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Effect of Compression Ratio on the Performance and Emission Characteristics of a CRDI-VCR Diesel Engine Fueled with Al_2O_3-Enhanced Biodiesel–Diesel Blends

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Abstract

The popularity of CI engine improvement with reduced exhaust emission to satisfy renewable fuels demand has renewed the interests in biodiesel/nanoparticle blends for CI engines. The effect of coupled compression ratio (CR) and Nano enhanced biodiesel on the performance emission trade-off is yet established, especially in case of Moringa oleifera biodiesel. In this paper, the experimental evaluations of the performance and emission characteristics of a common-rail direct-injection variable-compression-ratio (CRDI-VCR) diesel engine are conducted by varying the CR and adding Al_2O_3 nanoparticles. Moringa oleifera Methyl ester is added to diesel at 10% and 20% (MB10 and MB20) and Al_2O_3 NPs are added to these blends at 100 ppm. Experiments were performed at engine speed 1500 rpm, the injection pressure 600 bar, the injection timing 23°bTDC, brake loads between 0.88 and 3.50 kW, and compression ratios of 16:1, 17:1 and 18:1. The findings are presented here to prove that the improvement in the CR and in the engine load has, in general, improved the thermal performances and consequently reduced the fuel consumptions. Under the specified test conditions, CR18:1 at full load gave the maximum brake thermal efficiency of 29.59%, while the minimum value of BSFC, and BSEC were 0.29 kg/kWh and 12.17 MJ/kWh, respectively, for MB20+Al_2O_3 compared to 0.30 kg/kWh and 12.90 MJ/kWh, respectively, for diesel. The MB20+ Al_2O_3 blend also brought down the CO emission to 0.06% vol, as against 0.10% vol of diesel; HC level to 8 ppm, as against 13 ppm in diesel; and smoke opacity to 8.73%, down from 10.03% in the diesel fuel. For comparison, NO_x was found to rise with CR and load values, as Al_2O_3 was able to lower NO_x from 1124 to 1102 ppm in MB20 at the highest CR value of 18:1 and for full load; however, the NO_x production remained higher than the diesel. Overall the use of MB20+Al_2O_3 at CR 18:1 resulted in the best performance and lead to a decrease in CO, HC and smoke emissions also the control of NO_x will be of major interest for further optimisation. The results showed that adding 100 ppm Al_2O_3 is a promising approach to enhance the use of Moringa oleifera biodiesel–diesel mixtures in CRDI-VCR engines.

Keywords: Variable Compression Ratio; Common-rail direct Injection; Moringa oleifera biodiesel; Al_2O_3 nanoparticles

Abbreviation	
Al_2O_3	Aluminium oxide
ASTM	American Society for Testing and Materials
bTDC	Before Top Dead Centre
BP	Brake Power

BSEC	Brake Specific Energy Consumption
BSFC	Brake Specific Fuel Consumption
BTE	Brake Thermal Efficiency
CA	Crank Angle
CI	Compression Ignition
CO	Carbon Monoxide
UHC	Unburned hydrocarbons
NO_x	Nitrogen Oxides
CO_2	Carbon Dioxide
CR	Compression Ratio
CRDI	Common-Rail Direct Injection
VCR	Variable Compression Ratio
D100	100% Diesel
MOME	Moringa oleifera methyl ester
MB10	10% Moringa Biodiesel + 90% Diesel
MB10+Al_2O_3	MB10 with 100 ppm Al_2O_3 nanoparticles
MB20	20% Moringa Biodiesel + 80% Diesel
MB20+Al_2O_3	MB20 with 100 ppm Al_2O_3 nanoparticles

1 Introduction

Rising energy demand, shrinking petroleum reserves, and mounting environmental pressure have together pushed the search for renewable, low-emission alternatives to fossil fuels to the front of the agenda. Transport still leans heavily on compression-ignition (CI) engines, and for good reason—they are efficient, durable, and hold up under heavy-duty use. The problem is what comes out of the tailpipe: burning conventional diesel produces CO, UHC, NO_x, and particulate and smoke. This is why finding renewable fuels that can hold engine performance steady while cutting these emissions has become such a pressing line of research. Biodiesel, made from renewable biological feedstocks, stands out among the options: it is biodegradable, oxygenated, and renewable, and in most cases it can run in existing CI engines without any major hardware changes.

One of the best materials available, Moringa oleifera supplies a moderate amount of oil, is not a food source, is versatile in the climate it grows in, and is easy to grow sustainably for biodiesel production. Experiments have shown that Moringa biodiesel works in CI engines both on its own and blended with diesel. Ramalingam and Mahalakshmi [1] concluded that the use of blends of Moringa biodiesel and diesel in combination with alcohol was competitive with conventional diesel fuels in terms of performance and emissions using a B90-D5-H5 blend with a reported efficiency of 28.8% BTE under their test conditions. They additionally found that the fuel composition significantly influenced the cylinder pressure, heat release rate (HRR), ignition delay and exhaust emissions. The same direction is indicated on work carried out by Moringa as well as Jatropha methyl esters, demonstrating that blends of biodiesel can reduce NO_x and smoke production, maintaining comparably satisfactory behaviour in relation to the conventional diesel [2]. More current experiments have solidified this notion that fuels derived from Moringa can be used in part as a replacement to petroleum diesel in CI engines [3].

Although biodiesel has all of these benefits, it is not a direct substitute for petroleum diesel, as biodiesel's physical and chemical properties are different. It is generally higher in energy content, more dense, more viscous and has less energy content per unit, and those differences are translated into the characteristics of fuel atomization, spray penetration, evaporation, mixing with air, and combustion initiation. The direct

consequence is that the BSFC can increase and BTE can decrease depending upon the way the engine is operated when running biodiesel. However, the opposite is true the more oxygen you have, the more complete the burn, and the more CO, HC and smoke are reduced. The problem is that the same oxygen, as well as the higher combustion temperature, has the tendency to cause more NO_x to increase. Rebalancing in opposite directions like these, one thing is clear: Fuel reformulation alone will not be sufficient to achieve the balance between efficiency and emissions.

A promising approach to the problem of combustion that has been tried with biodiesel is to incorporate the nanoscale particles into this fuel. Nanoparticles are responsible for adding very high surface area per volume, improved thermal properties, and catalytic effect, which can change the fuel's evaporation, atomization, ignition, and oxidation. Recent reviews have called for the use of these additives because they can enhance the combustion of biodiesel in several ways, such as improving the fuel and air mixing, accelerating the oxidation reactions, reducing the ignition delay, and redistributing heat in the combustion chamber [4]. Among the different metallic oxides and metallic options, aluminum oxide (Al_2O_3) has consistently been the most interesting due to its high thermal conductivity, chemical stability, high melting point, and its catalytic effect on combustion.

Al_2O_3 nanoparticles have been evaluated in various types of diesel engines using various biodiesel feedstocks. For example, Rajesh et al. [5] reported that the thermal efficiency and the CO and HC emissions were found to be decreased with the coconut fatty acid distillate biodiesel when the concentration of Al_2O_3 was optimized at 25 ppm, 50 ppm and 100 ppm. Kayed et al. [6] extended their work to include jatropha, corn and waste cooking oil and then added Al_2O_3. The thermal efficiency was found to have risen by around 8%, 11% and 13% for 10%, 20% and 30% blends respectively when compared to plain biodiesel blends and all the CO, unburned hydrocarbons and smoke were found to have reduced significantly at 100 ppm. NO_x, however, increased with the increase in alumina fed—the hotter and more violent the combustion. These studies show that Al_2O_3 may indeed alter the combustion environment as explained, but not how the additive interacts with the operating parameters of the engine.

The positive effect of alumina nanoparticles has also been demonstrated for other biodiesel raw materials and modes of operation. Research conducted in that study on soya biodiesel showed that, with the addition of Al_2O_3 content in biodiesel–diesel blends, the BTE has increased, and the BSFC has decreased, despite increases in NO_x and CO_2 in certain operating conditions [7]. Likewise, the study in recent years for making biodiesel with the use of coconut oil showed that the addition of nanoparticles (Al_2O_3) not only enhances the thermal efficiency but also helps in the reduction of HC and CO emissions [5]. A further study on neem biodiesel showed that a CI engine running on neem biodiesel can be further optimized for its overall performance and emission characteristics using alumina (Al_2O_3) nanoparticles, with the simultaneous optimization of the concentration of the nanoparticles and the fraction of neem biodiesel [8]. These studies suggest that the impact of Al_2O_3 is very sensitively affected by the fuel composition, concentration of the nanoparticles, and operating conditions of the engines.

Compression ratio (CR) is the most significant parameter of an engine which determines the process of combustion for a CI engine apart from fuel formulation. An increase in CR changes the temperature and pressure of the compressed air prior to fuel injection, which affects ignition delay, combustion timing, premixed combustion, peak cylinder pressure, heat release and overall thermal efficiency. In general, a higher CR represents better thermal efficiency, thanks to the increase in compression temperature and expansion ratio. But large levels of raising CR can lead to increased combustion temperature and thus further contribute to NO_x generation. Hence, the effect of CR and fuel properties is significant when using oxygenated alternative fuels and catalytic nano-additives.

Shekh and Patel [9] have proved the effectual role of the simultaneous consideration of CR and injection pressure (IP) in biodiesel fired VCR Engine. They conducted a series of experiments by changing the values of CR and IP parameters to investigate and understand the emission of NO_x characteristics of the diesel engine used in the VCR, operating on Madhuca longifolia biodiesel. This investigation used CRs of 15:1, 16:1, 17:1 and 18:1, injection pressures of 300, 400, 500 and 600 bar, and different engine load conditions for diesel, B10, B20 and B30 fuels. They found that the influence of the combined variation of CR and IP on NOx formation was very marked from their results. The lowest NOx emission was achieved at 600 bar of 15:1 IP at 25% load. Moreover, a comparatively good NOx response in the tested operating conditions was obtained for a CR of ~16:1 and an IP of 600 bar at the increase of the engine load from 25% to full load.

Recent investigations also have shown the importance of CR in a Moringa oleifera engine fuels by biodiesel. Patel and Buch [10] experimentally tested diesel and Moringa biodiesel blends at compression ratios of 15:1, 16:1, 17:1 and 18:1 for operation in a VCR–common rail direct injection (VCR–CRDI) engine. The experimental conditions used were: 600 bar injection pressure; with 23° before top dead center (bTDC) injection timing; and 1500 rpm engine speed. Their results confirmed the dependence of CR and Moringa biodiesel concentrations on the engine performance and emissions level. This work comes into relevance because of the importance of considering the process of biofuels evaluation under controlled high-pressure condition in CRDI machines and not independently engine configuration.

Patel and Buch [11] further studied the characteristics of combustion of VCR–CRDI diesel engine using MOME as fuel after applying CR. Their findings show that the combustion parameters which included cylinder pressure, heat release, ignition delay and combustion duration were significantly affected by the changes in CR. The results obtained indicate that the thermodynamics of the charge before fuel injection has a major influence on the combustion characteristics of Moringa biodiesel. Nevertheless, this is not the case when Al_2O_3 nanoparticles were not added to the Moringa fuel blends. Hence the coaction of CR and alumina-assisted Moringa biodiesel combustion is poorly investigated.

Interactions between CR and the used nano-enhanced biodiesel are special, since both CR and nano enhanced biodiesel impact combustion in somewhat related but nonetheless distinct methods. While increase in CR brings higher pressure and temperature of compressed charge gas, Al_2O_3 nanoparticles can act as an improved medium to transfer heat, better fuel atomization and improve the properties of the fuel combustion, along with changing the ignition and combustion process. The synergistic effect of their simultaneous application could thus generate an improvement in combustion and thermal efficiency. However, when combustion is intensified, it can lead to higher peak cylinder gas temperatures and this can also lead to higher levels of NOx production. Therefore, it is necessary to determine the optimized CR for a specific formulation of biodiesel–nanoparticle to get optimum performance and emissions.

The interaction between compression ratio and use of nano enhanced biodiesel fuels has started to be investigated recently. Gopidesi et al. [12] studied the effect of CR on a low heat rejection diesel engine operated using biodiesel blended with Al_2O_3 and found that CR had significant influence on BTE, BSFC, smoke, CO, HC, and NOx emissions. The study established the significance of optimizing CR when using of nano enhanced biodiesel fuels. The study, however, used cotton seed-based biodiesel in a low heat rejection engine, and cannot be directly associated with the properties of Moringa biodiesel in the conventional VCR/CRDI.

Similarly, the studies carried out through alumina nanoparticles in combination with other non-edible biodiesels have shown that it was possible to combine nano-catalysts with enhanced combustion efficiency and less formation of products from incomplete combustion. For instance, the use of Al_2O_3

enriched neem biodiesel blends was also studied, both experimentally and through machine learning, showing that the biodiesel concentration and the dosage of alumina could be optimized to obtain a good combination of BTE, BSFC and emissions [8]. Studies related to castor biodiesel have also shown that Al_2O_3 nano-additives can enhance performance of engine and minimize the amount of exhaust gases [13]. The developments reflect the ramping up of interest in using renewable biodiesel feedstocks along with applicable metal-oxide (MO) nano-additives; however they also emphasize the necessity of optimizations for fuels and engines.

The literature therefore suggests three critical research directions, such as, first, the biodiesel produced from Moringa oleifera is a suitable and sustainable alternative fuel for the petroleum diesel-powered CI engines; second, it is observed that the use of nanoparticles such as Al_2O_3 has positive effects on increasing the combustion and enhancing various performance and emission parameters of the CI engine fuelled with renewable biofuels as biodiesel; third, it was seen that the compression ratio is one of the major parameters which greatly affects the combustion and thermodynamic environment of the CI engine. These three factors have, however, been studied rather in isolation. The research conducted for Moringa biodiesel has been primarily addressing blending of biodiesel, engine load, speed and/or compression ratio, while the studies conducted for Al_2O_3 have mostly involved other biodiesel feedstocks and constant compression ratio. The recent study specifically related to Moringa biodiesel and Al_2O_3 has not provided a proper conclusion on the effect of alteration of compression ratio on its consequent performance – emission compromise. A recent study for Moringa biodiesel with 1-hexanol and Al_2O_3 has shown the potentiality of Al_2O_3 to boost BTE with the corresponding reduction in several emissions, but no attention was paid to the influence of compression ratio particularly in this study [14].

Hence, the present research shows that there is a research gap regarding the synergistic effect of compression ratio and Al_2O_3 nano-addition on performance and emission parameter of the Moringa oleifera as a particulate source biodiesel–diesel blend for diesel engine. It is of particular importance to systematically investigate the effect of CR on the BTE, the BSFC, EGT, CO, CO_2, HC, NOx and smoke opacity under controlled injection conditions. An investigation is needed to determine if the benefits of alumina assisted combustion may be successfully derived at various compression ratios, while avoiding undesirable NOx emissions.

Thus, the performance and emission parameters of a diesel engine using Moringa oleifera biodiesel with Al_2O_3 nanoparticles were studied experimentally, varying the compression ratio. The influence of fuel composition and compression ratio is assessed in detail regarding the brake thermal efficiency, the brake specific fuel consumption, the exhaust gas temperature and the exhaust gas components of CO, HC, CO_2, NOx and smoke are taken into account. In this study, varying the compression ratio will be used to provide greater insights into the operating condition that achieves an optimum balance of energy conversion efficiency and reduction of exhaust gas emissions when a Moringa-based bio-diesel blend fuel is modified with nanoscale alumina. The results are expected to be of great help for developing optimized formulations of biodiesel enriched with nanoparticles, and as the basis for better performance and environmental friendly operation of the existing compression ignition engines.

2 Materials and Methods

In the present work, the effect of both compression ratio and Al_2O_3 nano-particles on the performance, combustion and emission behavior of a compression ignition (CI) engine operating on Moringa oleifera biodiesel–diesel blends was investigated. The experiments were conducted on CRDI-VCR single-cylinder, 4-stroke, water-cooled diesel engine. With an engine speed of 1500 rpm, three compression

ratios (16:1, 17:1 and 18:1) were explored. Injector pressure is kept at 600 bar and injection timing is kept at 23° before top dead centre. Considered were four engine loading conditions representative of brake powers equal to 0.88, 1.75, 2.66 and 3.50 kW. These conditions are identical to the CRDI-VCR engine range defined in the Moringa biofuel investigations.

The experimental program was divided into two groups; reference fuels and nano enhanced fuels. The reference fuel used was commercial diesel, and Moringa oleifera methyl ester (MOME) was blended with commercial diesel at a concentration of 10% and 20% v/v. The resulting blends, called MB10 and MB20 respectively. To investigate the effect of 100 ppm Al_2O_3 nanoparticles on each biodiesel–diesel ratio, a second set of test fuels was formulated. The nano enhanced fuels were labelled as MB10+Al_2O_3 and MB20+Al_2O_3. The baseline fuel used was Diesel without nanoparticles.

Table I Experimental Fuel Formulations and Al_2O_3 Nanoparticle Concentrations

Fuel Code	Diesel (Vol.%)	Moringa Biodiesel (Vol.%)	Al_2O_3 Concentration
D100	100	0	0
MB10	90	10	0
MB10+Al_2O_3	90	10	100 ppm
MB20	80	20	0
MB20+Al_2O_3	80	20	100 ppm

Here, 100 ppm means 100 mg of nanoparticles (Al_2O_3) per kg of the final fuel mix. It is important to report the concentration of the nanoparticles on a well-defined mass basis, as the term ppm might be used differently across different studies.

This experimental matrix was chosen to enable the examination of the effect of compression ratio, without changing the factors such as the injection timing, the injection pressure, the engine speed, the mode of fuel preparation etc. This could also provide a direct comparison of the respective neat biodiesel blends and their Al_2O_3-enhanced versions.

2.1 Production of Moringa oleifera biodiesel

Moringa oleifera seed oil was utilized as raw material to synthesize Moringa oleifera methyl ester (MOME) by single step transesterification process. The free fatty acid (FFA) content of extracted oil was low (<2%), which could suggest the use of a straight alkaline transesterification path. The reaction was performed in methanol as a medium and with the use of catalyst potassium hydroxide (KOH). Here, the molar ratio of methanol to oil was fixed at 5.5:1 and the KOH added at 1 wt.% of the oil.

The amount of Moringa oil, methanol, and KOH that were needed for the transesterification reaction, was added to a three-necked flask, equipped with a condenser on it, and placed on a magnetic stirrer. The reaction temperature maintained in the reaction was kept between 60–65 °C and the reaction mixture was continuously stirred for 1 h at a rate of 600 rpm. At the end of the reaction, the reaction mixture was filtered and settled for about 12 h. This allowed the heavier glycerol phase to separate from the MOME layer. After separating, biodiesel was collected which was subjected to water washing to remove the unevolved KOH and other water soluble impurities from it. In this purpose, the distilled water was heated carefully then added in the biodiesel and the washing process was continued until the amount of the

catalyst and the impurities were removed in a bigger amount. Washed MOME was then dried by dry heating at around 110 °C to sublime excess methanol and water. The biodiesel was then dried, allowed to cool down to room temperature and kept in a capped container for later mixing by the test fuel blends.
Using the chosen reaction conditions, the yield of the biodiesel production processes is about 96% MOME. The entire preparation process is shown schematically in Fig. 1.

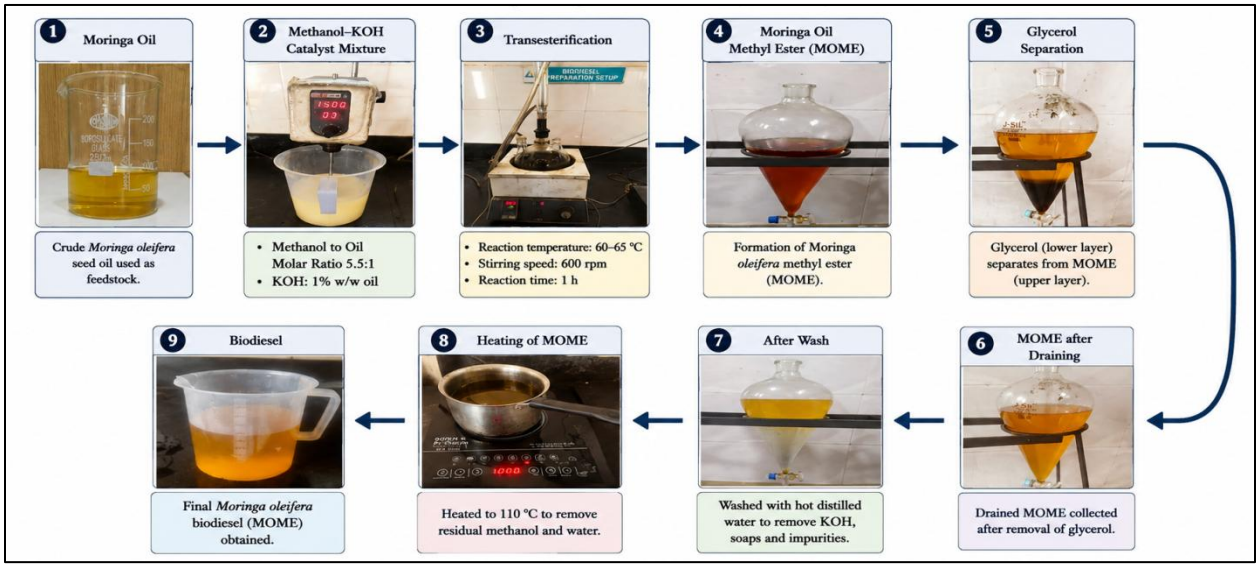


Figure 1 Moringa oleifera biodiesel (MOME) production process

2.2 The blending of Biodiesel, Mineral Diesel and Nano-Particle Additives

Biodiesel–diesel blends of pure diesel, MB10 and MB20 were used to prepare nano-enhanced fuel by adding a concentration of 100 ppm of Al_2O_3 nanoparticles. Appropriate mass of Al_2O_3 was precisely measured and then introduced slowly into each fuel mix while mechanically stirring to ensure a preliminary uniform dispersion. This mixture was then ultrasonicated for 30 min at a frequency of 40 kHz with the fuel temperature kept at around 40 °C. The ultrasonic treatment creates acoustic cavitations and generates localized shear forces in the fuel that break up the agglomerates of nanoparticles and distribute the Al_2O_3 in the biodiesel–diesel mixture [15–17]. The prepared nano-enhance fuels were then examined visually for uniformity after sonication and were stored for the engine testing in clean sealed container until the testing. To ensure uniform preparation conditions, the same weighing, stirring, and ultrasonication procedure was utilized for all fuel samples in the experimental investigation.

2.3 Properties of Moringa oleifera Biodiesel–Diesel Blends with Al_2O_3 Nanoparticles

The fuel properties were obtained by applying the appropriate test methods and measuring instruments, the details of which are given for each property in Table 2, which also gives an indication of the apparatus and procedure used. The property of the commercial diesel fuel, Moringa oleifera biodiesel and Biodiesel blended with Al_2O_3 nano particles employed in the experimental research is summarized in the Table 3. The measured value data were checked against the ASTM-limit values to derive the suitability of the prepared biodiesel blends for different engine tests.

Table II List of Equipment

Property	Equipment	Manufacturer	Test method

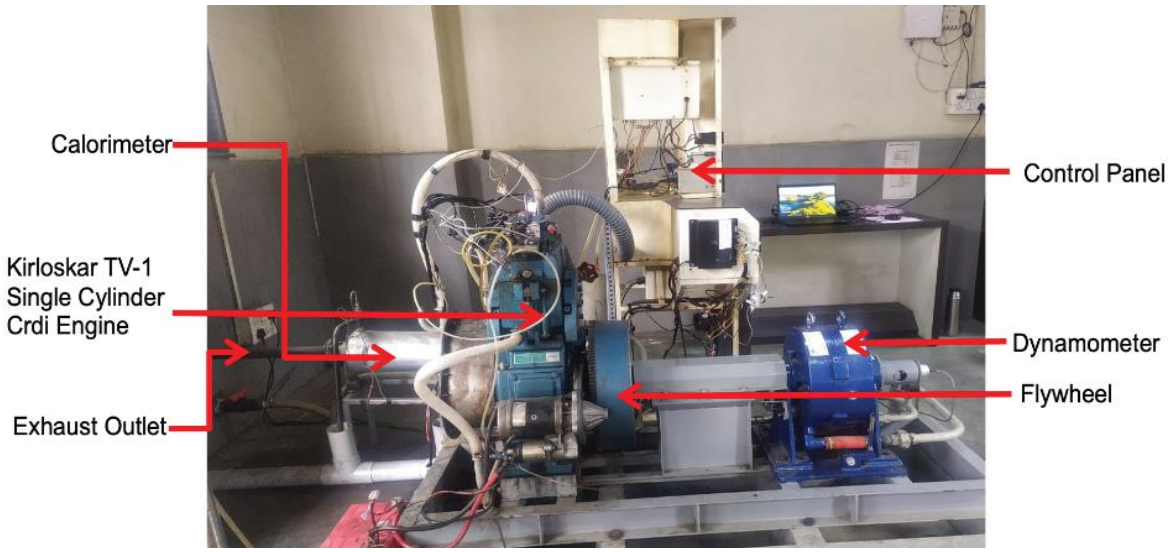
Calorific value	Semiautomatic digital bomb calorimeter	Hamco	D 4809
Flash point	Pensky marten flash point apparatus (Closed cup)	RICO	D 93-58 T
Density	Hydrometer	Leimco	D 287
Kinematic viscosity	Kinematic viscosity bath	Hamco	D 445

Table III. Properties of test fuels

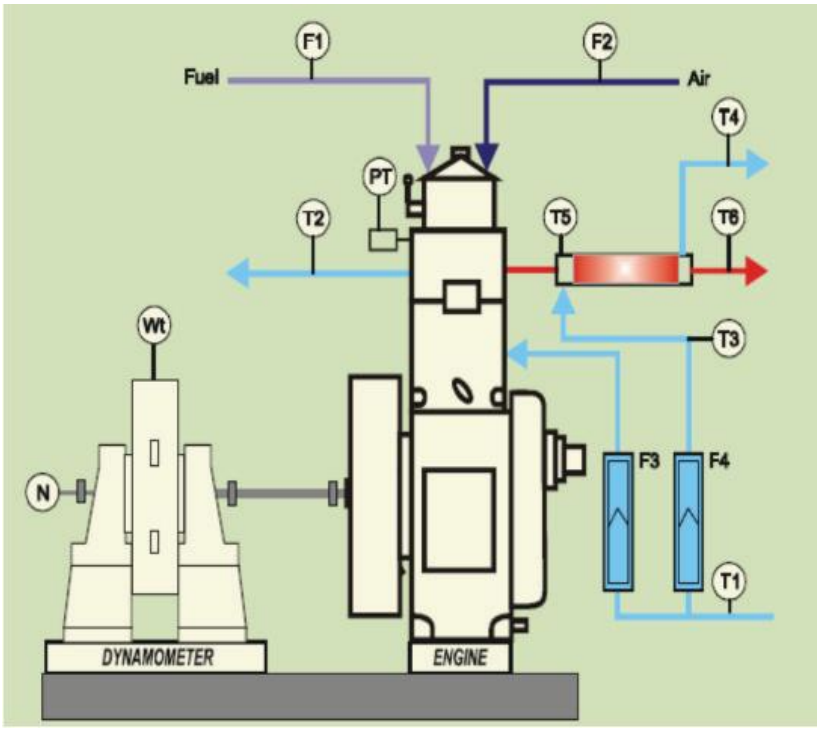
Property	**ASTM Standard**	**Diesel**	**MB100**	**MB10**	**MB10+ Al_2O_3**	**MB20**	**MB20+ Al_2O_3**
Acid Value (mg of KOH/gm of oil)	D 6751	0.04	0.044	0.06		0.09	
FFA (%)	—	0.02	0.22	0.03		0.05	
Calorific Value (kJ/kg)	D 4809	42987	39370	42631	42725	41822	41953
Flash Point (°C)	D 93-58 T	56	135	62	63	70	72
Density (kg/m³)	D 287	820	874	831	831	834	834
Kinematic Viscosity @ 40°C (cSt)	D 445	2.13	4.03	2.31	2.33	2.50	2.56
Dynamic Viscosity @ 40°C (cP)	D 445	1.75	3.52	1.91	1.93	2.09	2.13

2.4 Experiment Setup

The experiment was performed in a CRDI-VCR engine running with a variable compression ratio in a common-rail (CR) direct-injection system where the injection pressure was fixed as 600 bar and the injection timing was 23° bTDC on a single-cylinder, four-stroke, direct-injection, compression ignition engine. The engine performance tests were carried out at different loading conditions for compression ratio ranging from 16:1 to 18:1 and using neat diesel, Moringa oleifera biodiesel blends MB10 and MB20, and their associated 100 ppm Al_2O_3 nano-enhanced blends MB10+Al_2O_3 and MB20+Al_2O_3. Compression ratio was varied by tilting the cylinder block arrangement, so that the compression ratio could be changed without stopping the engine, or changing the cylinder block arrangement. A cylinder pressure, cylinder angle, air-flow rate, and fuel consumption sensor, as well as a measuring device for engine load, were installed in the test setup to record cylinder pressure, crank angle, air-flow rate, fuel consumption and engine load. The acquired signals were fed into computer via data acquisition system for further analysis. The experimental unit comprised an air box, two fuel tanks, a manometer, fuel flow measurement system, air flow and fuel flow transmitters, process indicator and a piezoelectric measurement unit of pressure. The flows of cooling water are monitored with rotameters to the engine. The development of online data acquisition and evaluation was done using a software that monitors and analyzes engine performance, called EngineSoft, developed by Apex Innovations Pvt. Ltd., which is based on Lab view. Experimental data was monitored, recorded using the software and engine power, thermal efficiency, fuel and air consumption and heat-release characteristics were determined. The photographic view of complete experimental setup and schematic layout of setup is shown in Fig. 2(a) and Fig. 2(b), respectively, and details of the sensors and measurement instruments placed on the test rig are given in Table 4. Table 5 shows a summary of the major specifications for the engine and test equipment.



(a)



(b)

Figure 2 (a) Photographic view of Experimental setup and (b) Schematic layout of the setup.

Table IV. Details of Sensors and Measuring Instruments

Sr. No.	Number	Description/Location
1	T1	Temperature of coolant at the inlet of an engine.
2	T2	Temperature of coolant at the outlet of an engine.
3	T3	Temperature of coolant at calorimeter inlet.
4	T4	Temperature of coolant at calorimeter outlet.
5	T5	Exhaust gas temperature at the inlet of the calorimeter.
6	T6	Exhaust gas temperature at the outlet of the calorimeter.
7	F1	Fuel Flow Transmitter.
8	F2	Air Flow Transmitter.
9	Wt	Load Cell Sensor.
10	PT	Cylinder Pressure Transducer.
11	N	Engine RPM (CA) Sensor.
12	F3	The mass flow rate of engine jacket cooling water.
13	F4	The mass flow rate of calorimeter cooling water.

Table V. Detailed specifications of the CI engine test arrangement.

Parameters	Description
Manufacturer and Model	Kirloskar, TV-1 Model.
Type of test engine	Mono cylinder, VCR-CRDI type, 4 stroke, water-cooled CI engine.
Length of stroke (mm)	110
Bore diameter (mm)	87.5
Range of Compression Ratio	12:1 to 18:1
Power output (kW)	3.5 kW @ 1500 rpm.
Displacement (cc)	661 cc.
Dynamometer type	Eddy current type, Water cooled

2.5 Uncertainty Analysis

Uncertainties in the measured results can be introduced by many factors, such as accuracy or calibration of the measuring instruments or experimental conditions, condition of the instruments, data acquisition, and fuel preparation. The experiments have been performed under controlled conditions, but there is always some uncertainty inherent in an experiment. Thus, an uncertainty analysis was performed to check the reliability of experimental results. The uncertainty of the parameters calculated was calculated as the difference in quantities of measurements. Uncertainties of parameters (BP, BTE, BSEC and BSFC) were analysed based on the percentage uncertainties of the measuring instruments. The individual uncertainties were then added to provide an estimate of the overall uncertainty in the experimental investigation. Uncertainties of the measuring instruments and calculated parameters are given in Table 6 and the overall experimental uncertainty was calculated from these values.

Total Uncertainty of experiment

$$U_{total} = \sqrt{U_{BTE}^2 + U_{BSFC}^2 + U_{BSEC}^2 + U_{BP}^2 + U_{CO}^2 + U_{CO_2}^2 + U_{HC}^2 + U_{NO}^2 + U_{Smoke}^2}$$
$$= \pm 2.44\%$$

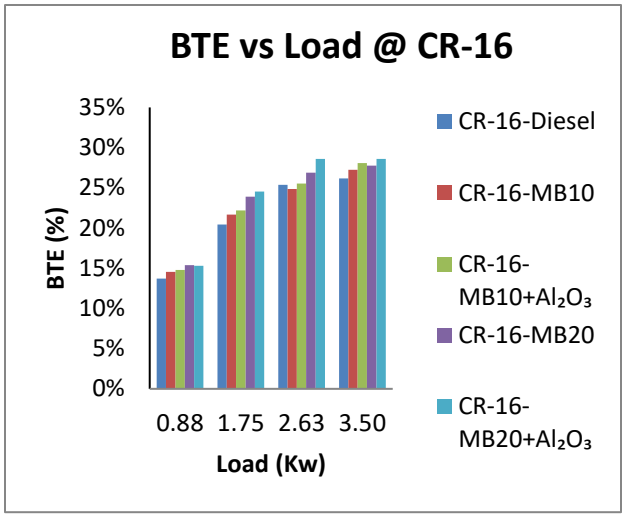
Table VI. Specifications and Uncertainty of the Measurement Instruments

Measurement	Device	Range	Resolution	Uncertainty
CO	AVL make Five gas analyzer, Model: Digas 444N	0-15% Vol	0.001 % Vol	±0.007
CO_2	AVL make Five gas analyzer, Model: Digas 444N	0-20% Vol	0.1 % Vol	±0.50
HC	AVL make Five gas analyzer, Model: Digas 444N	0-20000 ppm (Vol)	1 ppm (0-2000 ppm) 10 ppm (> 2000 ppm)	±0.005
NO_x	AVL make Five gas analyzer, Model: Digas 444N	0-5000 ppm (Vol)	1 ppm Vol	±0.02
Smoke	AVL makes Smoke meter Model: AVL-437	0-100 %	0.1%	±0.10

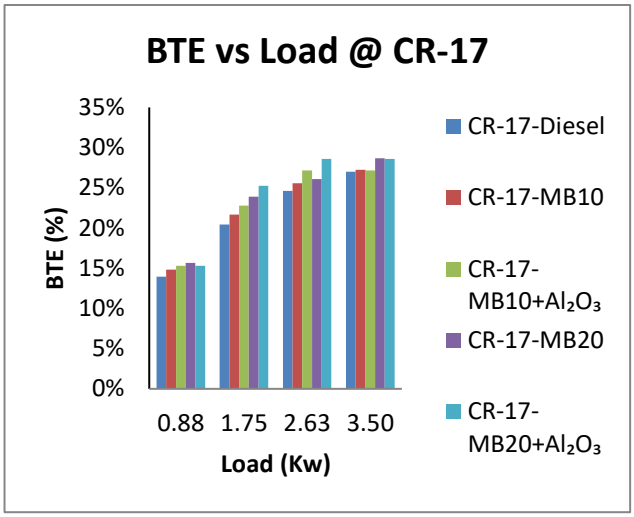
3 RESULTS AND DISCUSSION

3.1 Brake Thermal Efficiency

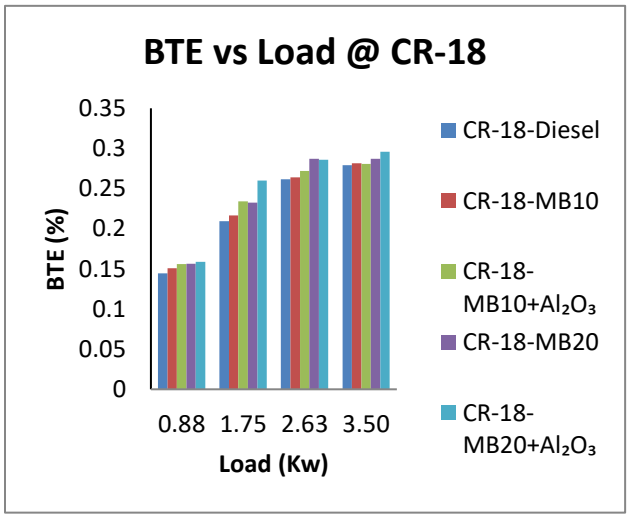
The brake thermal efficiency, BTE, increased steadily with the load of the engines with all the fuels and compression ratios used. This tendency is because the proportion of brake power becomes greater in comparison to the larger percentage of frictional and other constant losses at heavy loads. The BTE was further increased by increasing the compression ratio due to higher in-cylinder temperature and pressure, allowing better utilization of the fuel's chemical energy and giving improved combustion. Aluminum oxide (Al_2O_3) nanoparticles were incorporated in the MB20 blend which further improved the thermal performance which correlates to their advantageous effect on the fuel–air interaction and combustion behavior [18]. Figure 3 (a-c) shows the variation in BTE value of an engine in various loading conditions for different fuel blends and CR. The highest BTE of 27.92% for diesel and 29.59% for MB20+Al_2O_3 was achieved at CR18 and at full load. The higher values of BTE gained from MB20+Al_2O_3 suggests that the combined action of Moringa biodiesel and Al_2O_3 nanoparticles has been able to give the superior output in conversion efficiency of chemical energy to useful brake power especially for high load operating conditions. Generally, BTE increases with increase in the load and compression ratio is in line with those found in previous studies done on biodiesel and nanoparticle added fuels [19].



(a)



(b)



(c)

Figure 3 Variation of Brake Thermal Efficiency with Engine Load for Different Fuel Blends at Compression Ratios of (a) 16:1, (b) 17:1, and (c) 18:1.

3.2 Brake Specific Fuel Consumption

It is an important parameter to consider when assessing fuel economy in different load conditions that refers to the fuel usage of the engine for a unit of brake power [20]. As the increment in engine load, the required brake power also increases due to this condition the fuel consumption per unit power decreases which results in a lower BSFC. The change of BSFC of the engine for various fuel combinations at varying compression ratios is illustrated in Fig. 4 (a-c).

For diesel fuel, the minimum BSFC at full load was 0.32, 0.31, and 0.30 kg/kWh at compression ratios of 16:1, 17:1, and 18:1, respectively. For comparison, for minimum BSFC of the blend of MB20 with Al2O3 it was 0.30 kg/kWh at CR 16:1 and 17:1, and 0.29 kg/kWh at 18:1, both at full load. Accordingly, the minimum BSFC of 0.30 kg/kWh and 0.29 kg/kWh values were achieved by diesel and MB20+Al_2O_3, respectively, at full load condition and CR 18:1. It was also noted that for all the tested compression ratios

the MB20+Al_2O_3 always gave a lower BSFC than the diesel at full load. The enhancement could be attributed to the fact that the biodiesel contains more oxygen which can contribute to complete combustion, and also to the biodiesel's lubricity which may help to decrease fuel losses due to friction [14].

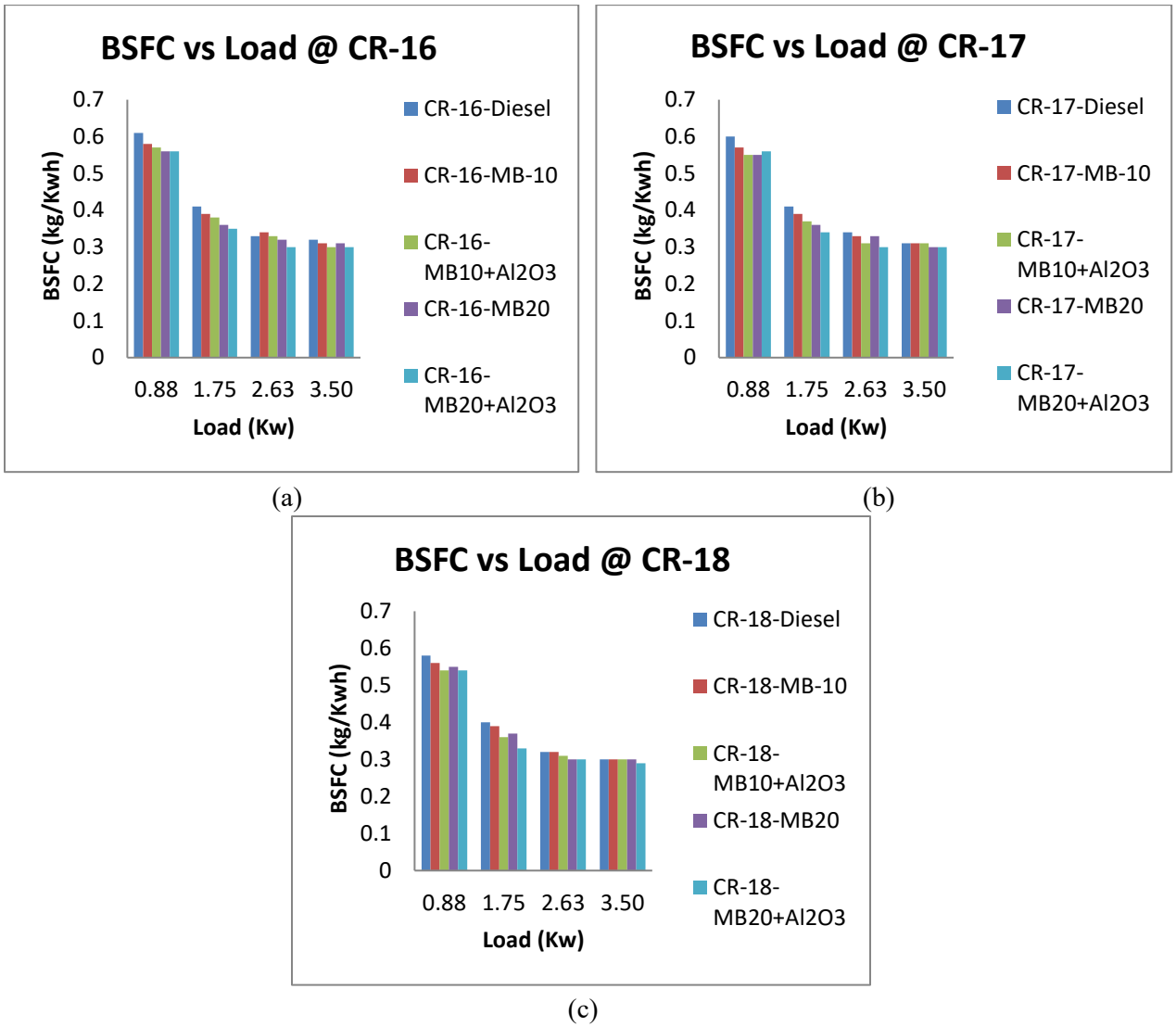
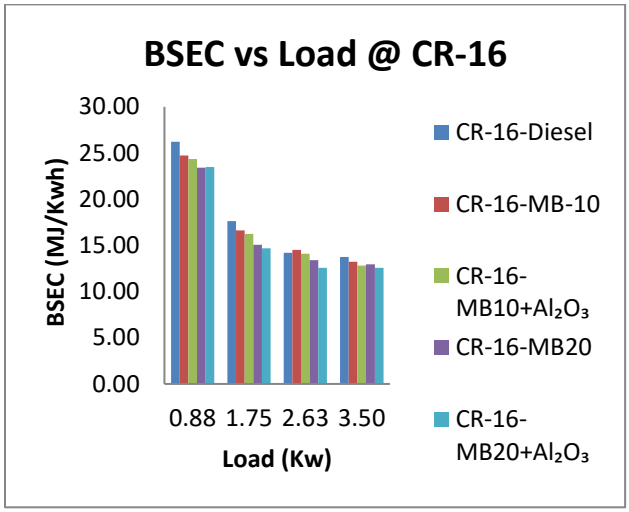


Figure 4 Variation of Brake Specific Fuel Consumption with Engine Load for Different Fuel Blends at Compression Ratios of (a) 16:1, (b) 17:1, and (c) 18:1.

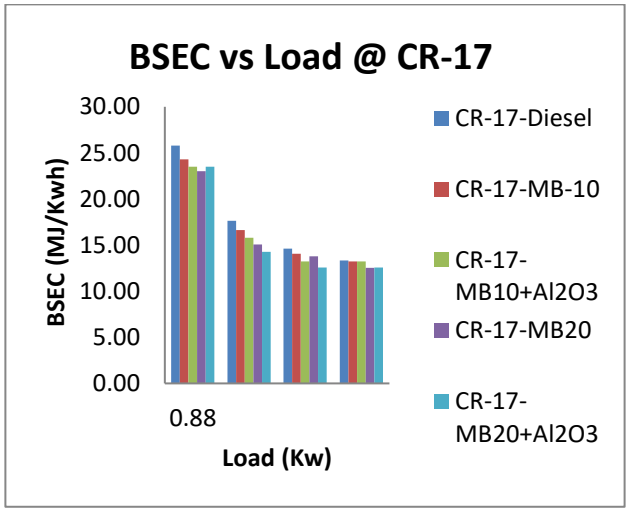
3.3 Brake Specific Energy Consumption

The selection of fuel in the present study is different in terms of calorific value and density, therefore, the value of BSFC cannot be used as an easy indicator of fuel utilization. Under these conditions BSEC is a more appropriate representation of the energy efficiency supplied by the fuel in producing useful brake work. The lower the BSEC, the more effective the use of the fuel energy. The results of BSEC variation with engine load were presented in Fig. 5(a–c) for the different fuel blends for CRs 16, 17, and 18. As can be seen from the results, all the tested fuels indicate that BSEC decreases as load and compression ratio increases for all the fuels. The minimum BSEC at full load and CR 18:1 to diesel and MB20+Al_2O_3 was 12.90 and 12.17 MJ/kWh, respectively. The lower BSEC can be related with the contents of oxygen in

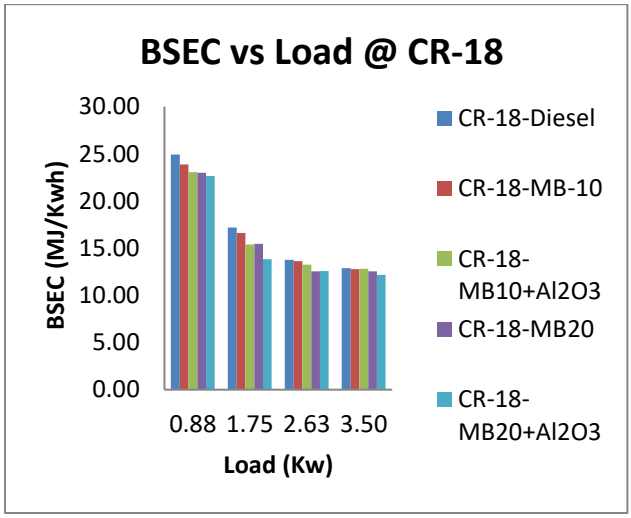
biodiesel, which results in more complete combustion during the process and thus improving the utilization of the energy released by biodiesel. This is in line with the increased BTE noted for the blend of biodiesel and diesel in the present study [21].



(a)



(b)



(c)

Figure 5 Variation of Brake Specific Energy Consumption with Engine Load for Different Fuel Blends at Compression Ratios of (a) 16:1, (b) 17:1, and (c) 18:1.

3.4 Analysis of Exhaust Gas Emission

3.4.1 CO Emission

A lack of oxygen in the combustion process allows some carbon molecules to burn without the complete oxidation which results into CO emissions. In the same way, when oxygen is deficient, not all of the fuel may be oxidized, and more fuel will be needed to generate the same amount of power output, leading to more CO emitted. The oxidation of the fuel is also affected by the changes in the combustion conditions, which are reflected by the level of CO emission. High exposure to CO can negatively impact human health by interfering with breathing, suffocation, and even impairment of consciousness, depending on concentration and duration of exposure [22, 24].

The changes of CO emissions for each tested blends of fuel are represented in Figure 6(a–c) for different loading conditions of engine and different compression ratios. It can be seen from the results that under full load conditions and compression ratio of 18:1, the lowest CO emission in diesel cases was 0.10% vol. while for biodiesel blends, the lowest CO emission was 0.06% vol. for MB20+Al_2O_3. Further, it has been found out that emissions of CO for the blends of biodiesel were lower than that of diesel in all compression ratios at full load operation. This reduction is due to the inherent oxygen content found in biodiesel, which supplies oxygen during combustion which results in more complete oxidation of the fuel, hence less production of CO [23].

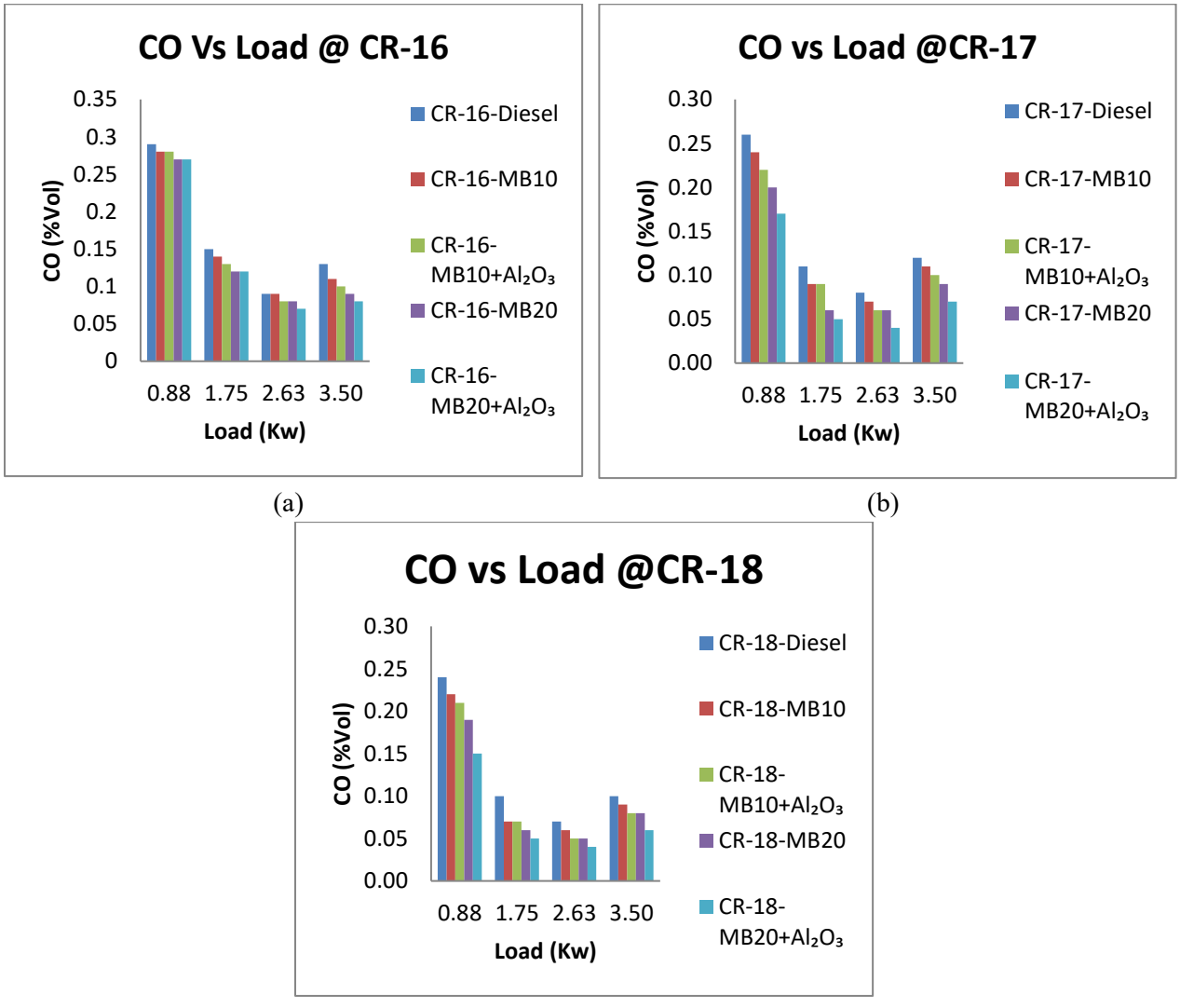


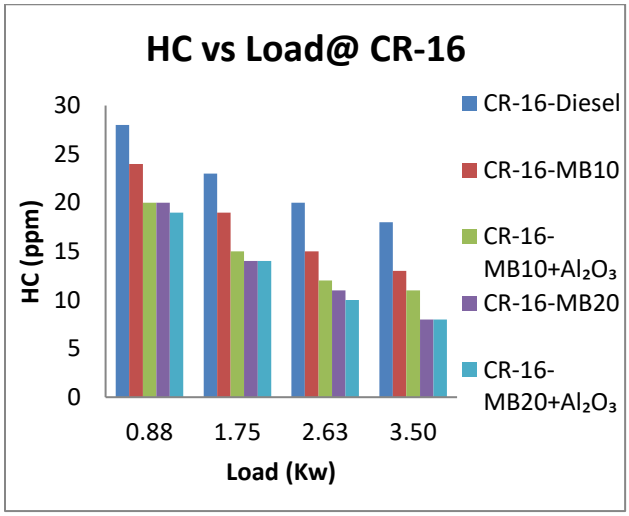
Figure 6 Variation of Carbon Monoxide (CO) Emissions with Engine Load for Different Fuel Blends at Compression Ratios of (a) 16:1, (b) 17:1, and (c) 18:1.

3.4.2 HC Emission

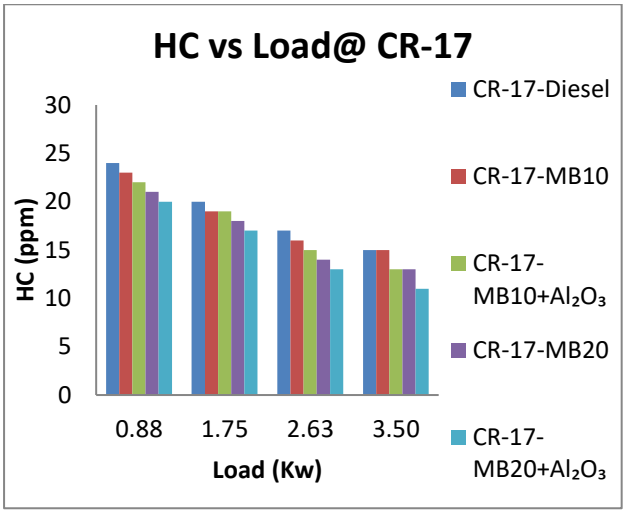
Unburned/partial combustion is mainly associated with the formation of the hydrocarbon (HC) emissions, so that essentially if there is not enough oxygen in fuels present to burn everything, then unburned/partial combustion occurs [25]. Exposure to these emissions continuously can create a bad effect on health of human and can cause skin irritation and eye disorders [26]. The results of HC emissions at various engine

loading conditions (minimum, optimum and maximum) for the investigated fuel blends and compression ratios are depicted in figure 7(a–c). The results show that the HC emissions reductions increase with the increase of the engine loads and the engine's compression ratio for all the investigated blends of fuel. The reduction in emission of HC with increased loads and compression ratios is because of the increase in the combustion temperature and pressure resulting in better oxidation of the fuel and hence better combustion of the fuel [6,18].

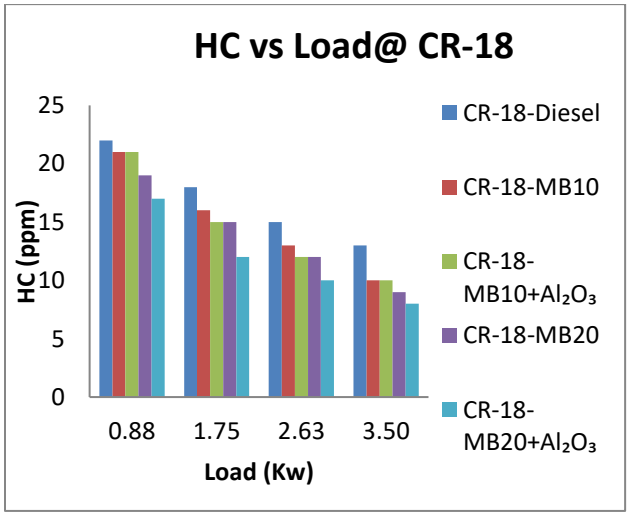
The lowest HC emission collected with diesel operation and MB20+Al_2O_3 blended fuel were 13 ppm and 8 ppm, respectively, with the highest compression ratio (18:1) at full load operation. The reduction in HC emissions for the MB20+Al_2O_3 is recorded due to improvement in combustion process. This leads to shorter combustion time and quicker ignition because the lower ignition delay allows unburned fuel time to burn before it has a chance to escape the combustion chamber. Therefore, the amount of unburned hydrocarbons at the exhaust was reduced and hence the emission of HC was reduced relative to diesel and the other fuel blends tested [27].



(a)



(b)



(c)

Figure 7 Variation of Hydrocarbon (HC) Emissions with Engine Load for Different Fuel Blends at Compression Ratios of (a) 16:1, (b) 17:1, and (c) 18:1.

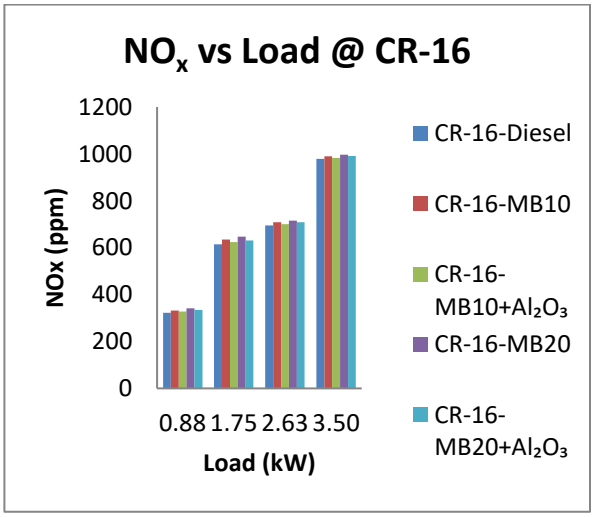
3.4.3 NO_x Emission

Nitrogen oxide (NO_x) is another major pollutant in exhaust gases, where primarily the two forms of nitric oxide (NO) and nitrogen dioxide (NO_2) are present. High combustion temperature and long reaction residence time are the most important factors controlling the formation of NO_x emissions. Diesel engines also produce a higher combustion temperature (probably >1,800 K) which results in a higher formation of NO_x than in other types of engines. Furthermore, the fuel properties and flame temperature and the availability of oxygen also play a role in the generation of NO_x. In the presence of O_2 and at high temperature, free nitrogen atoms form NOx. The higher oxygen content of biodiesel can potentially lead to more NO_x emissions because it can promote NO_x formation.

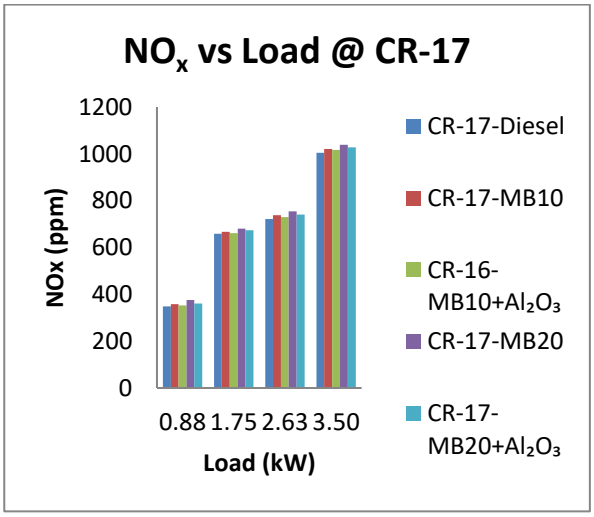
Figure 8(a–c) shows that the NO_x emissions change along with the change in load and compression ratios from 16:1 to 18:1 for various fuel blends, such as pure diesel (B0), biodiesel blends (MB10 and MB20), and Al_2O_3 nanoparticle-enhanced biodiesel blends (MB10+Al_2O_3 and MB20+Al_2O_3). NO_x emissions by engines rise with engine load and the compression ratio for all fuel blends. This trend has been derived from the detrimental increase in combustion temperatures as load and CR increases, leading to an increase in NO formation.

When the CR is 18:1 and loaded up, the NO_x emission for the diesel is 1063 ppm. However, the MB10 and MB20 had significantly greater levels of NO_x in comparison to pure diesel with levels of 1085 ppm and 1124 ppm at full load respectively. Biodiesel contains more oxygen than conventional petroleum-based fuels, which can lead to more complete combustion, which in turn can result in a higher combustion temperature and consequently greater amounts of NO_x production. These developments have also been observed by other scholars and researchers [28-30].

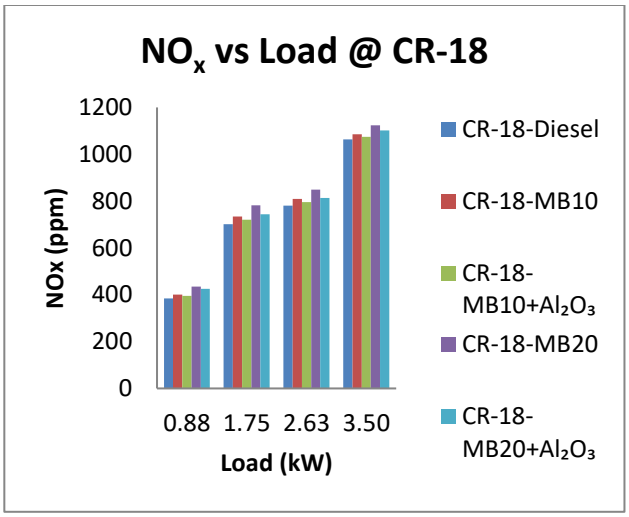
The use of Al_2O_3 nanoparticles in the biodiesel blends (MB10+Al_2O_3 and MB20+Al_2O_3) significantly reduced the emissions of NO_x similar to the fuels with biodiesel only, whereas with conventional fuel, the emissions were not reduced. NO_x emission of the MB10+Al_2O_3 and MB20+Al_2O_3 were 1074 ppm and 1102 ppm, respectively, at full load. This NO_x reduction is due to its better combustion characteristics, which can be obtained by adding Al_2O_3 nanoparticles.



(a)



(b)

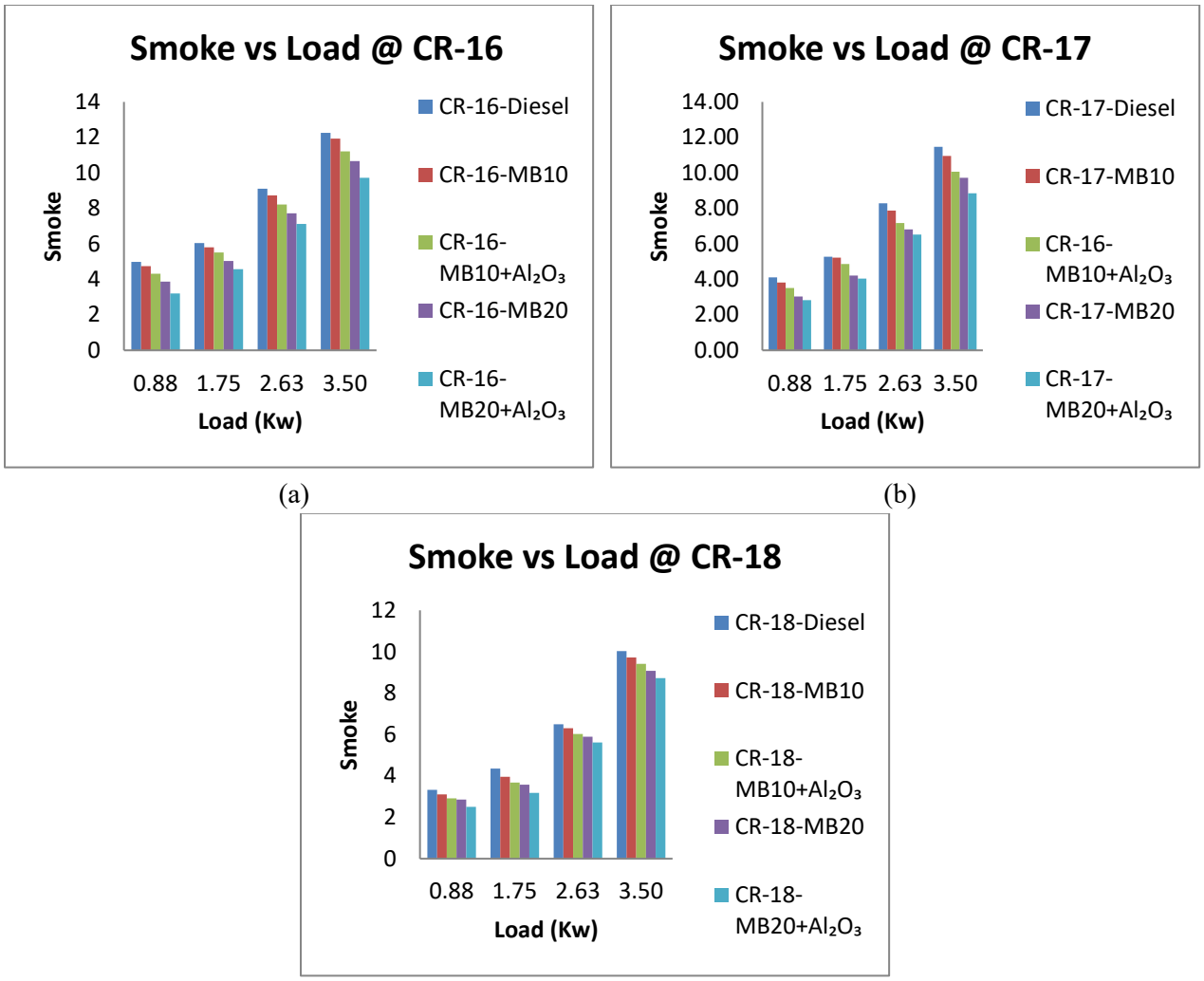


(c)

Figure 8 Variation of Nitrogen Oxides (NO_x) Emissions with Engine Load for Different Fuel Blends at Compression Ratios of (a) 16:1, (b) 17:1, and (c) 18:1.

3.4.6 Smoke Opacity

The amount of soot formed in the exhaust gases is a direct measure of smoke opacity and affects engine loading, compression ratio, fuel type and air–fuel mixing during combustion. This study analysed Diesel, MB10, MB20, MB10+Al_2O_3 and MB20+Al_2O_3 fuels at compression ratio of 16:1, 17:1 and 18:1. Smoke opacity typically increased with load on the engine, primarily as a result of the more amount of fuel fed into the engine at higher loads leading to locally-rich mixtures and diffusion combustion that encouraged conditions for soot formation [31, 34]. The compression ratios 16:1 to 18:1 of the engine helped the fuel to vaporize and the mixture of air-fuel to mix well, leading to more complete combustion and oxidation of the soot precursors. This was typically associated with reduced smoke development with higher compression ratios, as observed previously on VCR Engines [32]. However due to the presence of oxygen in Moringa oleifera biodiesel, it is also known to improve the availability of oxygen inside the combustion zone leading to the oxidation of soot. Lower quantities of smoke and particulate emissions from Moringa biodiesel blends were reported compared to diesel and the quantity diminished with increase in biodiesel content [29]. An extra benefit was obtained by adding 100 ppm Al_2O_3, which also improve the combustion process and promoted the oxidation of soot-forming species [6, 33]. The results of Smoke opacity at various engine loading conditions (minimum, optimum and maximum) for the investigated fuel blends and compression ratios are depicted in figure 9 (a–c). From the results, it has been observed that the lowest smoke opacity is 8.73% at CR 18:1 and full load for MB20+Al_2O_3 while 10.03% smoke opacity was obtained for diesel in the same condition. The lower amount of smoke detected for MB20+Al_2O_3 at the high compression ratio is attributed to the result of the improvement of in-cylinder condition and the oxygenated property of Moringa biodiesel blended with Al_2O_3 nanoparticles which shrinks the soot to facilitate the process of oxidation during combustion. In general, the experimental outcomes show that compression ratio is advantageous along with the blending of Al_2O_3 with biodiesel produced by Moringa oleifera for controlling the smoke emissions, especially for high loads running mode.



(a) (b)

(c)

Figure 9 Variation of Smoke Opacity with Engine Load for Different Fuel Blends at Compression Ratios of (a) 16:1, (b) 17:1, and (c) 18:1.

4 Conclusion:

In present study, the performance and emission characteristics of CRDI-VCR diesel engine running on Moringa oleifera biodiesel and diesel blends for different compression ratios and blends of biodiesel with 100 ppm Al_2O_3 nanoparticles are investigated. The key findings summarized:

- BTE increased with engine loading and CR; the highest value was found to be 29.59% along with engine Full load with MB20+Al_2O_3 while 27.92% was achieved with diesel.
- The reductions in BSFC and BSEC were 0.29 kg/kWh and 12.17 MJ/kWh respectively, at the same operating condition, in comparison to 0.30 kg/kWh and 12.90 MJ/kWh that were observed for diesel, which meant that fuel-energy utilization was enhanced.
- The CO, HC and smoke opacity were reduced using the nano enhanced biodiesel blend. For MB20+Al_2O_3 at CR 18:1 and full load, CO decreased to 0.06% vol, HC to 8 ppm, and smoke opacity to 8.73%, compared with 0.10% vol, 13 ppm, and 10.03% for diesel, respectively.

- NO_x emissions increased with load and compression ratio. NOx was 1124 ppm at CR 18:1 and full load with MB20 – which dropped to 1102 ppm when Al_2O_3 was added – but remained at a higher level than the diesel value of 1063 ppm.

As per overall results, from engine performance and emissions point of views, Moringa and Moringa blended with MB20+Al_2O_3 both at CR18:1 and full load resulted into the best performance thus showing the possibility of using 100 ppm Al_2O_3 as a nano-additive to Moringa biodiesel–diesel blend. Optimizing the concentration of nanoparticles and fuel-injection parameters is recommended to control NO_x emissions while retaining the improvements in performance.

Author contributions VC conducted the conceptualization, investigation, data analysis, and manuscript preparation. VB provided supervision, critical review, editing, and validation of the manuscript. VC wrote the main manuscript text and prepared the figures. All authors reviewed and approved the final manuscript.

Data Availability The data generated and analyzed in this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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