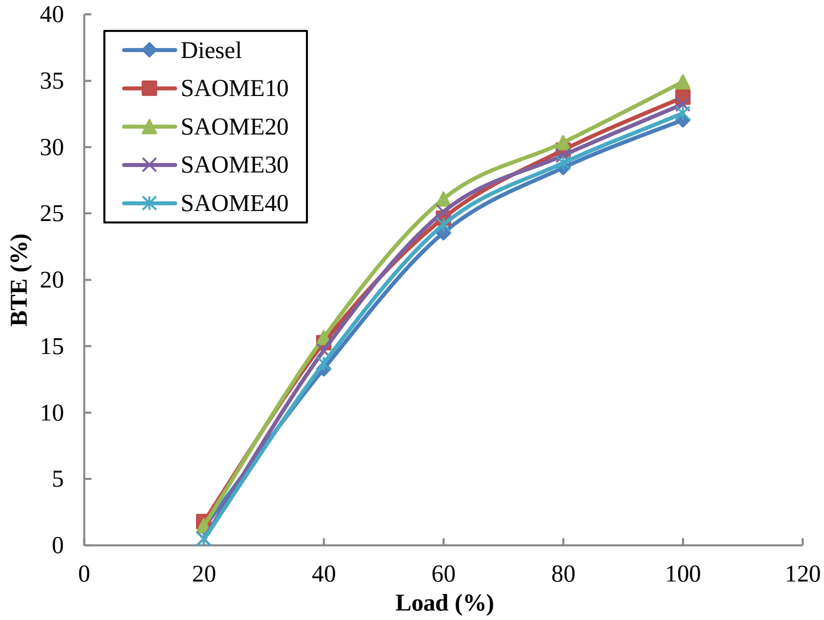
Figure 4 indicates the variation in the BTE at different loads for SAOME10, SAOME20, SAOME30, SAOME40 blends, and neat diesel at different CR of 16.5, 17.5, and 18.5. From the figure, it is witnessed that the BTE is lesser at low load. It is because of an increase in the ratio of air and fuel which leads to incomplete flame propagation. BTE increases with an elevation of load. It happens because of fuel combustion taking place completely while the fuel-air ratio increases [4], [17]. BTE increases with load and minimum losses are encountered at higher load [1]. As the CR increases from 16.5 to 18.5, BTE of the SAOME10, SAOME20, SAOME30 and SAOME40 at peak load increases by 2.78%, 4.18%, 1.12% and 1.25% respectively at CR 16.5 and further increases by 5.03%, 8.21%, 3.58% and 4.3% respectively at CR 18.5 as compared to diesel. Cylinder temperature and pressure also increases as CR increases which leads fuel to undergo complete combustion [3]. Higher BTE for SAOME20 is found when related to the usage of other blend combinations and diesel. It is because of the higher oxygen percentage in SAOME20 and in other blend combinations than diesel helps for the complete combustion. The other reason for higher BTE for SAMOE20 is due to a higher cetane number (higher ignition quality) of SAOME20 compared with other blends leads to a shortening of the ignition delay time [29]. In Figure 4a, the BTE decreases at high load due to lower CR 16.5 which affects the complete combustion of the test fuel.



(a) Variations in BTE corresponds to load at 16.5 CR



(b) Variations in BTE corresponds to load at 17.5 CR

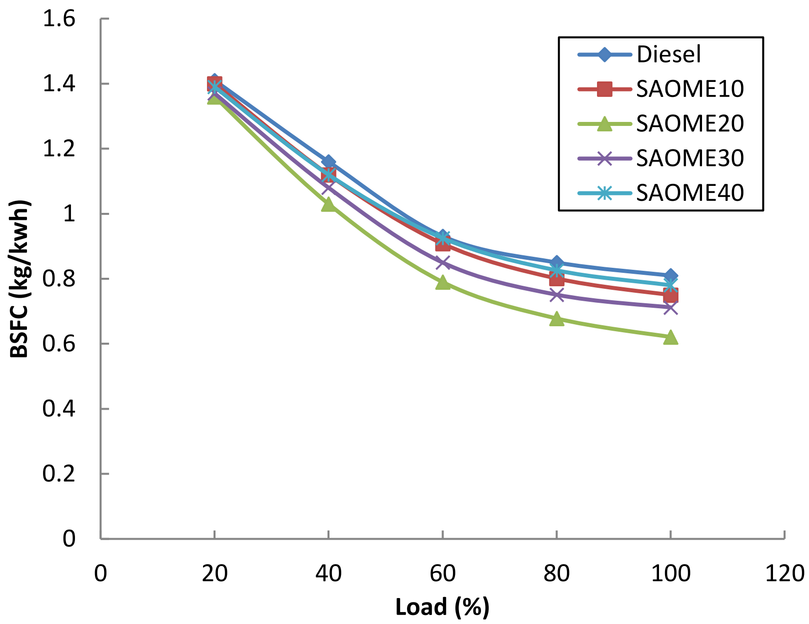


(c) Variations in BTE corresponds to load at 18.5 CR

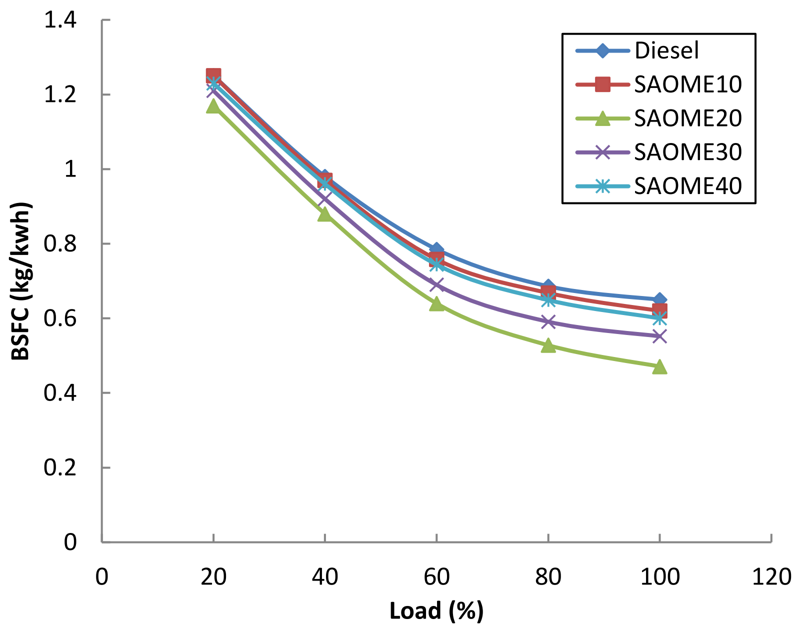
Figure 4. Variations in BTE corresponds to load at different CR

Brake Specific Fuel Consumption

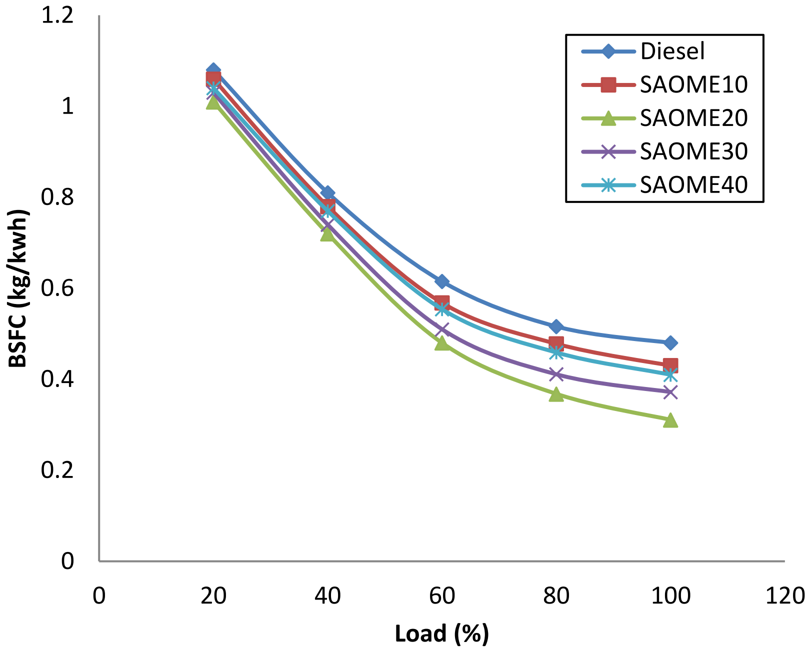
Figure 5 represents the variations in the BSFC at various loads for the blends SAOME10, SAOME20, SAOME30, SAOME40, and neat diesel at different CR of 16.5, 17.5, and 18.5. From the figure, it has been observed that, as load increases the BSFC decreases because of a decrease in heat loss which leads to better combustion at peak loads [2]. As the CR increases from 16.5 to 18.5, BSFC of SAOME10, SAOME20, SAOME30 and SAOME40 at peak load decreases by 7.4%, 27.7%, 12.09%, and 3.7% at CR 16.5 and further decreases by 10.41%, 35.2%, 22.5% and 14.58% at CR 18.5 respectively as related to diesel. CR increases as the temperature of combustion chamber increases which directs to complete combustion and delivers higher BTE and lower BSFC [3]. Diesel is having more BSFC than all the SAOME blends. It is because of the diesel containing more density. The higher diesel density increases the more amount of mass injection for the same volume. The BSFC of SAOME20 is very less as compared to test blend combinations and diesel. It happens due to the presence of more oxygen content in SAOME20 which directs to the complete combustion [4], [17]. The other reason for less BSFC of SAOME20 is the viscosity of SAOME20 comparatively less with other blends which gives good atomization during the fuel injection [29].



(a) Variations in BSFC corresponds to load at 16.5 CR



(b) Variations in BSFC corresponds to load at 17.5 CR

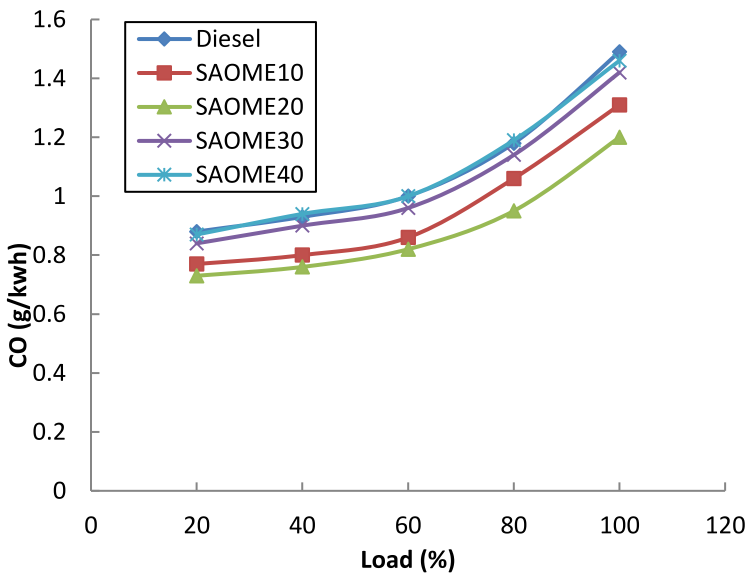


(c) Variations in BSFC corresponds to load at 18.5 CR

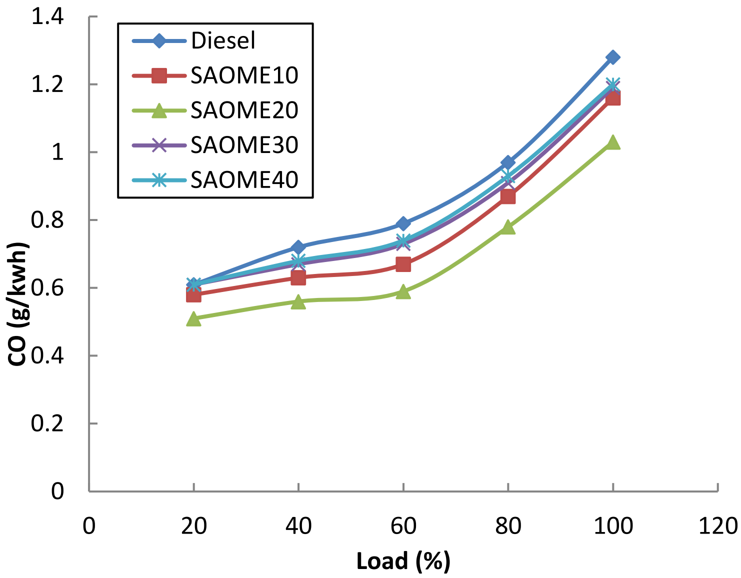
Figure 5. Variations in BSFC corresponds to load at different CR

Carbon Monoxide

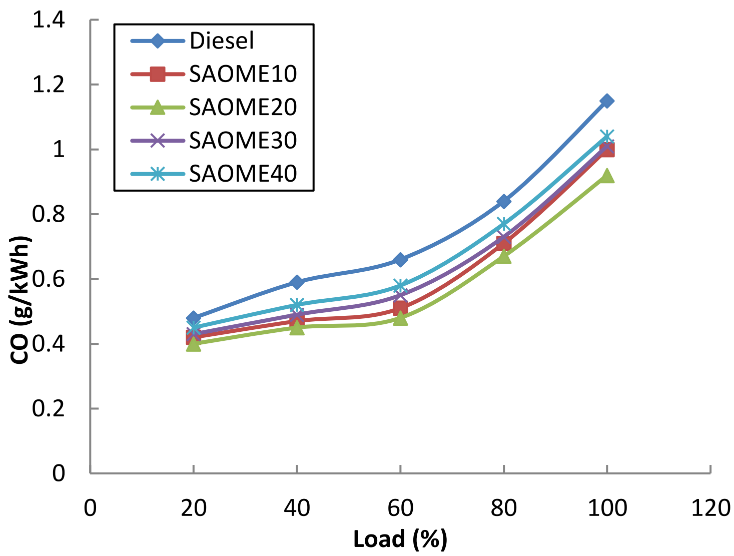
Figure 6 demonstrates the variations of the CO emission at various load conditions for the blend combinations SAOME10, SAOME20, SAOME30, SAOME40, and neat diesel at different CR values of 16.5, 17.5, and 18.5. The emission, CO is more for diesel than SAOME blends. It is due to the injection of the fuel-air rich mixture which leads to incomplete combustion. When CR rises from 16.5 to 18.5, the CO for test blends SAOME10, SAOME20, SAOME30, and SAOME40 is decreased by 12.01%, 19.43%, 9.56%, and 2.01% respectively when compared to diesel at CR 16.5 under peak load. Further, CO emission is decreased by 13.04%, 20.0%, 12.07%, and 4.69% with SAOME10, SAOME20, SAOME30, and SAOME40 respectively when comparing to diesel at CR 18.5 under peak load condition. As CR increases, the CO decreases because of oxygen content in SAOME blends increases [1]. As the CR increases from 16.5 to 18.5, the CO decreased by 14.28% for SAOME20 at peak load. As CR increases, the air temperature in cylinder increases and delay period decreases which led to complete combustion of fuel [3], [11]. Please note that the CO emission was measured as % volume and then converted into g/kWh for uniformity in all emissions.



(a) Variations of CO corresponds to load at 16.5 CR



(b) Variations of CO corresponds to load at 17.5 CR

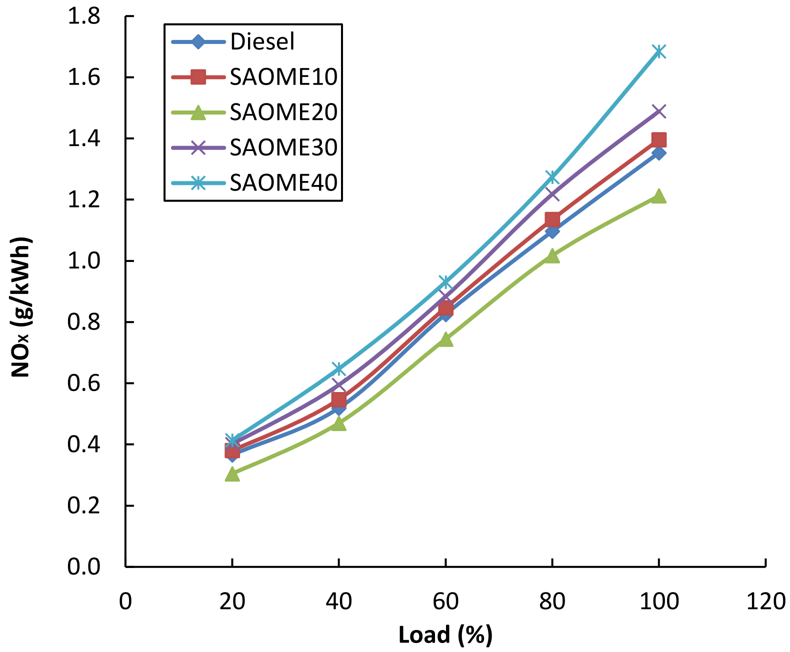


(c) Variations of CO corresponds to load at 18.5 CR

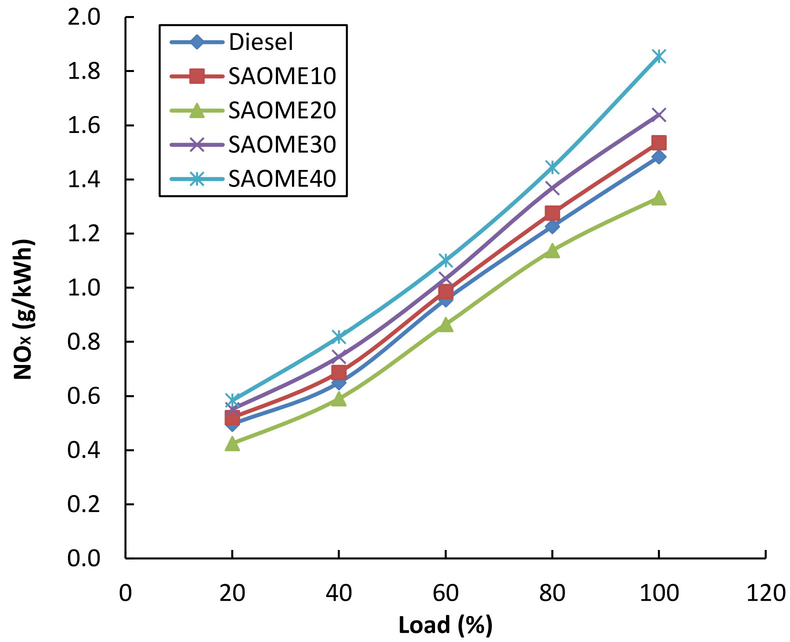
Figure 6. Variations of CO corresponds to load at different CR

Oxides of Nitrogen

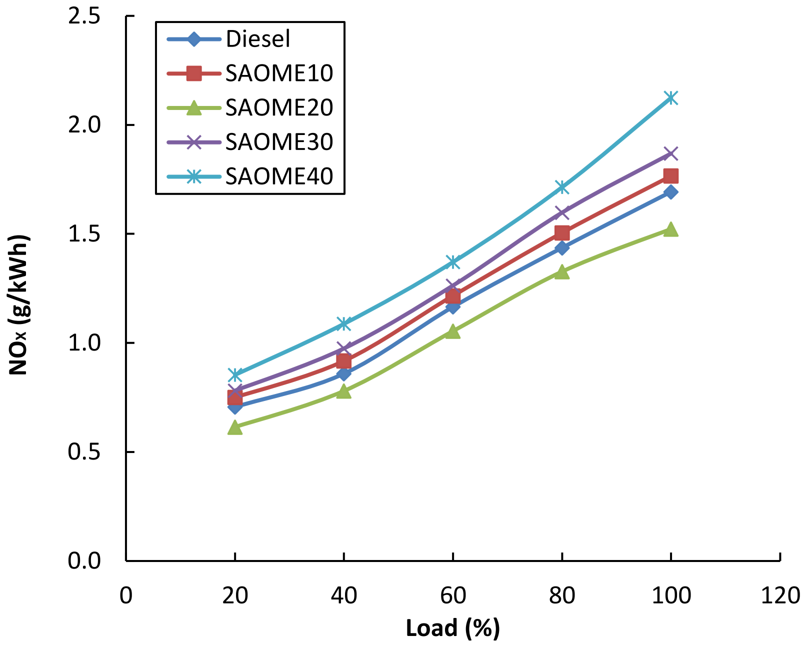
Figure 7 indicates the NO_X emission for SAOME10, SAOME20, SAOME30, SAOME40 of Sesbania aculeate methyl ester, and neat diesel at different CR 16.5, 17.5, 18.5, and peak load. NO_X increased with an elevation of load and an increase of CR. At peak load, the combustion chamber temperature increases, and it is also witnessed that the NO_X increased as the blend content increases in SAOME blends. The contribution of the small amount of nitrogen present in vegetable-based alternate fuel causes this increase in NO_X with an increase in blend content [9]. It is also noteworthy that NO_X increased while CO and smoke opacity decreased (refer to Figure 6 and 10) with SAOME blends. CR increases from 16.5 to 18.5 under peak load condition, the NO_X emission of SAOME10, SAOME20, SAOME30 and SAOME40 was increased by 3.08%, 10.34%, 9.13% and 19.6% respectively at CR 16.5; and further NO_X emission was increased by 4.13%, 10.04%, 9.41% and 24.52% respectively at CR 18.5 when comparing with diesel. It is happened due to a reduction in ignition delay duration which leads to high temperature and pressure and forms a higher NO_X emission [20]. At CR 18.5, the NO_X was observed for the blend SAOME40 and is increased by 24.52% and the blend SAOME20 is reduced by 10.04% than diesel. Please note that the NOx emission was measured as ppm and then converted into g/kWh for uniformity in all emissions.



(a) Variations of NO_X corresponds to load at 16.5 CR



(b) Variations of NO_X corresponds to load at 17.5 CR

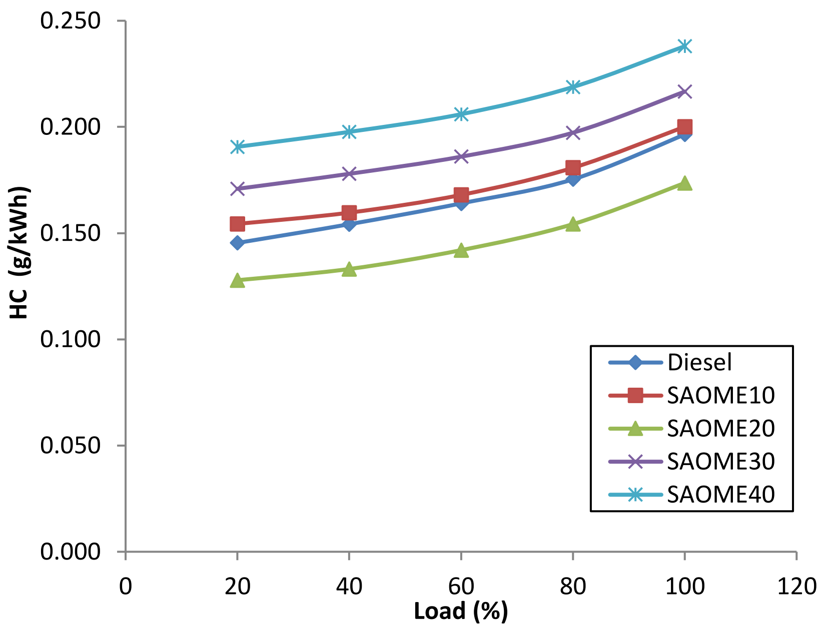


(c). Variations of NO_X corresponds to load at 18.5 CR

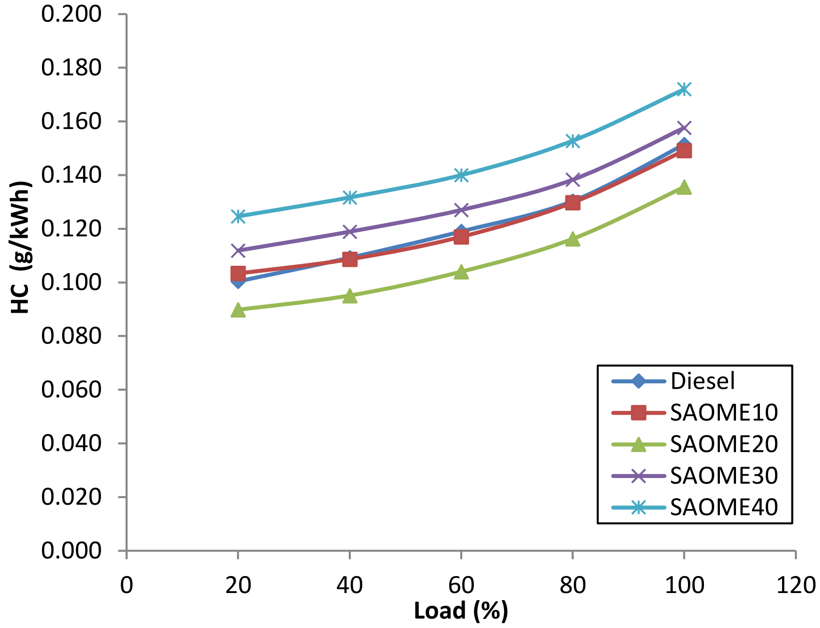
Figure 7. Variations of NO_X corresponds to load at different CR

Hydrocarbons

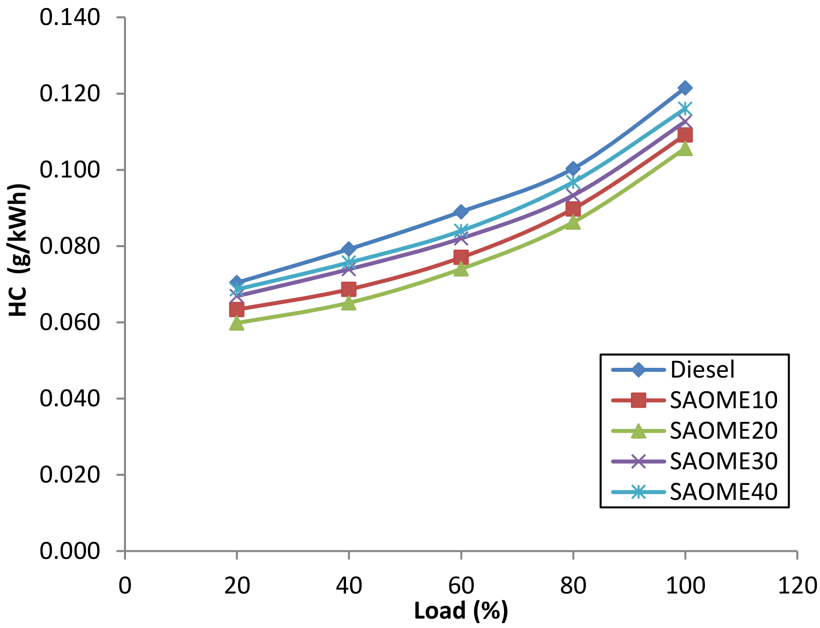
Figure 8 shows the deviation of HC emission for SAOME10, SAOME20, SAOME30, SAOME40 of Sesbania aculeate blends, and neat diesel at different CR 16.5, 17.5, and 18.5 at different load. The HC rises with a raise in load as a rich air-fuel mixture enters into the combustion chamber which in turn directs to improper combustion. As the CR increases from the 16.5 to 17.5 under peak load condition, HC emission of the blends (SAOME10, SAOME20, SAOME30 and SAOME40) was decreased by 9.91%, 12.39, 6.6% and 4.13% respectively at CR 16.5; and also HC emission of the blends (SAOME10, SAOME20, SAOME30 and SAOME40) further decreased by 17.6%, 26.89%, 15.96% and 8.82% respectively at CR 18.5 as compared with the diesel. It is because of the complete combustion of fuel. SAOME20 blend shows lower HC emission because of more amount of oxygen in SAOME20 and helps in complete combustion. Please note that the HC emission was measured as ppm and then converted into g/kWh for uniformity in all emissions.



(a) Variations of HC corresponds to load at 16.5 CR



(b) Variations of HC corresponds to load at 17.5 CR

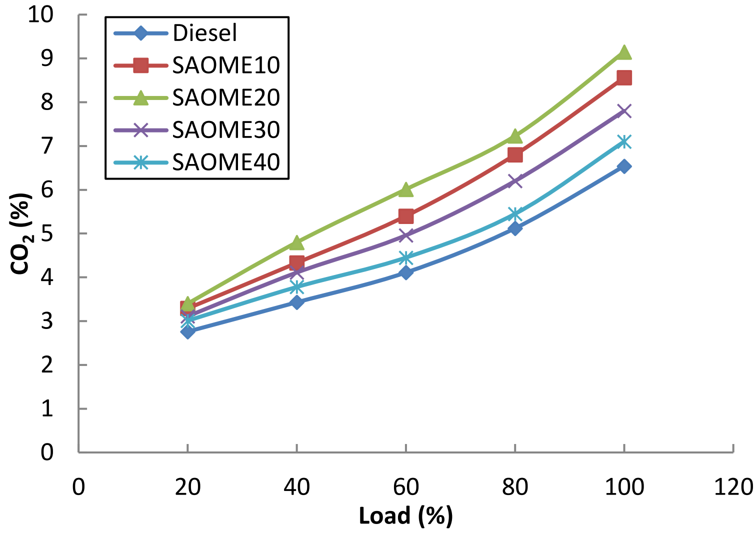


(c) Variations of HC corresponds to load at 18.5 CR

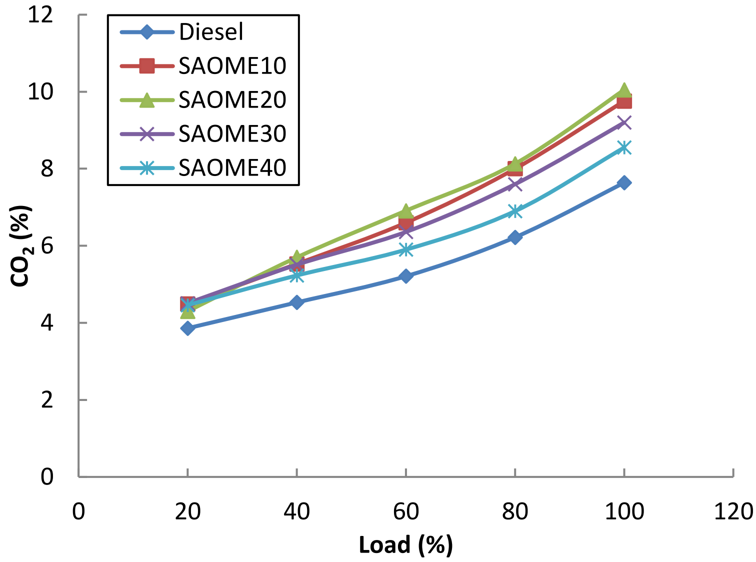
Figure 8. Variations of HC corresponds to load at different CR

Carbon Dioxide

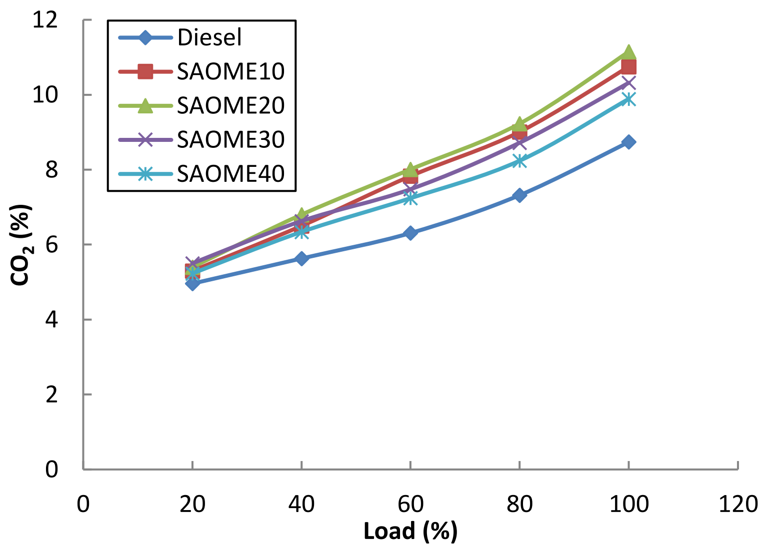
Figure 9 demonstrates the deviation of CO_2 emission for blends (SAOME10, SAOME20, SAOME30, SAOME40) of SAOME and neat diesel at different CR 16.5, 17.5, and 18.5 and different loads. The results show that at peak loads the CO_2 emission increases because of delay in combustion. The SAOME blends are having more CO_2 emission than diesel. It is because of more oxygen in SAOME blend led to more combustion [1]. As the CR increases from 16.5 to 18.5, CO_2 emission of SAOME blends SAOME10, SAOME20, SAOME30 and SAOME40 is increased by 18.69 %, 21.61%, 7.9%, 11.6% and 7.9% respectively at CR 16.5; and by 23.59%, 28.52%, 16.1% and 15.3% respectively at CR 18.5 when comparing with diesel under peak load condition. Since SAOME20 is having more oxygen percentage, it emits more CO_2 than diesel. The diesel produces less amount of CO_2 because it is having a high carbon content and less oxygen content than biodiesel blends.



(a) Variations of CO_2 corresponds to load at 16.5 CR



(b) Variations of CO_2 corresponds to load at 17.5 CR

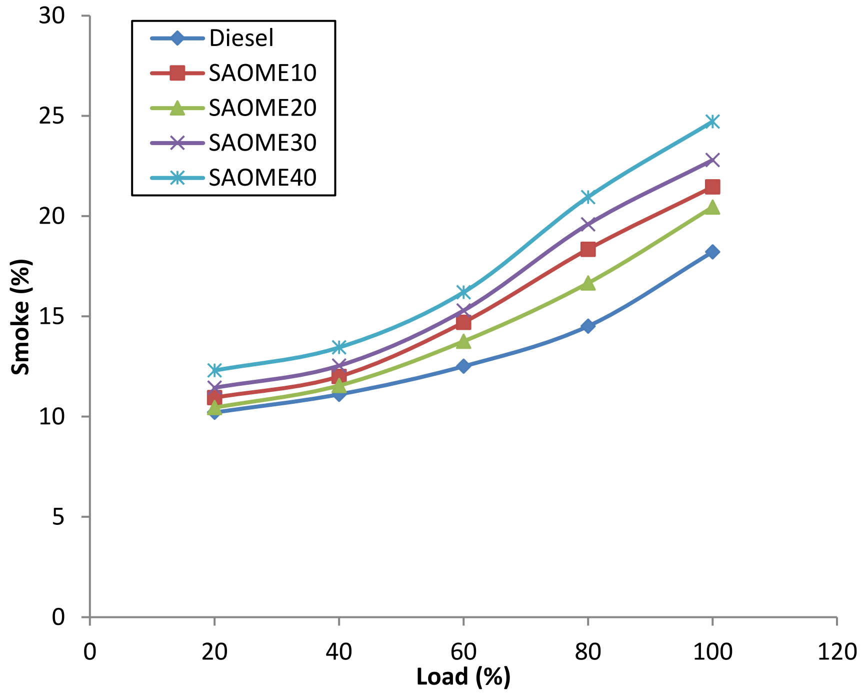


(c). Variations of CO_2 corresponds to load at 18.5 CR

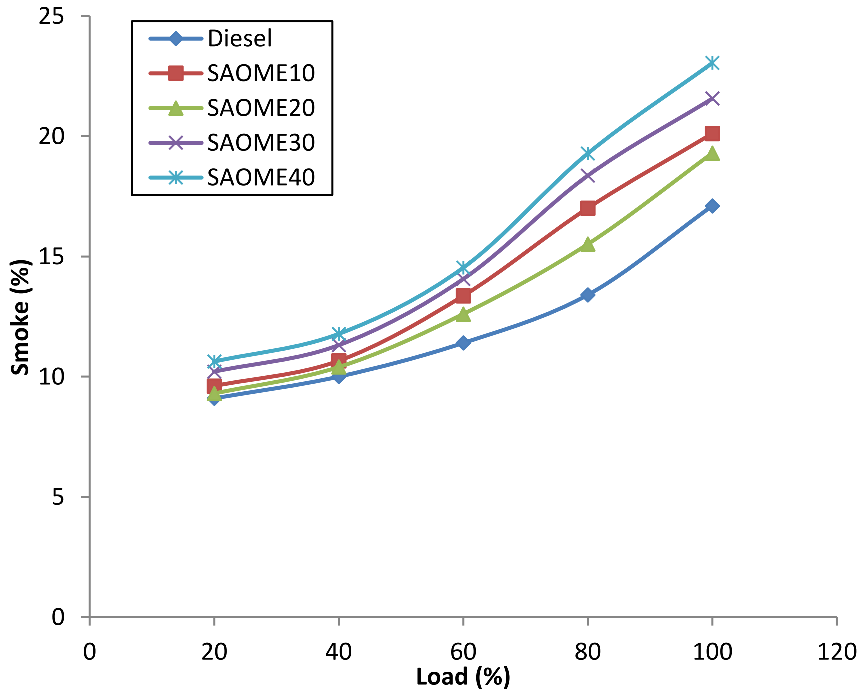
Figure 9. Variations of CO_2 corresponds to load at different CR

Smoke Opacity

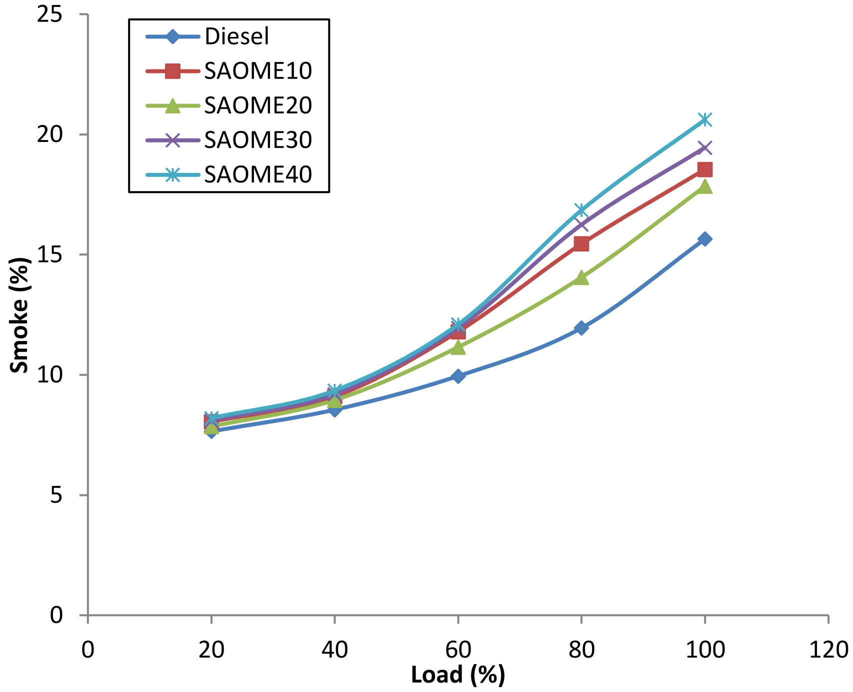
Figure 10 represents the smoke opacity for test blends (SAOME10, SAOME20, SAOME30, SAOME40) of SAOME and neat diesel at different CR 16.5, 17.5, and 18.5 and different loads. It shows that smoke opacity has elevated with an escalation in load and due to incomplete combustion. As CR increases from 16.5 to 18.5, the smoke opacity of SAOME blends SAOME10, SAOME20, SAOME30 and SAOME40 at peak load are respectively decreased by 15.08%, 10.93%, 19.55% and 24.08% at CR16.5 and 15.63%, 12.3%, 20.11% and 26.32% respectively at CR 18.5 but relatively little higher as compared to diesel. These results show that the SAOME emitted more soot particle than diesel. It is because of the higher sulphur in SAOME blends. The sulphates formed by the more sulphur present in the SAOME increase the smoke from the VCR engine. The blend SAOME40 is produced more smoke capacity than blends of SAOME and diesel, because of high sulphur content in the blend SAOME40. The blend SAOME20 is produced the lowest smoke emission than all the other blends which is slightly greater than diesel.



(a) Variations of smoke corresponds to load at 16.5 CR



(b) Variations of smoke corresponds to load at 17.5 CR



(c). Variations of smoke corresponds to load at 18.5 CR

Figure 10. Variations of smoke corresponds to load at different CR

CONCLUSIONS

The experimental studies are conducted on VCR diesel engine for SAOME blends and diesel at various load conditions say, 20%, 40%, 60%, 80%, and peak load (100%) and at different CRs (16.5, 17.5 and 18.5). The results of SAOME blends are compared with the emission and performance parameters of diesel. The following are the key findings from the experimental investigation:

1) For SAOME20, BSFC is decreased by about 12.3% (shows the fuel savings) and BTE is increased around 8.21% (shows the performance improvement) at peak load and CR at 18.5 as compared to diesel.

2) For SAOME20, the emissions like NO_X, CO, and HC are reduced by 10.04%, 14.28%, and 8.82% respectively at peak load and CR elevated from 16.5 to 18.5 when comparing to diesel.

The above results of the investigation show that SAOME20 can be used as a hopeful alternative fuel blend with diesel which produced notable performance on a VCR diesel engine under peak load condition and at various CRs (16.5, 17.5, and 18.5). Further investigations may be necessary in VCR diesel engine to achieve further improvements in performance parameters (including combustion pressure variation and amount of heat release) and to reduce various emissions by adding additives (like cerium oxide and aluminium oxide) along with SAOME blends or by adding another biodiesel with SAOME (a bi-fuel or tri-fuel) by emulsification process.

ACKNOWLEDGMENTS

The authors are very much obliged to both round one and round two reviewers and editors for the valuable comments and suggestions to improvise the previous versions of this research paper.

REFERENCES

[1] S. Jindal, B. P. Nandwana, N. S. Rathore, and V. Vashistha, "Experimental investigation of the effect of compression ratio and injection pressure in a direct injection diesel engine running on Jatropha methyl ester," *Applied Thermal Engineering*, vol. 30, no. 5, pp. 442–448, 2010, doi: 10.1016/j.applthermaleng.2009.10.004.

[2] S. Nagaraja, M. Sakthivel, and R. Sudhakaran, "Combustion and performance analysis of variable compression ratio engine fueled with preheated palm oil - Diesel blends," *Indian Journal of Chemical Technology*, vol. 20, no. 3, pp. 189–194, 2013, [Online]. Available: http://nopr.niscair.res.in/handle/123456789/18363.

[3] K. Sivaramakrishnan and P. Ravikumar, "Optimization of operational parameters on performance and emissions of a diesel engine using biodiesel," *International Journal of Environmental Science and Technology*, vol. 11, no. 4, pp. 949–958, 2014, doi: 10.1007/s13762-013-0273-5.

[4] B. De and R. S. Panua, "An experimental study on performance and emission characteristics of vegetable oil blends with diesel in a direct injection variable compression ignition engine," in *Procedia Engineering*, 2014, vol. 90, pp. 431–438, doi: 10.1016/j.proeng.2014.11.873.

[5] R. D. Eknath and J. S. Ramchandra, "Effect of compression ratio on energy and emission of VCR diesel engine fueled with dual blends of biodiesel," *Journal of Engineering Science and Technology*, vol. 9, no. 5, pp. 620–640, 2014.

[6] N. Ganesh and S. C. Chandrakishor, "Emission Characteristics of Diesel Engine Fueled with Algae Biodiesel-Diesel Blends," *International Research Journal of Engineering and Technology*, vol. 2, no. 4, pp. 1587–1592, 2015, [Online]. Available: https://www.irjet.net/archives/V2/i4/Irjet-v2i4262.pdf.

[7] V. Hariram and R. Vagesh Shangar, "Influence of compression ratio on combustion and performance characteristics of direct injection compression ignition engine," *Alexandria Engineering Journal*, vol. 54, no. 4, pp. 807–814, 2015, doi: 10.1016/j.aej.2015.06.007.

[8] B. Shalem Raju and K. Ravi Kumar, "Performance study on variable compression ratio (VCR) engine using different blends of neem biodiesel as an alternative fuel," *International Research Journal of Engineering and Technology*, vol. 5, no. 6, pp. 2349–2353, 2018, [Online]. Available: https://www.irjet.net/archives/V5/i6/IRJET-V5I6438.pdf.

[9] K. Sivaramakrishnan, "Investigation on performance and emission characteristics of a variable compression multi fuel engine fuelled with Karanja biodiesel–diesel blend," *Egyptian Journal of Petroleum*, 2018, doi: 10.1016/j.ejpe.2017.03.001.

[10] P. Somasekar and V. Pandurangadu, "Experimental investigation on the performance combustion and emission characteristics of a VCR DI diesel engine with methyl ester of mango seed," *International Journal of Current Engineering And Scientific Research*, vol. 5, no. 1, pp. 47–54, 2018, [Online]. Available: http://troindia.in/journal/ijcesr/vol5iss1part3/47-54.pdf.

[11] S. K. Nayak, S. K. Nayak, P. C. Mishra, and S. Tripathy, "Influence of compression ratio on combustion characteristics of a VCR engine using Calophyllum inophyllum biodiesel and diesel blends," *Journal of Mechanical Science and Technology*, vol. 29, no. 9, pp. 4047–4052, 2015, doi: 10.1007/s12206-015-0850-2.

[12] M. H. Mosarof *et al.*, "Optimization of performance, emission, friction and wear characteristics of palm and Calophyllum inophyllum biodiesel blends," *Energy Conversion and Management*, vol. 118, pp. 119–134, 2016, doi: 10.1016/j.enconman.2016.03.081.

[13] P. Bridjesh, N. Prabhu Kishore, M. V. Mallikarjuna, and N. Alekhya, "Performance analysis of variable compression ratio diesel engine using calophyllum inophyllum biodiesel," *Indian Journal of Science and Technology*, vol. 9, no. 35, 2016, doi: 10.17485/ijst/2016/v9i35/95577.

[14] R. U. D. M. Deepika Nadipudi, P. Sreenivasulu, and R. Sam Sukumar, "Performance and emission analysis of calophyllum inophyllum biodiesel using isobutene as additive," *International Journal of Current Engineering And Scientific Research*, vol. 5, no. 3, pp. 29–36, 2018, [Online]. Available: http://troindia.in/journal/ijcesr/vol5iss3part4/29-36.pdf.

[15] P. L. Navaneethakrishnan, M. K. Sathishkumar, B. Charles, and N. Udhayakumar, "Investigation on performance and emission characteristics of biodiesel blends extracted from trash fish oil," *International Journal of Scientific Development and Research*, vol. 1, no. 11, pp. 130–135, 2016, [Online]. Available: https://www.ijsdr.org/viewpaperforall.php?paper=IJSDR1611023.

[16] R. Senthil, E. Sivakumar, and R. Silambarasan, "Effect of di ethyl ether on the performance and emission characteristics of a diesel engine using biodiesel-eucalyptus oil blends," *RSC Adv.*, 2015, doi: 10.1039/c5ra08414h.

[17] H. Soukht Saraee, S. Jafarmadar, M. Sayadi, A. Parikhani, J. Kheyrollahi, and N. Pourvosoughi, "Green fuel production from Pistacia Khinjuk and its engine test analysis as a promising alternative," *Journal of Cleaner Production*, vol. 156, pp. 106–113, 2017, doi: 10.1016/j.jclepro.2017.04.053.

[18] X. Wang and P. Ni, "Combustion and emission characteristics of diesel engine fueled with diesel-like fuel from waste lubrication oil," *Energy Conversion and Management*, vol. 133, pp. 275–283, 2017, doi: 10.1016/j.enconman.2016.12.018.

[19] C. Ravikiran, K. Thirupathi, M. L. Reddy, and S. Devakumar, "Experimental investigation on performance and emission characteristics of a CI diesel engine using jute oil blends," *International Journal of Applied Engineering Research*, vol. 13, no. 2, pp. 141–145, 2018, [Online]. Available: https://www.ripublication.com/ijaerspl2018/ijaerv13n2spl_19.pdf.

[20] A. Uyumaz, "Combustion, performance and emission characteristics of a DI diesel engine fueled with mustard oil biodiesel fuel blends at different engine loads," *Fuel*, vol. 212, pp. 256–267, 2018, doi: 10.1016/j.fuel.2017.09.005.

[21] K. Ramarao, C. J. Rao, and D. Sreeramulu, "The experimental investigation on performance and emission characteristics of a single cylinder diesel engine using nano additives in diesel and biodiesel," *Indian J. Sci. Technol.*, vol. 8, no. 29, 2015, doi: 10.17485/ijst/2015/v8i29/75718.

[22] S. Nithya, S. Manigandan, P. Gunasekar, J. Devipriya, and W. S. R. Saravanan, "The effect of engine emission on canola biodiesel blends with TiO2," *International Journal of Ambient Energy*, vol. 40, no. 8, pp. 838–841, 2019, doi: 10.1080/01430750.2017.1421583.

[23] A. Saravanan, M. Murugan, M. Sreenivasa Reddy, and S. Parida, "Performance and emission characteristics of variable compression ratio CI engine fueled with dual biodiesel blends of Rapeseed and Mahua," *Fuel*, vol. 263, p. 116751, 2020, doi: 10.1016/j.fuel.2019.116751.

[24] S. Jaikumar, S. K. Bhatti, and V. Srinivas, "Experimental Investigations on Performance, Combustion, and Emission Characteristics of Niger (Guizotia abyssinica) Seed Oil Methyl Ester Blends with Diesel at Different Compression Ratios," *Arabian Journal for Science and Engineering*, vol. 44, no. 6, pp. 5263–5273, 2019, doi: 10.1007/s13369-018-3538-y.

[25] M. N. Mohiddin, A. A. Saleh, A. N. R. Reddy, and S. Hamdan, “A study on chicken fat as an alternative feedstock: Biodiesel production, fuel characterisation, and diesel engine performance analysis,” *International Journal of Automotive and Mechanical Engineering*, vol. 15, no. 3, pp. 5535–5546, 2018, doi: 10.15282/ijame.15.3.2018.10.0425.

[26] D. Singh, A. Deep, S. S. Sandhu, and A. K. Sarma, “Experimental Assessment of Combustion, Performance and Emission Characteristics of a CI Engine Fueled with Biodiesel and Hybrid Fuel Derived from Waste Cooking Oil,” *Environmental Progress & Sustainable Energy*, vol. 38, no. 4, p. 13112, 2019, doi: 10.1002/ep.13112.

[27] S. Ravulapalli, K. Ravindhranath, and M. Ramamoorty, “Preparation, characterization and feasibility analysis of methyl ester of Sesbania seeds oil (MESSO) as alternate liquid dielectrics in distribution transformers,” *RSC Advances*, vol. 9, no. 6, pp. 3311–3319, 2019, doi: 10.1039/c8ra08378a.

[28] D. Mallesham, J. Krishnaraj, and C. H. Ravikiran, “Selecting Optimal Combination of Operating Parameters of VCR Diesel Engine Adopting AHP,” *Indian Journal of Science and Technology*, vol. 12, no. 33, 2019, doi: 10.17485/ijst/2019/v12i33/146811.

[29] A. Gopinath, K. Sairam, R. Velraj, and G. Kumaresan, “Effects of the properties and the structural configurations of fatty acid methyl esters on the properties of biodiesel fuel: A review,” *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, vol. 229, no. 3. pp. 357–390, 2015, doi: 10.1177/0954407014541103.