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RESEARCH

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Outcome of novel combination of graphene nanoparticles and Moringa methyl ester fueled engine working under varying loads and compression ratios

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Abstract

The widespread use of petroleum products in modern times has led to a search for alternative resources. Biofuel is a promising alternative to petroleum fuel, but biodiesel has a lower calorific value and is slightly more denser than diesel. To address this, a novel combination of GNA emulsified MME20 fuel is being investigated. This study aims to analyze the impact of a novel Nano additive blended biodiesel on engine performance and optimize the best compression ratio for the selected blend. The novelty of the study lies in the production of novel GNA emulsified MME fuel and its influence on a conventional CI engine. To achieve the objectives of the study, MME was produced using a two-phase transesterification method, and GNA was added to the MME20 at concentrations of 30, 60, and 90 ppm using the ultrasonication method. Engine experiments were then conducted using the prepared samples at CRs of 16, 17.5, and 19, and the results were compared with the standard diesel and MME20 blend. The results showed that the CP of the MME20 + GNA30 fuel at a CR 19 revealed a 14% increase compared to diesel. The ID of the fuel decreased by 20% compared to diesel at CR19, and there was a 23.5% increase in the CD for the MME20 + GNA30 blend compared to diesel at CR19. The BTHE for the MME20 + GNA30 fuel showed increases of 2.64% and BSFC and EGT decreases of 3.6% and 3.9%, respectively, at CR19 compared to the other blends. In summary, the study found that MME20 with GNA30, along with VCR, significantly enhanced the engine attributes compared to the pure diesel-operated standard CI engine conditions.

Highlights

- A novel combination of the blend (MME + GNA) used in this study
- The BTHE was increased for GNA emulsified fuel with VCR
- The BSFC and EGT were decreased with the addition of the Nano additive
- The CP was increased with the decrease of ID, and CD increased for nano additive fuel at different CR

• The GNA emulsified fuel at various CRs produced fewer CO, HC, and smoke emissions than the MME 20 and diesel.

• The investigated optimized blend for the conventional engine used in this study is MME20 + GNA30 at CR19.

Keywords: Moringa methyl ester (MME20), Compression ratio (CR), Graphene nano additive (GNA), CI engine

Introduction

The constant need for petroleum products is increasing drastically in today's world, and the continual diminution of petroleum products is a significant concern. The use of energy resources in the form of fossil fuels is abundant as they are used in most industries to operate heavy machinery and are essential for the sustainable development of humankind. The world utilizes 80% of the energy from fossil fuels, and diesel is used in most of the major industries to produce goods. It is also utilized in the transportation sector, where a lot of energy has been consumed in the form of diesel and gasoline. All these factors will increase fuel prices, increase transportation costs, and lead to economic recession and global conflicts [1]. The surging increase in developing countries' economies will lead to fossil fuel resource consumption by 40–50 years. The emission rate and properties of the gases produced by fossil fuels contribute to most of the air effluence and global heating. For this reason, the countries have to resort to searching for a renewable and cleaner alternative fuel, which can help increase the economy of the country as well as help reduce the environmental consequences by reducing the harmful emissions to the environment, which in turn helps to reduce global warming [2]. All the major industry sectors can adopt the same to run their heavy machinery and for transportation purposes. Biodiesel is one of the most capable and feasible fossil-fuel substitutes for running a diesel engine, and its importance has rapidly increased as it practically reads several benefits. Biodiesel can be produced chemically by combining the crude oil extracted from vegetable seeds or visceral fat of animals with alcohol, such as methanol, ethanol, etc., through a transesterification process. Various studies and research have proven that biodiesel made of vegetable oil is possibly a better substitute fuel for running a CI Engine than conventional fuel [1]. Since most of India's economy is dependent on agriculture and a lot of vacant land is available, it can be used to grow plants that can provide crude oil for the production of biodiesel. Biodiesel fuel can be stored, utilized as fuel, and impelled the same way diesel fuels are used. Biodiesel can be used in two forms: pure biodiesel or biodiesel blend [2]. As biodiesel has characteristics similar to petroleum fuel, the energy industry will profit from using biofuel, which can be utilized all year round. It can even manufacture using the waste as raw materials, which proves to be an excellent example of answering to the crisis of our economy by reducing and reusing the waste. Since biodiesel fuel is manufactured from plant/vegetable seeds, which can be grown on self-owned agricultural land, it provides job opportunities to the ever-growing population. This economic growth will benefit emerging countries and contribute to the demand for world energy. Its properties are such that it is a reliable, non-depleting fuel with a lower percentage of pollutant emission as the sulfur presence is deficient. Various emission and health studies claim biodiesel to be the cleanest and the most prominent alternative for petroleum products under EPA's

Clean Air Act. About 85% of carcinogenic compounds are reduced when biodiesel fuel is used. Compared to regular petroleum diesel fuel, biodiesel has much better properties in terms of octane and cetane numbers. The engine life has improved because of the lubrication property of biodiesel. Graphene has grabbed the attention of people because of its surprising mechanical and electrochemical properties. Most of its novelty is because of its very inimitable optical, electrical, thermal, and mechanical prowess. Critically reviewing the test results of graphene combustion showed that the powders have an excellent specific area and a great potential to store energy, which primes greater reactivity. It has been proven that nanoparticles can be used as a catalyst and an energy carrier. Graphene has unique electrical and optical properties, and it contains a single atomic layer with the shrillest sp2 hybridized allotrope of carbon. Thus, it helps to enhance the reaction rates with various methods, namely enhanced heat transfer through particle and chemical reactivity (catalysis and carbon oxidation) [3]. Thus, in this work, different nanoparticle percentages were used with diesel and biodiesel to attain maximum development in the engine operating parameters and to lessen outgoing gases at the best level. To select the preeminent blend and CR, the impact of different mixing of blends and CRs on selected engines was tested, and the results were evaluated. Thus, the conventional engine functions under varying load, compression ratios, and Nano additive blends to characterize the results of GNA-MME on CI Engine. Pure diesel's properties were first studied to determine the standard comparison barrier and later compared with MME biofuel. Further, tests were conducted on different CRs (16, 17.5, and 19) using piston heads of various diameters, changing the compression ratio. The experiment was performed for multiple loads, blends, and compression ratios, and the results were tabulated. The compression ratio in an IC engine is the degree to which the fuel is compressed before ignition. The CR is the fraction between the total chamber volume (swept volume + clearance volume) and the clearance volume. The factors affecting compression ratio are fuel octane, cylinder volume, combustion chamber volume, piston-to-head clearance, and ignition timing. The CR can be varied by replacing the piston in the cylinder, and various CRs can obtained by machining the piston head. CR can be increased by using pistons that curve upwards compared to the flat-top pistons, but the drawback is that it also results in knocking and supercharging. An increase in charge proportional to rpm is seen, but the engine loads straightaway like an air conditioner pulley and Turbocharger. The selection of the three compression ratios (16, 17.5, and 19) was made based on various research papers studied in the past; it was suggested that for conducting the various experiments, the ideal compression ratio would be 17.5. Comparison research was done between standard diesel and biofuel with CRs of 16–21 in intervals of 0.5 in many papers, and the majority of the papers proved the ideal compression ratio to be selected should be between 16 and 21, but since the compression ratios above 19 proved to have shown lesser and mixed results in the improvement and enhancement of the properties concerning thermal engine characteristics and exhaust gas because engine overheats when a higher compression ratio is selected. Earlier research has also proved that choosing a lower CR can lead to an enhancement in the emission of carbon monoxide due to more dilution of fresh air and poor mixing of fuels occurring in the engine. Considering these factors and having a uniform difference space of 1.5 between the CRs, the selection of 16, 17.5, and 19 was done [4, 5].

Rajak U et al. (2023) explored the impact of zinc oxide (ZnO) emulsified diesel blends at different proportions of 0.025%, 0.05%, and 0.1% on engine working parameters. They conducted engine experimentation for various engine speeds (2000, 2250, 2500, and 2750 rpm) by using modified fuel. Their results concluded that the BTHE was enhanced by 11.4%, SFC lessened by 1.67%, CP was increased by 2.3%, and NO_x was reduced by 10.67% for the blend DF + 0.1%Zno at 2500 rpm [6].

Tiwari C et al. (2023) investigated the CI engine behavior for spirulina microalgae biodiesel at different proportions of 20%, 40%, 60%, 80%, and 100% at standard operating conditions. Their results inferred that the B20 blend gave a maximum CP of 101.65 while reducing the ignition delay of 2.57% for optimized load 52.57 and CR18.5 compared to other proportions of biodiesel [7].

Abishek M. S et al. (2024) used the multi-fuel variable compression ratio (MFVCR) engine to analyze the influence of alumina (Al_2O_3) and titanium nanoparticles on diesel–*Guizotia abyssinica* (L.) blended fuel. The results showed that nano additive blended fuel gave the highest BTHE of 32.99% and the lowest BSFC of 0.362 kg/kWh compared to other fuels [8].

Sinha A. A et al. (2023) investigated the utilization of waste heat from the gas turbine to reduce the temperature gradient in solid oxide fuel cells (SOFC). The result of the study is that extreme exergy demolition originates in SOFC, followed by water heat exchangers and gasifiers. The highest thermal efficiency for this study is 62.12% at a pressure ratio of 4 and turbine inlet temperature (TIT) of 1250 K [9].

Kumar R et al. (2023) used jatropha methyl ester (JME) and tire pyrolysis oil (TPO) as fuel for the conventional engine. Their studies claimed that the blend JME80% + TPO20% gave improved results than the other blends. Further, they experimented with three different pre-heating conditions, such as 50°, 60°, and 70 °C for the blend JMETPO20, and were amazed by the engine performance attributes [10].

Soudagar, Afzal, and Kareemullah, (2020) performed a study to assess the behavior of the modified CI engine using Mahua methyl ester and its different proportions with zinc oxide as nano particle. The results obtained were that the zinc oxide blend Mahua biodiesel resulted in the overall enhancement in the CI engine characteristics [11].

Prabu (2018) chose three blends of methyl ester that is (B20A30C30), i.e., 20% B100 (pure biodiesel) + 80% diesel + 30 ppm (parts per million) aluminum oxide (Al_2O_3) + 30 ppm (parts per million) cerium oxide (CeO_2) and biodiesel–nanoparticles (B100A30C30), i.e., 100% B100 (pure biodiesel) + 30 ppm (parts per million) Al_2O_3 + 30 ppm (parts per million) CeO_2 for his experimental investigation on conventional CI engine. The results were that the brake thermal efficiency improved significantly when nanoparticles were dispersed in the test fuels, a diminution in ignition delay was observed with the addition of nanoparticles, and a significant decrease in exhaust gases [12].

From S. Gavhane et al. (2020), zinc oxide nanoparticles were synthesized and steadily blended with SBE25, which is the quarter ratio of the soybean methyl-ester to diesel at varying loads as well as compression ratios on a VCR engine with one cylinder at a continual rate of 1500 rpm and IT of 23°BTDC to improve SBMBE25 fuel properties and overall enhancement of engine characteristics of a VCR diesel engine. The conclusions drawn validate the enhancement of performance and burning attributes and reduction in discharge gas characteristics of a CRDI engine when nanoparticles of zinc oxide (ZnO) were added at a compression ratio of 21.5 to the biodiesel blend [13].

Praveena, Venkatesan, and Gupta (2018) conducted the experiment to understand the exhaust and performance attributes of the CI when nano additives are added to selected fuel. The main disadvantages are the exhaust gases from diesel engines and the reduction of fuel consumption. A measured quantity of aluminum oxide (Al2O3) in ppm was added with Mahua methyl ester 20% + diesel 80% (MME20D80), which resulted in a reduction of BSFC by 7.66% at maximum load, an increase in BTE by 1.58%, and a decrease in NOx emissions by 35%for CNT with MME20 fuel. The cost of these has forced more research into the future [14].

Awogbemi (2018) conducted a research study to understand the excellence of engine parameters such as BTE, power of brakes, and fuel properties, i.e., cetane number, cloud point and cv, and also the emission characteristics, economic feasibility, and finally, greenhouse gas emission [15].

Soudagar et al. (2019) conducted a study in which dairy scum oil biodiesel was experimented with the addition of Graphene oxide nanoparticles at amounts of 20, 40, and 60 ppm by the ultra-sonication procedure. Testing was conducted at fluctuating load conditions and at a uniform speed. Improvement in the performance and discharge gas features were seen [16].

Soudagar et al. (2020) prepared diverse combinations of the biofuel (B20-B100 with an interval percent of 20) along with different proportions of 1-propanol and isobutanol, and the engine characteristics were tested. The outcomes showed better engine characteristics when compared to any other combination of biofuels.20% blend achieved better than the other pure blends [17].

Vellaiyan, (2019) performed an experiment to evaluate improvement in thermal attributes in a CI engine. It was experimented with neat petro-diesel, soybean biodiesel, and 50% Soybean biodiesel along with carbon nanotube (CNT) [18].

Kumar, Dinesha, and Bran, (2017) studied the blends of biofuel (Pongamia–B20), including the addition of ferrofluid at several volumetric scopes utilized as fuel. The investigation, performed on diesel engines at different loads, revealed that for a selected fuel, the reduction in BSFC up to 8% was equated to a nano particle fuel. A reduction in CO and HC emission was obtained for biodiesel with Nano-additive when compared to pure biodiesel. Maximum efficiency was obtained with reduced emission for blend B20 with 1% Ferro fluid when equated to other fuel proportions [19].

Prabakaran and Udhoji, (2016) investigated the result of the addition of Nano particle zinc oxide with biodiesel blends. Solubility tests were conducted for all the fuel samples under various temperature conditions. As per ASTM standards, a stable blend was obtained at 5 °C, 15 °C, and above 25 °C. Two hundred fifty parts per million of zinc oxide was added in successive amounts. They found considerable enhancement in the BSFC and burning cylinder pressure and lessening in BTE, exhaust, and opacity as compared to conventional fuel [20].

Özgür, Özcanli, and Aydin (2014), the effects of nanoparticle addition containing oxygen to biofuel attributes were tested, and the effects on engine working attributes were analyzed. Nanoparticles magnesium oxide (MgO) and silicon dioxide (SiO_2) were added to biodiesel at the additional dosage of 25 and 50 ppm. The results obtained showed that the engine emission values of NO_X and CO were lessened and improved in the performance values for nano particle-dispersed fuel blends [21].

Karthikeyan, Elango, and Prathima (2014) studied the conventional engine working parameters at uniform engine speed with various blends under 100% load condition. The tested results indicated that the dispersion of nanoparticle zinc oxide improves the early ignition during power stroke, truncates the explosion delay, and increases NO_X [22].

Venu and Madhavan (2017) conducted a comparative study in which the addition of diethyl ether (DEE) and alumina nanoparticle (Al_2O_3) was added to biodiesel at various amounts. Their analysis inferred that the incorporation of DEE in biodiesel augmented the emissions and BSFC, but it also lowered the NO_X and opacity. These were the results obtained due to the greater value of phase change heat and low burning temperature. The incorporation of Al_2O_3 in a biodiesel ethanol mixture (40% biodiesel, 40% diesel, and 20% ethanol) results in higher NO_X and lower CO, CO_2, HC, and BSFC [23].

Wakil et al. (2015) showed the effect of the biofuel mixture of rice bran and Moringa on the engine working attributes. The physiochemical properties were measured, and engine tests were performed, which resulted in an improvement when compared to regular diesel in aspects of BSFC, emission properties, and temperature of the exhaust, which proved that the selected alternate fuel is the practicable preference for biodiesel as they satisfy ASTM standards [24].

Das et al. (2018) studied an experiment in which biodiesel was prepared using transesterification with NaOH as a catalyst. Experiments on porous sphere outcome data were used to illuminate the thermal attributes in the burning chamber. The discussions inferred that the early burning rate, hasty enhancement of pressure, and quicker continuous burning for selected fuel samples [25].

Knothe (2005) studied the properties of biodiesel. Sources of biodiesel vary with the location, and it is crucial to have data on how the concentration of different fatty acids can influence the fuel properties of biodiesel. The overall fuel properties of the fuel depend on the properties of the various individual fatty esters that are included in biodiesel. Cetane number, heat of combustion, viscosity, emissions, oxidative stability, and lubricity are the crucial fuel properties [26].

Norhafana et al. (2019) performed a strict review to find the effect on an engine's combustion and performance characteristics by using various vegetable feedstock available that can be used as a base and as a metal-based nano additive. Nano metal additives with feasible physiochemical properties were tested, and the outcomes inferred that biofuel produced from uneatable oil sources is the better substituent for conventional fuel and leads to better working characteristics and reduced emissions [27] (Table 1).

Raheman and Phadatare, (2004) Presented the Karanja biodiesel from 20 to 80% in a conventional engine, and engine tests were conducted, which led to the results of improved engine working attributes except for BSFC and lowered the exhaust gases [28].

Deore, Jahagirdar, and Patil, (2013) investigated the influence of duel fuel mixtures on engine various parameters. They used Jatropha and Karanja mixtures in different quantities for the experimentation at 16 and 18 CR. Their results inferred that the burning delay period was augmented for Jatropha than that of Karanja due to its high viscosity [29].

Table 1 Fuel properties

Parameters	Diesel	MME20	MME20 + GNA 30 ppm	MME 20 + GNA 60 ppm	MME20 + GNA 90 ppm	MME 100
Density (kg/m^3)	830	835	836.95	838.9	840.85	855
Kinematic viscosity	6	3.24	3.18	3.16	3.1536	4.2
Flamboyant point	52	74.8	71.3	67.8	64.3	164
Fire point	58	81.7	78.2	74.7	71.2	168
Gross calorific valued	44,000	44,402.12	44,602.12	45,192.12	45,212.12	39,852.6
Puff point	14	3.29	3.16	3.02	2.89	4
Pour point	−9	−19	−17.09	−15.2	−13.3	−6
Acid number	0.38	Nil	Nil	Nil	Nil	Nil

Santhoshkumar, Thangarasu, and Anand, (2019) focused on producing biodiesel fuel and the ideal conditions. It is also optimized by the response surface method (RSM), and the investigation was done for conventional engine. The optimal conditions were to be found at 45 °C, 120 min, and 6:1 alcohol ratio around which the BTHE was lesser, and NO_x emissions and brake-specific energy were higher [30].

Pandhare and Padalkar, (2013) illustrated the impact of the Jatropha blend in a CI engine (1-cylinder) at a rate of 1500 rpm. Results showed that for VCR-equipped engine B100 blend, the fuel consumption was the peak point compared to diesel as well as the BTHE, temperature of exhaust gas and CO_2 emission were higher while the harmful emissions were lower [31].

Chavan et al. (2015) conducted a study to examine the emissions produced by different blends in the VCR diesel engine. They investigated a blend made from Jatropha, which was prepared at 40 °C and tested on an engine with VCR. The results indicated that the blended biodiesel generated lower levels of CO and HC, while the measured NO_X was higher [32].

Rajak U et al. (2020) conducted tests on engine performance using Moringa oleifera Biodiesel (MOB) and Jatropha curcas methyl esters (JB) at proportions of 20%, 40%, and 60%. The investigations revealed that both biodiesels produced lower NOx and smoke emissions and higher combustion efficiency (CD) and cylinder temperatures than conventional fuel. The study concluded that JB outperformed MOB. Furthermore, they estimated the cost of MOB to be INR 68 and JB to be INR 76 [33].

Verma T. N et al. (2021) studied the impact of roselle biodiesel (LA) concentrations ranging from 20 to 100% in 20% intervals. They also varied the injection timing (IT) from 19° to 21° in 2° intervals to analyze their influence on conventional engine working parameters. The results showed that the LA20 blend produced lower NO_x and smoke emissions, which increased with higher IT. Additionally, the BTHE decreased while BSFC increased [34].

Rajak U et al. (2021) investigated the influence of first, second, and third-generation feedstocks at different CR of 16.5, 17.5, and 18.5 on CI working parameters. Their studies highlight that VE and smoke decreased, while NO_x increased with the increase in CR [35].

Rajak U et al. (2019) studied the engine's behavior when operated with Aegle methyl ester. They conducted experiments at various biodiesel concentrations of 20%, 40%, and

100%. The results revealed an increase in BSFC, CO_2, and NO_x and a reduction in indicated thermal efficiency, mechanical efficiency, and smoke for the 20% blend at 220 bar [36].

The novelty of the current work

Based on the previous literature studies, it has been observed that there is limited research on the use of Moringa crude oil for biodiesel production. There is also insufficient research on the use of graphene nanoparticles as an additive with Moringa methyl ester. Additionally, there is limited research on the effects of varying compression ratios with Nano additive fuel. The combination studied in this research, MME + GNA with varying compression ratios of 16, 17.5, and 19, has not been extensively explored in existing literature. Therefore, the present study aims to investigate the impact of a unique combination of Moringa methyl ester (MME20) at a 20% blend with graphene nano additive (GNA) at concentrations of 30, 60, and 60 PPM at CR of 16, 17.5, and 19 on the performance attributes of an internal combustion engine. The objective of this study is to determine the effects of CR and blend ratio on diesel engine performance in order to identify the best fuel blend and CR. The study aims to analyze the impact of GNA30, 60, and 90 ppm and MME20 blends on a diesel engine under different load conditions and CR of 16, 17.5, and 19 to assess the influence of the selected fuel blend on engine characteristics. The study results were used to select an optimized blend and CR that produces acceptable performance, combustion, and emission results in the CI engine.

Therefore, the current study focused on evaluating the performance and emissions characteristics, such as BTHE, BSFC, VE, EGT, CP, NHRR, MFB, ID, CD, CO, HC, CO_2, NO_x, and smoke opacity, of the novel MME20 and GNA emulsified fuel (30, 60, 90 ppm) under varying compression ratios of 16, 17.5, and 19. The detailed discussions on the engine findings are presented in the Results and discussion section.

Materials and methods

Biodiesel extraction

Determination of free fatty acid (FFA)

One milliliter of oil is filled in the conical flask, and then 10 ml of isopropyl alcohol is incorporated into it. Phenolphthalein is used as an indicator, and 2–3 drops are added to the flask. NaOH (0.01%) is taken in the burette. Titration is performed, during which process, the crude oil color turns to a pale pink color. The burette reading is noted at this point. The yellow solution turns pale pink; the indicated endpoint is 2 ml. This shows the 2% FFA value. Setups for the FFA test are illustrated in Figs. 1 and 2.

Based on the FFA test results, it was determined that the acid value of the oil is less than 4%. Therefore, this work conducted the transesterification process using the single-phase method. It was also determined that the amount of NaOH to be added with 200 ml of methanol for 1 L of crude oil can be calculated using the following relation:

$$3.5 + X = L \tag{1}$$

where,

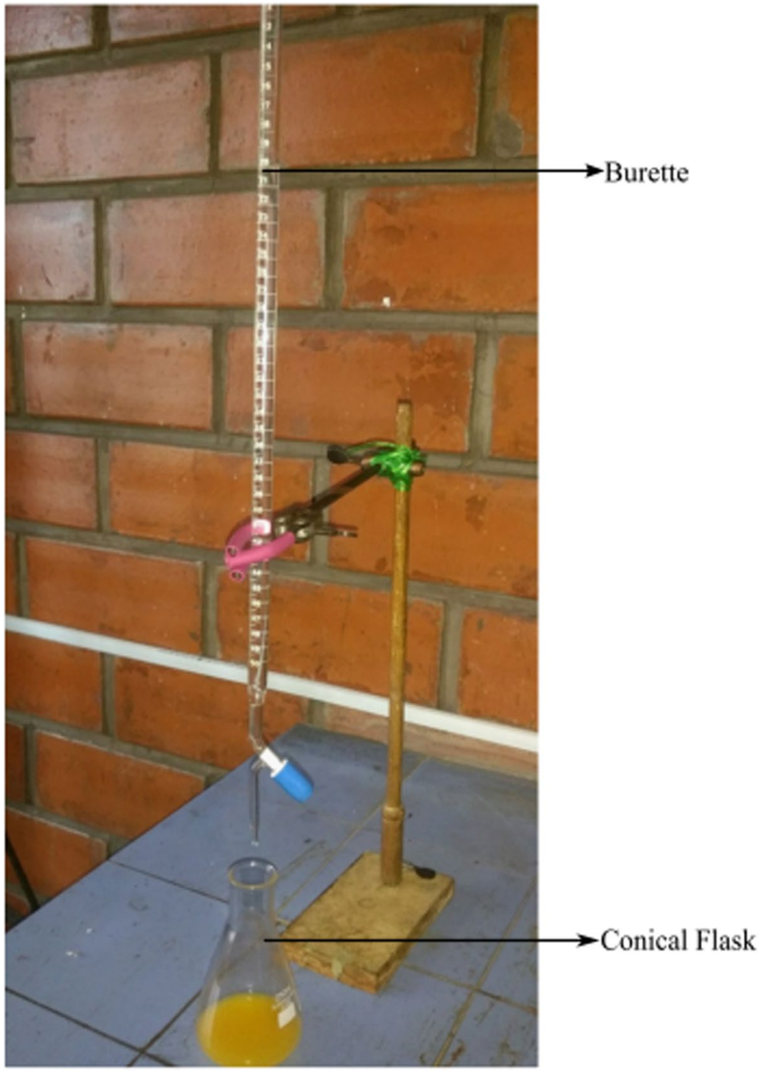


Fig. 1 Photographic view of titration test

Fig. 2 Change in color of crude Moringa oil

L = total amount of NaOH required to transesterify the triglycerides in the oil. 3.5 gm is nothing but 3.5 ml = amount of NaOH required to transesterify the triglycerides in the oil (standard).

X = 2 gm/2 ml (amount of NaOH required to neutralize the FFA).

$$3.5 + 2 = 5.5$$

5.5 gm is nothing but 5.5 ml of NaOH required to transesterify the triglycerides in the oil. Add 200 ml of methanol + 5.5 ml of NaOH + crude oil to produce biodiesel during the transesterification process.

Single-phase transesterification method

A single-phase transesterification process is chosen because the quantity of FFA in the raw vegetable oil is lower than 4%. In the single-phase transesterification process, a restrained quantity of methanol (CH_3OH) and sodium hydroxide (NaOH) are mixed carefully with a quantified amount of vegetable oil (extracted oil). This is then heated constantly at 60 °C for 2 h and then made to undergo natural cooling. This causes a deposit at the bottom (Glycerol), which is unglued out with the help of a separating funnel. Thus, the leftovers in the conical flask are vegetable oil (esterified), whose commercial name is biodiesel. The Transesterification test setup is depicted in Fig. 3. After the transesterification process, the oil is subjected to the gravity separation method in a settling flask to remove unwanted glycerol and this is carried out for few hours.

Water washing process

To ensure that there is no glycerol content in MME, wash the esterified fuel with warm water until clear water is obtained. When washing the esterified fuel, add 25–30 ml of acetic acid to warm water to prevent emulsification, and sprinkle it evenly (Fig. 4). Allow 30 to 45 min for the contaminated water containing some glycerol to settle and separate.

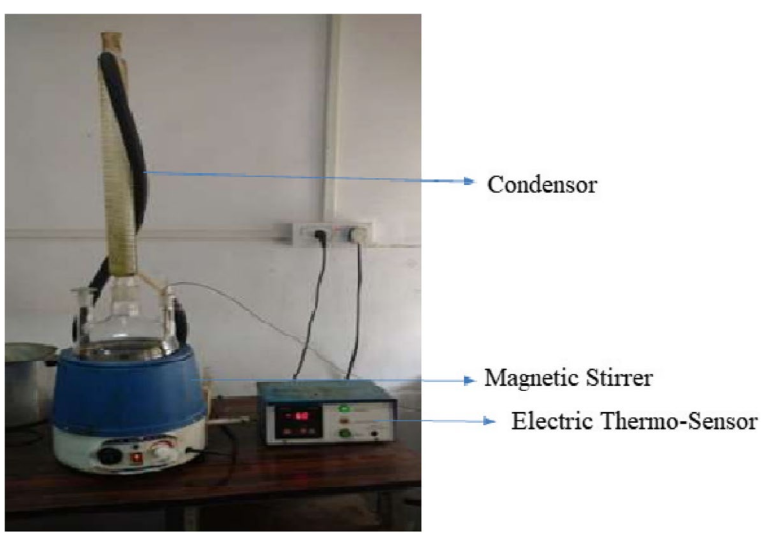


Fig. 3 Photographic view of transesterification setup

Fig. 4 Mixing of GNA with MME20

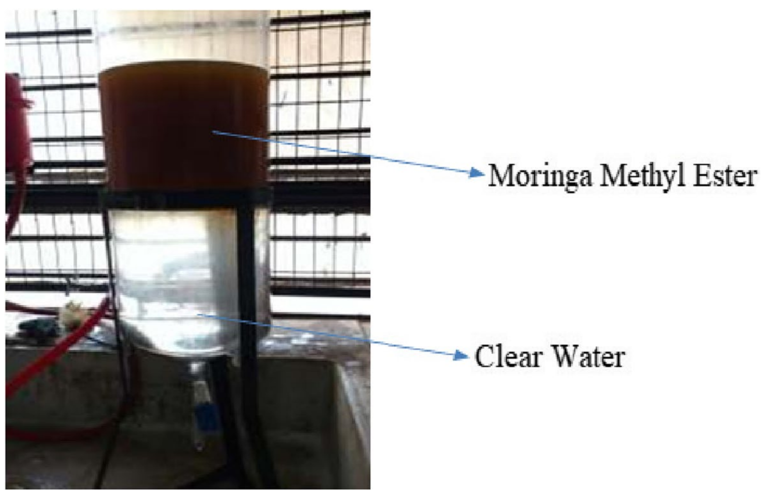


Fig. 5 Final water washing

Repeat the water washing process until all the glycerol content in MME is removed. The photographic view of the water-washing method is portrayed in Fig. 5.

Heating

After the water washing process is complete, MME should be collected. There might be some moisture content in the MME, which needs to be removed. To eliminate the moisture, the MME is heated to 110 °C. This heating process is illustrated in Fig. 6. Following these steps, pure biodiesel is obtained. A visual representation of the pure MME can be seen in Fig. 7. Additionally, nanoparticles are mixed into the MME, and a photograph of this process is shown in Fig. 4.

Fig. 6 Heating process

Testing in CI engine

A single-cylinder diesel engine with a four-stroke cycle is connected to an eddy current dynamometer, which is used to load the engine. The compression ratio can be adjusted by changing the piston heads without affecting the combustion chamber's geometry. In the experiment, the pressure was maintained at a constant 200 bar, and the fuel injection timing was set at 23°BTDC. The engine is equipped with tools to measure combustion pressure and crank angle, and the obtained signals are connected to a computer through an engine indicator for a graphical representation of Pθ−PV. Additionally, provisions are made for interfacing fuel flow, temperatures, airflow, and various load measurements. The arrangement has a panel box that consists of an air box, fuel tank, manometer, fuel measuring unit, transmitters for air and fuel flow measurements, process indicator, and engine indicator (Figs. 8 and 9). For cooling water, it has rotameters, and for water flow measurement, it has a calorimeter. This setup aids the study of engine performance for indicated power, brake power, frictional power, IMEP, BMEP, BTE, ITE, Mechanical efficiency, volumetric efficiency, specific fuel consumption, heat balance, and A/F ratio. Lab view-based Engine Performance Analysis software package "Engine soft" is provided for online performance evaluation. The schematic diagram and Photographic view Engine setup are shown in Figs. 10, 11, and 16. During experimentation, the load on the engine was varied along with CR of 16, 17.5, and 19 to estimate the engine's working parameters (Fig. 12). The photographic view of different CRs and PBGs is depicted in Figs. 13, 14, and 15. Piston specifications are shown in Table 2. Initially, diesel was used as a fuel for the experiment, and later, MME20 and its Nano additive blends were used. Figure 9 shows the view of the fuel mixture used, and the properties are specified in Table 1. The fuel tank and fuel lines were completely drained out after every test run, and the engine was initially run for 5 to 10 min to ensure a new fuel supply to the engine. In order to obtain accurate results, readings were noted down only when the oil temperature was observed to be constant for a period of at least 5 min. The specifications of the test engine are shown in Table 3. The photographic view of the gas analyzer and smoke meter is shown in Fig. 12. Biodiesel blend (MME20)

Fig. 7 Moringa methyl ester

is obtained using a transesterification process, and various nano fuel blends of graphene are prepared by adding quantities of graphene at 30 ppm, 60 ppm, and 90 ppm, and a uniform mixture of each blend was obtained using an ultrasonicator. The photographic view of the ultrasonicator is portrayed in Fig. 8. The required amount of biodiesel (Moringa methyl ester) (B20, i.e., MME-20) is to be filled in the fuel tank located at the back of the electronic unit. The electronic unit was switched ON after connecting all the main plug-ins, and the

Fig. 8 Ultrasonicator

Fig. 9 Blends of Moringa methyl ester (MME20, MME20 + 30 ppm, MME20 + 60 ppm, MME20 + 90 ppm)

indicators and temperature sensors were set to the default readings. The piston head is fixed to the cylinder head in order to set the compression ratio to 16. Switch ON the compression ignition engine for preheating. The fuel is filled into a burette located at the back of the electronic unit (converts electronic to mechanical energy). It is fed into the engine once the preheat temperature is reached during the intake stroke. The load is gradually increased, starting from 0 to 100%. The load is then increased to 25%, and the time taken for 10 mL

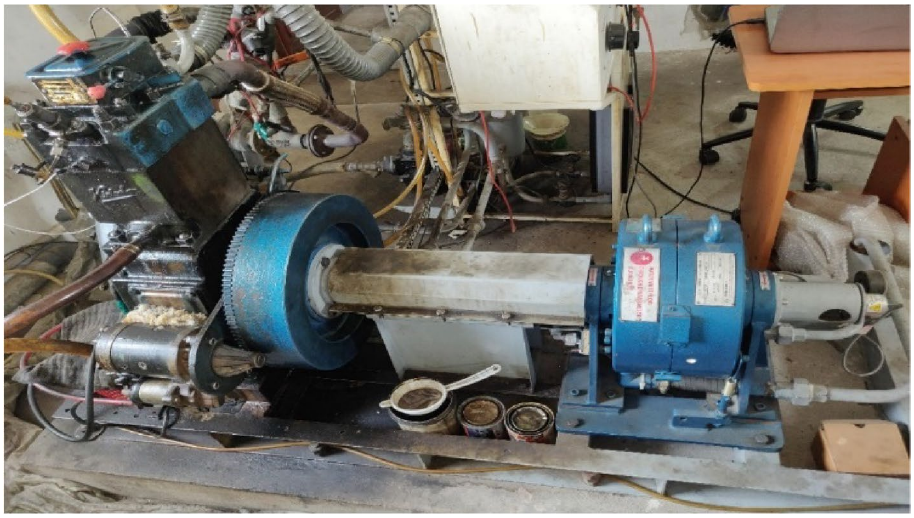


Fig. 10 Compression ignition engine setup

Fig. 11 Electronic unit

of fuel to be consumed is determined using a stopwatch. AVL 5 gas analyzer and smoke meter were used to measure the quality and amount of gas liberated from the engine. A software named Engine Soft LV is used for performance and combustion monitoring. This software can be used for monitoring, data entry, data logging, and reporting. The software evaluates power, efficiencies, fuel consumption, and heat release. It is configurable as per engine setup. The performance, combustion, and emissions data obtained are represented graphically and are discussed in the results and discussion section. The engine is put to rest, and the same procedure is repeated for blends MME-20 with 30 ppm, 60 ppm, and

Fig. 12 Gas analyzer and smoke meter

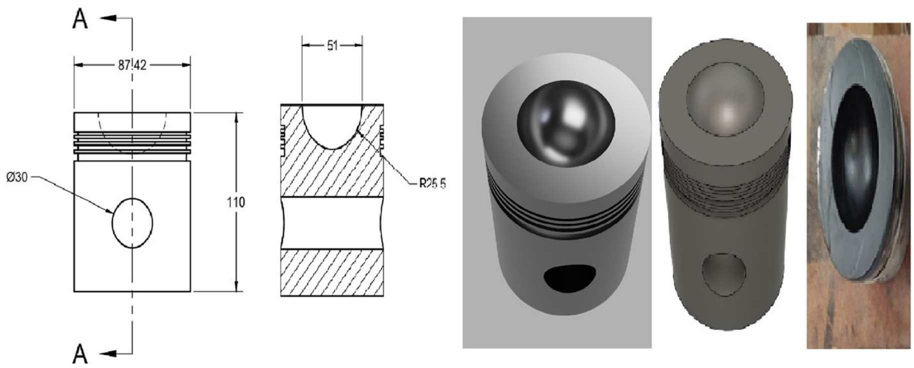


Fig. 13 Photographic and CAD model of piston with compression ratio 16

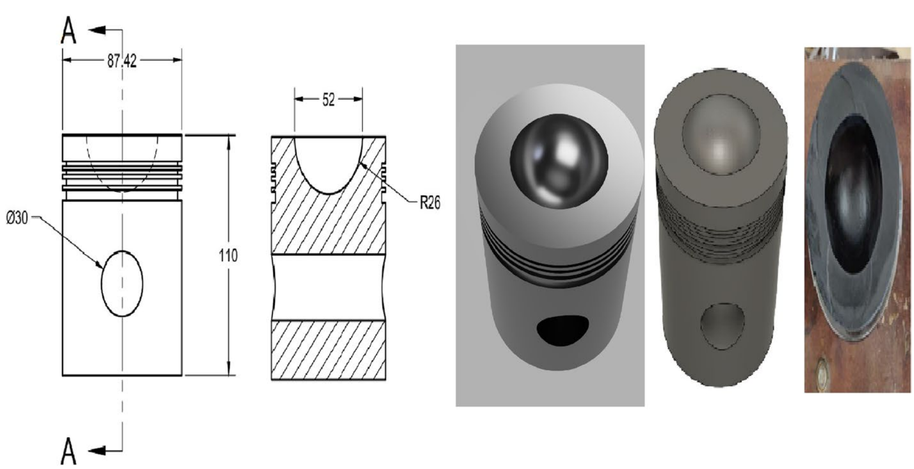


Fig. 14 Photographic and CAD model of piston with compression ratio 17.5

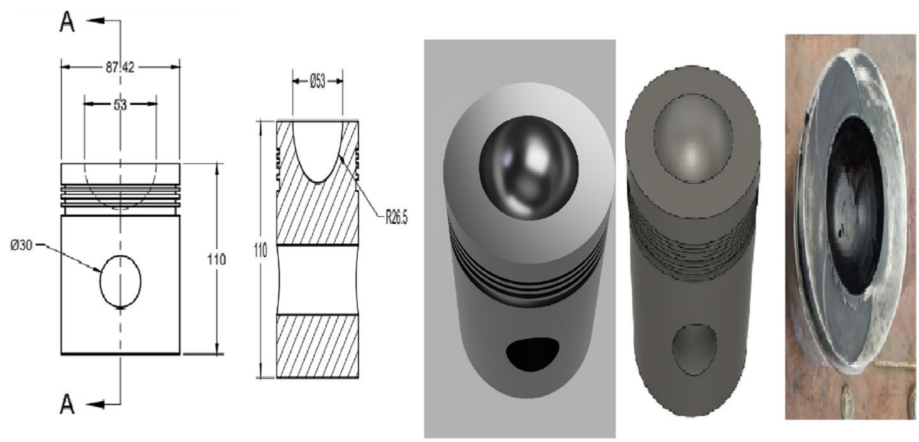


Fig. 15 Photographic and CAD model of piston with compression ratio 19

Table 2 Piston specifications

Particulars	Type of piston		
	Std CR 17.5	**CR16**	**CR19**
Bowl volume (mm^3)	36,811.08	34,727.95	38,975.907
Throat diameter (mm)	52	51	53
Bowl depth (mm)	26	25.5	26.5
Piston diameter (mm)	87.42	87.42	87.42

Table 3 Engine specifications

Rated power	5.2 kW
Make	Kirloskar
speed	1500 rpm
Inner diameter (D)	87.5 mm
Piston displacement (L)	110 mm
Compression ratio	17.5:1
Diesel heating value	420,000 kJ/kg
Diesel density	830 kg/m^3

90 ppm graphene addition at CR16. Once all the fuels are tested, the piston head of CR 16 is removed from the cylinder head and fitted with another piston head of CR 17.5, and the procedure is repeated. The same is done for CR 19; the results are tabulated, and the inferences are drawn.

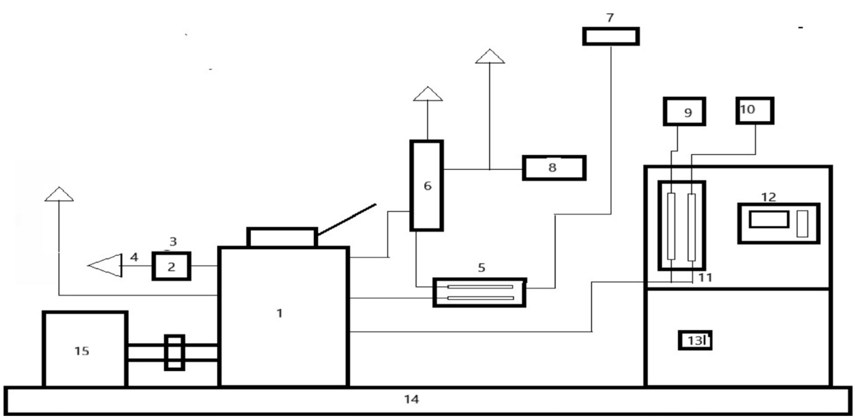
The uncertainty of the equipment employed in the engine setup was calculated and arranged in Table 4 (Fig. 16).

Results and discussion

The following chapter contains the results and discussions on the different engine characteristics (performance, combustion, emission) of Moringa methyl ester (MME) with GNA fueled variable compression ignition engine. Various tests were experimented with

Table 4 Improbability, accurateness, and range of different measuring devices

Sl. No	Device name	Magnitude	Range	Accurateness	Improbability (%)	Method of evaluation
1	Load indicator	Load(W)	250–6000	± 10W	0.2	Strain gauge type load cell
2	Temperature indicator	Exhaust Temperature (°C)	0–900	± 1 °C	0.1	Thermocouple
3	Barrette	Fuel consumption (cc)	1–30	± 0.2 cc	1	Volumetric measurement
4	Speed sensor	Speed (rpm)	1500–6000	± 10 rpm	0.2	Magnetic pickup type
5	Exhaust gas analyzer	CO	(0–15% Vol)	± 0.02%	0.1	Non-dispersive infrared sensor (NDIR)
		HC	(0–20,000 ppm Vol)	± 20 ppm	0.1	
		CO_2	(0–20% Vol)	± 0.03%	0.15	
		O_2	(0–25% Vol)	± 0.02%	0.1	Ultrasonic oxygen sensor
		NOX	(0–6000 ppm Vol)	± 10 ppm	0.2	Electrochemical measurement
6	Smoke meter	Smoke	(0–100%)	0.1%	0.1	Smoke meter
7	Pressure transducer	Pressure (bar)	0–110	± 1 bar	1	Piezoelectric sensor
8	Crank angle encoder	Crank angle	0–720	± 1	0.1	Magnetic pickup type



1. VCR Engine
2. Air Tank
3. CR Lever
4. Orifice meter
5. Water Flowmeter
6. Exhaust Calorimeter
7. Water Tank
8. Exhaust Gas Analyzer
9. Diesel Tank
10. Petrol Tank
11. Fuel Consumption
12. Computerized Data Acquisition system
13. Main Switch
14. Engine bed
15. Eddy Current Dynamometer

Fig. 16 Schematic representation of the compression ignition engine

after ensuring the full warm-up of the engine. Different tests were conducted for different blends of the fuel and repeated five times for each kind to enhance the experimental results' reliability. These tests were experimented with based on varying loads and varying compression ratios. The varying compression ratios included 16, 17.5, and 19, and the loads ranged from 0 kg, 4.5 kg, 9 kg, 13.5 kg, and 18 kg.

Analysis of engine performance, thermal, and emissions attributes for GNA-MME blends

The variation in BTHE for different fuel blends at different CRs is presented in Fig. 17. BTHE for all fuel blends was lower when linked to pure diesel for varying CR and loads. This was due to less heating value, high denser, and low power available at the engine flywheel. The fuel competency is reduced because of poor atomization inside the combustion chamber due to lower calorific value and higher viscosity. At maximum load, the BTHE increased by 3.34% (MME20 + GNA30), 3.04% (MME20 + GNA60), and 2.54% (MME20 + GNA90) when compared with the (MME20) at CR 17.5. The values that were obtained experimentally at full load conditions showed that the BTE decreased by 4.16% (MME20), 0.7% (MME20 + GNA30), 0.75% (MME20 + GNA90), by comparing CR 16 with CR 17.5 and decreased by 0.66% (MME20), 3.27% (MME20 + GNA60), 3.45% (MME20 + GNA90), by comparing CR 17.5 with CR 19 resulted in poor combustion of fuel which was due to lower compression temperature. The BTHE for blend (MME20 + GNA30) was almost similar to diesel at CR 19 at a 75% load. The BTHE for blend (MME20 + GNA30) increased by 3.87% when compared with blend (MME20) at CR 19. Blend MME20 at CR 16 shows the highest BTHE compared to all the other blends. An enhancement in BTHE was seen with load increase, and the loss of heat was lesser at greater engine load. Graphene nanoparticles, due to their high reactive surface area, act as a catalyst through the stage of combustion, causing a micro-detonation of petroleum droplets, which results in better burning parameters like burning pressure and more HHR, consequently increasing the BTHE.

Galande et al. [37] studied the impact of TiO_2 nanoparticle dispersion at concentrations of 25 ppm, 50 ppm, and 75 ppm in a microalgae biodiesel blend (MAB20). They conducted experiments at CR of 17, 19, and 21. The results showed that in the MAB20 blend with increasing nanoparticle concentration (specifically, 75 ppm TiO_2 nanoparticle in MAB20 at CR 21), the Brake Thermal Efficiency (BTHE) decreased by 0.95%

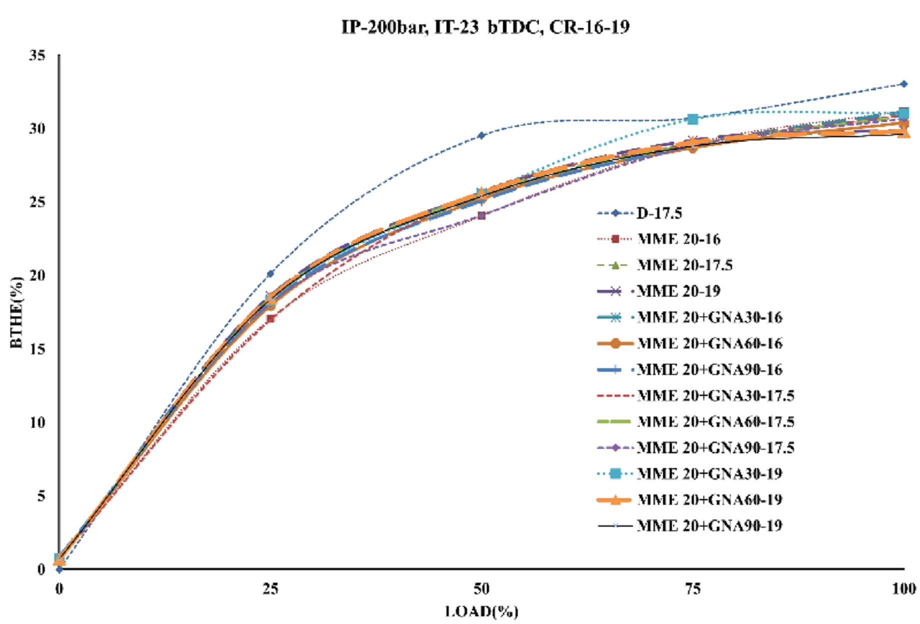


Fig. 17 Change in BTHE for different loads and CRs 16, 17.5, and 19

compared to neat diesel at full load. However, in the current study, the BTHE decreased by 0.92% compared to neat diesel in MME20 + GNA30 at CR16. Kaki Sanatha et al. [38] used Baheda oil biodiesel blend (BOME20), dispersant (DSP-QPAN80), and zinc oxide (ZnO) nanoparticles at concentrations of 50 ppm, 75 ppm, and 100 ppm for CR16.5, 17.5, 18.5, and 19.5 respectively. They found that the blend BOBD20 + ZnO 75 + DSP 75 at CR19.5:1 achieved a higher BTHE of 34.89%. R. Hussain Vali et al. [39] investigated the effects of ZnO nanoparticle-blended diesel-water emulsion on the performance and emission characteristics of a VCR diesel engine at various compression ratios (16.5, 17.5, and 18.5). Their results showed that the maximum BTHE of 31.06% was achieved at CR 18.5 for DW10Z100 (Diesel + 10%water + 100 ppm ZnO) blend. In the current investigation, the highest BTHE achieved was 31.14% at CR16 for MME 20 + GNA30. This was attributed to Nano additive biodiesel fuel having a high calorific value, enhancing the surface-to-volume ratio, improving oxidation, and requiring less ignition timing, leading to complete combustion at varying CR. Similar conclusions were reached by Das AN, M. et al. (2023), Prabhu A et al. (2017), Balasubramanian Prabakaran et al. (2017), and Rahul Kumar Mishra et al. (2017) [4, 12, 20, 40].

Variation of BSFC for different loads and CRs 16, 17.5, and 19 are depicted in Fig. 18. BSFC is enhanced for all blends of fuel at lower load conditions. Still, with an increase in the engine loads, BSFC starts decreasing, and this is because of an increase in temperature inside the engine cylinder at higher loads. At such high temperatures, the fuel's viscosity decreases, leading to proper atomization. The engine produces higher brake power at a higher load, so the BSFC decreases. It can be seen that the BSFC of MME20 at CR 16, 17.5, and 19 increases by a percentage of 3.84%, 11.53%, and 11.53% when compared with that of diesel. At CR 17.5, the BSFC of the Nano additive blends, when

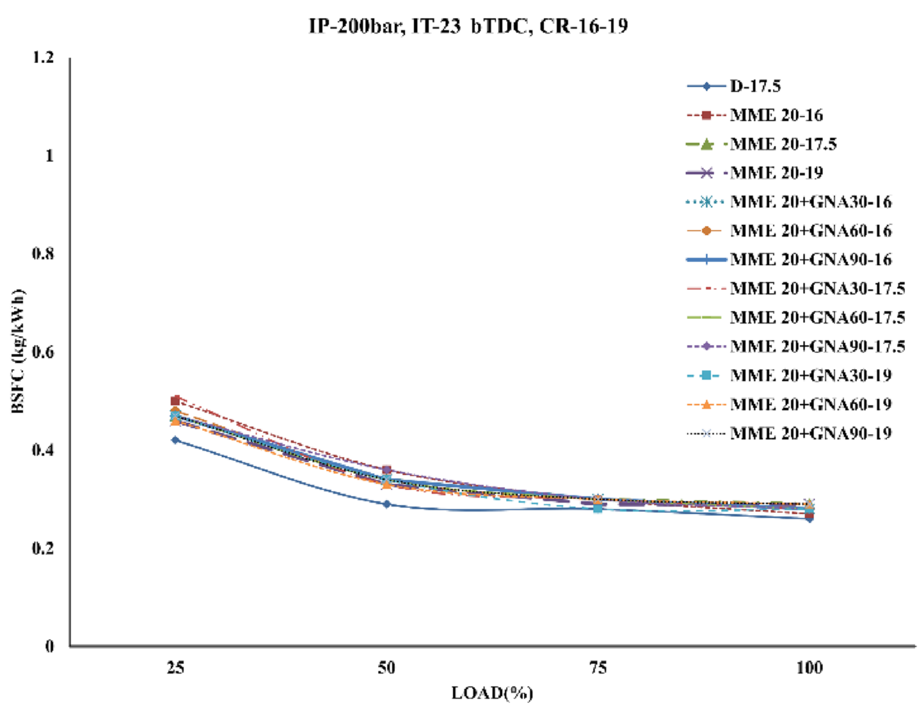


Fig. 18 Change in BSFC for different loads and CRs 16, 17.5, and 19

compared with pure blend, decreased by 3.44%. This is because nanoparticles enhance the secondary atomization, mixing of fuel–air, and micro-explosion of fuel droplets, which results in lower BSFC. Blends (MME20 + GNA30, GNA60, and GNA90) for CR 16 and 17.5, along with blends (MME 20 + GNA30) at CR19, show a constant and lower BSFC when compared to other blends among the lot. Galande S et al. [37] investigated the effect of TiO_2 nanoparticle dispersion (25 ppm, 50 ppm, and 75 ppm) in a blend of microalgae biodiesel (MAB20). The experiment was conducted at CR 17, 19, and 21. Their results showed that at full load, the BSFC increased by 1.66% for the MAB20 blend with an increase in nanoparticle concentration (75 ppm TiO_2 nanoparticle in MAB 20 at CR 21) compared to neat diesel. In this study, a rise of 1.07% in BSFC was observed for MME20 + GNA30 at CR16. Kaki Sanatha et al. [38] used Baheda oil biodiesel (BOME20), dispersant (DSP-QPAN80), and zinc oxide (ZnO) nanoparticles with proportions of 50 ppm, 75 ppm, and 100 ppm for CR16.5, 17.5, 18.5, and 19.5 respectively. They found that the blend BOBD20 + ZnO 75 + DSP 75 at CR19.5:1 had the least BSFC at 0.305 kg/kWh. R. Hussain Vali et al. [39] investigated the effect of ZnO nanoparticles blended diesel-water emulsion on a VCR diesel engine's performance and emission characteristics at CR16.5, 17.5, and 18.5. Their results showed that the lowest BSFC of 0.291 kg/kWh was obtained at 18.5 CR for the DW10Z100 (diesel + 10% water + 100 ppm ZnO) blend. In this current investigation, the least BSFC observed was 0.28 kg/kWh at CR16 and 19, full load condition for MME 20 + GNA30 and GNA60. This might be due to the addition of Nano additives, which improve the flash point and heating value and enhance fuel and air atomization, leading to complete combustion for varying CR. Similar conclusions were drawn by Das AN, M. et al. (2023), Rahul Kumar Mishra et al. (2017), M. Santosh et al. (2016), and Dr. S. Karthikeyan et al. (2014) [4, 5, 22, 40].

Change in VE for different loads and CRs 16, 17.5, and 19 is represented in Fig. 19. The volumetric efficiency represents the efficiency of a compressor cylinder to compress the gas. It can be seen that the values of VE of blends at CR 17.5 and 19 have slightly lower values compared to that of the Standard diesel by percentages of 0.98% and 2.122% for MME20. There is an increase in the efficiency values of 0.55% and 0.52% for blends MME20 and MME20-GNA30 for CR 16 when compared with diesel at a fully operating load. At lower CR16, VE increases compared to the engine operating at higher CR17.5 and 19. This is mainly due to the fact that at lower compression ratios, there is more air available in the manifold. However, the increase in surface area to volume ratio, as proportions of GNA are added in the selected fuel samples, leads to slightly less air available during the atomization of fuel. The results have been compared, and it has been observed that similar variations in results were also demonstrated by Das AN, M. et al. (2023), Gavhane Rakhamaji et al. (2020), Dr. S. Karthikeyan et al. (2014), and R.D. Eknath et al. (2014) [13, 22, 29, 40].

Figure 20 indicates the influence of diesel and GNA-MME mixtures on burning gas exhaust temperature for different CRs. During combustion, the exhaust gas temperatures reveal the temperature reached inside the cylinder. As the load on the engine increases, the cylinder pressure increases, and a large amount of fuel is burnt, which increases the temperature. The results show an increase in EGT for the fuel blends when operated at max load condition when equated with diesel due to its lower cetane number. Lower cetane number leads to a longer ignition delay period, contributing to higher

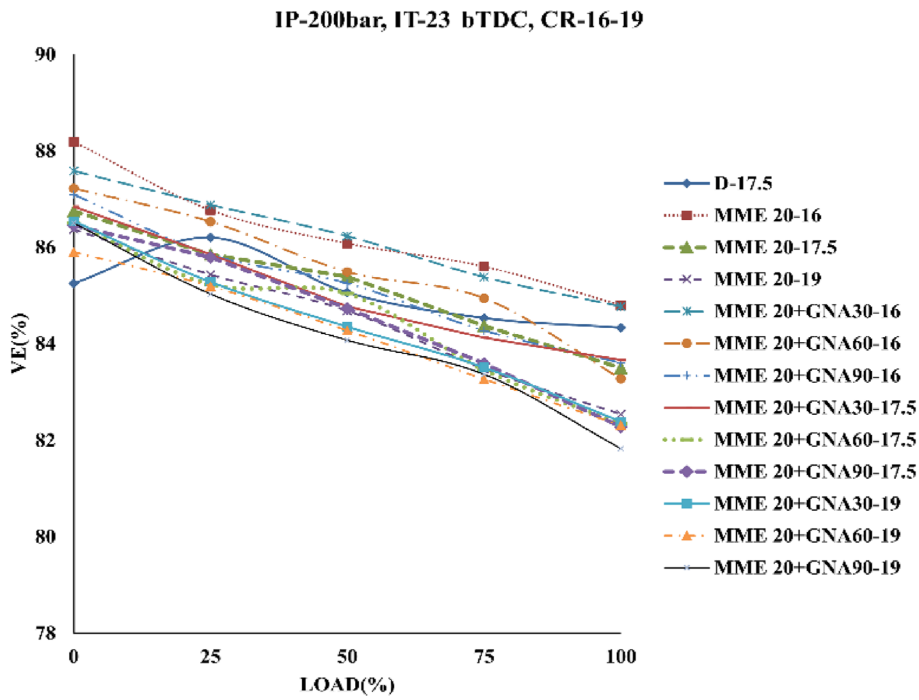


Fig. 19 Change in VE for different loads and CRs 16, 17.5, and 19

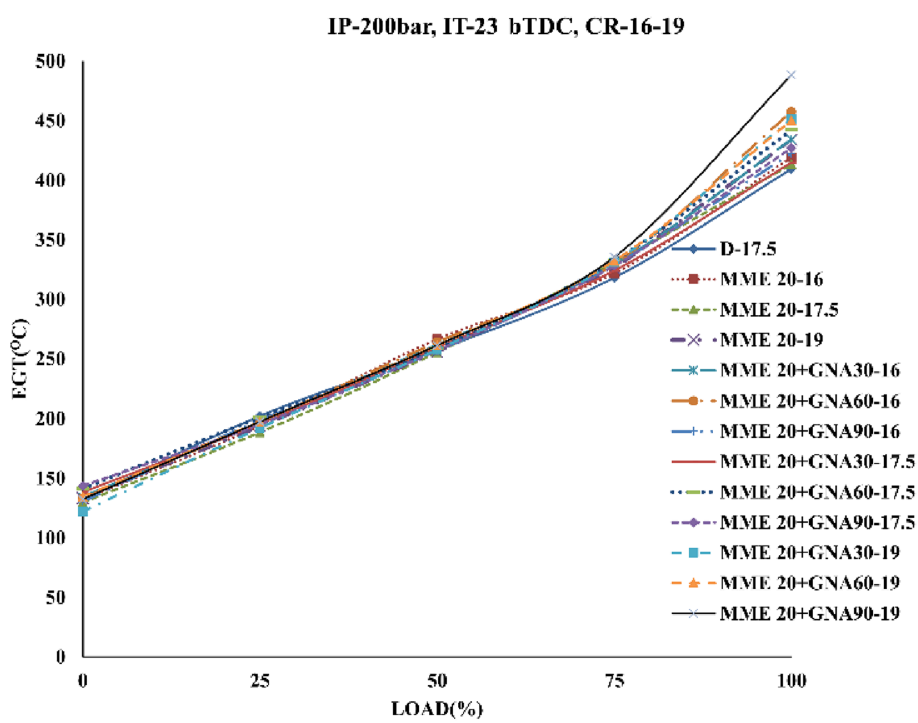


Fig. 20 Change in EGT for different loads and CRs 16, 17.5 and 19

exhaust gas temperature and slower burn rate. Among those blends, the values of (MME 20) at CR17.5 and (MME 20 + GNA30) at CR17.5 have the lowest exhaust gas temperature of about 413 °C and 414 °C that are very close to that of the EGT of the diesel. The temperature for all the remaining blends had higher values of EGT. This is because of its high calorific value (CV). Hence, more heat is released in the combustion chamber, leading to higher temperatures. Galande S et al. [37] conducted an investigation into the effect of TiO_2 nanoparticle dispersion (25 ppm, 50 ppm, and 75 ppm) in a microalgae biodiesel (MAB20 at CR of 17, 19, and 21. Their results showed that as the nanoparticle concentration increased, the EGT decreased by 5.86% compared to neat diesel at full load. However, in the present study, the EGT increased by 2.42% for MME20 + GNA30 at CR16. The EGT was found to be slightly lower for the GNA emulsified biodiesel blend as the compression ratio increased. This was mainly due to a decrease in the ignition delay period, which controlled the cylinder temperature and led to a high convective heat release rate affecting the EGT. Similar inferences were drawn by Das AN, M. et al. (2023), Suresh Vellaiyan et al. (2019), Rahul Kumar Mishra et al. (2017), and Dr. S. Karthikeyan et al. (2014) [4, 18, 22, 40].

Figure 21 depicts the change in cylinder pressure for different crank angle positions and CRs 16, 17.5, and 19 at 100% load. The highest cylinder pressure during power stroke was noticed to be 63.36 bar at CR16 for fuel (MME 20 + GNA30). It might be due to a longer explosion delay period, which caused for a larger quantity of fuel to pass into the burning chamber. The same trend follows with CR 17.5 and 19. The combustion pressures are maximum for the blend (MME20 + GNA30), when the obtained observations were equated with that of Standard diesel. The combustion pressures are lower for the blends at CR 16 and 17.5; this is due to the intense pre-combustion phase of diesel, which has resulted in a rapid pressure rise as more quantity of fuel is gathered during the

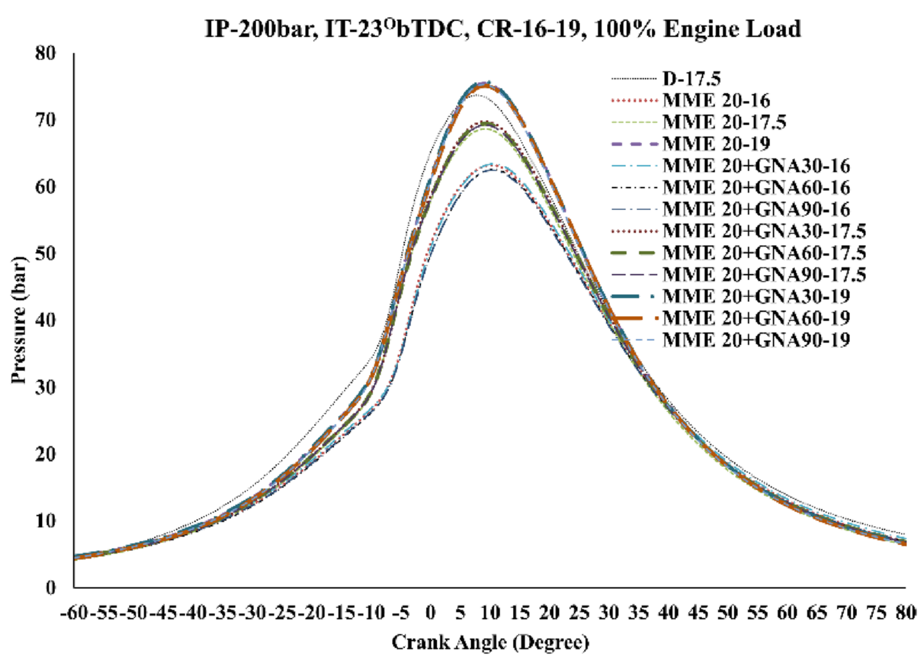


Fig. 21 Variation of combustion pressure for different crank angles and CRs 16, 17.5, and 19

delay period. The decrease in burning pressure for the blend (MME 20 + GNA30) at CR 16 and 17.5 is 13.99% and 5.30% when linked with diesel. The highest burning pressure is obtained for the same blend at CR 19 is 75.69 bar, i.e., 2.741% more when compared with diesel. Galande S et al. [37] investigated the effect of TiO_2 nanoparticle dispersal at concentrations of 25 ppm, 50 ppm, and 75 ppm in microalgae biodiesel (MAB20). The experiment was conducted at CR of 17, 19, and 21. Their results showed that the MAB20 with an increased nanoparticle concentration (75 ppm TiO_2 nanoparticle in MAB 20 at CR 21) increased the maximum cylinder pressure by 11.75% compared to neat diesel at full load. However, in the present study, the maximum cylinder pressure increased by 2.741% for MME20 + GNA30 at CR19 compared to neat diesel at full load. Kaki Sanatha et al. [38] used Baheda oil biodiesel blend (BOME20), dispersant (DSP-QPAN80), and zinc oxide (ZnO) nanoparticles at proportions of 50 ppm, 75 ppm, and 100 ppm for CR16.5, 17.5, 18.5, and 19.5, respectively. They found that the blend BOBD20 + ZnO 75 + DSP 75 at CR19.5:1 had the highest cylinder pressure of 72.52 bar. The increase in flash and fire point of this specific mixture may cause a shorter ignition span and increase the cylinder pressure. Similar conclusions were drawn by Das AN, M. et al. (2023), M. Santosh et al. (2016), Suresh Vellaiyan et al. (2019), and Dr. S. Karthikeyan et al. (2014) [5, 18, 22, 40].

The Variation of HRR for different crank angles and CRs 16, 17.5, and 19 is represented in Fig. 22. Thermodynamics first law is utilized in order to estimate the heat release rate (HRR). The experimental results showed that NHRR was the highest for diesel, i.e., 36.66 J/deg. This recorded result was due to the accumulation of fuel in the cylinder due to the long delay. At CR 17.5, the NHRR observed for the following blends (MME20), (MME20 + GNA30, 60, and 90 ppm) were 29.5, 31.47, 29.62, 30.28 J/deg, and a decrease of 14.15% can be seen when associated with diesel. The NHRR of all the blends have values below the reference line because of the heat generated in the previous cycle during the compression stroke. When the CR increases, there is a slight decrease in the NHRR, and this is due to lesser air–fuel mixing in the combustion chamber and due to air entrainment. The maximum HRR for blends of biodiesel were less when compared with pure biodiesel. It was noted that the HRR obtained for MME20 is lower than that of standard diesel due to a shorter ignition delay period. Galande S et al. [37] investigated the effect of TiO_2 nanoparticle dispersion (25 ppm, 50 ppm, and 75 ppm) in the microalgae biodiesel (MAB20). The experiments were conducted at CR of 17, 19, and 21. Their results showed that the MAB20 blend with an increase in nanoparticle concentration 75 ppm TiO_2 nanoparticle in MAB 20 at CR 21 resulted in NHRR increase of 10.84% compared to MAB20. In the current study, the blend MME20 + GNA30ppm at CR 17.5 exhibited the highest NHRR of 31.47 J/°CA among the blends, which was 6.7% higher than the MME20.

Kaki Sanatha et al. [38] used Baheda oil biodiesel blend (BOME20), dispersant (DSP-QPAN80), and zinc oxide (ZnO) nanoparticles at concentrations of 50 ppm, 75 ppm, and 100 ppm for CR16.5, 17.5, 18.5, and 19.5, respectively. They found that the blend BOBD20 + ZnO 75 + DSP 75 at CR19.5:1 exhibited the highest NHRR BSFC of 61.22 J/°CA compared to neat diesel at full load. However, in the present study, MME20 + GNA30ppm at CR 17.5 showed the highest NHRR of 31.47 J/°CA among the blends. At higher CR, the cylinder pressure and temperature are also high, causing

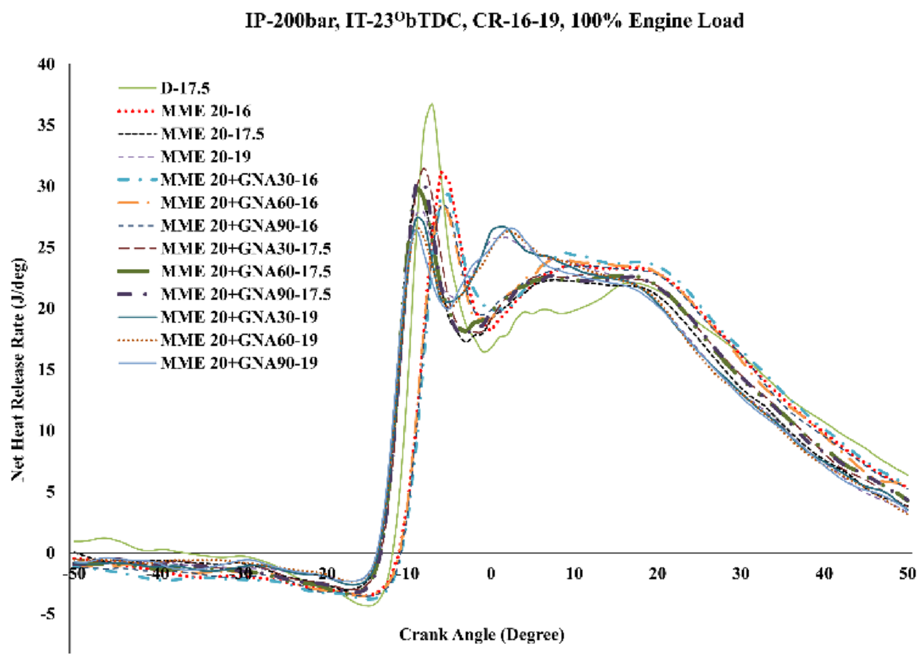


Fig. 22 Discrepancy of net heat release rate (NHRR) for different crank angles and CRs 16, 17.5, and 19

lower HRR for the MME20 than the diesel. The emulsification of GNA into the MME20 enhances the surface-to-volume ratio and improves oxidation, resulting in lesser ignition timing and complete combustion for varying CR, leading to higher HRR. Similar findings were reported by Das AN, M. et al. (2023), Gavhane Rakhamaji et al. (2020), Suresh Vellaiyan et al. (2019), Dr. S. Karthikeyan et al. (2014) [13, 18, 22, 40].

The mass fraction burned in relation to crank angle for CR 16, 17.5, and 19 for diesel and diverse proportional blends of biodiesel are portrayed in Fig. 23. It can be seen that the MFB for all the blends at CR16 occurs at 2°CA, 3°CA, 3°CA, and 2°CA later than the MFB of the diesel, and at approximately 2°CA, 2°CA, 2°CA, and 1°CA later than standard condition (blends of biodiesel at CR 17.5) at 50% load. Seventy-five percent of MFB occurs at 2°CA, 0°CA, 2°CA, and 2°CA earlier than Standard diesel conditions and at approximately 2°CA earlier than standard condition for CR 19. And 90% of MFB occurs at more or less the same CA for all blends and CRs. From the results inference, it can be noted that early MFB occurred at high CR, and this might be due to shorter ignition delay and high flame temperature in the combustion chamber at high CRs, causing early charge burning. The MFB is highest for CR 16 due to the existence of supplementary O_2 content of blends, thereby sustaining the burning process. In a study by Venu, H et al. [41], the influence of Jatropha biodiesel–zirconium oxide (Zr_2O_3) nano-additives fuel on MFB was examined. The results showed that the maximum MFB was found for the B20 blend (20% Jatropha biodiesel + 80% diesel fuel + 20 ppm Zr2O3). In the present investigation, the mass fraction burnt was found to be higher for all blends at CR16 compared to the MFB of diesel. Similar findings were also reported by Das AN, M. et al. in 2023, M. Santosh et al. in 2016, and R.D. Eknath et al. in 2014 [5, 29, 40].

The delay of ignition for different crank angles and CRs 16, 17.5, and 19 is shown in Fig. 24. The delay of ignition is the time duration between the first batch of biofuel

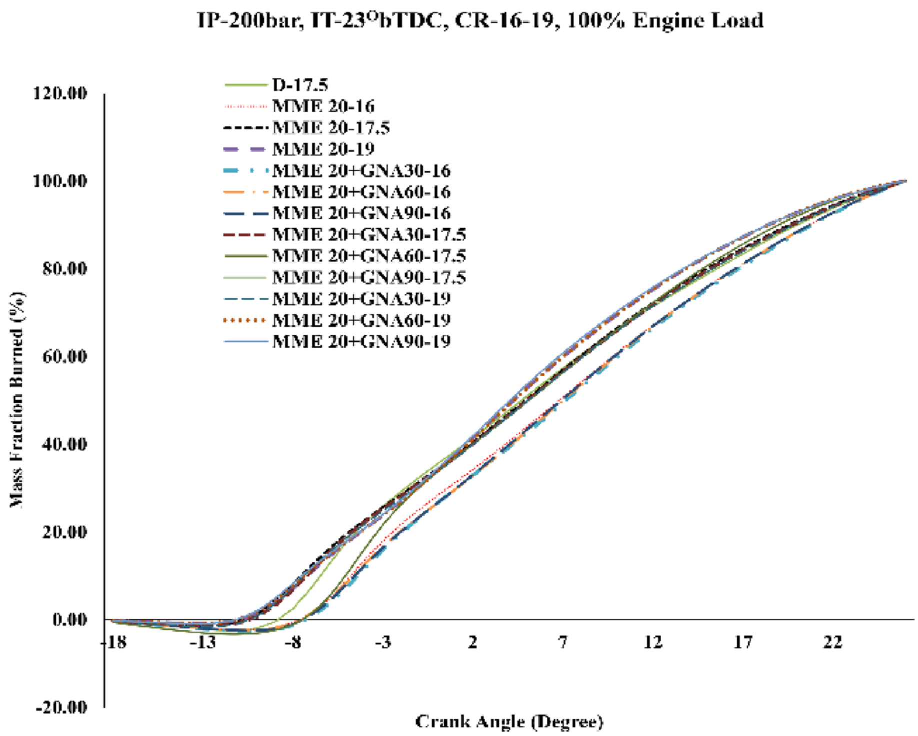


Fig. 23 Variation of mass fraction burn (MFB) for different crank angles and CRs 16, 17.5, and 19

inflowing towards the burning chamber till the propagation of the first flame. It has been seen that the delay of the ignition period decreases with an upsurge in CR and engine loading, and this is because of a rise in the temperature and pressure for all blends of fuel. A shorter ignition delay period is obtained because of pressure rise, which results in the mixture of molecules coming closely together, improving the chemical reactions due to the active molecule collisions. Experimental results showed that the ID period for blends (MME20 + GNA30), (MME20 + GNA60), (MME20 + GNA90) for both CR 17.5 and 19 have drastically reduced by 13.33% and by 20% for (MME 20 + GNA30) at CR19 in particular, at 100% load. Graphene nanoparticles in the fuel blend led to a better-premixed combustion phase and improved the burning rate, reducing the ignition delay. S. Gavhane et al. [13] investigated the blending of zinc oxide (ZnO) nanoparticles with soybean biodiesel (SBME25) at three different dosage levels (25, 50, and 75 ppm) using sodium dodecyl benzene sulphonate (SDBS) surfactant for CR 18.5 and 21.5. They found that for CR 21.5, the SBMEZnO50 blend resulted in a 25.02% and 5.38% reduction in ID compared to neat diesel and SBME20. For CR 18.5, the reduction was 24.37% and 2.18% respectively. In the current study, the lowest ID was observed for MME 20 + GNA30 at CR 19 compared to diesel, with a 20% decrease. Ibrahim et al. [42] analyzed the impact of changing CR from 14 to 18 at equal intervals of 1 on waste cooking oil biodiesel. They found a shorter ID for the maximum blend B50 and maximum CR18, and the present study showed a similar trend with a shorter ID at maximum CR19. The shorter ID was mainly due to the nano additive biodiesel, which improved the flash point and heating value, enhancing fuel and air atomization leading to a shorter ignition delay period

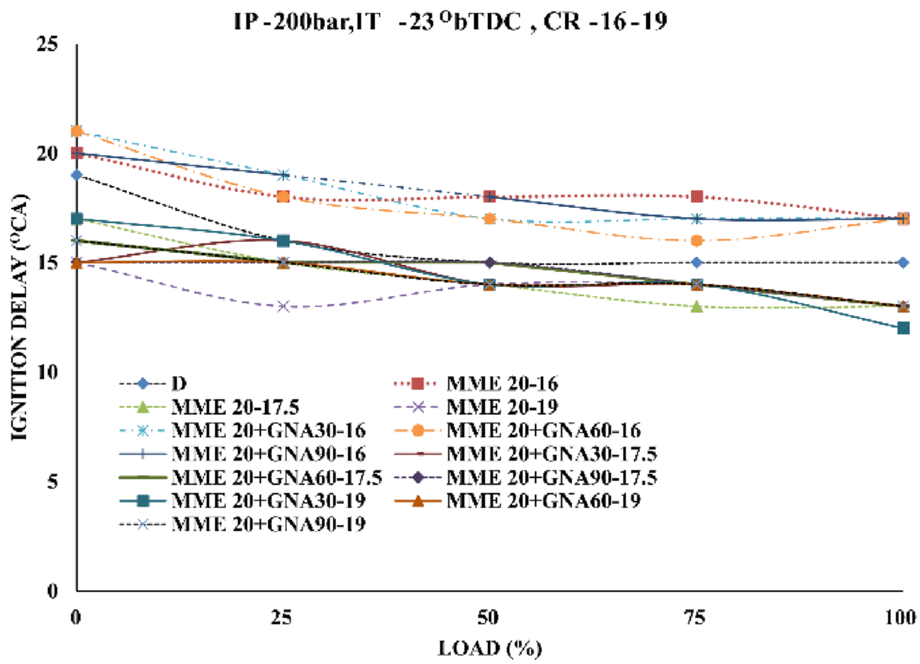


Fig. 24 Variation of ignition delay (ID) for different crank angles and CRs 16, 17.5, and 19

for varying CR. Similar variations in results were also demonstrated by Gavhane Rakhamaji et al. (2020), M. Santosh et al. (2016), and R.D. Eknath et al. (2014) [5, 29].

Variation of combustion duration (CD) for different crank angles and CR16, 17.5, and 19 is depicted in Fig. 25. Combustion duration gives the duration of time for the complete combustion of fuel. It can also be stated as the crank angle rotation period between the start and end of combustion. From the outcomes obtained, it can be observed that the CD increases with increases in load and compression ratio. Standard diesel has the least value for combustion duration, and this is because of the more ignition delay period of the diesel, which in turn leads to more fuel accumulating into the cylinder, and hence the total fuel is ready for atomization along with proper mixing. A 17.65% increase in CD has been obtained for blends MME20, MME20 + GNA60, and MME20 + GNA90 for compression ratios 17.5 and 19 when compared with diesel at a fully operating load. This bears a reason, i.e., the latent heat of vaporization for biodiesel is greater when related to diesel. Hence, biofuel takes longer to get vaporized, which in turn causes a longer combustion duration than diesel. A percentage increase of 23.53% is seen for MME20 + GNA30 at CR19 when compared with diesel at 100% load. Ibrahim et al. [42] conducted a study on the impact of changing the CR from 14 to 18, with an interval of 1, on waste cooking oil biodiesel. Their studies concluded that the CD decreases with increasing CR and increases with higher proportions of biodiesel blend. In a separate experiment, Kumar, S.S et al. [43] investigated the effects of alumina nanoparticles on rubber seed biodiesel mixtures. They found that the combustion duration for the B25Al50 blend is shortened by 2°CA, 5°CA, and 3°CA, respectively, compared to diesel, B25, and B25Al25. In the current study, the combustion duration is enhanced by 3°CA for MME20 + GNA30 at CR19. This improvement is attributed to Nano additives that improve the flash point and

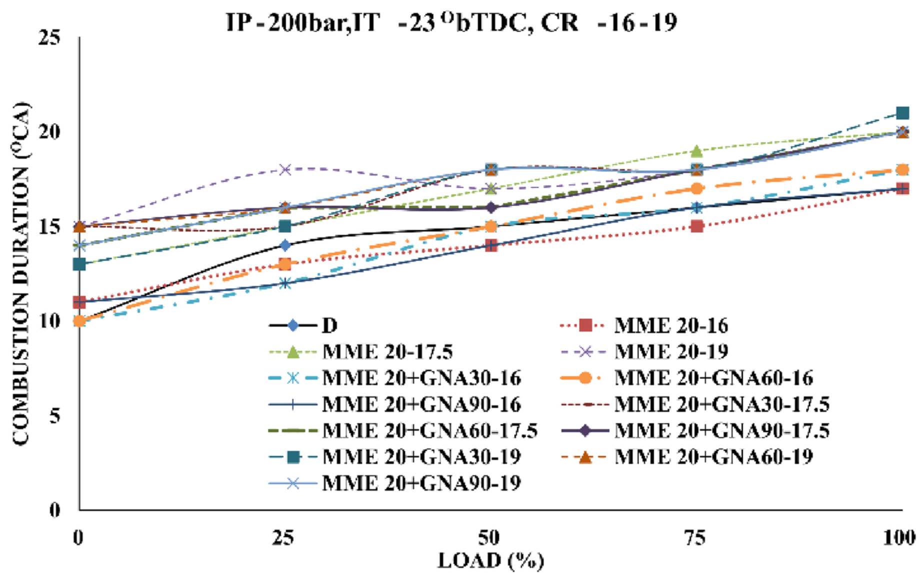


Fig. 25 Variation of combustion duration (CD) for different crank angles and CRs 16, 17.5, and 19

heating value of the fuel, leading to better fuel and air atomization and complete combustion at varying compression ratios. Similar result variations were also reported by Santhoshkumar, Thangarasu, and Anand in 2019 [30].

The discrepancy in emissions of CO for different crank angles and CRs 16, 17.5, and 19 is depicted in Fig. 26. Emissions of carbon monoxide are formed as a result of incomplete combustion during the combustion phase. It can be seen from the experimental results that the blends (MME20), (MME20 + GNA30), (MME20 + GNA60), and (MME20 + GNA90) at compression ratio 16 have a lesser rate of CO emission when compared with that of diesel by 10.50%, 18.29%, 2.72%, and 18.29%, at fully operating load. This is because of the high temperature in the burning chamber, which lessened the ignition lag and achieved complete fuel burning. The blends among the various blends with the lowest CO emissions are (MME20 + GNA30) and (MME20 + GNA90) at CR 16 when equating with diesel. The lessening in the CO was also due to the higher oxygen content and lower carbon-to-hydrogen ratio of the biodiesel, which promotes the combustion process. In a study by Galande S et al. [37], the effect of TiO_2 nanoparticle dispersion (25 ppm, 50 ppm, and 75 ppm) in microalgae biodiesel MAB20 was investigated. The experiments were conducted at CR of 17, 19, and 21. The results showed that the blend MAB20 with an increase in nanoparticle concentration (75 ppm TiO_2 nanoparticle in MAB20 at CR 21) led to a decrease in CO emissions by 18.60% compared to MAB20 and 30.69% compared to neat diesel at full load. It was also found that CO emissions decreased with an increase in CR. Another study by Kaki Sanatha et al. [38] utilized Baheda oil biodiesel blend (BOME20), dispersant (DSP-QPAN80), and zinc oxide (ZnO) nanoparticles in proportions of 50 ppm, 75 ppm, and 100 ppm for CR 16.5, 17.5, 18.5, and 19.5 respectively. The findings demonstrated that the blend BOBD20 + ZnO 75 + DSP 75 at CR 19.5:1 had 0.08% CO emissions compared to neat diesel. R. Hussain Vali et al. [39] investigated the effect of ZnO nanoparticles blended diesel-water emulsion on the

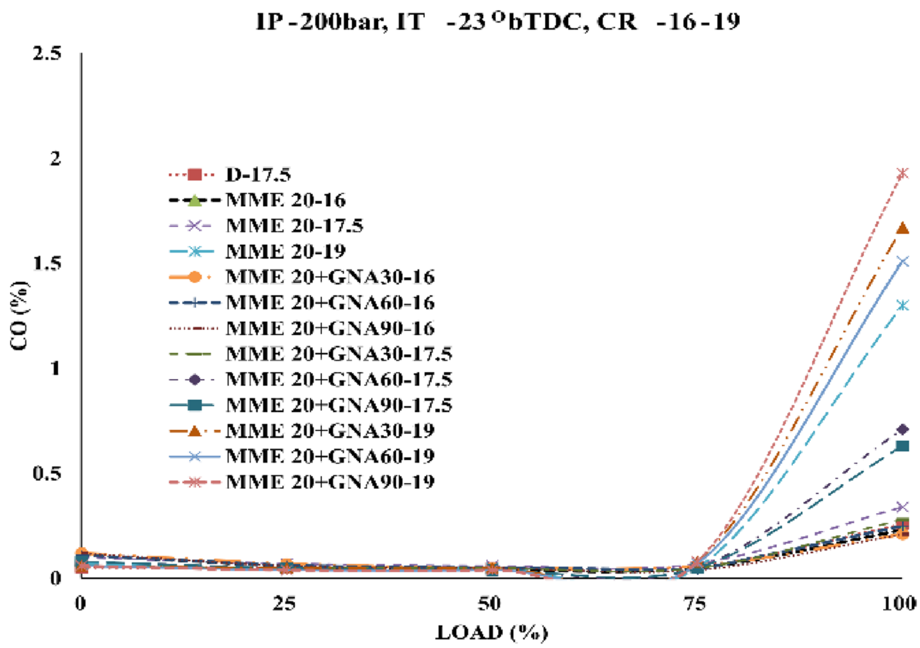


Fig. 26 Chang in CO emission for different loads and CRs 16, 17.5, and 19

performance and emission characteristics of a VCR diesel engine at various compression ratios (16.5, 17.5, and 18.5). Their results showed that CO emissions were lowered by 14.3% and 17.2% at 18.5 CR for DW10Z100 (Diesel + 10% water + 100 ppm ZnO) blend compared to diesel and DW10.In the current investigation, the CO emissions for MME20-GNA30 and MME20-GNA90 at CR 16 were found to be lower by 18.29% for both blends when compared with the values of diesel. It was observed that CO emissions increased as CR increased. The variation of CR is limited during engine operation due to biodiesel's higher oxygen content in the blends leading to shorter ignition delay aiding in complete combustion, resulting in the conversion of all CO into CO_2. This study was compared with and its effects were also inferred by Das AN, M. et al. (2023); Santhosh and Padmanaban (2016); S. Gavhane et al. (2020) and Karthikeyan, Elango, and Prathima (2014) [5, 13, 22, 40].

The emission of HC for different loads and CRs 16, 17.5, and 19 is depicted in Fig. 27. It was measured that the emission of HC reduced with a rise in CR and mixtures. Fuel characteristics, different engine operating conditions, and fuel spray properties are the main factors that affect HC emissions. As was seen, the HC emissions reduced with the increase in CRs for the MME20 by 18.37%, 20.40%, and 23.57% when compared with diesel. A significant decrease in HC emission was seen for blends MME20 + GNA30, MME20 + GNA60, and MME20 + GNA90 when linked to both MME20 and Standard diesel. When equating to MME20, the percentage decrease in HC emissions at CR16 was 20%, 15%, and 20% for all three nano additive mixtures. At lower CR, the emission of HC is higher because of ignition delay and flame quenching in the cylinder wall, causing incomplete fuel combustion. Analogous rise in HC emissions due to a lower compression ratio was reported. Galande S et al. [37] investigated the effect of TiO_2 nanoparticle dispersion (25 ppm, 50 ppm, and 75 ppm) in a microalgae biodiesel (MAB20). The experiments were conducted at CR17, 19, and

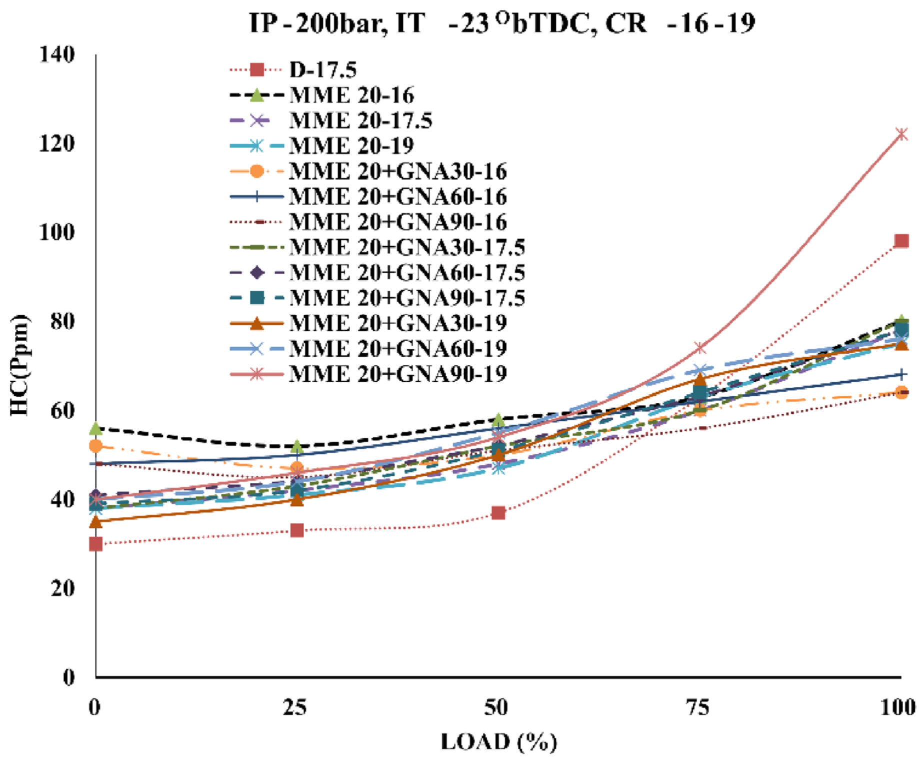


Fig. 27 Chang in HC emission for different loads and CRs 16, 17.5, and 19

21. Their results showed that the d MAB20 with an increase in nanoparticle concentration (75 ppm TiO_2 nanoparticle in MAB 20 at CR 21) resulted in a 22.36% decrease in HC emissions compared to MAB20 and a 41.58% decrease compared to neat diesel at full load. Additionally, they found that CO emissions decreased with an increase in CR. Kaki Sanatha et al. [38] used Baheda oil biodiesel (BOME20), dispersant (DSP-QPAN80), and zinc oxide (ZnO) nanoparticles in proportions of 50 ppm, 75 ppm, and 100 ppm for CR 16.5, 17.5, 18.5, and 19.5, respectively. Their findings indicated that the blend BOBD20 + ZnO 75 + DSP 75 at CR 19.5:1 had 25 ppm HC emissions, lower than neat diesel. R. Hussain Vali et al. [39] investigated the effect of ZnO nanoparticles blended diesel-water emulsion on a VCR diesel engine's performance and emission characteristics at CR16.5, 17.5, and 18.5. Their results showed that HC emissions were lowered by 10.8% and 15.3% at 18.5 CR for DW10Z100 (diesel + 10% water + 100 ppm ZnO) blend compared to diesel and DW10. The HC emissions decreased for all blends compared to diesel values at 16 and 17.5 CRs. For blends MME20 GNA 30 and 90 for CR 16, emissions were reduced by 34.70% compared to diesel. In the Present investigation, HC emissions decreased as CR increased. Therefore, the variation is up to a certain limit and cannot be increased further during engine operation. This is due to the high oxygen available in GNA blended fuels and the shorter ignition delay leading to complete combustion, resulting in lower HC emissions. Similar results were reported by Das AN, M. et al. (2023); Deore, Jahagirdar, and Patil (2013); Pandhare and Padalkar (2013); and Karthikeyan, Elango, and Prathima (2014) [22, 29, 31, 40].

An increasing trend in carbon dioxide emission is seen in Fig. 28 with increasing loading conditions and CRs. During combustion, the carbon molecules join with molecules of oxygen to yield carbon dioxide emissions. For CR17.5, the MME 20 + GNA30 has a lower CO_2 emission value because of complete combustion and lesser formation of carbon molecules post-combustion process compared to diesel by 7.76% at a total operating load. Compared with diesel, the CO_2 emission is slightly higher for the blends of MME20, i.e., by 9.7%, 7.76%, and 13.5%, at CR 16, 17.5, and 19. The emissions that were produced by the blend MME20-GNA30 at 17.5 CR had a lower emission rate because of the larger surface area of the Graphene nanoparticle, which enables the complete combustion of hydrocarbon molecules. R. Hussain Vali et al. [39] studied the impact of ZnO nanoparticles blended diesel-water emulsion on a VCR diesel engine's performance and emission characteristics at different CR16.5, 17.5, and 18.5. Their results showed that CO_2 emissions increased by 3.3% and 5.4% at 18.5 CR for DW10Z100 (diesel + 10% water + 100 ppm ZnO) blend compared to diesel and DW10, whereas the increase was 2.8% and 5.5% at CR16.5. S. Gavhane et al. [13] investigated zinc oxide (ZnO) nanoparticles blended with soybean biodiesel (SBME25) at three dosage levels (25, 50, and 75 ppm) with sodium dodecyl benzene sulphonate (SDBS) surfactant for CR 18.5 and 21.5. Their results indicated that for CR 21.5, the CO_2 emission was lower for the SBMEZnO50 blend compared to other blends. The CO_2 emissions for SBME25ZnO50 were 21.66% and 2.36% lower than for SBME25 and diesel. In the present investigation, the CO_2 emissions for all blends increased as the CR increased. The MME20-GNA30 blend at 17.5 CR showed lower CO_2 emissions compared to CR16 and CR19.5. This

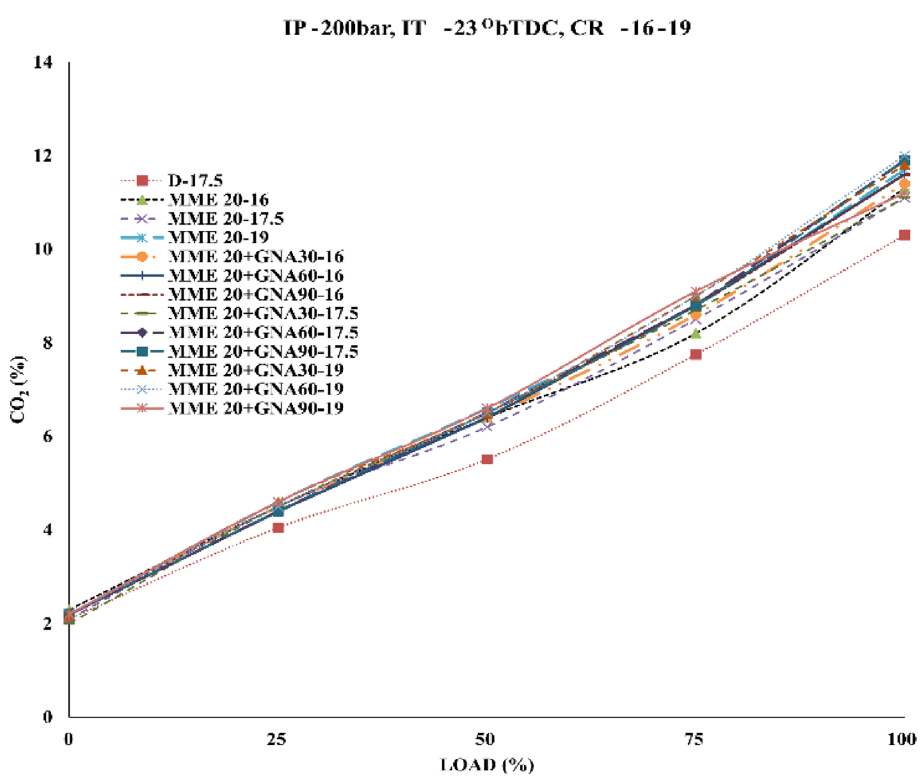


Fig. 28 Chang in CO_2 emission for different loads and CRs 16, 17.5, and 19

was attributed to the larger surface area of GNA emulsified fuel, improved combustion parameters, and shorter ignition delay, enabling complete combustion and resulting in reduced CO_2 emissions. Similar effects of the comparable study were also observed by Das AN, M. et al. (2023); Vellaiyan (2019); S. Deore, Jahagirdar, and Patil (2013) [18, 29, 40].

Chang in NO_x emission for different loads and CRs 16, 17.5, and 19 is shown in Fig. 29. A decrease in the Emission of NO_x can be seen from the experimental results. The fuel blends, MME20 at CR16, MME20 at CR19, MME20 + GNA30 at CR16, MME20 + GNA60 at CR16, MME20 + GNA90 at CR16, MME20 + GNA30 at CR19, MME20 + GNA60 at CR19, MME20 + GNA90 at CR19, and MME20 + GNA30 at CR17.5, MME20 + GNA60 at CR17.5, show a significant decrement in the NO_x emissions by 8.51%, 16.55%, 8.88%,7.31%, 5.74%, 23.2%, 19.34%, 37.34%, 3.44%, and 2.47%, when linked with diesel at 100% load. This might be due to the reduction in ignition delay, which causes complete burning. The higher temperature in the burning chamber leads to more NO_x emissions for pure blend at CR 17.5 by 0.36% when compared with diesel, and it was because of the increase in burning temperature, thus helping in better burning of fuel. The rise in combustion temperature is due to the oxygen content in the biodiesel. In a study by Galande S et al. [37], the effect of TiO_2 nanoparticle dispersion at concentrations of 25 ppm, 50 ppm, and 75 ppm in microalgae biodiesel MAB20 was investigated. The experiment was conducted at CR17, 19, and 21. The results indicated that with an increase in CR from 19 to 21, emissions at different blends of nanoparticle concentration (25 ppm, 50 ppm, and 75 ppm) increased by 4.73%, 4.40%, and 1.58% respectively. It was concluded that NO_x levels increased with an increase in CR, with the minimum NO_x observed for the blend B20 + NPC 75 at CR 17. In another study,

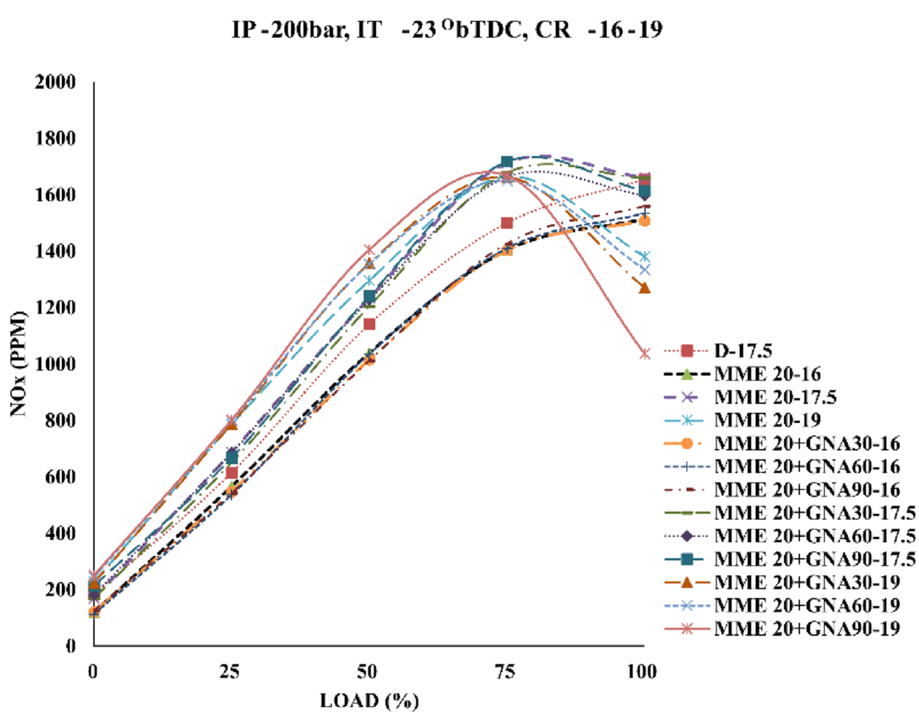


Fig. 29 Chang in NO_x emission for different loads and CRs 16, 17.5, and 19

S. Gavhane et al. [13] investigated the blending of zinc oxide (ZnO) nanoparticles with soybean biodiesel (SBME25) at three dosage levels (25 ppm, 50 ppm, and 75 ppm) with sodium dodecyl benzene sulphonate (SDBS) surfactant for CR 18.5 and 21.5. The results showed that NO_x emissions were lower at 18.5 CR compared to CR 21.5. It was concluded that there was a slight increase in NO_x for higher CR. In the present investigation, it was observed that NO_x levels were slightly higher at CR 17.5 by 0.36% and decreased for the remaining compression ratios. This could be due to a reduction in ignition delay causing complete burning. The higher temperature in the burning chamber led to higher NO_x emissions for the pure blend at CR 17.5 by 0.36% compared to diesel. Similar effects were also observed in studies by Das AN, M. et al. (2023); Santhosh and Padmanaban (2016); Prabu (2018); Vellaiyan (2019); Deore, Jahagirdar, and Patil (2013); and Das, A. M (2023) [5, 12, 29, 40, 44].

The smoke emissions, i.e., the test for opacity at CRs 16, 17.5, and 19, are illustrated in Fig. 30. Unfinished burning in the combustion chamber of HC particles, poor fuel vaporization, and a rich air-to-fuel mixture are the basis of smoke emissions. The experimental results showed that the smoke emissions have lowered by a significant percentage when compared with diesel at a fully operating load. The MME20 at CR 16, 17.5, and 19 have lower smoke emission values, i.e., 3.46%, 3.33%, and 5% compared to diesel. The GNA-MME mixture enhanced the occurrence of air–fuel mixing and micro-explosion, causing lesser smoke, i.e., the blends MME20 + GNA30 at CR17.5, MME20 + GNA60 at CR17.5, MME20 + GNA90 at CR17.5, decreased by 1.46%, 2.38%, and 1.19%, when compared with (MME20) at CR17.5. Graphene nanoparticles enhance combustion because of their large surface area, resulting in complete combustion. With the increase in the

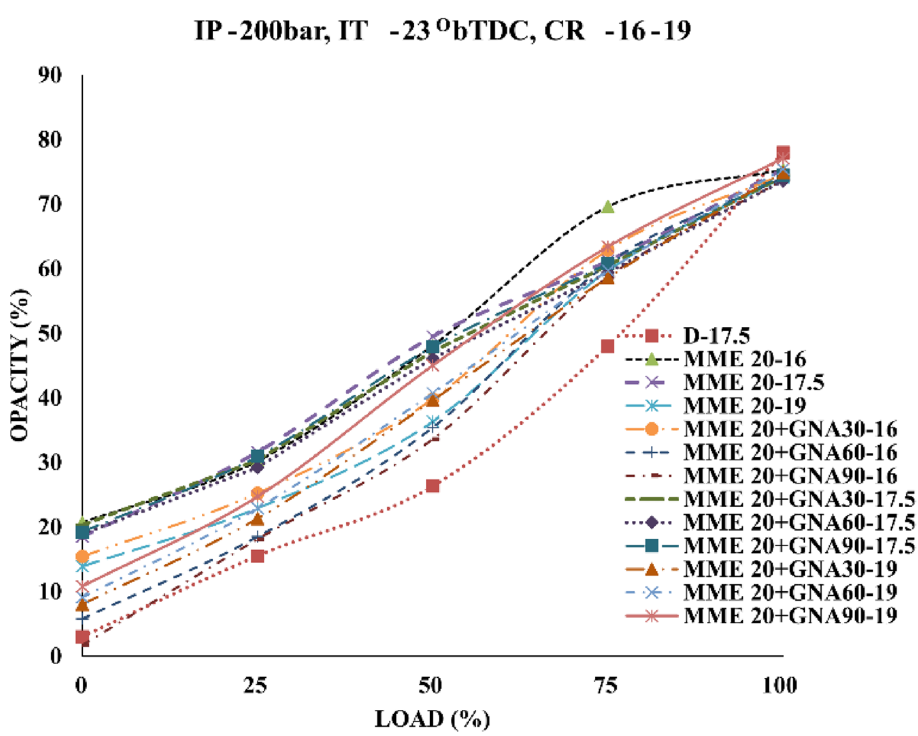


Fig. 30 Chang in opacity for different loads and CRs 16, 17.5, and 19

CR, the temperature during the compression stroke rises, leading to better mixing of air and fuel. In addition, the dilution of the fuel charge by residual gases is reduced with an increase in CR. Researchers Galande et al. [37] studied the impact of dispersing TiO_2 nanoparticles at concentrations of 25 ppm, 50 ppm, and 75 ppm in a microalgae biodiesel MAB20. They conducted experiments at CR of 17, 19, and 21. The results indicated that the B20 + 75 ppm blend at CR 21 exhibited a minimum smoke emission of 14.63% lower than that of neat diesel. Additionally, they observed a decrease in smoke emission with an increase in compression ratio. Another study by S. Gavhane et al. [13] involved investigating the blending of zinc oxide (ZnO) nanoparticles with soybean biodiesel (SBME25) at three dosage levels (25 ppm, 50 ppm, and 75 ppm) with sodium dodecyl benzene sulphonate (SDBS) surfactant for CR of 18.5 and 21.5. Their results showed a decrease in smoke emissions for SBME25ZnO50 at CR 18.5 and 21.5 by 19.95% and 22.54% compared to diesel. The present research indicated that smoke emissions were reduced at all compression ratios due to improved thermal properties of the blends, leading to the oxidation of incompletely burned hydrocarbons and soot particles. This resulted in faster vaporization, shorter ignition delay, and improved combustion, reducing smoke emissions. The study and its effects were also referenced by Das AN et al. (2023), S. Gavhane et al. (2020), Prabu (2018), Santhosh and Padmanaban (2016), and Das, A. M (2023) [5, 12, 13, 40, 44].

Conclusions

The main aim of the current study is to study the effects of graphene nanoparticles and blends of Moringa methyl ester fueled at dissimilar loads and by changing the CRs on the CIDI Engine. In the investigation, the experiment was conducted on different blends of fuel, i.e., MME20, MME20 + GNA30, MME20 + GNA60, and MME20 + GNA90, at three compression ratios of 16, 17.5, and 19. The inferences drawn after the experimentation and comprehensive study of the fuel blends are

Influences on performance characteristics:

- The BTHE of all fuel blends was lower than diesel at different CRs and loads. This is because of the lower heating value, higher density of the blend, and lower power available at the engine flywheel. The BTHE for the blend (MME20 + GNA30) increased by 3.87% compared to the MME20 at CR 19. The BTHE value of MME20 at CR 16 has the highest efficiency compared to other blends. The increase in BTHE of the Nano additive biodiesel blend is due to an increase in its highly reactive surface area, which acts as a catalyst during the combustion stage, resulting in micro-detonation of petroleum droplets and better-burning parameters.
- The blends MME20 + GNA60 and GNA90 at CR 19 exhibited a consistent BSFC compared to other pure blends. This is due to the nanoparticles enhancing secondary atomization, fuel-air mixing, and micro-explosion of fuel droplets, resulting in lower BSFC.
- The VE of the MME20 and MME20-GNA30 blends at a CR of 16 increased by 0.55% and 0.52%, respectively, compared to diesel at full loads. At a lower CR of 16, the VE increased more than the engine operating at higher CRs of 17.5 and 19. This was mainly because at lower CR, there is more actual air available in the

manifold. However, the increase in the surface area to volume ratio as GNA proportions are added in the selected fuel samples leads to slightly less air available during the atomization of fuel.

- The EGT values of MME 20 at CR17.5 and MME 20 + GNA30 at CR17.5 showed the lowest temperatures of 413 °C and 414 °C, respectively, which is very close to the EGT values of Diesel. This is due to the shorter ignition delay and complete combustion of the blend at CR16.

Influences on combustion characteristics

- The combustion pressure for the blend MME 20 + GNA30 at CR 19 is 75.69 bar, the highest for the fuels tested compared with diesel. The increase in flash and fire point of this specific mixture may cause a shorter ignition span and lead to the highest combustion pressure at CR19.
- The NHRR is lower than diesel in all blends. At a CR 17.5, the blend of MME20 + GNA30 has the highest NHRR at 31.47 J/deg, which is a 14.15% decrease compared to diesel's NHRR 36.66 J/deg. This is due to the shorter ignition delay. The high calorific value of the GNA emulsified fuel leads to high combustion pressure and temperature.
- The MFB is higher for all blends at compression ratio CR16 when compared with the MFB of diesel, i.e., 2°CA, 3°CA, 3°CA, and 2°CA, occurring earlier than the 2°CA diesel. This is because the blends have extra oxygen content, which helps in the prolonged burning process, and due to the low viscosity and density of the GNA emulsified blend.
- The ID for the blend is found to be the lowest for MME 20 + GNA30 at CR 19, compared to diesel, as the ID has decreased by 20%. A shorter ignition delay period is obtained due to the rise in pressure, which results in the molecules coming closely together, thus improving the chemical reactions caused by the active molecule collisions.
- The combustion duration is the longest for the blend MME 20 + GNA30 at CR 19 and 100% load. There was a 23.53% increase in CD for this blend compared to diesel. This is because the latent heat of vaporization for biodiesel is greater than that of diesel, causing biodiesel to take longer to vaporize and leading to a longer combustion duration than diesel.

Influences on emission characteristics

- The CO emissions for MME20 + GNA30 and MME20 + GNA90 at CR 16 were 18.29% lower for both blends than diesel. This is because biodiesel has a higher oxygen content, resulting in a shorter ignition delay that aids in complete combustion. As a result, all CO is converted into CO_2.
- The HC emissions decreased for all blends when compared with diesel values at both 16 and 17.5 CRs. For blends MME20 + GNA 30 and 90 for CR 16, the reduction was 34.70%, and thereby, it can be regarded as the best fuel blend for reduced HC emissions. This is due to the high oxygen available in GNA-blend fuels and the

shorter ignition delay leading to complete combustion, which is the reason for less HC emissions.

- The CO_2 emissions of MME 20 + GNA30 at CR 17.5 were lower than 7.76% of those of the MME 20 blend at CR16. The CO_2 emissions of all the blends at CR16, 17.5, and 19 were slightly higher than those of conventional fuel at full load. This was due to the large surface area of GNA emulsified fuel, improved combustion parameters, and shorter ignition delay, which enabled complete combustion, resulting in higher CO_2 emissions and lower CO emissions.
- The NO_x emissions of the MME20 + GNA90 + CR19 blend decreased by a significant percentage of 37.34%, the highest reduction in emissions among all the blends. This decrease may be attributed to the reduced ignition delay, resulting in more complete combustion. In the case of pure blend at CR 17.5, the higher temperature in the combustion chamber leads to a 0.36% increase in NO_x emissions compared to diesel.
- The smoke emission values for most fuel blends decreased compared to diesel. The pure blends at CRs 16, 17.5, and 19 showed emissions decreased by 3.46%, 3.33%, and 5%, respectively. When comparing blends MME20 + GNA30, 60, and 90 to MME20 at CR 17.5, there was a decrease in harmful emissions by 1.46%, 2.38%, and 1.19%, respectively. This was due to the enhanced thermal properties of the blends at varying compression ratios, which led to more efficient combustion and reduced smoke emissions.

Based on the above observations, it can be confirmed that the performance of the Moringa methyl ester graphene nano additive 30 ppm at CR 19 (MME20 + GNA30 + CR19) mixture is improved when combined with the standard diesel. The test results and findings confirm that the graphene nanoparticles in Moringa methyl ester biodiesel (MME20) improve performance and combustion while reducing emissions from Compression Ignition engines. The experimental results show that MME20 + GNA30 + CR19 is a superior alternative to traditional diesel fuel.

Limitations of the present study and future recommendations

Based on the investigation of the MME of a 20% blend with various concentrations of GNA at different compression ratios, the following limitations and future work have been identified:

Limitations

- Emulsifying GNA particles into a biodiesel blend is challenging, as it increases viscosity and density, which leads to sedimentation during long-term storage.
- The compression ratio of a conventional engine cannot be decreased or increased to a maximum value, as the engine fails to achieve complete combustion at higher and lower compression ratios. This results in lower thermal efficiency and increased exhaust emissions. Therefore, the compression ratio should be varied within a limited range.
- The engine noise needs to be controlled at higher compression ratios.

Future work

- There are no extensive studies on the blend chosen for this work. Therefore, the experiment can be carried out on the MME with GNA emulsified fuel by adjusting other engine operating conditions, such as injection timing and pressure.
- Dual-fuel mode experimentation can also be performed using the fuel investigated in the present study.
- A study is to be conducted on the production of low-cost MME-GNA emulsified fuel for economic feasibility.
- Efforts should be made to use MME blended fuel in actual running vehicles. This will allow researchers to investigate fuel consumption, engine efficiency, and engine working conditions practically for running vehicle engines.
- The present work could be expanded to analyze the use of biodiesel in various types of engines, such as V6, V8, and V12, which are commonly found in sports vehicles.

Abbreviations

BSFC	Brake-specific fuel consumption
BTHE	Brake thermal efficiency
°CA	Crank-angle degree
CD	Duration of combustion
CI	Compression ignition
CO	Carbon monoxide
CO_2	Carbon dioxide
CP	Combustion pressure
CR	Compression ratio
EGT	Exhaust gas temperature
FFA	Free fatty acid
HC	Hydrocarbons
ID	Ignition delay
MFB	Mass fraction burnt
MME20	20% Moringa methyl ester + 80% diesel
MME20 + GNA30	20% Moringa methyl ester + diesel + 30 ppm graphene nano additive
MME20 + GNA60	20% Moringa methyl ester + diesel + 60 ppm graphene nano additive
MME20 + GNA90	20% Moringa methyl ester + diesel + 90 ppm graphene nano additive
NHRR	Net heat release rate
NO_x	Nitrogen oxides
O_2	Oxygen
ppm	Parts per million
VCR	Variable compression ratio
VE	Volumetric efficiency

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s44147-024-00498-4.

Supplementary Material 1.

Authors' contributions

MDAN conducted the experiments and assisted in manuscript preparation. MRH assisted in conducting the experiments and preparing the manuscript. SN prepared the complete manuscript. UH helped to prepare the manuscript and reduce plagiarism. JS also contributed to preparing the manuscript and reducing plagiarism. AK also assisted in preparing the manuscript and reducing plagiarism. Finally, all authors read and approved the final manuscript.

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Availability of data and materials
The data that support the findings of this study are not openly available due to reasons of sensitivity and are available from the corresponding author upon reasonable request.

Declarations

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

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References
1. Huang D, Zhou H, Lin L (2012) Biodiesel: an alternative to conventional fuel. Energy Procedia 16:1874–1885. https://doi.org/10.1016/j.egypro.2012.01.287
2. Curran MA (2012) Assessing environmental impacts of biofuels using lifecycle-based approaches. Manag Environ Qual 24(1):34–52. https://doi.org/10.1108/14777831311291122
3. Ban F, Majid S, Huang N, Lim H (2012) Electrochemical science graphene oxide and its electrochemical performance. Int J Electrochem Sci (7):4345–4351. http://www.electrochemsci.org/papers/vol7/7054345.pdf
4. Mishra RK, Soota T, Singh R (2017) Effect of variable compression ratio on performance of a diesel engine fueled with karanja biodiesel and its blends. IOP Conf Ser Mater Sci Eng 225:012064. https://doi.org/10.1088/1757-899x/225/1/012064
5. Santhosh M, Padmanaban KP (2016) Experimental studies on variable compression ratio engine fuelled with cottonseed oil methyl ester biodiesel. Int J Oil Gas Coal Technol 12(1):81. https://doi.org/10.1504/ijogct.2016.075842
6. Rajak U, Reddy VN, Ağbulut Ü, Sarıdemir S, Afzal A, Verma TN (2023) Modifying diesel fuel with nanoparticles of zinc oxide to investigate its influences on engine behaviors. Fuel 345:128196. https://doi.org/10.1016/j.fuel.2023.128196
7. Tiwari C, Dwivedi G, Verma TN (2023) Sustainability evaluation, optimization and research dynamics of microalgae methyl ester in a research diesel engine. In: Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, p 09544089231162318. https://doi.org/10.1177/09544089231162318
8. Abishek MS, Kachhap S, Rajak U, Verma TN, Singh TS, Shaik S, Cuce E, Alwetaishi M (2024) Alumina and titanium nanoparticles to diesel–Guizotia abyssinica (L.) biodiesel blends on MFVCR engine performance and emissions. Sustain Energy Technol Assess 61:103580. https://doi.org/10.1016/j.seta.2023.103580
9. Sinha AA, Ansari MZ, Shukla AK, Verma TN, Choudhary T (2023) Thermodynamic assessment of biomass-fueled solid oxide fuel cell integrated gas turbine hybrid configuration. Sustain Energy Technol Assess 57:103242. https://doi.org/10.1016/j.seta.2023.103242
10. Kumar R, Yadav AS, Sharma A, Rajak U, Verma TN, Alam T, Tiwari N, Jawahar CP (2023) Experimental analysis of a diesel engine run on non-conventional fuel blend at different preheating temperatures. In: Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, p 09544089231190754. https://doi.org/10.1177/09544089231190754
11. Soudagar MEM, Afzal A, Kareemullah M (2020) Waste coconut oil methyl ester with and without additives as an alternative fuel in diesel engine at two different injection pressures. In: Energy sources, part A: recovery, utilization, and environmental effects, pp 1–19. https://doi.org/10.1080/15567036.2020.1769775
12. Prabu A (2018) Nanoparticles as additive in biodiesel on the working characteristics of a DI diesel engine. Ain Shams Eng J 9(4):2343–2349. https://doi.org/10.1016/j.asej.2017.04.004
13. Gavhane RS, Kate AM, Pawar A, Safaei MR, Soudagar MEM, Mujtaba Abbas M, Muhammad Ali H, Banapurmath NR, Goodarzi M, Badruddin IA, Ahmed W, Shahapurkar K (2020) Effect of zinc oxide nano-additives and soybean biodiesel at varying loads and compression ratios on VCR diesel engine characteristics. Symmetry 12(6):1042. https://doi.org/10.3390/sym12061042
14. Praveena V, Venkatesan S, Gupta T (2018) Effects of nano additives with biodiesel fuels in internal combustion engines – a review. IOP Conf Ser Mater Sci Eng 402:012208. https://doi.org/10.1088/1757-899x/402/1/012208
15. Awogbemi F (2018) Performance and emissions of compression ignition engines fuelled with waste cooking oil methyl ester -a critical review. Int J Appl Eng Res 13:9706–9723
16. Soudagar M, Elahi M, Nik-Ghazali N-N, Kalam MA, Badruddin IA, Banapurmath NR, Yunus Khan TM, Bashir MN, Akram N, Farade R, Afzal A (2019) The effects of graphene oxide nanoparticle additive stably dispersed in dairy scum oil biodiesel-diesel fuel blend on CI engine: performance, emission and combustion characteristics. Fuel 257:116015. https://doi.org/10.1016/j.fuel.2019.116015
17. Soudagar MEM, Banapurmath NR, Afzal A, Hossain N, Abbas MM, Haniffa MACM, Naik B, Ahmed W, Nizamuddin S, Mubarak NM (2020) Study of diesel engine characteristics by adding nanosized zinc oxide and diethyl ether additives in Mahua biodiesel–diesel fuel blend. Sci Rep 10(1):15326. https://doi.org/10.1038/s41598-020-72150-z
18. Vellaiyan S (2019) Enhancement in combustion, performance, and emission characteristics of a diesel engine fueled with diesel, biodiesel, and its blends by using nanoadditive. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-019-04356-2
19. Kumar S, Dinesha P, Bran I (2017) Influence of nanoparticles on the performance and emission characteristics of a biodiesel fuelled engine: an experimental analysis. Energy 140:98–105. https://doi.org/10.1016/j.energy.2017.08.079
20. Prabakaran B, Udhoji A (2016) Experimental investigation into effects of addition of zinc oxide on performance, combustion and emission characteristics of diesel-biodiesel-ethanol blends in CI engine. Alex Eng J 55(4):3355–3362. https://doi.org/10.1016/j.aej.2016.08.022

21. Özgür T, Özcanli M, Aydin K (2014) Investigation of nanoparticle additives to biodiesel for improvement of the performance and exhaust emissions in a compression ignition engine. Int J Green Energy 12(1):51–56. https://doi.org/10.1080/15435075.2014.889011
22. Karthikeyan S, Elango A, Prathima A (2014) Diesel engine performance and emission analysis using canola oil methyl ester with the nano sized zinc oxide particles. Indian J Eng Mater Sci 21:83–87. https://14.139.47.15/bitstream/123456789/27454/1/IJEMS%2021%281%29%2083-87.pdf
23. Venu H, Madhavan V (2017) Effect of diethyl ether and Al2O3 Nano additives in diesel-biodiesel-ethanol blends: performance, combustion and emission characteristics. J Mech Sci Technol 31(1):409–420. https://doi.org/10.1007/s12206-016-1243-x
24. Wakil MA, Kalam MA, Masjuki HH, Sajjad H, Rashed MM, Rashedul HK (2015) Performance evaluation of rice bran and moringa blended biodiesel in CI engine. Appl Mech Mater 775:147–151. https://doi.org/10.4028/www.scientific.net/amm.775.147
25. Das M, Sarkar M, Datta A, Santra AK (2018) An experimental study on the combustion, performance and emission characteristics of a diesel engine fuelled with diesel-castor oil biodiesel blends. Renew Energy 119:174–184. https://doi.org/10.1016/j.renene.2017.12.014
26. Knothe G (2005) Dependence of biodiesel fuel properties on the structure of fatty acid alkyl esters. Fuel Process Technol 86(10):1059–1070. https://doi.org/10.1016/j.fuproc.2004.11.002
27. Norhafana M, Noor MM, Sharif PM, Hagos FY, Hairuddin AA, Kadirgama K, Ramasamy D, Rahman MM, Alenezi R, Hoang AT (2019) A review of the performance and emissions of nano additives in diesel fuelled compression ignition-engines. IOP Conf Ser Mater Sci Eng 469:012035. https://doi.org/10.1088/1757-899x/469/1/012035
28. Raheman H, Phadatare AG (2004) Diesel engine emissions and performance from blends of karanja methyl ester and diesel. Biomass Bioenerg 27(4):393–397. https://doi.org/10.1016/j.biombioe.2004.03.002
29. Deore ER, Jahagirdar RS, Patil MS (2013) Effect of compression ratio on energy and emission performance of diesel engine fueled with karanja biodiesel. J Sustain Energy Eng 1(2):127–147. https://doi.org/10.7569/jsee.2012.629508
30. Santhoshkumar A, Thangarasu V, Anand R (2019) Performance, combustion, and emission characteristics of DI diesel engine using mahua biodiesel. Adv Biofuels 291–327. https://doi.org/10.1016/b978-0-08-102791-2.00012-x
31. Pandhare A, Padalkar A (2013) Investigations on performance and emission characteristics of diesel engine with biodiesel (jatropha oil) and its blends. J Renew Energy 2013:1–11. https://doi.org/10.1155/2013/163829
32. Chavan SB, Kumbhar RR, Kumar A, Sharma YC (2015) Study of biodiesel blends on emission and performance characterization of a variable compression ratio engine. Energy Fuels 29(7):4393–4398. https://doi.org/10.1021/acs.energyfuels.5b00742
33. Rajak U, Chaurasiya PK, Nashine P, Verma M, Kota TR, Verma TN (2020) Financial assessment, performance and emission analysis of Moringa oleifera and Jatropha curcas methyl ester fuel blends in a single-cylinder diesel engine. Energy Convers Manage 224:113362. https://doi.org/10.1016/j.enconman.2020.113362
34. Verma TN, Rajak U, Dasore A, Afzal A, Manokar AM, Aabid A, Baig M (2021) Experimental and empirical investigation of a CI engine fuelled with blends of diesel and roselle biodiesel. Sci Rep 11(1):18865. https://doi.org/10.1038/s41598-021-98382-1
35. Rajak U, Nashine P, Chaurasiya PK, Verma TN, Patel DK, Dwivedi G (2021) Experimental & predicative analysis of engine characteristics of various biodiesels. Fuel 285:119097. https://doi.org/10.1016/j.fuel.2020.119097
36. Rajak U, Nashine P, Verma TN (2019) Performance analysis and exhaust emissions of aegle methyl ester operated compression ignition engine. Therm Sci Eng Prog 12:100354. https://doi.org/10.1016/j.tsep.2019.05.004
37. Galande S, Pangavhane DR (2024) Influence of TiO_2 nano-additive and compression ratio on the performance parameters in a VCR diesel engine using microalgae biodiesel. Int J Ambient Energy 45(1):2326159. https://doi.org/10.1080/01430750.2024.2326159
38. Kaki S, Kaur BS, Sagari J (2021) Influence of ZnO nanoparticles and dispersant in Baheda oil biodiesel blend on the assessment of performance, combustion, and emissions of VCR diesel engine. Appl Nanosci 11:2689–2702. https://doi.org/10.1007/s13204-021-02233-4
39. Hussain Vali R, Marouf Wani M (2020) Optimal utilization of ZnO nanoparticles blended diesel-water emulsion by varying compression ratio of a VCR diesel engine. J Environ Chem Eng 8(4):103884. https://doi.org/10.1016/j.jece.2020.103884
40. Das AN, Harish GM (2023) Graphene nanoparticle as an additives and its influence on pure diesel and biodiesel fuelled CIDI engine. Aust J Mech Eng 21(2):574–594. https://doi.org/10.1080/14484846.2021.1876604
41. Venu H, Appavu P, V DR (2022) Influence of Zr_2O_3 nano additives on particle size diameter (PSD), mass fraction burnt (MFB) and engine characteristics of Jatropha biodiesel fuelled DI diesel engine. Aust J Mech Eng 22(2):387–405. https://doi.org/10.1080/14484846.2022.2100042
42. Ibrahim A, El-Adawy M, El-Kassaby MM (2013) The impact of changing the compression ratio on the performance of an engine fueled by biodiesel blends. Energ Technol 1(7):395–404. https://doi.org/10.1002/ente.201300048
43. Kumar SS, Rajan K, Mohanavel V, Ravichandran M, Rajendran P, Rashedi A, Sharma A, Khan SA, Afzal A (2021) Combustion, performance, and emission behaviors of biodiesel fueled diesel engine with the impact of alumina nanoparticle as an additive. Sustainability 13(21):12103. https://doi.org/10.3390/su132112103
44. Das AM, Haseebuddin MR, Shreyas N, Shivanand HK, Chethan S (2023) Effect of split and re-entrant type piston bowl geometry and preheated Calophyllum Inophyllum methyl ester on the conventional CI engine performance. J Inst Eng India Ser D 1–12. https://doi.org/10.1007/s40033-023-00571-x

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