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Effect of different configurations of hybrid nano additives blended with biodiesel on CI engine performance and emissions / Gad, M. S., Hashish, H. M. A., Hussein, A. K., Ben Hamida, M. B., Abdulkader, R., & Nasef, M. H.
Scientific Reports Volume 14 (2024) 19528 Pages 1-16 https://doi.org/10.1038/s41598-024-69957-5 (Database: Nature Portfolio)

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(2024) Pages 1-16
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Volume 11 Issue 1 (2025) Pages 1–15
https://doi.org/10.14744/thermal.0000899
(Database: Yıldız Technical University Press, İstanbul, Turkey)

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Volume 2283 (2020) 020131 Pages 1-11
https://doi.org/10.1063/5.0024978
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(Database: ScienceDirect)

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An experimental investigation of hydrogen-enriched and nanoparticle blended waste cooking biodiesel on diesel engine

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HIGHLIGHTS

- H_2 enriched and CeO_2 added waste cooking palm biodiesel is used in diesel engine.
- The hydrogen flow rate and dosage of is fixed at 10 L/min and 75 ppm respectively.
- The BTE and BSFC is improved on addition of nanoparticles and hydrogen.
- The emissions of CO, HC and smoke are reduced by 30%, 50% and 42% respectively.
- Higher ICP and HRR are observed on addition of both CeO_2 and hydrogen.

ARTICLE INFO

Article history:
Received 17 April 2023
Received in revised form
6 June 2023
Accepted 8 June 2023
Available online 04 July 2023

Keywords:
CeO_2 nanoparticles
CRDI engine
Emission characteristics
Hydrogen enrichment
Performance characteristics
Waste cooking palm biodiesel

ABSTRACT

The hazardous effect of the pollution of fossil fuels has brought the necessity of shifting conventional energy sources to renewable and clean ones. In this study, the effect of hydrogen addition and CeO_2 nanoparticle addition in waste cooking palm biodiesel on a CRDI engine is evaluated. The dosage of the nanoparticle is fixed at 75 ppm and a hydrogen flow rate of 10 L/min is selected for the engine operations. The crystalline structure of the nanoparticles is determined by XRD analysis. Results showed that on the addition of both H_2 and CeO_2 in a B20 biodiesel blend (80% diesel and 20% biodiesel) the performance, emission, and combustion parameters of the diesel engine improved compared to neat diesel. The brake thermal efficiency was improved by 3.53% and brake fuel consumption was reduced by 16.12% in comparison to diesel at 90% loading condition. The addition of both nanoparticles and hydrogen in the biodiesel blend lowered the emissions of CO by 30%, and HC and smoke by 50% and 42% respectively. However, NO_x increased by 11% as compared to diesel. A 6% higher HRR values and 8% higher in-cylinder pressure were obtained while using hydrogen and CeO_2 nanoparticle blended biodiesel. This blend also shows the lowest ignition delay period at full load condition which results in more engine power and efficiency. This experimental study has helped pave the way for the use of hydrogen-enriched and nanoparticle-blended biodiesel in place of fossil fuel for the applications of diesel engines.

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https://doi.org/10.1016/j.ijhydene.2023.06.088

Introduction

The usage of fossil fuels is increasing day by day in the world's energy sectors. In the transportation and power energy sectors, fossil fuel plays the dominant role as an energy source. So far petroleum has become the most effective and dependable energy source to run both the transport vehicles as well as power energy industries. While there are benefits such as economic growth, and the use of efficient systems, there are negative drawbacks too. The rising demand for petroleum fuels by overpopulation, industrialization, and urbanization has become a fear of its extinction [1]. The emission of harmful gases from petroleum fuels has also become a threat to the environment. The emissions from internal combustion engines are the primary reasons for the greenhouse gas effect, ozone layer degradation, and climatic change. Thus, it has become a need of the hour to find an alternate fuel that is not only clean and green but also economically viable and reduces overall energy consumption [2].

Biodiesel is one of the alternative fuels found to be effective for all the above criteria and can be substituted for petroleum diesel. Biodiesel can be made directly from edible or nonedible oils, waste cooking oil, and animal fats like tallow and lard [3]. The renewable nature of biodiesel has overcome the problem of depletion of fossil fuels as well as the lesser emission from engines make it cleaner and greener energy. The continuous availability of sources, the environmentally friendly nature, recyclability of resources, lesser modification of the engine, and ease of storage make biodiesel popular among researchers [2]. Biodiesel can be blended with conventional diesel to get maximum performance in an engine without modifying the engine.

Besides all the incredible performance features like in-cylinder pressure (ICP), brake thermal efficiency (BTE), heat release rate (HRR), brake-specific fuel consumption (BSFC), CI engines release harmful emissions such as Carbon monoxide (CO), Oxides of nitrogen (NO_x), Unburned hydrocarbon (UHC), Smoke opacity, Carbon dioxide (CO_2), soot, etc. Among these, NO_x is the primary concern while using biodiesel as a fuel source and there has been a lot of research to attain low NO_x emissions from CI engines [3]. Installation of a diesel particulate filter (DPF) is one of the efficient methods to control particulate matter (PM) emissions from the tailpipe of the engine. Various regeneration technologies related to DPF have also been introduced such as filter structure, accurate soot prediction, new catalyst formula, etc which help to reduce the emissions of PM [4,5]. Complete combustion of fuel can limit these pollutants to affect the environment. The reformulation of fuel is one of the remedies to attain a high combustion rate [6]. One such technique is the addition of nanoparticles. The nanoparticles addition in fuel improves engine performance, and combustion characteristics of the engine and reduces exhaust emissions [3]. It also improves the fuel properties such as density, viscosity, Sulphur content, and volatility. Metal-based nano-additives increase flash points and reduce viscosity and pour points. Oxygen-containing nano-additives improve combustion due to the presence of oxygen content. The antioxidant nature of nano additives improves the oxygen stability of fuel, increases flash point and cetane number, and decreases the calorific value. The ignition delay and the ignition temperature of the engine are improved by cetane improver nano additives [7,8]. CeO_2 nanoparticle is chosen in this study because of their effective antioxidant property. This nanoparticle shows a quick oxidation state transition from Ce^{4+} to Ce^{3+} resulting in excellent catalytic activities [9]. Due to their high surface-to-volume ratio, nanoparticles allow for better interaction between the fuel and the oxidizer. This reduces emissions either directly reacting with carbon to lower oxidation temperature or indirectly reacting with water to form hydroxyl radicals that accelerate soot oxidation [7]. The influence of CeO_2 nanoparticles significantly reduced the CO and HC emission levels and also improved the combustion level. It has been reported from the literature that single biodiesel blended fuel operation in diesel engines resulted in little lesser efficiency and higher emissions. This brings the necessity of fuel formulation [10].

In nano fuel research, different metal oxides including magnesium, cerium, aluminum, copper, boron, manganese, zinc, and iron have been employed. Sajith et al. [11] conducted experiments in a diesel-jatropha biodiesel blend adding cerium oxide (CeO_2) nanoparticles in a four-stroke, single-cylinder diesel engine. They reported an increase of 1.5% in BTE and a 40% and 30% reduction in the emission of hydrocarbon (HC) and NO_x respectively with the addition of nanoparticles. Kalaimurugan et al. [12] looked into the impact of cerium oxide while using algae oil methyl ester blended with diesel fuel in a single-cylinder four-stroke engine. They found that the addition of nanoparticles in the fuel blend improved the calorific value as well as the kinematic viscosity of the fuel. The BSFC got reduced, and BTE improved while using CeO_2 blended fuel compared to B20 fuel. Hosseini et al. [13] investigated the effect of carbon nanotube (CNT) mixed with B5 and B10 waste cooking oil biodiesel blends with diesel in a single-cylinder CI engine. They used 30, 60, and 90 ppm concentrations of CNT for each fuel blend. At all engine speeds, CNTs added to fuel blends resulted in significant increases in BTE (8.12%), power (3.67%), and EGT (5.57%). The influence of adding CNTs in the diesel-biodiesel blend also resulted in a considerable reduction in BSFC, CO, UHC, and soot emissions, whereas NO_x emissions increased. Kanth et al. [14] conducted engine testing adding iron nanoparticles (INP) in a diesel soapnut biodiesel blend. They observed that 75 ppm of INP in the B20 blend resulted in a 3.2% increase in BTE while decreasing SFC by 4% compared to diesel. The HC and NO_x emissions were reported to be decreased by 7.3% and 8.5%, respectively. Hawi et al. [15] investigated the effect of iron-doped cerium oxide nanoparticles as an additive in waste cooking oil methyl ester blended with diesel. They used two types of nanoparticles that are CeO_2 doped with 10% iron and CeO_2 doped with 20% iron. They discovered a 15.7% decrease in NOx emissions while finding no significant variations in UBHC output. The B30 with 20% $FeCeO_2$ was superior to the B30 with 10% $FeCeO_2$ in terms of emissions and cylinder pressure. As a result, they found that the blend with 20% $FeCeO_2$ had a greater engine performance compared to other blends. El-Seesy et al. [16] conducted experiments using graphene nanoplatelets (GNP) in diesel-jatropha biodiesel blend fuel. The fuel had been tested with additions of 25, 50, 75, and 100 mg/L GNP at various concentrations. The BTE increased by

25% and the BSFC was found to decrease by 20% with the addition of GNPs at doses of 25–50 mg/L. The engine emissions of UHC, CO, and NO_x, were also reduced by 65%, 65%, and 55% respectively in the same dosing level of GNP. They found that 50 mg/L of GNP is the most suggested concentration for improving engine performance. Recent trends of using hybrid nanoparticles in fuel blends are also emerging. Perumal Venkatasan et al. [17] investigated the engine characteristics by using diesel water emulsion mixed with hybrid nanoparticles. They prepared the test fuel by mixing CeO_2, Al_2O_3, and TiO_2 nanoparticles in diesel water emulsion at a concentration of 50, 100, and 150 ppm and using Span 80, Tween 80 surfactant. The experiments showed an 8.3% increase in BTE, a 14.42% reduction in BSFC, and 10.2%, 27.5%. 36.5% and 27.77% reduction in emissions of CO, smoke, NO_x, and HC respectively. Chinnapan et al. [18] made hybrid SiO_2 and CeO_2 nanoparticles blended tire pyrolysis oil blends. They found that BTE improved by 2% BSFC reduced up to 0.03 kg/kWh while using 70 mg/L of hybrid nanoparticles. The ICP and HRR were also found to be reduced for hybrid nanoparticles than that of individually mixed fuel.

In the background of using various renewable sources of energy, the use of H_2 as an energy source is attracting researchers as it is renewable, clean, and sustainable in various specific conditions. The future of hydrogen (H_2) is emerging in various energy sectors. Many automobile manufacturers are now working on hydrogen-powered automobiles. H_2 can be used as a fuel in fuel cells, where it is converted to clean energy through an electrochemical reaction. However, this is still a very expensive technology that is still under development and will take several years [19]. H_2 is a colorless, odorless, and zero-harmful emission fuel when burned with oxygen. It can be produced from biomass, nuclear energy, renewable sources, and natural gas. H_2 has distinct physical and chemical features that make it ideal for broad use as a fuel (energy carrier) in internal combustion (IC) engines. Because H_2 is a carbon-free fuel, it produces no carbon-based pollutants such as CO, CO_2, HC, or smoke/soot/particulate matter when used in internal combustion engines. Moreover, H_2 has the highest energy content per unit mass of any fuel, and it has some beneficial qualities such as fast flame, a high heating value, a short quenching distance, and high diffusivity, all of which can contribute to high combustion efficiency. As hydrogen is burned in IC engines, water, and steam are produced as by-products. As a result, it can be described as a clean and green fuel in addition to being a source of energy [20].

Many researchers have studied the enrichment of hydrogen in diesel or diesel-biodiesel blends as it makes a promising alternative. Because of the HRR and pressure, the addition of H_2 to fuel raises BTE. Because of the long chain of HC groups, biodiesel with an H_2 blend has a higher cetane number than pure diesel [21]. The calorific values of biodiesels are stated to be lower than those of neat diesel in several different types of literature. Hydrogen added to biodiesel, though, can make it more effective. Kumar et al. [22] evaluated the performance of the engine while using hydrogen in a single-cylinder CI engine fuelled with jatropha oil. The results showed an increase of BTE at 7% hydrogen mass share with jatropha oil whereas with diesel the BTE increased at 5% hydrogen mass share. They found that the ignition delay of both diesel and Jatropha oil increased at full load. However, the greater combustion temperature made it difficult to lower the NO_x emissions. Serin et al. [23] varied the hydrogen flow rate from 5 L/min to 10 L/min while investigating tea seed oil biodiesel blends in a 4-stroke CI engine without modifications. The torque and BSFC were found to be improved while enriching H_2 than the case without enrichment of H_2. CO and CO_2 emissions decreased due to the absence of carbon atoms in H_2. The main drawback of H_2 enrichment is the increased emission of NO_x up to 75%. The emissions of NO_x can be controlled by the exhaust gas regulation (EGR) technique. Rahman et al. [24] reduced EGT by 12.8% and NO_x emissions by 20% at full load by employing the EGR system. They investigated the performance and emission of CI engines fuelled with 40% blends of biodiesel and kept the hydrogen flow rate at 4 L/min.

Using injection parameters in engines running on rice bran biodiesel at different mixes, Kanth et al. [25] studied the performance and emissions of a single-cylinder diesel engine. The hydrogen flow rate was fixed at 7 L/min. Results indicated that the blend which had 10% rice bran biodiesel with H_2 provided 3.32% higher BTE and reduced the fuel usage by 13% compared to diesel. This fuel mixture was responsible for the highest cylinder pressure and HRR possible. Further, compared to diesel, they found reduced smoke opacity, CO, and HC emissions by 16%, 17%, and 22% respectively. However, NO_x emissions were still increasing. Kanth et al. [26] investigated the effects of honge biodiesel blends on the performance, combustion, and emissions parameters of a diesel engine by varying the hydrogen flow rate from 10 to 13 L/min. The BTE went up by 2.2% while the fuel consumption went down by 6% for a given flow rate of 13 L/min. Exhaust gas emissions, including hydrocarbons and carbon monoxide, were reduced by 24% and 21%, respectively. There was also a modest rise in oxides of nitrogen emission compared to diesel, perhaps as a result of the high pressure in the cylinder. For load settings ranging from 30% to 100%, Das et al. [27] injected hydrogen at 7 L/min and 10 L/min. Hydrogen increased the number of combustion parameters, including HRR, ICP, and ignition delay (ID), while decreasing combustion duration (CD). At full load, the blend with 10 L/min H_2 showed better results.

The main drawback of using biodiesel blends in CI engine applications is the emissions of nitrides of oxides. Exposing this pollutant to the environment is harmful to the ecosystem around us. Many researchers have suggested NO_x-controlling techniques by applying multiple fuel injection strategies. Tan et al. [28] investigated the effects of fuel pre-injection in a four-stroke diesel engine fuelled with diesel/methanol/n-butanol (DMB) blends. They varied the pre-injection timing (PT) and pre-injection fuel mass ratio (PMR) to investigate the emission parameters as well as combustion characteristics. Results showed that emissions of NO_x and HC were reduced by 46.43%–87.18% and 24.05%–38.03% respectively at optimal conditions of PT -45°CA and PMR 0.3.

From the pertinent literature, it can be proved that there are good numbers of research using H_2 as secondary fuel for CI engines. The addition of hydrogen in diesel engine applications showed better results than single fuel operations. Simultaneously, it can also be seen that the addition of nanoparticles in the fuel blend improves the fuel quality as well as the engine performance, combustion, and emission characteristics. Under the background of using H_2 alone in CI engine applications, the need for using it with formulated fuel becomes necessary. Also, various kinds of literature investigated the role of nanoparticles in CI engine applications while using biodiesel as a fuel. However, there is limited research on the addition of nanoparticles in biodiesel blend along with enrichment of H_2 to investigate the engine characteristics [29,30]. The purpose of this investigation is to suggest an alternative to conventional energy sources which can perform equivalently as diesel. Therefore, it focuses on the improvement of engine characteristics using CeO_2 nanoparticles with H_2 enrichment while fuelled with diesel and WCO biodiesel blends.

Materials and method

Production of Waste cooking oil biodiesel

For the production of biodiesel, the transesterification process has been carried on. This process produces biodiesel with lower viscosity [2]. The triglycerides present in the oil are transformed into methyl esters through a chemical reaction. The triglycerides react with alcohol in the presence of catalysts. The catalyst can be homogenous or heterogeneous having acidic, basic, or enzymatic nature. For this research work, the waste cooking oil (WCO) had been collected from the college canteen of NIT Silchar. The collected oil was first filtered with filter paper to remove any suspended particles present in WCO and then preheated at 60 °C for half an hour to remove moisture. A mixture of methanol and KOH as a homogenous catalyst had been prepared for the transesterification reaction. The reaction was carried out by using methanol to oil ratio at 6:1, catalyst percentage 1% at 60 °C for 2 h in a magnetic stirrer hot plate connected with a reflux condenser. After completion of the reaction, the reaction mixture was transferred to a separating funnel and kept overnight. Two distinct layers of biodiesel and glycerol can be seen in the funnel. The by-product glycerine was removed from the separating funnel and the produced methyl ester was washed with warm water to wash out any remaining glycerol. The washing process is repeated till the water gets clear. After that, the waste cooking methyl ester was dried using a hot air blower to evaporate moisture. The drying process was done until the mixture becomes crystal clear and finally kept it stored in a sealed glass container for further use.

Nanoparticle characterization

XRD analysis

For structural analysis of CeO_2 nanoparticle X-Ray diffraction technique has been used. The test is performed using a Bruker D8 advanced X-ray diffractometer with Cu K (1.54 Å) radiation. Fig. 1 shows the XRD patterns of the nanoparticle which was operated within the 2θ range of 20–80°. The diffraction peaks of (1 1 1), (2 0 0), (2 2 0), (3 1 1), and (2 2 2) for CeO_2 were all indexed to cubic planes and had good correlation with the standard JCPDS data (JCPDS No. 00-033-0334). These peaks appeared at 2θ angles of 30.40°, 35.25°, 50.70°, 60.28°, and 63.25° and ascribed to d-values of 2.938 Å, 2.544 Å, 1.799 Å, 1.534 Å, and 1.469 Å respectively. The strong peaks obtained in the pattern confirm the crystalline structure of the nanoparticle. The purity of the nanoparticle is confirmed by the absence of any extra peaks in the XRD pattern. Similar results were found by Akhter et al. [31] (see Table 1).

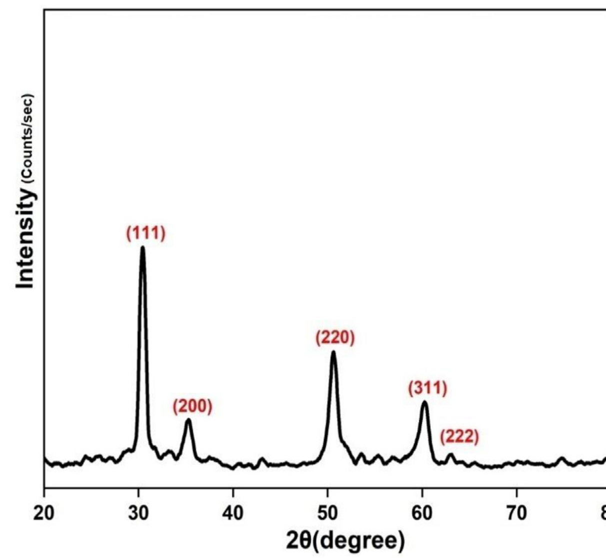

Fig. 1 – XRD pattern of CeO_2 nanoparticle.

Test fuel preparation

The nanoparticle added in this investigation is the Cerium oxide (CeO_2) due to its non-toxicity and the increased energy surface area. The dose number of nanoparticles is kept constant at 75 ppm for all test samples. This CeO_2 nanopowder procured from Nanoshel India is of 99.5% purity and has an average particle size of less than 80 nm. Detailed specifications of the above-mentioned nanomaterial are tabulated in Table 2. A hydrogen tank with a pressure of 170 bar is utilized to provide hydrogen in biofuel mixes with nanoparticles. The hydrogen regulator was utilized to change the flow rate of hydrogen, which is kept constant at 10 L/min. The flow rate of hydrogen and dosage of CeO_2 nanoparticles are adopted by considering the pertinent literature of Das et al. [29] as a reference. The fuel blends taken for the engine testing are WCB20 (20% WCO biodiesel+80% diesel), WCB20 + 10H_2 (WCB20 blend+ 10 L/min H_2), WCB20 + 75CeO_2 (WCB20 blend+75 ppm CeO_2), WCB20 + 75CeO_2+10H_2 (WCB20 blend+ 75 ppm CeO_2+10 L/min H_2), D100 (Neat diesel) and D100+H_2 (Neat diesel+ 10 L/min H_2). A standard magnetic stirrer and a probe sonicator (Model: Nabarupayan 650UP, 20 kHz, 490 W) are used to prepare the nanoparticle-added biodiesel blends. Sonication is done for 30 min to remove possible agglomeration of nanoparticles in the fuel blend.

Experimental setup and procedure

The current study used a water-cooled, single-cylinder, four-stroke, CI engine spinning at 1500 revolutions per minute. A simplified diagram of the engine is shown in Fig. 2(a) while the

Table 1 – Physio-chemical properties of WCO and WCO biodiesel.

Properties	Unit	ASTM standard	Diesel	WCB20	WCB20 + $75CeO_2$
Density	kg/m^3	D-4052	830	833	829.1
Kinematic viscosity at 40 °C	mm^2/s	D-445	3.34	4.73	5.6674
Cetane no	–	D-613	50	58	53.26
Calorific value	kJ/kg	D-240	45,448	41,652	43,467
Cloud point	°C	D-2500	6.6	−1	−4
Pour point	°C	D-97	4	−4	−4
Flash point	°C	D-92	62	176	177.2

pictorial view is shown in Fig. 2(b). The engine's output power is measured by connecting it to an electrical dynamometer. Crank angle encoders have a crankshaft for taking readings of the crank angle The pressure inside the cylinder is estimated via a piezoelectric pressing factor transducer installed on the chamber head. The coolant temperature is constantly hidden to prevent the engine from overheating. To put a stop to the dregs statement and unfavorable fuel line replies, a new petrol tank and fuel line are installed. To keep the engine in top testing condition, the fuel channel is cleaned at regular intervals. A high-speed data gathering system was used to link the pressure signals with the computer, where the combustion parameters could be stored. Table 3 contains the specifications of the CI engine. Emission parameters like HC, CO, and NO_x are recorded with the use of an AVL DIGAS 444 five-gas analyzer (Model AVL444 N). The smoke opacity is measured by AVL 437 smoke meter. Table 4 represents the specifications of the AVL gas analyzer.

Hydrogen is supplied to the engine cylinder through the intake manifold. The pressure regulator assists in supplying hydrogen which is kept under high pressure to the engine at a pressure of about 2 bar. A control valve and flow meter are used to keep the flow rate at 10 L/min. A flame arrester has been added to the hydrogen flow line to stop any potential backfire. During each H_2 enrichment investigation, the engine oil was checked.

The engine was first run with diesel at no load condition. After achieving a stable condition, the readings were noted at all load conditions and taken as reference values. After that, it was operated with enrichment of hydrogen (10 L/min) and readings were noted down. The same procedure has been followed for the prepared biodiesel blends such as WCB20, WCB20 + $10H_2$, WCB20 + $75CeO_2$, and WCB20 + $75CeO_2$+$10H_2$. The injection timing is fixed at 23° before the top dead center (bTDC) and the injection pressure is kept at 600 bar.

Measurement errors are inevitable during analysis because they depend on factors like instrument accuracy, environmental conditions, human perception, and more. The degree of uncertainty indicates how reliable and valid the study is. Fixed mistakes occur during the direct estimate and are easily measurable, but random errors can produce values in rate uncertainty. The overall uncertainty is calculated using Eq. (1) [32] and results as ± 2.16%. Table 5 represents the percentage uncertainties of each parameter.

Table 2 – Properties of CeO_2 nanoparticle.

Parameters	Specification
Supplier	Nanoshel India
Purity	99.5%
Particle size	<80 nm
Molecular weight	172.12 g/mol
Form	Powder
Color	White
Density	7.15 g/cm^3
Boiling point	3500 °C

$$\text{Overall Uncertainty} = \text{sqrt of [uncertainty of }\{(BTE)^2 + (BSFC)^2 + (EGT)^2 + (HC)^2 + (CO)^2 + (NOx)^2 + (smoke)^2\}] \quad (1)$$

The obtained experimental uncertainties are found to be similar to the previous literature [29,30].

Results and discussions

To evaluate the effects of H_2 and CeO_2 on the performance, emission, and combustion characteristics of the diesel engine, the neat diesel (D100) was taken as the base fuel or reference fuel. Among the performance characteristics BTE, BSFC, and EGT for all prepared fuel blends are evaluated and compared with that of diesel. For the engine exhaust study, the emissions of CO, NO_x, HC, and smoke are investigated. As well as for combustion characteristics the rate of variation of in-cylinder pressure and the rate of heat release with different crank angles are investigated. These parameters are investigated from the part load (40%) to full load (100%) conditions.

Performance characteristics

Brake thermal efficiency (BTE)

Fig. 3 illustrates the variation of BTE at different loading conditions for all test fuels such as D100, D100+H_2, WCB20, WCB20 + $10H_2$, WCB20 + $75CeO_2$, and WCB20 + $75CeO_2$+$10H_2$. In general, the BTE increases with the load, indicating a better performance at a higher load. Compared with neat diesel, the WCB20 blend shows lower BTE at all load conditions. Poor atomization and a longer ignition delay are the results of biodiesel's increased density and viscosity compared to conventional diesel. However, a lower cetane number of biodiesels also results in poor output of the engine [8,33]. The addition of CeO_2 nanoparticles to fuel mixtures could improve their thermal efficiency, resulting in lower overall fuel consumption. The blend WCB20 + $75CeO_2$ shows a 15.89% increase in BTE as compared to a neat biodiesel blend. The available oxygen-storing capability, high thermal stability, and the increased catalytic activity of CeO_2 promoted the fuel to burn more efficiently and resulted in improved BTE

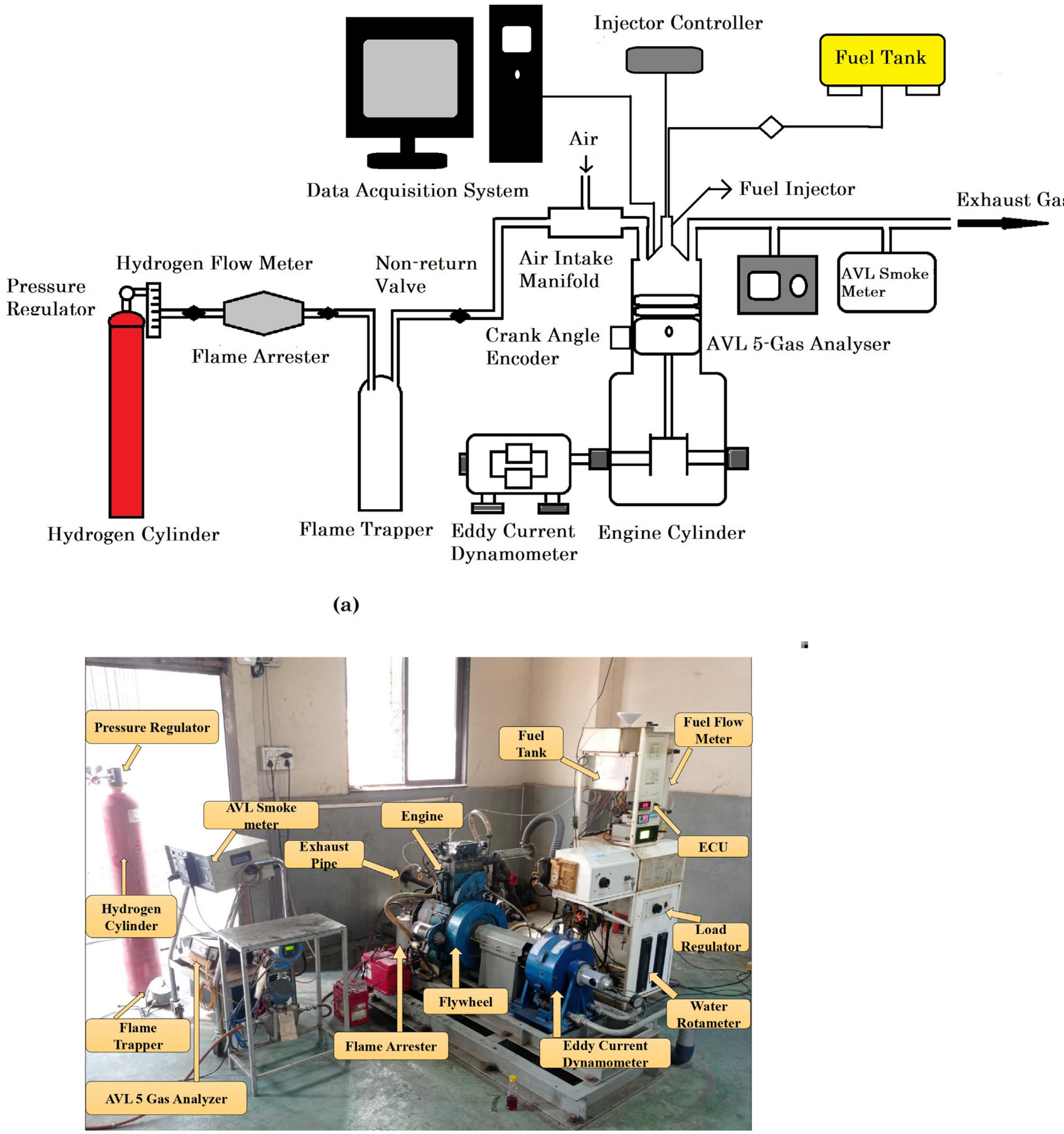

Fig. 2 – (a) Schematic view, (b) Pictorial view of the engine setup.

[11,34,35]. Further, the addition of nanoparticles enhances air-fuel mixing and helps in burning more thoroughly due to their faster evaporation rates [29].

With the addition of 10 L/min H_2 in biodiesel blend, the BTE of WCB20 + 10H_2 increases by 10.92% than that of WCB20, still it can be observed as 4.91% lower BTE in comparison to D100 at full load. The BTE of the engine can be improved by adding hydrogen to the air intake manifold. D100 + 10H_2 shows 28.52% BTE at optimum load. The BTE of the engine can be improved by adding hydrogen to the air intake manifold. At full power, D100 + 10H2 has a BTE of 28.52%. The rapid flame velocity and increased flammability of hydrogen fuel is the primary reason for this. Improved thermal efficiency also results from the hydrogen's better mixing which contributes to the flame's speed of movement within the cylinder [2,36]. According to the investigation, the combination of hydrogen and CeO_2 nanoparticles can boost the engine's power and efficiency. The blend WCB20 + 75CeO_2+10H_2 shows a 3.65%

Table 3 – Specifications of the engine.

Parameters	Specifications
Model and make	Kirloskar/TV1
No of cylinders	Single cylinder
No of stroke	Four-stroke
Rated power	3.5 kW at 1500 rpm
Fuel injection	Direct injection
Stroke and Bore length	110 mm and 87.5 mm
Swept volume	661.45 cc
Cooling system	Water cooled
Compression ratio	18.00
Connecting rod length	234.00 mm
Dynamometer	Eddy current type

Table 4 – Specifications of exhaust gas analyzer.

Equipment	Emission gas	Range	Accuracy
AVL DIGAS 444	CO	0–10%	0.01
	HC	0–20000 ppm	+10 ppm
	NOx	0–5000 ppm	+10 ppm
AVL 437	Smoke opacity	0-100 (BSN)	+1%

Table 5 – Accuracy and percentage of the uncertainty of parameters.

Parameters	Accuracy	Uncertainty (%)
BTE	–	±1.051
BSFC	–	±0.329
EGT	±1C	±0.23
CO	±0.01 ppm	±0.364
NOx	±10 ppm	±0.872
Smoke	±1%	±1.24
HC	±10 ppm	±1.0

increase of BTE compared to D100 at 90% loading condition. Hydrogen diffusivity and enhanced evaporation of CeO_2 nanoparticles both contribute to the increase in BTE. A rise in oxidation rate and the catalytic impact of nanoparticles can clarify power advancements [8,29]. However, at maximum load, BTE decreases as the nanoparticles lose their strength.

Brake-specific fuel consumption (BSFC)

The mass fuel flow rate to the engine power is known as the BSFC. It is a measure of how effectively an engine uses fuel depending on the fuel characteristics [8,37]. Researchers have found that the BSFC of biodiesel-fuelled engines is increased. In Fig. 4, the blend WCB20 shows a 16.12% increase in fuel consumption compared to D100 at 90% loading conditions. The low calorific value of biodiesel could be the reason for it. It more explicitly means that more fuel will need to be injected to maintain the same level of power [8]. However, the addition of nanoparticles and hydrogen to the fuel blend shows a decreasing tendency with the increase in load for each type of fuel blend. The addition of 75 ppm of CeO_2 in the biodiesel blend improves the consumption of fuel in the engine by 13.88% compared to WCB20. Still, it is 1.61% higher than neat diesel. This is due to the presence of oxygen molecules in the biodiesel and nanoparticle which lead to the complete burning of fuel inside the cylinder which reduces fuel consumption [8,34].

When hydrogen is added to the biodiesel blend the BSFC decreases compared to WCB20. The blend WCB20 + $10H_2$ shows an 8.33% reduction of BSFC compared to WCB20, still which is 6.45% higher than neat diesel. However, the addition of both CeO_2 and H_2 together in the biodiesel blend reduces the BSFC by 27.77% compared to the neat biodiesel blend, and as well as it is showing similar results as diesel. Due to the rapid flame speed, high heating value, wider flammability

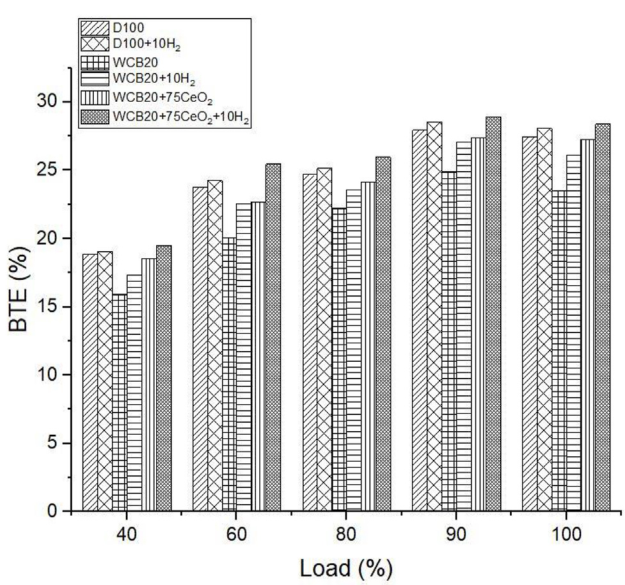

Fig. 3 – Variation of BTE against load.

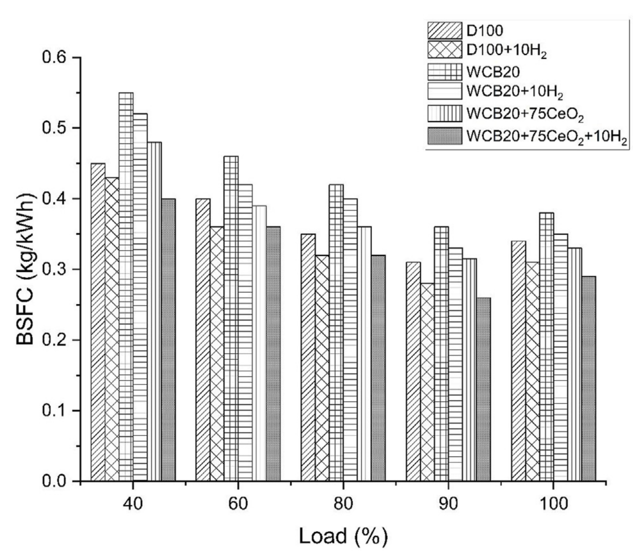

Fig. 4 – Variation of BSFC against load.

range, and short quenching distance, hydrogen has been used to fuel for complete combustion. The higher calorific value of H_2 raises the temperature inside the cylinder, enabling a faster combustion process, resulting in an increased mean indicated pressure and a lower BSFC [8,38]. At 90% load condition, all the fuel blends show the lowest BSFC. At full load, as the engine speed increases more fuel needs to be injected into the cylinder for which the BSFC increases [27].

Exhaust gas temperature (EGT)

The exhaust gas temperature can be measured utilizing going out heat along with exhaust gases. For all fuel samples, the value of EGT, which represents the qualitative information of combustion, rises monotonically with the increase in load. This is due to consuming more fuel to match the load demand, which causes more heat to be produced inside the cylinder [26]. Fig. 5 represents the variation of EGT at various load conditions. The EGT increases with the increase in load condition. The biodiesel blend shows higher EGT as compared to diesel. Due to the biodiesel's high viscosity and poor atomization, unburned fuel accumulates during the premixed combustion phase and keeps burning during the succeeding diffusion combustion phase, increasing the EGT [27]. Despite the load regime, adding H_2 to conventional diesel fuel improves the EGT values. The trend of adding H_2 to biodiesel blends was comparable to that of diesel as shown in Fig. 5. The blend WCB20 + $10H_2$ shows a 10.78% increment in EGT compared to D100. By burning fuel more quickly, the improvement of EGT produces additional energy during the combustion phase and raises the self-ignition value of hydrogen [1]. From Fig. 5 it can be observed that in addition to CeO_2 nanoparticles, the EGT increased by 6.78% and 14.2% compared to WCB20 and D100 respectively. The increased oxygen usage by the CeO_2 nanoparticle blended fuel stimulated the burning process, increasing the temperature and thereby improving the EGT [12,39]. At 90% load, the blend WCB20 + $75CeO_2$+$10H_2$ shows the highest EGT. Compared to D100, the EGT values were found to be 15.79% higher on the addition of both CeO_2 and H_2 together in the biodiesel blend, which is a result of the combined effect of hydrogen and nanoparticle. Similar results were found by Das et al. [29], Elwardany et al. [40].

Emission characteristics

CO emissions

CO emission depicts the losses of chemical energy that cannot be utilized fully to develop engine power. It can be determined majorly by the fuel-to-air equivalence ratio. Fig. 6 represents the variation of CO emissions at various load conditions for all tested fuel blends. CO emissions rise with the load because of the incomplete combustion brought on by excess fuel in the cylinder to maintain a constant speed during high load conditions [26]. When biodiesel blends were utilized instead of diesel, CO emissions were significantly reduced over the engine speed range. WCB20 blend shows a 25% reduction compared to D100 at 90% loading condition. The oxygen-rich structure of biodiesel helps in the complete burning of the fuel resulting in less CO emissions. The addition of 10 L/min H_2 further reduces the CO emission by 10% in comparison to WCB20. By boosting the hydrogen-to-carbon ratio and enhancing air/fuel mixing, hydrogen enrichment minimizes the need for carbon-based fuel. Hydrogen's high diffusivity leads to a faster combustion time and a more uniform mixture [8].

Also, the addition of CeO_2 nanoparticles further reduced the emissions of CO by 15% compared to WCB20 at full load. By utilizing nanoparticles with strong catalytic activity and a high surface-to-volume ratio, thermal and combustion efficiency can also be increased. The biodiesel blends with both 75 ppm CeO_2 and 10 L/min hydrogen shows the lowest CO emissions which is a 30% reduction from WCB20 at 100% load. The combined effect of the carbon-free structure of hydrogen and CeO_2's high energy surface area results in a complete combustion reaction which minimizes CO emissions [1,8].

HC emissions

Similar to CO emissions, unburned HC emission results from incomplete combustion of a too-rich or too-lean mixture of

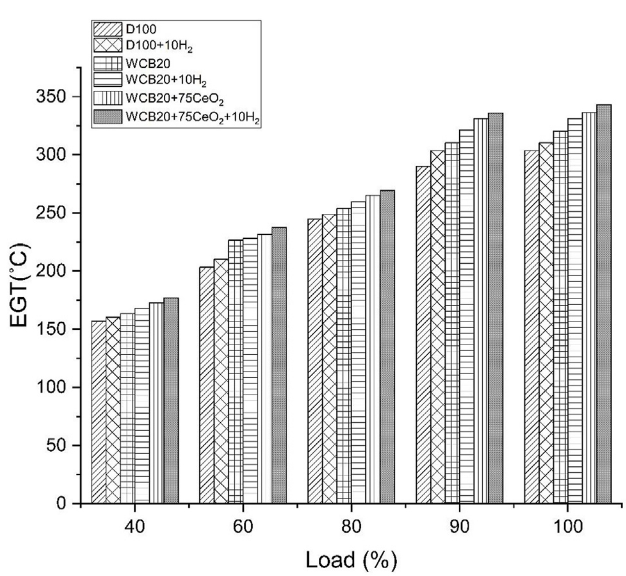

Fig. 5 – Variation of EGT against load.

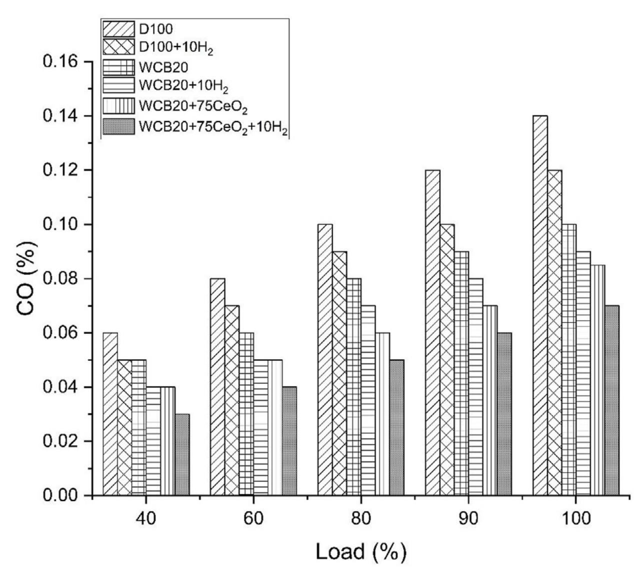

Fig. 6 – Variations of CO against load.

fuel [26]. From Fig. 7 it can be observed that the HC emission increases as the load condition increases from 40% to 100%. Poor mixture formation is caused by many factors, including poor atomization, low injection pressure, under- or over-penetration, and sac volume/hole dribbling. Over-lean mixes can be caused by high injection pressure, small nozzle holes, and long ignition delays which lead to HC generations [13]. However, results indicate that WCB20 emits 28.6% lower HC compared to D100 and D100+H_2. This is due to the presence of oxygen molecules in the biodiesel blend. With the addition of CeO_2 in the biodiesel blend, the HC emissions were found to be reduced. As an oxidation catalyst, CeO_2 reduces the activation temperature for carbon combustion and hence boosts HC oxidation, encouraging full combustion [11].

The addition of 10 L/min H_2 shows a further 35.7% reduction of HC emissions than diesel at 100% loading condition. The lack of carbon atoms in hydrogen fuel decreases the HC emissions. Results from Fig. 7 indicate that the blend WCB20 + 75CeO_2+10H_2 shows the lowest HC emissions among all fuel blends. At full load, it shows a 50% reduction of HC emissions from D100 and a 30% reduction from the WCB20 blend. Due to the short quenching distance, high flammability range, and increased temperature caused by the combustion of H_2 with biodiesel, HC emission production is reduced. The effect of a high surface/volume ratio of nanoparticles in hydrogen-enriched biodiesel aids in the complete combustion of fuel resulting in minimal HC emission. Das et al. [29] also found similar results.

NO_x emissions

One of the emissions caused by combustion that diesel engines generate is NO_x. It has significant negative consequences on the environment and human health. Therefore, attempts to reduce it are of the greatest priority. Fig. 8 depicts the effect of adding hydrogen and CeO_2 nanoparticles in various load conditions. It can be observed from Fig. 8 that NO_x emission increases as the load increases. The biodiesel blends WCB20 shows 4.19% higher NO_x emission compared to diesel at 90% loading condition. This is due to the relatively higher oxygen content of biodiesel which helps in complete combustion resulting in higher cylinder temperature and promoting NO_x emissions. The CeO_2 nanoparticles added blend shows a 9% increase in NO_x emissions compared to D100. When employing a greater CeO_2 concentration, the extra oxygen added to the fuel due to the nanoparticles is solely the reason for the creation of NO_x [13,41]. Also, the improved thermal conductivity of nanoparticles helps in better evaporation of fuel which boosts in-cylinder temperature resulting in NO_x emissions.

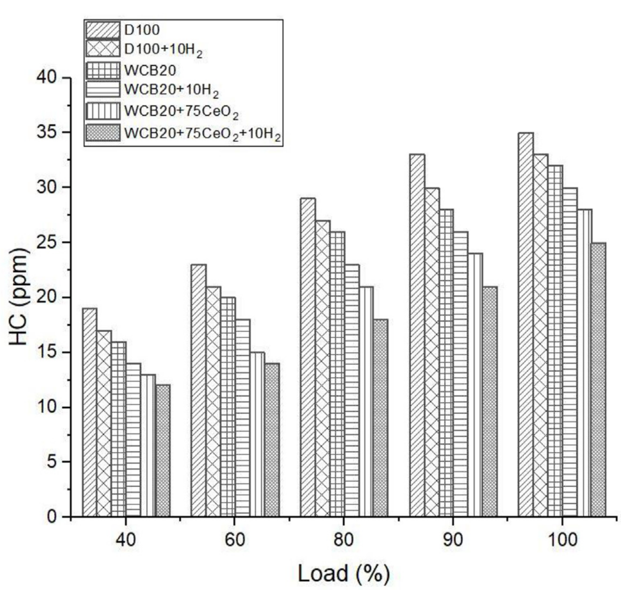

Fig. 7 – Variations of HC against load.

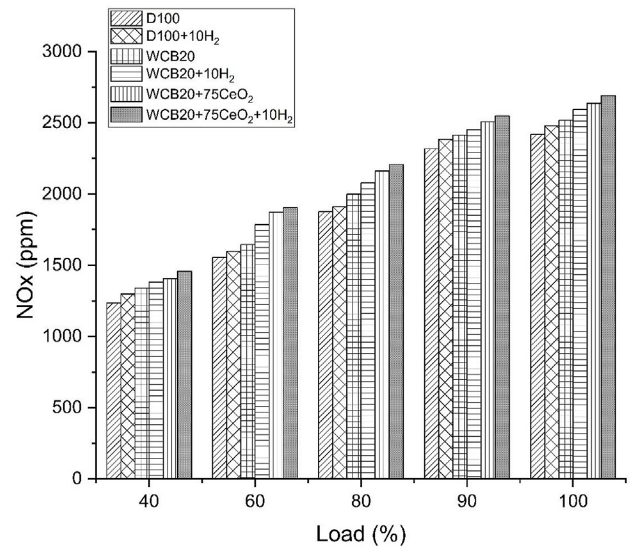

Fig. 8 – Variations of NO_x against load.

Enrichment of hydrogen produces further NO_x emissions. The blends D100+H_2 and WCB20 + 10H_2 produce 2.48% and 7.23% higher NO_x emissions as compared to diesel. The higher calorific value of H_2 may increase the cylinder temperature which results in NO_x emissions [2]. The hydrogen and nanoparticle-added blend shows the highest NO_x emission at all load conditions of 40%–100%. This blend produces 11% higher NO_x at 100% loading conditions compared to diesel. Maximum NO_x emissions are promoted by the interaction of increased hydrogen combustion characteristics and improved nanoparticle air-fuel mixing. Additionally, an important factor in the overall amount of NO_x created throughout a cycle is the length of time the high temperature stays in the cylinder [26,42].

Smoke emissions

Fig. 9 shows the variation of smoke emissions at different loading conditions for all fuel blends. Smoke formation in CI engines is primarily caused by a heterogeneous fuel-air combination, which reduces as the air-fuel mixture's homogeneity level rises. It typically develops in rich fuel pockets with a lack of oxygen atoms. Results indicate that with increasing load percentages the smoke emissions are increasing. Smoke emissions increase since more fuel is injected at higher loads to match the demand, but not all of the injected fuel is burned [43]. The biodiesel blends WCB20

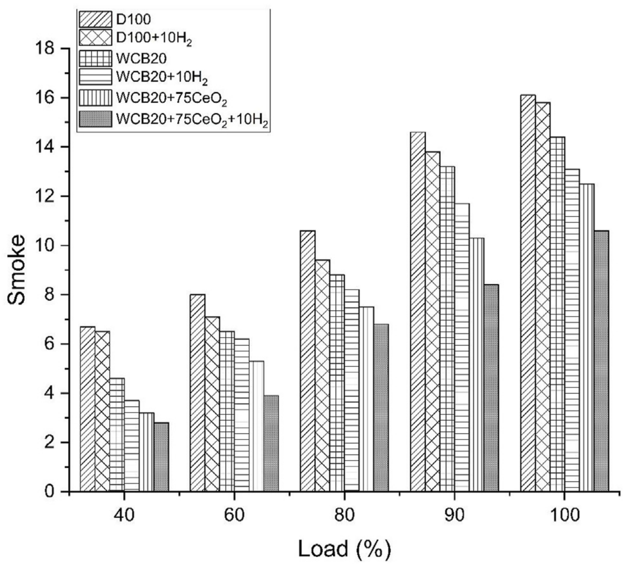

Fig. 9 – Variations of smoke against load.

show 10% lower smoke emissions compared to D100. This is because biodiesel has a higher oxygen content in its molecular structure, resulting in more complete fuel burning within the cylinder. However, smoke generation from inefficient atomization is affected by biodiesel's viscosity [44].

The addition of 10 L/min of H_2 reduces the smoke emissions by 18% at 100% loading conditions. Since better combustion occurs due to the increased homogeneity of fuel from H_2 induction and its high heating value causes the soot particles to be oxidized at high temperatures [43]. The addition of CeO_2 in the biodiesel blend shows a further reduction of 22.36% smoke compared to WCB20, however, the blend WCB20 + $75CeO_2$+$10H_2$ shows the lowest smoke emissions among all fuel blends. It shows a reduction of 42% when compared with diesel and 36.36% when compared with WCB20 at 90% loading condition. The reduction of smoke opacity is due to the oxygen content present in the nanoparticles which improved the combustion characteristics. These are primarily caused by nanoparticles' high surface area or volume ratio, which improves fuel-air mixing and speeds up the evaporation in the combustion chamber [45]. The cumulative effect of adding nanoparticles and the improved combustion characteristics of hydrogen help in reducing smoke production. However, at full load, the smoke emissions increased by 20% for the blend WCB20 + $75CeO_2$+$10H_2$ since more fuel is injected into the engine cylinder.

Combustion characteristics

In-cylinder pressure

The in-cylinder pressure is the pressure generated while burning the fuel inside the engine cylinder. Fig. 10 shows the variations of in-cylinder pressure at different crank angles for all test fuel blends. In comparison to diesel, WCB20 has a peak pressure of 65.95 bar, a difference of 21%. Since the biodiesel blend has weak evaporation characteristics and a low calorific value, the pressure inside the cylinder drops rapidly. Poor evaporation characteristics lead to poor air-fuel mixing which results in poor combustion characteristics. According to Fig. 10, the nanoparticles added biodiesel blend WCB20 + $75CeO_2$ show a 25% greater in-cylinder pressure than neat biodiesel blends, which suggests improved combustion and a faster rate of heat release [7]. This is possible because of the active cerium atoms released by CeO_2. They enhance combustion by generating H_2 at high temperatures [46,47]. Also, the oxygen contents present in the CeO_2

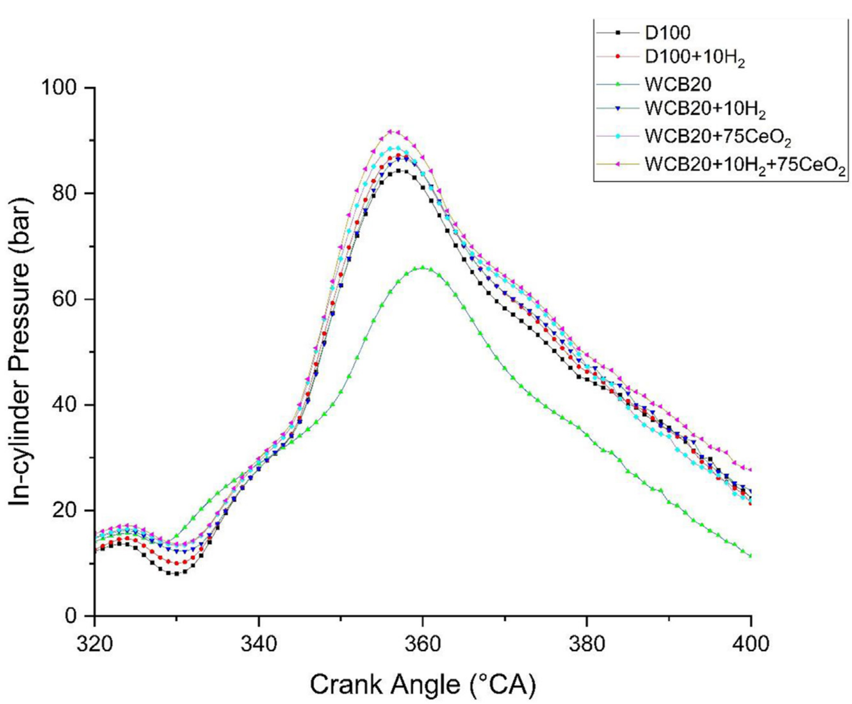

Fig. 10 – Variation of in-cylinder pressure with the crank angle at full load condition.

nanoparticle provide enough contribution to completely burn the fuel which reduces the ignition delay. This reduced ignition delay is another reason for improved combustion characteristics and higher ICP.

Results showed that the addition of H_2 in biodiesel blend attains 2.5% and 23.75% higher in-cylinder pressure than D100 and WCB20 blends. With the addition of H_2, the pressure increased at higher loading conditions. The rapid and thorough oxidation of the charge caused by the hydrogen's high flame speed increases the in-cylinder pressure. Under low load conditions, the hydrogen-air mixture becomes too lean to get ignited and burn with a sufficiently high flame speed. The results also reveal that the in-cylinder pressure was 24.4% and 3.4% higher than WCB20 and neat diesel while using D100 + $10H_2$. This happens due to the higher calorific value and small quenching gap of hydrogen as compared to neat diesel [43]. In addition to both nanoparticles and H_2 together the fuel blend WCB20 + $75CeO_2$+$10H_2$ shows a maximum cylinder pressure of 91.67 bar at 356° crank angle which is 8% higher than D100. The combined effect of nanoparticle's better fuel evaporation properties and hydrogen's combustion properties helps in complete combustion resulting in higher ICP. Das et al. [29] found similar results.

Net heat release rate

Fig. 11 shows the changes in net heat release rate with the crank angle for all test fuel blends. Due to its larger calorific value, results show that diesel fuel releases a greater heat rate than WCB20. Additionally, the presence of hydrogen in diesel (D100 + $10H_2$) accelerates the rate of heat release and also increases the amount of heat release. In dual-fuel engines, combustion occurs in two stages. Heat release increases quickly during premixed combustion, followed by a moderate and regulated HRR during the diffusion phase [7]. Since less fuel engages in combustion at part load, producing a lean mixture, HRR declines with H_2 enrichment. The maximal HRR is increased by H_2 enrichment at a high load because hydrogen has a high diffusivity [27]. When examining Fig. 11, it is clear that a negative HRR value was obtained before starting the combustion. This is due to the evaporation of the accumulated liquid fuel during the ignition delay period, as well as heat absorption from the environment. When the combustion begins, the HRR value becomes positive. The blend WCB20 + $10H_2$ shows 18.5%% higher HRR at a crank angle of 361° compared to WCB20 according to Fig. 11. The blend WCB20 shows 17% lesser HRR than D100 due to the lower calorific value, and higher viscosity of biodiesel compared to diesel. The high viscosity of the oil results in larger fuel entering the cylinder. The temperature inside the cylinder is inadequate to shatter these fuel droplets under part load circumstances. The increasing in-cylinder temperature under full load, on the other hand, causes these droplets to split into smaller particles, leading to more uniform combustion and better HRR [27,47]. CeO_2 nanoparticles improve fuel combustion by increasing the rate at which heat is transferred from the fuel to the surrounding air. The physical and chemical lag times are thereby reduced. Thus, the rate of heat production increases because combustion starts sooner and more energy is stored in the premixed combustion mixture [7]. From Fig. 11, the blend WCB20 + $75CeO_2$ shows 19.5% higher HRR compared to WCB20. On addition of both nanoparticles and hydrogen together in the biodiesel blend increases the HRR. The blend WCB20 + $75CeO_2$+$10H_2$ shows 6% and 21.5% higher HRR than D100 and WCB20 respectively. The rapid combustion of hydrogen and high heating value of CeO_2 helps complete fuel burning, leading to a higher heat release rate [48].

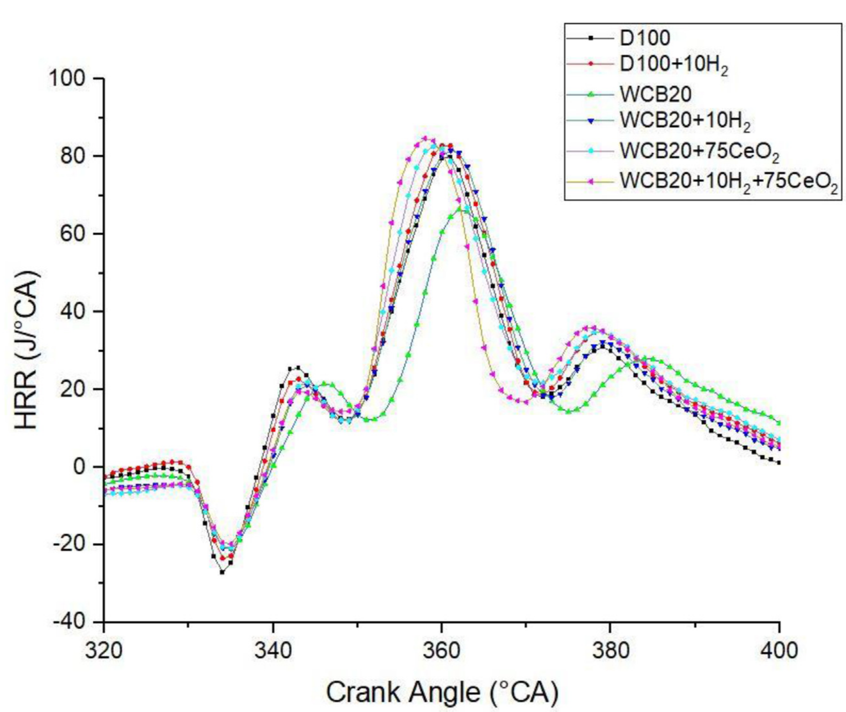

Fig. 11 – Variation of heat release rate with the crank angle at full load condition.

Ignition delay

In CI engine applications, the period between the beginning of fuel injection into the engine cylinder and the beginning of combustion is known as the ignition delay (ID). In diesel engines, there are two types of ignition delay: chemical ignition delay and material or physical delay. While chemical ignition delay is ascribed to pre-combustion reactions, material ignition delay comprises the atomization, vaporization, and mixing of air and fuel [49]. The chemical processes are affected by operating variables and fuel characteristics. The key factors for ignition delay are the compression temperature and pressure. Fig. 12 shows the ignition delay results for each test fuel blend against each loading condition. Results showed that with the increase in engine load the ignition delay decreases for test fuel blends. Low engine load conditions cause the residual gas temperature, the temperature of the cylinder wall, and the pressure to drop, delaying the start of combustion process and increasing ignition delay. As a result, majority of the fuel gas burned during the expansion stroke which reduces the engine's power and efficiency [49]. Earlier fuel injection increases the in-cylinder temperature and pressure which reduces the ignition delay time. The biodiesel blend WCB20 exhibits a prolonged ignition delay period than neat diesel. At 40% load, it shows 11% as well as at 100% load it shows 10% increased ID period compared to diesel. This is because of the moderate vaporization occurs due to the high viscosity of biodiesel blend leading to significant heat absorption and longer ID [50,51].

On addition of hydrogen to the fuel blends the ID period decreases. At full loading condition, compared to diesel, the blend WCB20 + $10H_2$ possesses 5.1% increased ID period, while in comparison to WCB20, it gets reduced by 7%. Hydrogen having a higher self-ignition temperature and faster flame speed results in an increase in the cylinder wall temperature which reduces the ignition delay time and exhibits rapid and complete combustion of the fuel-air mixture. The higher cetane number of hydrogen with biodiesel blend exhibits a stronger chemical reaction which is another reason for reduced ignition delay period [52]. In addition of nanoparticle to the fuel blends also results in reduced ignition delay. From the Fig. 12 it can be seen that the blend WCB20 + $75CeO_2$ shows 16.6% reduction of ID at 100% loading condition compared to WCB20. It's high surface area to volume ratio helps in good atomization of fuel and high evaporation rates resulting in improved combustion as well as reduced ignition delay. Oxygenated additives like metal oxide nanoparticles provide sufficient oxygen for the complete combustion of fuel. On addition of H_2 and CeO_2 together, the biodiesel blend WCB20 + $75CeO_2$+$10H_2$ shows a reduced ignition delay than WCB20 at all load conditions. At 100% load conditions, it gives 11% reduced ID period compared to diesel. The combined effect of hydrogen and nanoparticles results in reduced ignition delay than diesel at full load conditions. The high thermal conductivity of metal-oxide nanoparticles and the diffusive nature of hydrogen increases the heat transfer rate which results in lowest ignition delay period [7].

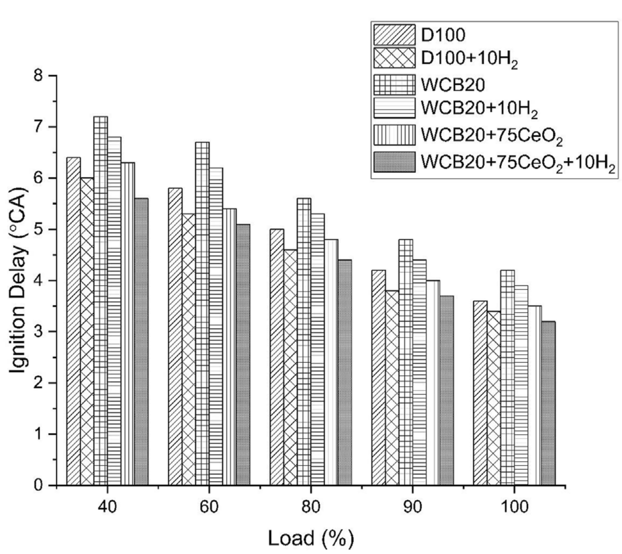

Fig. 12 – Variation of ignition delay period against load.

Conclusions

The current study examines the influence of hydrogen enrichment at 10 L/min and CeO_2 nanoparticle dosing at 75 ppm on the characteristics of CI engines powered by a waste cooking oil biodiesel blend. On addition of CeO_2 nanoparticles and H_2 together in the biodiesel blend shows better performance in the case of engine characteristics compared to other fuel blends. The following are the conclusions that may be derived from the experimental findings:

- The performance parameters are found to be enhanced with the addition of H_2 and CeO_2 nanoparticles. The BTE of the engine increased by 10.92% for WCB20 + $10H_2$, and 15.89% for WCB20 + $75CeO_2$ compared to the biodiesel blend. The combined effect of nanoparticles and hydrogen in the biodiesel blend presents the highest BTE which provides more power to the engine. The blend WCB20 + $75CeO_2$+$10H_2$ shows a 3.53% enhancement in BTE compared to neat diesel.
- The BSFC of biodiesel blends is found to be increased compared to neat diesel. H_2 enrichment in the fuel blend improves the fuel consumption in the engine. With the addition of H_2 and CeO_2 together, the fuel blend WCB20 + $75CeO_2$+$10H_2$ shows a 16.12% reduction in fuel consumption compared to neat diesel. The high heating value of H_2 and the presence of oxygen molecules in nanoparticles as well as biodiesel aid in to complete combustion of fuel inside the cylinder.
- The EGT increases with the increase in load for all fuel blends. The blends WCB20 + $10H_2$, WCB20 + $75CeO_2$, and WCB20 + $75CeO_2$+$10H_2$ show enhancement of 10.78%, 14.20%, and 15.79% respectively in comparison with neat diesel. On addition of both nanoparticles and H_2 together increase the exhaust gas temperature. However, the employment of the EGR system may reduce the same.
- The use of oxygenated fuel in CI engine applications reduces the emissions of carbon monoxide. The CO emissions have been improved with the addition of H_2 and CeO_2 additives in the biodiesel blend. The fuel blend WCB20 + $75CeO_2$+$10H_2$

shows a 30% reduction of CO emissions compared to the neat biodiesel blend at 100% load.

- The HC and smoke emissions are also found to be reduced with the addition of H_2 and nanoparticles together in the biodiesel blend. The absence of carbon atoms in hydrogen fuel and the presence of oxygen content in CeO_2 result in the complete combustion of fuel which leads to the lowest HC and smoke emissions. The fuel blend WCB20 + 75CeO_2-+10H_2 emits 50% and 42% less HC and smoke respectively in comparison to diesel.
- The emissions of NO_x are affecting the environment while using biodiesel blends as base fuel. It is found to be increased by 7.23%, 9%, and 11% for the blends WCB20 + 10H_2, WCB20 + 75CeO_2, and WCB20 + 75CeO_2-+10H_2 respectively compared to neat diesel. However, remedies may be taken by employing relevant systems to reduce such harmful emissions.
- The blend WCB20 + 75CeO_2 and WCB20 + 10H_2 show 5% and 2.5% higher in-cylinder pressure compared to D100 respectively. With the addition of both nanoparticles and H_2 together the fuel blend WCB20 + 75CeO_2+10H_2 shows the peak in-cylinder pressure of 91.67 bar at 356° crank angle.
- The addition of nanoparticles in the biodiesel blend gives 19.5% higher HRR and the addition of H_2 gives 18.5% higher HRR in comparison to WCB20. When compared to pure diesel, due to the combined effect of CeO_2 and H_2, the HRR values of biodiesel blends are observed to be higher. The blend WCB20 + 75CeO_2+10H_2 shows the maximum HRR values which is 6% higher than neat diesel.
- The ignition delay period is found to be decreased with the increase in load conditions. In combination with both CeO_2 nanoparticles and H_2 together the biodiesel blend WCB20 + 75CeO_2+10H_2 gives 11% reduced ID period when compared to diesel.

These findings conclude that the H_2 enriched and nanoparticles added biodiesel blend can be a better alternative to conventional diesel in CI engine applications as it performs in a better way than the former one.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Nomenclature

bTDC: Before top death centre
BSFC: Brake specific fuel consumption
BTE: Brake thermal efficiency
CeO_2: Cerium oxide
CO_2: Carbon dioxide
CO: Carbon monoxide
CRDI: Common rail direct injection
°*CA:* Degree crank angle
D100: Diesel
$D100 + 10H_2$: Diesel +10 L/min hydrogen
EGT: Exhaust Gas Temperature
H_2: Hydrogen
HRR: Heat release rate
HC: Hydrocarbon
ICP: In-cylinder pressure
IP: Injection pressure
IT: Injection timing
NO_x: Nitrogen oxides
WCO: Waste cooking oil
WCB20: Waste cooking biodiesel blend (20% biodiesel+80% diesel)
$WCB20 + 10H_2$: Waste cooking biodiesel blend + 10 L/min hydrogen
$WCB20 + 75CeO_2$: Waste cooking biodiesel blend + 75 ppm Cerium oxide
$WCB20 + 75CeO_2 + 10H_2$: Waste cooking biodiesel blend+75 ppm cerium oxide+ 10 L/min hydrogen
XRD: X-ray diffraction

ARTICLES FOR FACULTY MEMBERS

COMPARATIVE ANALYSIS OF WASTE COOKING OIL BIODIESEL MIXED WITH NANOPARTICLE ADDITIVES ON PHYSICOCHEMICAL PROPERTIES AND DIESEL ENGINE PERFORMANCE

Application of CuO nanoparticles on performance and emission characteristics of ternary blends of diesel, waste cooking oil and pumpkin seed oil biodiesel in an IC engine / Raj, R. S., Madhu, P., Dhanalakshmi, C. S., & Prakash, M. A.

Indian Journal of Chemical Technology (IJCT)
Volume 32 Issue 1 (2025) Pages 33–40
https://doi.org/10.56042/IJCT.V32I1.14501
(Database: National Institute of Science Communication and Policy Research (NIScPR))

Indian Journal of Chemical Technology
Vol. 32, January 2025, pp. 33-40
DOI: 10.56042/ijct.v32i1.14501

Application of CuO nanoparticles on performance and emission characteristics of ternary blends of diesel, waste cooking oil and pumpkin seed oil biodiesel in an IC engine

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Received 18 October 2024; accepted 6 January 2025

The aim of this work is to demonstrate the effect of copper oxide (CuO) nanoparticles doped biodiesel on the performance and emission characteristics of a compression ignition (CI) engine. The base fuel (B20) is a ternary blend of 10% waste cooking oil (WCO) biodiesel, 10% pumpkin seed oil (PSO) biodiesel, and 80% conventional diesel. The B20 blend has been doped with CuO nanoparticles at four different dosage of 20, 40, 60 and 80 ppm. The tests are conducted on a single-cylinder diesel engine with no modifications and under standard operating conditions. WCO and PSO were identified for this work due to their good economic viability, and the oils are converted into biodiesel through the transesterification process. The performance parameters, such as brake thermal efficiency (BTE) and brake specific fuel consumption (BSFC) under different load conditions are evaluated. The emission characteristics of carbon monoxide (CO), hydrocarbons (HC), and oxides of nitrogen (NOx) are also considered for this study. From the results, it is found that the use of a ternary blend with CuO for an IC engine gives higher BTE with reduced BSFC. It is also perceived that the emission of CO and HC from the engine can be controlled with the addition of CuO nanoparticles.

Keywords: Biodiesel, Compression ignition engine, Emission characteristics, Non-edible oil, Ternary blend

Introduction

Internal combustion (IC) engines are machines utilized for energy conversion, particularly in the transportation sector. The automotive industry is continuously developing with advanced technologies, but at the same time, numerous ecological issues related to its use are becoming more serious[1]. Much effort is being concentrated on combustion technology to increase the performance and reduce the consumption of fossil fuels. Reduction of pollutants from IC engine is an important one, since the elevated levels of pollution observed in urban areas pose health risks to humans and all living organisms[2]. Due to its widespread utilization in all industries, fuel for IC engines is always in demand globally[3]. In order to fulfill the demand, the majority of research focused on renewable energy sources[4]. The most significant role in biodiesel research has been played by plant-based oils, which are utilized for a variety of applications, such as automobiles, ships, power generations and others. Biofuels have the ability to improve environmental stability by lowering greenhouse gas emissions[5]. They can also aid in the protection of ecosystems and natural resources. Biofuels have the potential to improve energy security and lessen global dependency on fossil fuels. It can offer a low-carbon transportation option, particularly for large trucks, ships, and aircraft. Compared to diesel, biodiesel is a green energy source that has less aromatic and sulphur contact, as well as a higher flashpoint, a cetane number and lubricity[6]. Reduced oxidation stability, higher pour point, viscosity and lesser heating value are some of the drawbacks of biofuel. Many researchers have produced and utilized biodiesel from different non-edible oils for engine operations[7]. From these experiments, it was noted that the biodiesel-fueled engines produce less emissions than diesel-fueled engines, but there is a small surge in nitrous oxide (NOx) emissions[8]. However, it was not advised to use 100% biodiesel for IC engines. As a result, under controlled laboratory conditions, biodiesel and diesel were combined in specific amounts. The choice of oil for biodiesel production is heavily influenced by many factors, including availability, cost, and production methods[9]. Recently, there has been a lot of worry about the use of edible oils for IC engine operations since they compete with food ingredients. As a result, the usage of non-edible oils for energy purposes is recommended[10].

A significant portion of the price of biodiesel production depends on raw materials. Usage of low-cost raw materials is one technique to minimize the cost of production. Finding less expensive, non-edible oils is a main objective for biodiesel generation[11]. As a result, waste cooking oils and non-edible oils have attracted increased interest as feedstock for the generation of biodiesel[12]. In this series, WCO and PSO are recommended as raw materials for biodiesel. Disposal of used cooking oil into the environment primarily affects the quality of the land and groundwater[13]. Repeated use of cooking oil for food production beyond certain standards is carcinogenic. It is a cause of obesity and various health diseases[14]. Due to the availability of WCO, the researchers working on alternative fuel have pushed the production of biodiesel for IC engine operations. The converted WCO biodiesel through the transesterification process has many advantages over conventional diesel, including a higher cetane index and a lower sulphur level. Without any structural change, biodiesel can be used for engine operation. Yu *et al*. reported the effects of engine emission and combustion using WCO biodiesel[15]. The authors tested the biodiesel in an IC engine and exposed it to higher peak pressure than diesel fuel and they found coke-like deposition inside the chamber, and the oil they investigated had emissions rates higher than diesel. Experimental research on the use of WCO biodiesel was directed by Rao *et al*.[16]. Through an experimental study, the authors found a higher in-cylinder pressure and a higher heat release rate (HRR). In terms of performance, the WCO biodiesel showed lower BTE due to the poor heating value. The experimental work on IC engines using WCO biodiesel conducted by Pauline *et al*. showed increased power output with decreased fuel consumption and emissions[17]. The basic properties of the fuel revealed that it complied with biodiesel regulations. Under partial load conditions, the output and emission analysis were doneat compression ratios of 14:1 and 16:1. The WCO in the engine showed reduced BTE with increased SFC[18]. The experimental results showed 21.75% reduction in CO with a minor increment in CO_2 and NOx. In comparison to other types of vegetable oils, PSO has a price advantage. Since it is not frequently used as edible oil, the seeds contain approximately 45% oil, giving them a significant advantage over other vegetable oils[19]. PSO biodiesel has been utilized for IC engine operation by various authors in various countries[20–22]. From this collected works, it was established that the usage of PSO biodiesel can limit the emission of harmful gases from the engine.

Biodiesel with nanoparticlesis are novel class of fuel that uses nanoparticles as additives to lower emissions while improving engine performance[23]. According to Javed *et al*. nanoparticles have the capability to improve volumetric energy density of fuels, which in turn has the potential to reduce ignition lag by improving heat transfer[24]. When aluminium oxide nanoparticles were added to tamarind seed biodiesel, Raju *et al*. noticed an increased BTE and decreased CO and HC emissions[25]. With titanium oxide nanoparticles, palm oil biodiesel showed considerable progress in cetane number and calorific value[26]. The experimental study combined with water-diesel emulsion and aluminium oxide nanoparticles showed effective combustion[27,28]. The effective combustion of the fuel is due to its fast evaporation. During the experiment, it was also noted that the engine operated smoothly with reduced noise. According to Mirzajanzadeh *et al*. nanoparticles dispersed in the biofuel increased favourable fuel properties, including calorific value[29]. It is also a guide to proper atomization, vaporization and air-fuel mixing[30]. For the TV1 type Kirloskar engine, Thirugnanam *et al*. used nickel oxide (NiO) nanoparticles with palmyra oil biodiesel[31]. The study found that a NiO-dosed with B20 resulted in 1.3% improved BTE. The results of the emission analysis showed reduced CO and HC productions by 12–22% and 18–24%, respectively. However, the nanoparticles with biodiesel slightly increased NOx emissions. Tewari *et al*. explored the effects of carbon nanotubes in honge oil-derived biodiesel[32]. The biodiesel with nanotubes improved BTE and NOx production while minimizing CO and HC.

It is evident that very few authors have looked into ternary biodiesel blends with nanoparticles for IC engines. In the current work, ternary blends of two distinct biodiesels were produced from WCO, PSO and diesel for IC engine operation. The ternary blended fuel was mixed with CuO nanoparticles to assess engine operating characteristics. Analysis and comparison were done on the experimental data for BTE, SFC, CO, HC,and NOx emissions.

Experimental Section

Oil collection and extraction

The WCO used for this work was gathered from a local restaurant in Coimbatore, India. It is a collection of waste palm oil used for frying purposes. In order to maintain uniform properties, the required amount of WCO was collected at a single time and stored separately. PSO is not available on the market because it is not currently produced commercially. Therefore, the required quantity of seeds was collected and further processed to obtain the required quantity of PSO. The seeds were gathered and exposed in sunlight for a month to dry them. Several methods, including hydraulic pressing, solvent extraction could be used to extract oil from the seeds. According to our earlier research, solvent extraction was considered as the most effective one to extract oil from the seeds[33]. In addition, this approach is less expensive. Therefore, the oil from pumpkin seeds was extracted via soxhlet extraction method.

Biodiesel production

The methyl esters of the oils were prepared using the transesterification process. For that, the stoichiometric oil-to-alcohol ratio was found to be 6:1. The weight of NaOH was calculated to be 1% of the oil. Methyl alcohol and NaOH were combined to create a 100 ml methoxide solution. Using a magnetic stirrer, 500 mL of WCO was placed in a bottle and blended at 400 rpm and 60°C. The produced solution was poured onto the oil. A thermometer was set at 60°C. The process was continued for up to 60 min with the formation of glycerin and biodiesel. The phase separation process was then finished after 6 h of standing time. The separating funnel was clear of the glycerin phase, even though the biodiesel was found with a minor amount of glycerin, salt and methanol. These chemicals were separated and purified from the biodiesel using a washing procedure. Finally, the waste cooking oil methyl ester (WCOME) was obtained and stored in a separate glass column. The procedure was repeated for pumpkin seed oil methyl ester (PSOME). Nearly 81% of the biodiesel was produced for WCOME, and 93% for PSOME. The physiochemical characteristics of both biodiesels were found and reported in Table 1.

Ternary blend production

Due to higher free fatty acids (FFA), WCO and PSO cannot be used directly for engine analysis. The prepared methyl esters had good atomization properties. The specified oils are widely accessible. Consequently, there is a feasibility to combine WCOME and PSOME with petroleum fuel. By directly combining, the ternary blends are created. For engine analysis, the B20 blend was made by combining 80% diesel and 10% of each biodiesel.

Preparation of nano biodiesel

For engine operation, four types of nanofuel were prepared and represented as BxCy (x represents volume fraction and y represents ppm). For example, B20C20 (B20-20% biodiesel, 80% diesel and C20-20 ppm CuO). The homogeneous B20C20, B20C40 and B20C60 B20C80 (different dosages of 20 ppm, 40 ppm, 60 ppm, and 80 ppm) fuels were prepared using an ultrasonicator. The nano CuO was supplied by M/s. Sigma-Aldrich, USA. This study is limited to the usage of B20 since it shows similar readings of diesel during the trial experiment. Therefore, the nano particles at different dosages were mixed with B20. The properties of the tested fuel are recorded in Table 2. Compared to standard diesel, B20C80 has greater calorific value.

Engine set up

A single-cylinder, direct-injection, water-cooled diesel engine was employed for this work. Table 3 displays the specifications of the test rig. The engine is

Table 1 — Properties of the biodiesel

Properties	WCOME	PSOME	Unit	Test standard
Density	852	895	kg/m^3	ASTM D 1798
Kinematic viscosity	3.94	5.8	cSt	ASTM 445
Flash point	142	174	°C	ASTM D 93
Cetane index	57	54	-	ASTM D 613-84
Calorific value	37.82	40.70	MJ/kg	ASTM D 240

Table 2 — Fuel properties

Properties	B20	B20C20	B20C40	B20C60	B20C80	Diesel	Unit
Density	819	823	824	825	827	815	kg/m^3
Kinematic viscosity	2.95	3.14	3.14	3.16	3.18	2.90	cSt
Flash point	65	66	67	67	68	59	°C
Cetane number	52	54.1	54.3	54.9	55.1	51	-
Calorific value	42.90	43.10	43.35	43.55	43.70	43.60	MJ/kg

Table 3 — Engine specification

Brand	Kirloskar
Model	TV1
Number of cylinder	1
Compression ratio	17.5:1
Rated power	5.2 kW
Rated speed	1500 rpm
Number of stroke	4
Cooling type	Water
Stroke	110 mm
Bore	87.5 mm
Injection pressure	210 bar
Fuel timing	23 °BTDC
Peak pressure	77.5 kg/cm^2
Gas analyzer	AVL DiGas
Loading	Eddy current dynamometer

mated with an alternator and then to a load bank. For all the trials, the engine was operated at 1500 rpm. For every fuel, the load was increased from 0 to 100% with five equal distributions of 20%, 40%, 60%, 80% and 100%. Initially, the engine was ran with diesel and then operated in biofuel mode. The readings were noted after the coolant and oil temperatures had stabilized. The emissions were recorded with the aid of AVL DiGas 44 (AVL India private limited). Fig. 1 displays the graphical representation of the experimental setup.

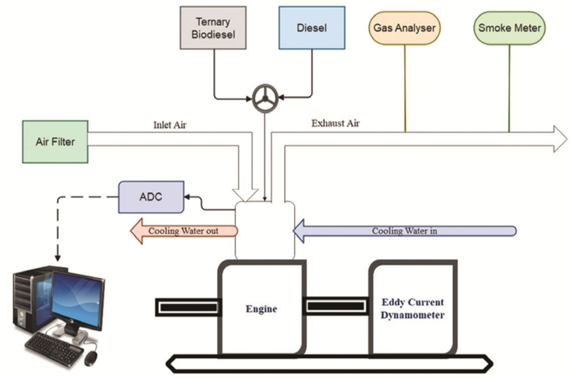

Fig. 1 — Schematic of the experimental setup

Results and Discussion

Variation in brake thermal efficiency

The BTE demonstrates how effectively the fuel's energy may be transformed into mechanical energy. The difference in BTE according to engine load is depicted in Fig. 2. It is obvious that the BTE of the engine rises as the load increases from 0% to 100%, and the BTE for B20 is the lowest among all the tested fuels. For higher biodiesel blends, the calorific value of the fuel decreases, and fuel consumption increases. The viscosity of the blend is high, which can lead to poor atomization[34]. For example, the B20 blend has a higher viscosity of 2.95 cSt than diesel (2.90 cSt), which results in a lower BTE. The physical delay is shortened by the inclusion of nanoparticles with the blended fuel, which also shortens the evaporation duration. The higher thermal conductivity of the nanoparticle results in higher heat transfer rates during the delay period and starts early combustion. The lower efficiency with B20 under all loads is due to the higher density, improper mixing and low heat transfer. Thus, the efficient energy use using nanomaterials was made potential, which increased the engine efficiency. Under maximum load condition the BTE of the engine at B20, B20C20, B20C40, B20C60, B20C80 and diesel was 31.12, 32.68, 33.86, 35.78, 34.91 and 33.42%, respectively. Compared to B20 and diesel, B20C60 showed 13.02% and 6.6% more efficiency at 100% load conditions. At maximum load, 5.01%, 8.8% and 12.18% of the increment were recorded for B20C20, B20C40, B20C80, respectively, compared to B20. Improved combustion inside the chamber is caused by increased oxygen levels in the fuel, improved evaporation, and a higher surface-to-volume ratio in nanofuel[35, 36]. The BTE increased up to the dosage of 60 ppm CuO, and the value decreased beyond that level. The higher viscosity may be the reason of the decreasing efficiency with higher dosage[37]. Compared to other combinations, B20C60 showed better results. The increased nanoparticle dosage might enhance the momentum of the nanofuel and reduce turbulence, which could result in improper fuel mixing and incomplete combustion, which could cause a significant drop in performance[38].

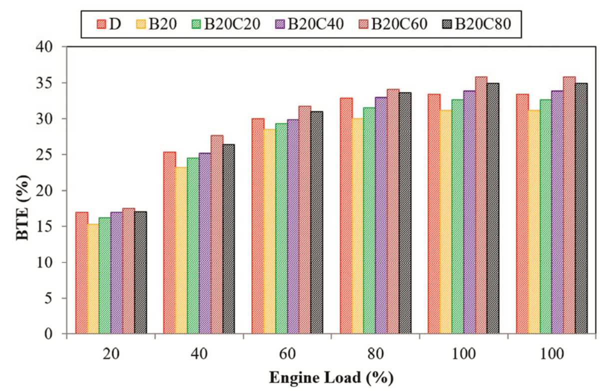

Fig. 2 — Variation in BTE

Variation in BSFC

The impact of CuO nanoparticle addition to B20 on BSFC is depicted in Fig. 3. At 1500 rpm speed, the biodiesel with 20 ppm, 40 ppm and 60 ppm CuO consumed less fuel than B20 under all load conditions,

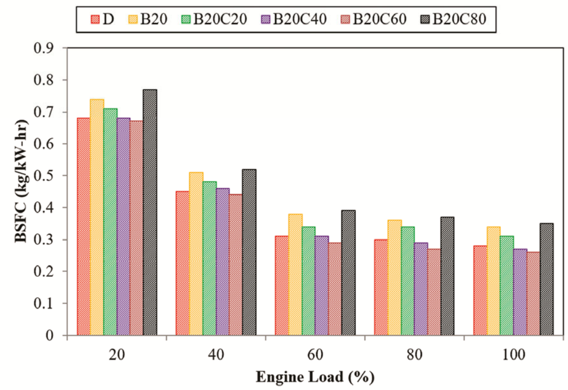

Fig. 3 — Variation in brake specific fuel consumption

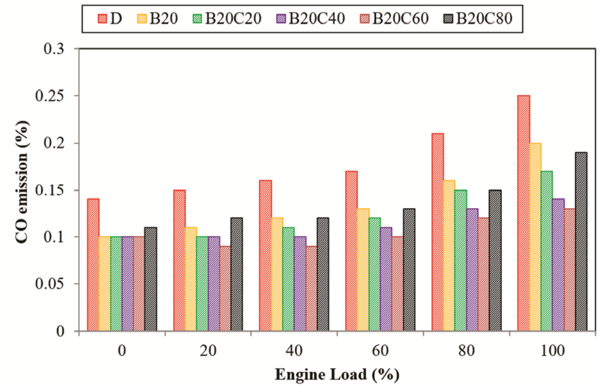

Fig. 4 — Variation in CO emission

while B20C80 consumed more fuel than all other tested fuels. At 100% load, B20, B20C20 and B20C80 consumed more fuel than diesel. When compared to other concentrations, B20 biodiesel with 60 ppm CuO has improved combustion characteristics. This combination consumed a lower quantity of fuel due to improved quality and a shorter ignition delay[39]. The density is improved in biodiesel-diesel fuel, which lowers the heating value of biodiesel blends[40]. In general, adding CuO improves combustion, increases power, and decreases BSFC. At 100% load conditions, the BSFC for B20, B20C20, B20C40, B20C60, B20C80 and diesel are 0.28, 0.34, 0.31, 0.27, 0.26 and 0.35 kg/kW-h, respectively. In comparison to B20, engines operating at B20C20, B20C40, and B20C60 showed 8.82%, 20.59%, and 23.53% reduced BSFC, respectively, and in comparison to diesel, engines operating at B20C40, B20C60 showed 3.57% and 7.14% reduced SFC. The fuel-containing nanoparticles can act as an oxygen donor during combustion[41]. Shaisundaram *et al.* have reported the same behaviour under cerium oxide nanoparticles[42].

Variation in CO emission

Fig. 4 shows the differences in CO emissions caused by changes in loading rates for diesel, biodiesel and nanofuel. With increased load, the CO production level continuously increases. This is caused by the variations in air-fuel ratio[43]. The existence of carbon and oxygen at the level of combustion are the major reasons for the development of CO during combustion. When a fuel is burned, the carbon in it releases CO, which is then transformed into CO_2. If there was less oxygen available, the incomplete combustion resulted in more CO[44]. At partial and full load operating conditions, the concentration of CO emitted from the engine is low for all biodiesel. This phenomenon is connected to the concentration of oxygen and the higher cetane number[45]. These findings demonstrate that CO emission is significantly decreased when the nanoparticle content is increased. The mechanism is ascribed to the addition of CuO encouraging the conversion of CO into CO_2[46]. The wide surface contact areas of the CuO nanoparticles used in this study increase chemical reactivity and decrease the ignition delay dramatically. The ignition delay can be shortened to optimize the combustion process. As a result, CO has decreased[47]. CO emissions at full load for B20, B20C20, B20C40, B20C60, and B20C80 and diesel are 0.25, 0.20, 0.17, 0.14, 0.13, and 0.19%, respectively. The concentration of CO in emitted gas is associated with the amount of OH radicals present during combustion. More CO is reduced as a result of more OH radicals produced with higher CuO concentration. In this study, at 80 ppm dosage level, the OH radical is at its minimum, causing lower CO reduction. A similar trend was observed with rapeseed biodiesel[48].

Variation in HC emission

Fragments of partially burned fuel is the reason for the development of HC emissions. Due to higher oxygen available in biodiesel, numerous researchers discovered that biodiesel-diesel blend results in thorough combustion[49]. The addition of nanoparticle can dramatically lower the formation of unburned hydrocarbon. Higher cetane index and amount of relative air-fuel ratio of biofuel reduce the ignition delay, which drops higher production of HC[50]. The oxygenated additive in the CuO nanoparticles promotes complete combustion compared to diesel. Fig. 5 exemplifies the variation in HC emissions as a function of load. Similar to CO emission, a rise in load causes an increase in HC emission. For all load condition, the lower and higher HC production was

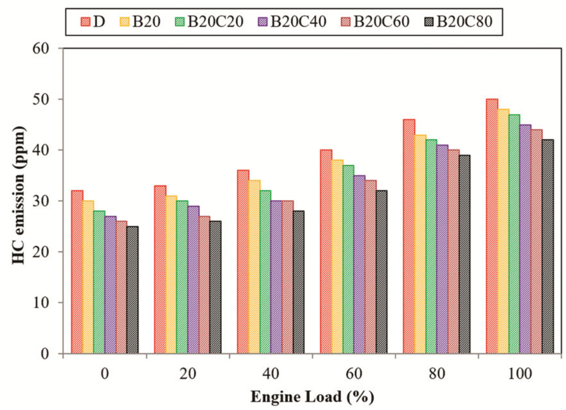

Fig. 5 — Variation in HC emission

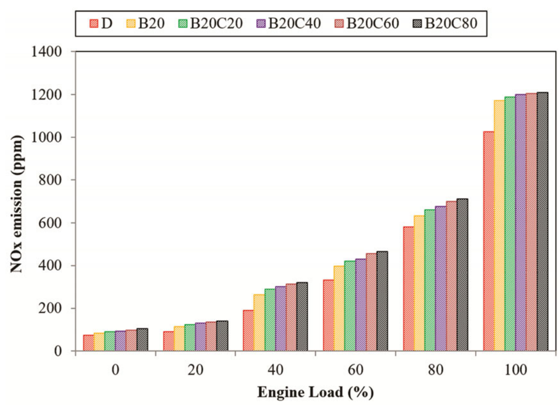

Fig. 6 — Variation in NOx emission

note down for diesel and B20C80, respectively. From Figure, the mean HC emissions of B20, B20C20, B20C40, B20C60, B20C80 and diesel were 48, 47, 45, 44, 42 and 50 ppm, respectively. Compared to diesel, the reduction of HC for the above fuel blend at 100% load is 4, 6, 10, 12 and 16%. In this study the maximum reduction of HC was noted with 80 ppm CuO. The diesel at higher load burn partially leads to the emission of higher HC.

Variation in NOx emission

NOx emissions are caused by nitrogen oxidation at high temperatures. Fig. 6 portrays the difference in NOx emissions. The emission of NOx is a role of temperature of the cylinder. At elevated combustion temperature, the process is closer to stoichiometric and leads to NOx production[51]. The production of NOx is observed as an increasing trend with increased load. With increased load, the temperature of the chamber also increases, resulting increased NOx. For all loads, the use of biodiesel showed increased NOx emissions due to higher oxygen inside the cylinder. The thorough combustion increased the temperature of the chamber. It is noted that the NOx production for diesel is very minimum related to other tested fuels. The NOx is further increased with the increased dosage level of CuO with biodiesel-diesel blend due to higher pressure and temperature[52]. At 100% load condition, the value of NOx in the exhaust showed 1172, 1189, 1201, 1204, 1210 and 1026 for B20, B20C20, B20C40, B20C60, B20C80 and diesel, respectively. Similar trends were also reported by the literature[53,54]. The increased NOx from engine exhaust can be controlled by selective catalytic reduction (SCR) to alter NOx into nitrogen. Moreover, a few other process modifications including low-NOx burners, reburning, combustion staging, gas recirculation, water injection, and low excess air firing can lessen engine NOx emissions.

Conclusion

In this study, engine tests were conducted with the blends of waste cooking oil biodiesel, pumpkin seed oil biodiesel and diesel with CuO. Physical and chemical characteristics of the blends have been found. The tests were carried out from no load to full load, and the corresponding performance and emission characteristics were compared to diesel. With the addition of CuO to the B20 ternary blend, BTE was found to be increased by 13.02%. This improved BTE demonstrates the occurrence of catalytic activity by the nanomaterial. Also, the reduction in BSFC compared to the ternary blend for B20 with the dosage of 20, 40 and 60 ppm was 8.82%, 20.59% and 23.53%, respectively. The use of a ternary blend with CuO was much more helpful in reducing CO and HC emissions compared to diesel. It was also found that NOx emissions decreased dramatically. Thus, changing the engine operating parameters can improve engine performance and reduce harmful emissions.

Nomenclature

D	Diesel
WCO	Waste cooking oil
PSO	Pumpkin seed oil
WCOME	Waste cooking oil methyl ester
PSOME	Pumpkin seed oil methyl ester
IC	Internal combustion
CI	Compression ignition
CuO	Copper oxide
B20	10% WCOME +10% PSOME +80% D
B20C20	B20+20 ppm CuO
B20C40	B20+40 ppm CuO
B20C60	B20+60 ppm CuO
B20C80	B20+80 ppm CuO

ASTM	American society for testing and materials
VCR	Variable compression ratio
BTE	Brake thermal efficiency
BSFC	Brake specific fuel consumption
CO	Carbon monoxide
HC	Hydrocarbon
NOx	Oxides of nitrogen
ppm	Parts per million

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COMPARATIVE ANALYSIS OF WASTE COOKING OIL BIODIESEL MIXED WITH NANOPARTICLE ADDITIVES ON PHYSICOCHEMICAL PROPERTIES AND DIESEL ENGINE PERFORMANCE

Effect of different configurations of hybrid nano additives blended with biodiesel on CI engine performance and emissions / Gad, M. S., Hashish, H. M. A., Hussein, A. K., Ben Hamida, M. B., Abdulkader, R., & Nasef, M. H.

Scientific Reports
Volume 14 (2024) 19528 Pages 1-16
https://doi.org/10.1038/s41598-024-69957-5
(Database: Nature Portfolio)

scientific reports

OPEN

Effect of different configurations of hybrid nano additives blended with biodiesel on CI engine performance and emissions

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The use of nano additives to improve the cold properties of biodiesel is encouraged by its drawbacks and incompatibility in cold climate. Waste cooking oil (WCO) was transesterified to create biodiesel. A 20% by volume was used for combination of diesel and methyl ester. Current study aims to evaluate diesel engine emissions and performance. TiO_2, alumina, and hybrid $TiO_2 + Al_2O_3$ nanoparticles are added to WCO biodiesel mixture at 25 mg/liter. When B20 combined with nano materials such as TiO_2, Al_2O_3, and hybrid nano, the highest declines in brake specific fuel consumption were 4, 6, and 11%, respectively. As compared to biodiesel blend, the largest gains in thermal efficiency were 4.5, 6.5, and 12.5%, respectively, at maximum engine output power. Introduction of TiO_2, Al_2O_3, and hybrid nano particles to B20 at 100% load resulted in the highest decreases in HC concentrations up to 7, 13, and 20%, and the biggest reductions in CO emissions, up to 6, 12, and 16%. Largest increases in NOx concentrations at full load were about 7, 15, and 23% for B20 + 25TiO_2, B20 + 25 Al_2O_3, and B20 + 25TiO_2 + 25 Al_2O_3, respectively. Up to 8, 15, and 21% less smoke was released, correspondingly, which were the largest reductions. Recommended dosage of 25 ppm alumina and 25 ppm TiO_2 achieved noticeable improvements in diesel engine performance, combustion and emissions about B20.

Keywords WCO biodiesel, Hybrid nano, Performance: combustion chracteristics, Emissions

Due to risks from global warming, fossil fuel resources shortage, stronger environmental laws in the global energy market and the use of renewable energy sources have been increased during the past ten years. Biodiesel is one of the forms of sustainable energy. Biodiesel is frequently used by scientists as a substitute fuel. Because of its higher density, lower cetane number, and lower calorific value, pure biodiesel cannot fully replace conventional diesel in diesel engines. However, it may be utilized in diesel engines. Using biodiesel in cold areas might cause problems with the fuel filter and injection system. Issues with fuel atomization and spray were observed[1].

Numerous studies indicate that high viscosity fuels have a number of detrimental consequences on diesel engines. Opium poppy (OP) oil methyl ester-diesel mixtures' impact on the efficiency and emissions of CI engines was investigated. The thermal efficiency of the OP10 and OP20 blend ratios fell were decreasesd by roughly 5.73% and 13.05% related to crude diesel due to the lower calorific value of OP biodiesel. CO emissions were reduced by OP10 and OP20, however NO_X emissions were raised. In low temperature and cold start circumstances of diesel engine, impact of iron nano materials added to B20 on carbon monoxide and HC concentrations was studied[2]. Using biodiesel in marine operations offers benefits such as reduced carbon emissions, enhanced air quality, increased energy security, support for sustainable agriculture, and alignment with global environmental goals.

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Using biodiesel in the marine industry is a viable opportunity to significantly advance environmental stewardship and sustainability[3]. Since most engines use extra biodiesel and has a reduced thermal efficiency due to its high viscosity and carbon residue, it is imperative to determine the appropriate alternative fuel and ideal mixture percentage for diesel engine combustion. When rubber seed oil (RSO) was used in dual fuel mode with hydrogen and diethyl ether, smoke and nitrogen oxides were greatly decreased and engine performance was improved[4].

By using nano materials, these problems are remedied while also improving engine performance, combustion, and exhaust pollution reduction. Another breakthrough in fuel development is the result of advances in nanotechnology. Nanoparticles are blended with liquid fuel using a novel process known as modified fuel. Iron nanoparticles were combined with palm methyl ester and B20 to create 500 ppm diluted homogenous mixture. The viscosity of blend biodiesel was reduced by 14% with the use of iron nanoparticles. BSFC, CO, and hydrocarbons emissions were decreased by 10%, 42%, and 54%, respectively.The declines in CO and HC emissions from 0 to 10 °C were up to 31% and 23.7%, respectively, while the increase in nitrogen oxide emissions were from 79 to 90 ppm[5]. Various diesel fuel/mono ethylene glycol supported emulsion (MEGSE) molar ratios was studied. At 15.6% MEGSE, the engine's output was at its peak and its exhaust emissions were at their lowest[6].

The experiments were done to find the best blending for enhanced fuel characteristics, improved engine combustion, and declined exhaust emissions. Impact of hybrid ZnO:TiO_2, TiO_2:Al_2O_3, CeO_2:CuO, and MnO_2:Al_2O_3 in various ratios was examined. The biofuel and the sol–gel process were used to create the nanoparticles, which were then characterised by scanning electron microscopy (SEM).By combining nanoparticles with the gasoline, BTE was raised from 1.11 to 2.21%. In comparison to standard diesel oil, the combined biodiesel with nano additions had lower NOx, HC, and CO emissions by 16.29–23.76%, 14.07–17.32%, and 5.51–8.27%, respectively[7]. The impact of biodiesel-diesel blends of 25 and 50% on the emissions of marine diesel engines at varying loads was investigated. Biodiesel blends increased nitrogen oxides emissions while reducing HC and smoke concentrations are due to the oxygen concentration in fuel[8]. Limits of using methyl ester in CI engines were evaluated by included high NOx, cold weather, low cetane number, high viscosity, engine parts, fuel tanks, and fuel filters replacement[9]. Methyl ester properties may be enhanced by the utilization of nano materials**.** Impact of magnetic nanoparticles inclusion to biofuel (40 and 80 vol.%) on emissions and CI engine performance were studied. With the inclusion of nano materials, the engine's performance and combustion considerably were enhanced, and NOx emissions significantly were decreased[10].

Diesel engine emissions and performance using mixed of waste frying oil (WFO) methyl ester and crude diesel at blended ratios of 0%, 5%, 20%, and 100% were studied. As the biodiesel mixture ratio increases, the engine brake power and thermal efficiency were decreased[11]. WFO biodiesel use results in higher NO, lower CO_2 and CO emissions[12]. Areca nut husk (ANH) nano additive impact on engine pollutants and performance were displayed[13]. PGB-derived oil water diesel emulsion (D10EPO) mixture was used to power the engine. ANH was combined at 5, 10, and 15 ppm concentrations. Compared to D10EPO, the specific fuel consumption was reduced by 9.1% and NOx emissions was increased. In comparison to D10EPO, CO, HC, and smoke for D10EPO of 15 ppm dose were declined by 17.9, 14.7, and 17.6% at full load, respectively. Experimental research on the effects of titanium dioxide (TiO_2) addition to Mahua oil biodiesel on engine's emissions and performance was done**.** When compared to the other blends, the Mahua oil biodiesel mixture with 150 ppm TiO_2 reduced CO emissions. When compared to other mixtures, biodiesel containing TiO_2 (150 ppm) has the lowest NOx emissions. Nano titanium oxide at a concentration of 150 ppm can be utilised as a useful addition to reduce emissions while boosting engine performance[14]. Effects of main alcohols as ethanol, methanol, n-butanol and aluminium inclusions on emissions at various loads and constant speed were examined**.** Al_2O_3 nanoparticles were introduced to alcohol/diesel blends at ratios of 25–100 ppm. The lowest levels of carbon dioxide, nitrogen oxides, and smoke were produced by inclusion of methanol and nano additives[15].

The use of silver thiocyanate from 7.23 to 7.98 nm as a supplement to enhance diesel engines' performance and emissions was studied. Several diesel/WCO biodiesel (D50B50) blends containing 200, 400, and 600 ppm silver thiocyanate nanoparticles were created. In comparison to other mixtures, a dose of 400 ppm nanosized silver thiocyanate exhibits greater performance and emissions.If 400 ppm concentration of nanoparticles were utilised, the improvement rate in brake thermal efficiency was 11.6%. Dose of 600 ppm of silver thiocyanate nanoparticles produced 20.7% decrease in exhaust gas temperature. At 600 ppm and 200 ppm, respectively, concentrations of carbon monoxide and UHC were lowered by ratios of 50.3% and 40.0%. In compared to pure diesel D100B0 and a D50B50 mixture, 400 ppm of silver thiocyanate nano materials reduced the smoke opacity by 55.3% and 32.0%, respectively[16]. Aluminium oxide nanoparticles at various dose levels were studied for their impact on honge oil biodiesel and diesel oil mixtures. Preparation of nanofuel blends involved dispersing of aluimena in HOME(B20). Sodium dodecyl sulphate (SDS) was utilised to stabilise the diffusion of these nanoparticles in fuel mixtures. Aluiminum oxide nano additives doses of 20, 40, and 60 ppm were found in B20. Nano materials at a concentration of 40 ppm in methyl ester blend significantly reduced CO, HC, and smoke concentrations by 47.43%, 37.72%, and 27.84%, respectively. All nanofuel blends' higher NO_X emissions are brought on by higher flame temperature and oxygen content[17].

Influence of introducing nanoparticles to biodiesel and diesel mixtures on diesel engine and exhaust concentrations were described. In comparison to methyl ester, application of nanofuel resulted in an increase in NO_Xemissions from 2.78 to 19.01%. The decline was brought on by the nanoparticles catalytic activity and secondary atomization which raise the rate of oxidation[18]. Utilization of nanoparticles in CI engine using B20 waste frying oil was studied**.** BTE, soot, and CO concentrations were increased by nano particles addition[19]. Engine performance and emissions powered by B20 WCO biodiesel-diesel mixtures doped with nanomaterials were depicted[20]. At 10 N.m engine load and nano additive concentration of 98 ppm, the engine operates at its best condition. Inclusion of NPs improves the biodiesel's HC, CO, and NO_X emissions. Impact of mixed nano particles on diesel engines was studied. High performance fuel (HPF), combination of biodiesel, diesel, and ethanol that also contains alumina nanoadditives, was used to power the engine. Different injection timings of

21°, 22°, 23°, and 24° TDC are applied to HPF. The ideal working condition was blending with a 20 ppm alumina nano addition at 22° TDC because it boosted performance while minimising HC and CO emissions[21]. Impact of nano TiO_2 and Al_2O_3 inclusions to crude diesel in percentages of 25, 50, 100, and 150 ppm was shown. BTE was raised from 18.9 to 24.25%[22]. The behaviour of C. racemosa algal oil biodiesel with nano additive in diesel engines was researched**.** Due to the lowered viscosity and enhanced volatility of the blend, which improves atomization, vaporisation, and air–fuel mixing formation, C. racemosa algal oil biodiesel-diesel mixture with nano additions can be used as substitute fuel in CI engine[23]. The impact of ternary blend of 80% D80E10nB10, 10% ethanol, and 10% n-butanol on engine combustion and emission was studied**.** Nano TiO_2 addition increased the thermal efficiency by 23.24%[24].

The effects of adding Fe_2O_3 and Al_2O_3 nanoparticles (30, 60, and 90 ppm) as well as Fe_2O_3–Al_2O_3 hybrid nanoparticles to pure diesel fuel on diesel engine's performance, combustion, and emission characteristics were studied. The findings demonstrated that the inclusion of the nanoparticles enhanced the peak cylinder pressure by 4% and improved the heat release rate by 15% when compared to pure diesel. The effects of Fe_2O_3 fuel blends on brake power, BTE, and CO emissions were greater than those of Al_2O_3 fuel blends; they increased power and thermal efficiency by 7.40 and 14%, respectively, and decreased CO emissions by 21.2%. Additionally, blends containing Al_2O_3 nanoparticle additives performed better in reducing of BSFC (9%), NOx (23.9%), and SO_2 (23.4%) than blends without such additives[25]. Among the most well-known biofuels for use in diesel engines is biodiesel. Because free fatty acids, monoglycerides, and diglycerides are components of biodiesel and contribute to improve its lubricating characteristics and reduce friction more than other mixtures. The friction coefficient was decreased as the proportion of biodiesel increased. Because lower viscosity leads to oxidation, which facilitates the biodiesel's exposure to air at higher temperatures, friction and wear of diesel mixtures including biodiesel increase at higher rotational speeds. When it comes to lubricity, biodiesel outperforms conventional fuel mixtures[26].

It is clear from the previous evaluation of the literature review, several research investigations have been done to show and further throwlight on the effect of introduction different types with different configurations of nanoparticles to biodiesel blended with diesel oil on the emissions and performance characteristics of diesel engines. Pure biodiesel may be used in diesel engines, but it cannot completely replace conventional diesel due to its greater density, lower cetane number, and lower calorific value. Injection system and fuel filter issues arise when biodiesel is used in cold climates. There were produced problems in fuel atomization and spray. These issues are resolved by adding nano compounds, which also enhance engine performance, combustion and lower exhaust emissions. The introduction of nano additives highlights the disadvantages and limitation of using biodiesel. Disposal of waste cooking oil (WCO) requires higher cost and causes pollution and risks in water sources and environment. Other studies do not see waste cooking oil as edible, despite the assertions made in prior studies by several other researchers that it is not edible. Consequently, it might be argued that utilising the oil as a feedstock for biodiesel in safer application. Waste oil can be transformed to useful energy. The analysis reveals that, however, no studies on the performance and emissions of diesel engines employing mixtures of WCO methyl ester and diesel with nanoparticle additions such TiO_2 and aluimena have been documented. Previous research has mostly concentrated on analyzing different types of nano additives or their concentrations. Nevertheless, not all of the intended benefits could be obtained by using a single kind of nano additive. Investigating the combination of these two nanoadditives as Al_2O_3 and TiO_2 is necessary to fill in any research gaps that may emerge. Hybrid nanoparticles can improve a base fluid's physical, chemical, thermal, evaporation and heat transfer characteristics. As a result, the present experimental investigation specifically uses B20 diesel mixture with biodiesel to examine how hybrid nanoparticles TiO_2 and Al_2O_3 additions affect CI engine emissions, combustion and performance characteristics. Waste cooking oil was converted to biodiesel and blended with diesel oil in 20% by volume. Aluimena and TiO_2 nano additives of 25 mg/litre concentrations were blended with B20.

Materials and methods

Biodiesel production

WCO can not be utilised directly in CI engines due to its high viscosity, so it is converted to biodiesel. The methyl ester and the oil are divided during transesterification. By preheating the oil to 110 °C, WCO was filtered and the moisture iseliminated. After that, the oil was added to a flask that was held steady by a thermometer, condenser, and magnetic stirrer. 1.5% of potassium hydroxide (KOH) by weight was dissolved in 1:9 molar solution of methanol and alcohol to obtain methoxide. To create the glycerin and methyl ester, the oil and methoxide combination were vigorously agitated for 90 min at 60 °C[27]. Mixture was left to sit for 24 h in the separating funnel in order to separate the ester about glycerin[28]. The catalyst, impurities, and unreacted methanol were flushed away with warm water. After the water had been removed, the biodiesel was dried using a rotary evaporator. Biodiesel and diesel oil were combined at a volume ratio of 20%.

Biodiesel blends with nano additives preparation

The biodiesel mixture included titanium oxide (TiO_2) and alumina (Al_2O_3) as additions. The nanomaterials were supplied by Nanotech Egypt. Scanning electron microscope (SEM) (Model: Quanta FEG250) and a transmission electron microscope (TEM) (Model: JOEL JEM-2100) were used to examine the internal structure of nano additives. Figures 1 and 2 display TEM and SEM photos, respectively. Alumina and titanium oxide both have typical diameters of 10 and 35 nm in TEM images, indicating their spherical form. By using ultrasonication, the nano additives were evenly distributed throughout the biodiesel mixture. The mixture was continually stirred for 30 min to ensure even dispersion of additives. A biodiesel mixture with nano material content of 25 mg per litre was created. Using good dispersion and stability conditions, titanium and alumina nanoparticles were mixed in the current study with WCO biodiesel of 20% (B20), B20 + 25 TiO_2, B20 + 25 Al_2O_3, and B20 + 25 Al_2O_3 + 25 TiO_2.

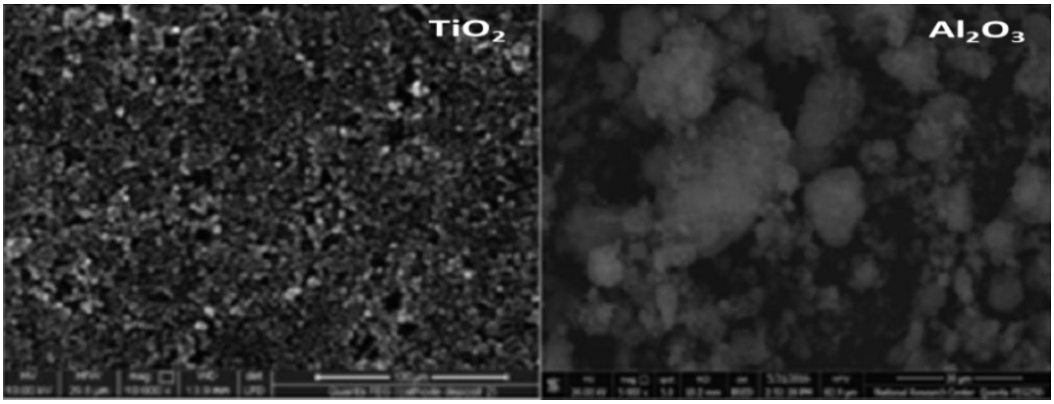

Figure 1. SEM image of Al_2O_3 and TiO_2.

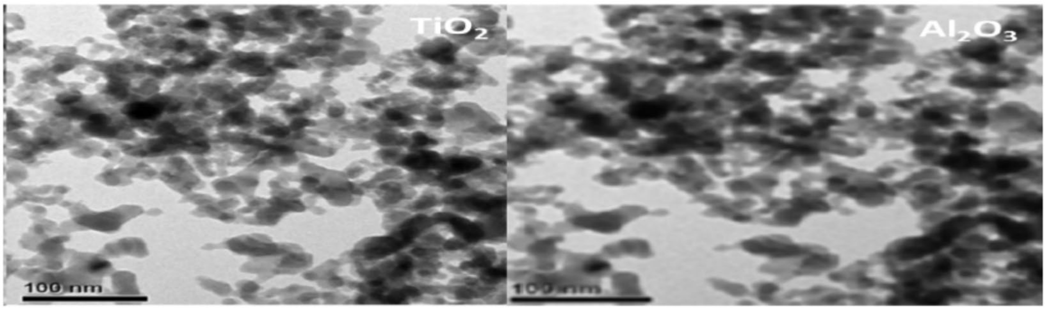

Figure 2. TEM image of TiO_2 and Al_2O_3.

Nano materials were supplied from Nanotech company, Egypt in the form of powder, water soluble, spherical shape and white color. The bulk densities of TiO_2 and Al_2O_3 are 0.24 and 3.95 gm/cm^3, respectively. The averge size from TEM images of aluimena and titanium oxide are 10 ± 2 nm and 35 ± 5 nm, respectively. Methyl ester and diesel oil blend with nano additives characteristics were stated in Table 1. Viscosity and density of Al_2O_3 were lower than TiO_2. Lower calorific value and cetane number of Al_2O_3 were greater than TiO_2. Improved physical and chemical properties of alumina about TiO_2 were shown. Average size of alumina is lower than titanium oxide which improves the dispersion, homogeneity and air- fuel mixing. Higher oxygen content in alumina about TiO_2 leads to the highest emissions reductions. All these advantages of Al_2O_3 about TiO_2 lead the highest engine performance improvement and emissions reduction.

Experimental test rig

A four-stroke, single-cylinder, air-cooled diesel engine with a maximum output of 7.5 kW at 1500 rpm was used for the testing. The engine has 100 mm diameter, 105 mm stroke, and 17.5:1 compression ratio. Figure 3 displays a schematic description of the experimental equipment used in this investigation. AC generator with highest power of 10.5 kW was connected with the test engine to show the engine's maximum output power. Flow rate of intake air is observed using an air box equipped with an orifice. The amount of time needed to consume a fixed measured fuel volume of 25 cm^3 was used to compute the fuel flow rate. In order to evaluate the intake air and exhaust temperatures, K type calibrated thermocouples were utilised. A gas analyzer (Germany's MRU DELTA

Fuel properties	Biodiesel	Diesel oil	B20	B20 + 25 TiO_2	B20 + 25 Al_2O_3
Density at 15 °C, kg/m^3 (D1298)	878	830	844	849	847
Kinematic viscosity at 40 °C, cSt (D445)	4.2	2.73	2.8	3.1	3
Flash point, °C (D92)	148	58	79	80	81
Cetane number	52	48	49	50	51
Pour point, °C (D2500)	− 7	− 33	− 21	− 20	− 20
Lower heating value, MJ/kg (D240)	39.8	42.7	41.9	42.1	42.2

Table 1. WCO methyl ester and its mixtures properties.

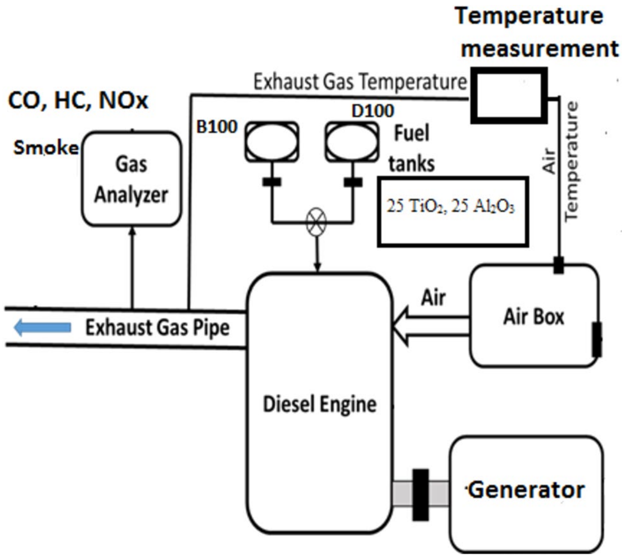

Figure 3. Test setup schematic diagram.

1600-V model) was used to monitor the emissions of HC, NOx, and CO. To measure smoke emission, a smoke metre (Model: OPA, France) was employed. When fully loaded, an engine operating between 800 and 1800 rpm was used for the testing. A water-cooled piezoelectric pressure transducer with an accuracy of 1.118% and sensitivity of 16.5 pc/bar was used to monitor cylinder pressure up to 250 bar. The piezoelectric pressure transducer was flush mounted with the cylinder head. The pressure measurements across 125 engine cycles were averaged. Using a data acquisition system, the pressure crank angle diagrams were recorded and examined to determine the combustion parameters. The engine was then warmed until the exhaust temperature was consistent without loading with pure diesel fuel. After switching the fuel line that was being tested, the engine load was then managed. Readings were eventually recorded after the steady state condition was reached. Each test was measured three times to check for repeatability errors.Calculations showed that the greatest degree of uncertainty for the entire experiment was 3.33%. To decrease repeatability errors, each measurement was repeated three times. Biodiesel engine performance indicators including BSFC, EGT, BTE, as well as exhaust CO, HC, smoke, and NOx concentrations were tested.

Throughout the testing, the load fluctuated between no load and full load, yet the rated speed of 1500 rpm was consistently maintained. To ensure the stability of the engine's state, pure diesel fuel was first used for the warm-up, and the engine was run without load until the exhaust temperature was stabilised. To ensure the precision and coherence of the results, each test was conducted three times. The thermocouples had a notable range of 0–1300 K, with an uncertainty of ± 0.15 and a precision of ± 1 °C. The load indicator covered a range of 250–5000 Watt with an accuracy level of ± 10 Watt and an uncertainty of ± 0.2. The following ranges were used to test exhaust gases: NO (1–4000 ppm), HC (0–20,000 ppm), and CO (0–10%). There was ± 0.2 uncertainty and ± 1, ± 1, and ± 0.5 accuracy for each gas. With a precision level of ± 1 and an uncertainty of ± 2, the pressure transducer measured pressure between 0 and 250 bar. Based on the calculation of Eq. (1), the total uncertainty of the experiment was found to be maximum of 3.33%.

$$W_R = \left[\left(\frac{\partial R}{\partial x_1} w_1 \right)^2 + \left(\frac{\partial R}{\partial x_2} w_2 \right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n} w_n \right)^2 \right]^{1/2} \tag{1}$$

The whole uncertainty of the test rig is represented by W_R. The independent and dependent measurements are indicated by the parameters R and x, respectively.

Results and discussions

At constant loads of 0%, 20%, 40%, 60%, and 80%, the engine was put through the tests while running at rated speed of 1500 rpm. WCO biodiesel-diesel mixture (B20) with TiO_2 and Al_2O_3 nanoparticle concentrations of 25 mg/l are the two fuels utilised to run the engine. In order to achieve best fuel utilisation in diesel engines, the calorific value and kinematic viscosity requirements for effective atomization, vaporization and combustion are met by the 20% blending ratio. These experimental tests are used to evaluate the engine emissions and performance parameters.

Carbon monoxide (CO) emission

Figure 4 studies how CO concentrations of methyl estermixtures blending with nano additives varies with load. Up to around 60% load, CO concentration steadily declines with the load increase; after that, the trend shifts to

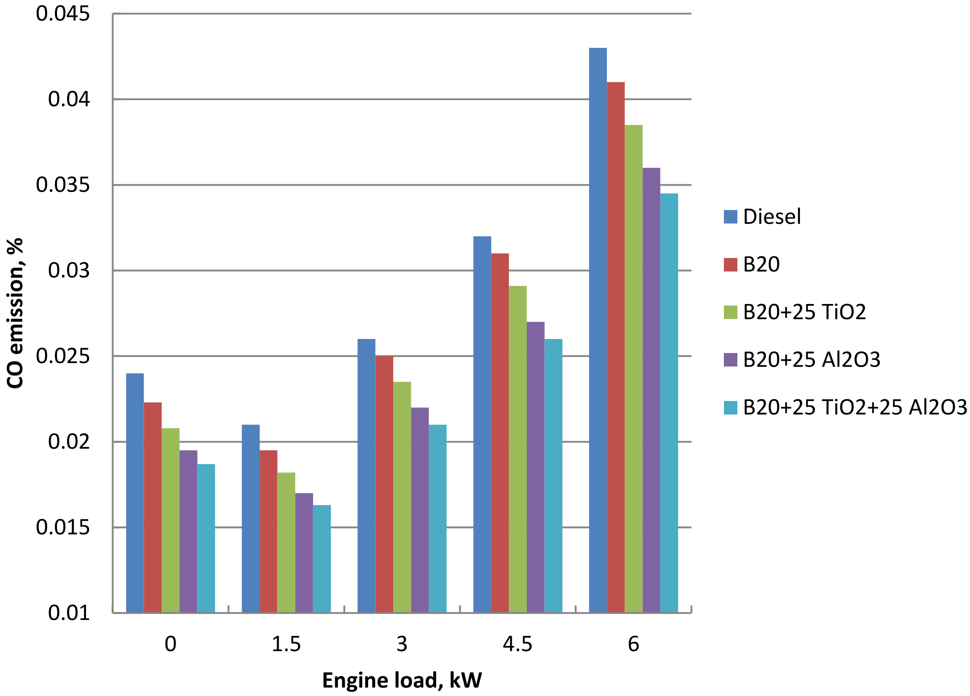

Figure 4. Impact of nano materials mixed with B20 on carbon monoxide emission.

increased CO concentration with load. More fuel was delivered to the engine under situation of high load, this may be the result of incomplete combustion. Rich combustion conditions at high loads results in increased CO emissions for all evaluated fuels. Due to the increased oxygen content of biodiesel compared to conventional diesel fuel, there was a drop in CO emissions at all engine loads[23]. The nanomaterial's increased surface contact area reduces the ignition delay and increases chemical reactivity. The surface reactivity of nanoparticles ensures that combustion is complete and lowers CO when combined with the nano additive's oxidation capabilities. It is important to note that, compared to B20, blended biodiesel with TiO_2 and Al_2O_3 nanoadditives has much lower carbon monoxide concentrations. This can be explained by the fact that the decreased ignition delay of nanoparticles boosts rapid combustion processes[29]. When compared to diesel without nanoparticles, the necessary fuel–air mixing and improved fuel atomization to ensure complete combustion have a significant impact on lowering CO concentrations[30]. Increasing the amount of titanium oxide and alumina nanoparticles lowers the CO emission. Hybrid nano additives of aluiminum and titanium oxides improve the thermal, physical and chemical properties about single nano material. At 100% engine load, the combination of alumina and titanium oxide nanoparticles reduces CO on average respectively by 6% for B20 + 25 TiO_2, 12% for B20 + 25 Al_2O_3, and 16% for B20 + 25 TiO_2 + 25 Al_2O_3.

Oxides of nitrogen (*NOx*)

Maximum heat release rate, combustion time, and burning temperature all have major impact on NOx generation in engines. Figure 5 depicts the variance in NOx emission for B20 engine running at constant speed with and without titanium dioxide and alumina nanoparticles. Because of the higher cylinder temperature and adiabatic flame temperature produced under high load, NOx emissions were increased with load for all examined fuels[31]. When mixtures of biodiesel feedstock are used, the higher combustion temperatures that result from the greater heat released rate cause the increase in NOx emissions. Across the whole engine load range, the B20 emits more NOx. At all operating circumstances, NOx emissions for B20 with nanoparticles were steadily higher than for B20 without nanoparticles[32]. The catalytic behaviour of nanoparticles, which encourages heterogeneous combustion and lessens the breakdown of hydrocarbon molecules, is most likely to increase the likelihood of thermal NOx generation.With increasing engine load, this impact is lessened and the likelihood of thermal NOx generation is increased. Nitrogen oxides are created in the reaction zone during the diffusion combustion phase. Amount of nanoparticles has very an impact on biodiesel blends' ability to increase NOx[33]. Aluiminum and titanium oxide hybrid nanoadditives enhance the thermal, physical, and chemical characteristics of a single nanomaterial. At peak load, the nano materials mixing with methyl ester mixture B20 exhibits average increase in NOx of 7% for B20 + 25 TiO_2, 15% for B20 + 25 Al_2O_3, and 23% for B20 + 25 TiO_2 + 25 Al_2O_3.

HC emission

Figure 6 displays the HC emissions of a biodiesel blend containing nanoparticles at various engine brake power. Since there is substantially less oxygen and more fuel at higher loads, HC trends showed decreased emissions at lower engine loads followed by an increase at greater engine loads. The greatest levels of HC were released

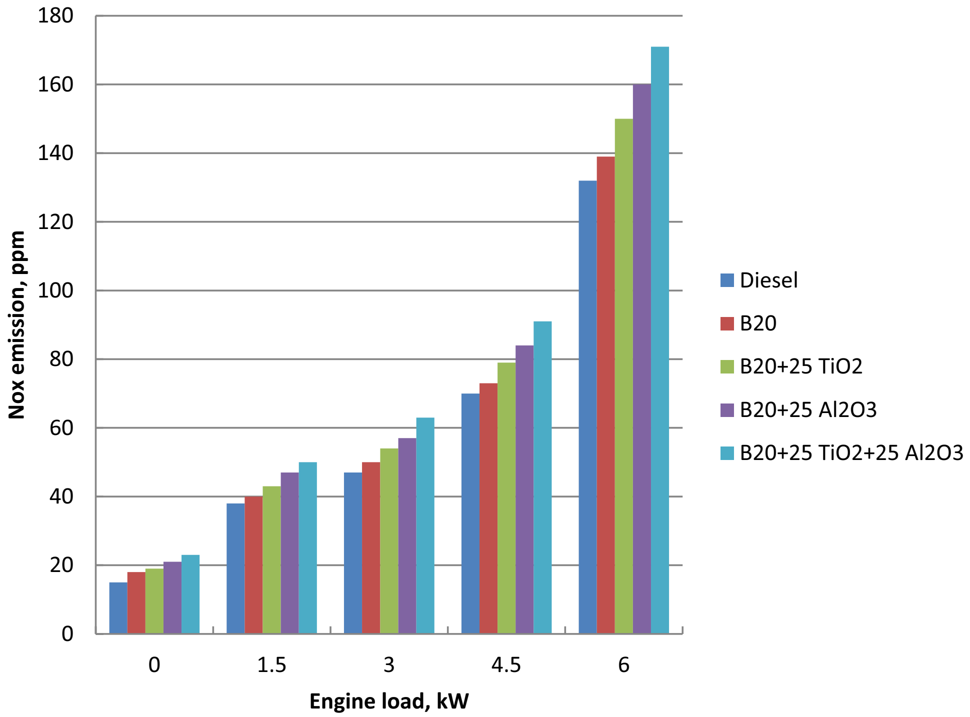

Figure 5. Influence of nano materialsmixed with biodiesel on NO_xconcentration.

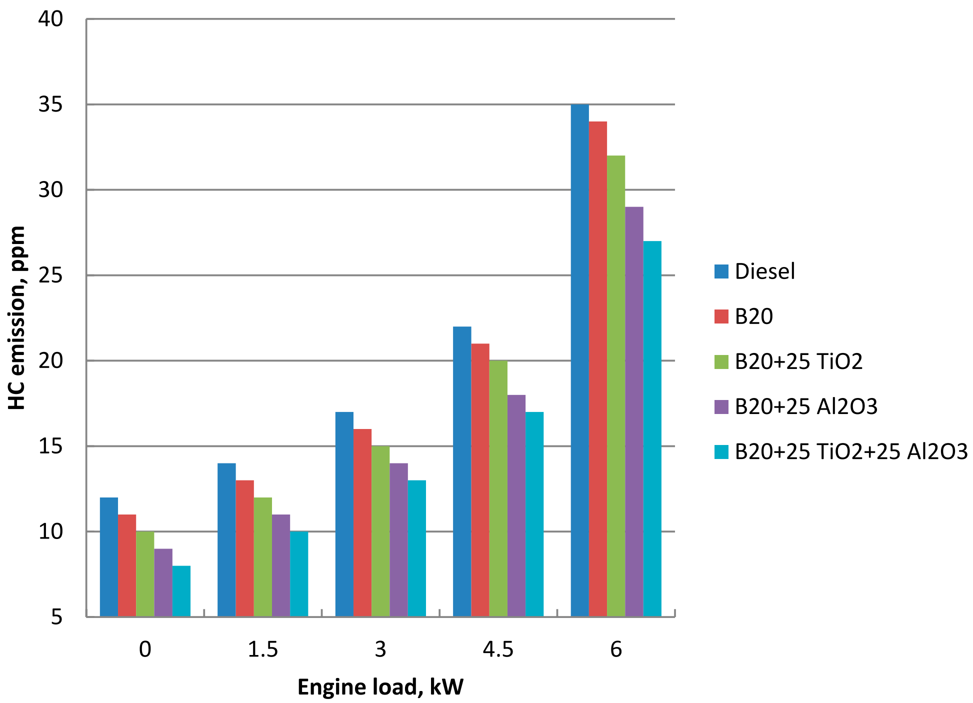

Figure 6. Influence of nano particlesinclusionon hydrocarbons concentrations.

at greater engine loads due to decreased oxygen availability and increased fuel consumption. In comparison to diesel oil, all of the assessed biodiesel feedstock blends have lower HC emissions due to their shorter ignition delay, higher cetane number and higher oxygen content[34]. Adding nano additions to the biodiesel blend increases its surface to volume ratio, air–fuel mixing degree, vaporization, and catalytic activity. These improvements contribute to an efficient burning process with reduced HC emissions. The fast ignition of biodiesel resulted in the decrease in HC emissions from diesel oil. Nano additions improve fuel–air homogeneity and vaporisation when added to biodiesel blends[35]. The subsequent fuel atomization is encouraged by the nanoparticles' lower size. This enables complete combustion and enhances reactant mixing. Catalytic activity, surface reactivity and surface-to-volume ratio all promote combustion and lessen the amount of unburned hydrocarbons produced[36]. The introduction of nanoparticles led to the improvements in fuel oxidation and lower activation temperature for carbon combustion. Aluiminum and titanium oxide hybrid nanoadditives enhance the thermal, physical, and chemical characteristics of a single nanomaterial. When compared to a biodiesel mixture, nanoparticles of B20 + 25 TiO_2, B20 + 25 Al_2O_3, and B20 + 25 TiO_2 + 25 Al_2O_3 each reduced HC emissions by 7, 13, and 20%, respectively when used at highest engine brake power.

Smoke opacity

Variations in smoke of tested fuels across the engine output power is shown in Fig. 7. Due to rising fuel consumption and rich air–fuel mixture, smoke concentrations were increased with the engine load increase. Because biodiesel blends include more oxygen than crude diesel, they burn more efficiently and produce less smoke. High concentrations of nano additives enhance fuel–air homogeneity and accelerate vaporization development when applied to biodiesel[37]. Furthermore, the nanoscale size of nano aluminum oxide enhances the secondary fuel atomization. As a result, this enhances reaction mixing and guarantees improved combustion. Difference in smoke concentrations between the waste cooking biodiesel blend and crude diesel is because of the oxygen presence which improves combustion[24]. Improved combustion, shorter ignition delay and higher fuel combustion during the combustion diffusion stage are responsible for the decrease in smoke. Utilization of nano particles results in catalytic reactivity and larger surface area to volume ratio, which also enhance ignition, combustion characteristics, and minimise smoke[28]. Hybrid nano additives of aluiminum and titanium oxides improve the thermal, physical and chemical properties about single nano material. In relation to B20 at full load, addition of TiO_2, Al_2O_3, and hybrid nanoparticles to waste cooking biodiesel blends reduces smoke by up to 8, 15, and 21%, respectively.

Brake specific fuel consumption (BSFC)

This section discusses the performance aspects of methyl ester mixture in tested engine, both with and without nanoparticles. Figure 8 illustrates how BSFC varies depending on engine load and the different used fuels. All fuels shown an inverse connection between specific fuel consumption and engine load.

Brake specific fuel consumption was increased for biodiesel blend about diesel oil due to the greater density, viscosity and lower calorific value. All these leads to the problems in fuel atomization and vaporization. Because of how nanoparticles affect the physical characteristics of fuel and shorten the ignition delay, the blended biodiesel's BSFC was lower than diesel and WCO biodiesel. Because of the better combustion and catalytic activity brought about by the higher surface/volume ratio, less fuel was used[38]. By adding nanomaterials, the fuel's physical delay and evaporation time were decreased, and its attributes relative to pure biodiesel were enhanced. The air–fuel mixing and micro-explosion are enhanced by the addition of alumina and titanium oxide. Additionally, it falls with the addition of nanoparticles, and this fall becomes more dramatic with higher nanoparticle concentrations since titanium oxide and aluimena nano additives improve combustion efficiency and the atomization

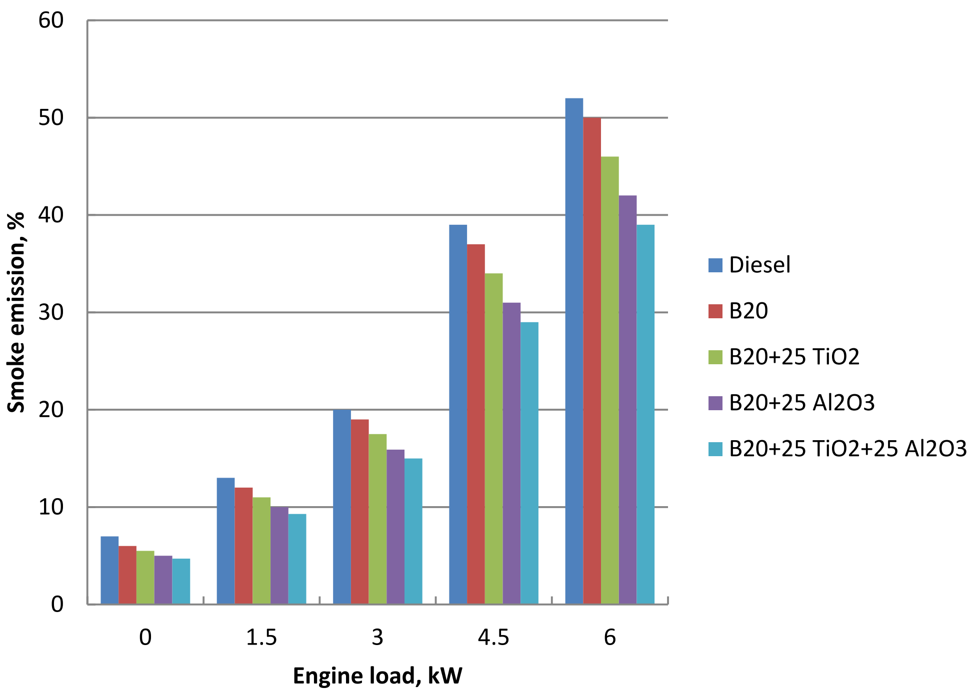

Figure 7. Smoke emissions of nano materials blended with B20.

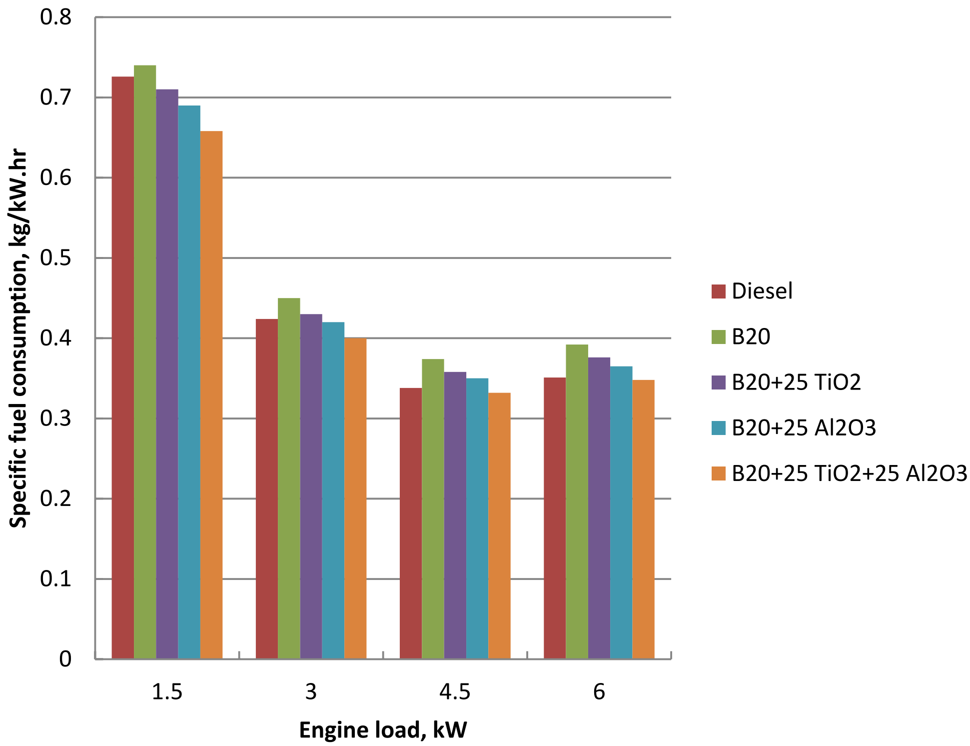

Figure 8. Nano additives inclusion effect on BSFC.

process[39]. The higher oxygen supply provided by nanoparticles, which is required to complete the chemical processes, may be the cause of drop in BSFC. Incorporating nanoparticles lessens the buildup of carbon residue, which lowers the cylinder's friction losses and lowers fuel consumption. The engine requires more fuel than diesel engine to yield the same output power because of biodiesel's higher molecular weight and lower calorific value. Decrease of BSFC for blending biodiesel with nano may be ascribed to the quick evaporation, which led to the enhancement in combustion efficiency[40]. Aluiminum and titanium oxide hybrid nanoadditives enhance the thermal, physical, and chemical characteristics of a single nanomaterial. In comparsion to B20 at full load, waste cooking biodiesel blends with nano additions B20 + 25 TiO_2, B20 + 25 Al_2O_3, and B20 + 25 TiO_2 + 25 Al_2O_3 achieve BSFC reductions of up to 4, 6, and 11%, respectively.

Brake thermal efficiency (BTE)

Figure 9 illustration of BTE for methyl estermixture and nano fuels at varying engine loads shows that it rises as engine load rises. This is true since BSFC decreases as engine output power rises. The higher density, higher viscosity, and lower calorific value of biodiesel mixture over diesel oil resulted in the increase in brake-specific fuel consumption. All of them contribute to the atomization and vaporization issues with fuel. The efficient combustion and energy conversion of fuel is enhanced by the use of nanomaterials. An increase in the surface to volume ratio of the nanoparticles led to an increase in the rate of heat transfer[23]. The dispersion and spread of injected fuel droplets are facilitated by the presence of nano additives. Both fuel air mixing and combustion properties are enhanced by the presence of nanoparticles. Carbon deposits were oxidized and less fuel was used when nanoparticles were present. Compared to pure diesel, the diesel–biodiesel nano mixtures have higher thermal efficiency[41]. The dose of nanoparticles in the fuel was increased, resulting in enhanced combustion and efficient energy transfer from fuel to usable work. Higher oxygen supply provided by nanoparticles, which is required to complete the chemical processes, may be to blame for the decline in BSFC. By using nanoparticles, the accumulation of carbon residue is reduced, which minimizes friction losses in the cylinder and reduces fuel consumption[22]. Hybrid nano additives of aluiminum and titanium oxides improve the thermal, physical and chemical properties about single nano material. At full load, biodiesel mixture B20 with titanium oxide nano materials (B20 + 25 TiO_2, B20 + 25 Al_2O_3, and B20 + 25 TiO_2 + 25 Al_2O_3) demonstrates average increases in BTE of 4.5%, 6.5%, and 12.5%.

Exhaust gas temperature (EGT)

Figure 10 displays EGT for mixtures of diesel–biodiesel, and nano additives at various engine loads. The exhaust gases temperature increases with the load rise. This rise may be the consequence of the engine cylinder's temperature rising, which causes more fuel to be used to accommodate the increased load requirements. As the peak output power, there is a rise in the exhaust gas temperature. Fuel usage was increased due to the biodiesel mixture's higher viscosity, and lower calorific value compared to diesel oil[15]. They're all part of the problems with fuel atomization and vaporization. Because of the greater engine cylinder temperature and increased fuel burning to

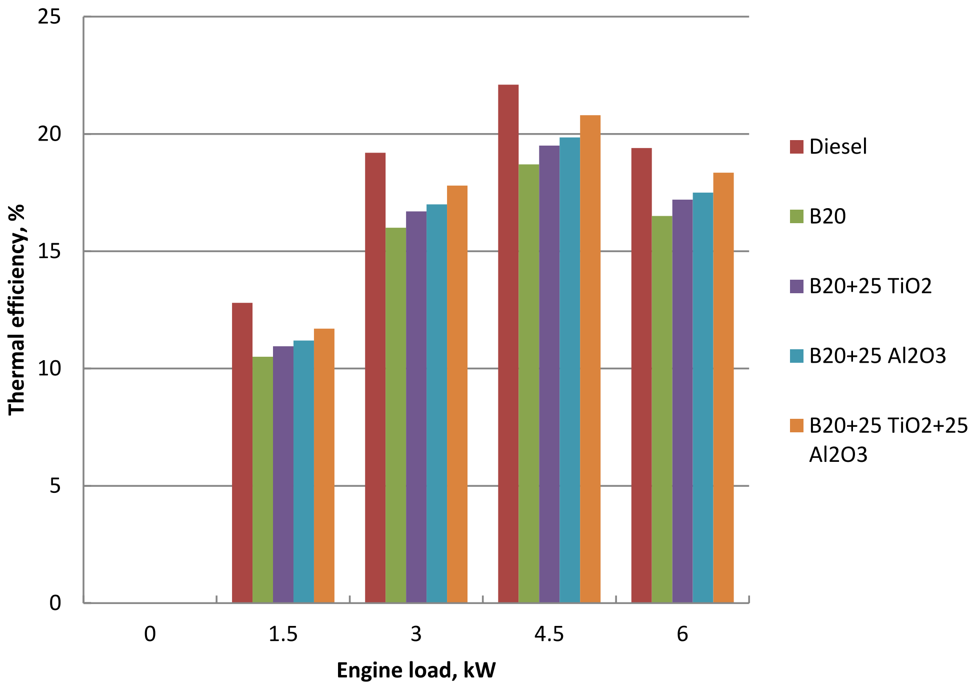

Figure 9. Effect of nano materialsintroductionon BTE.

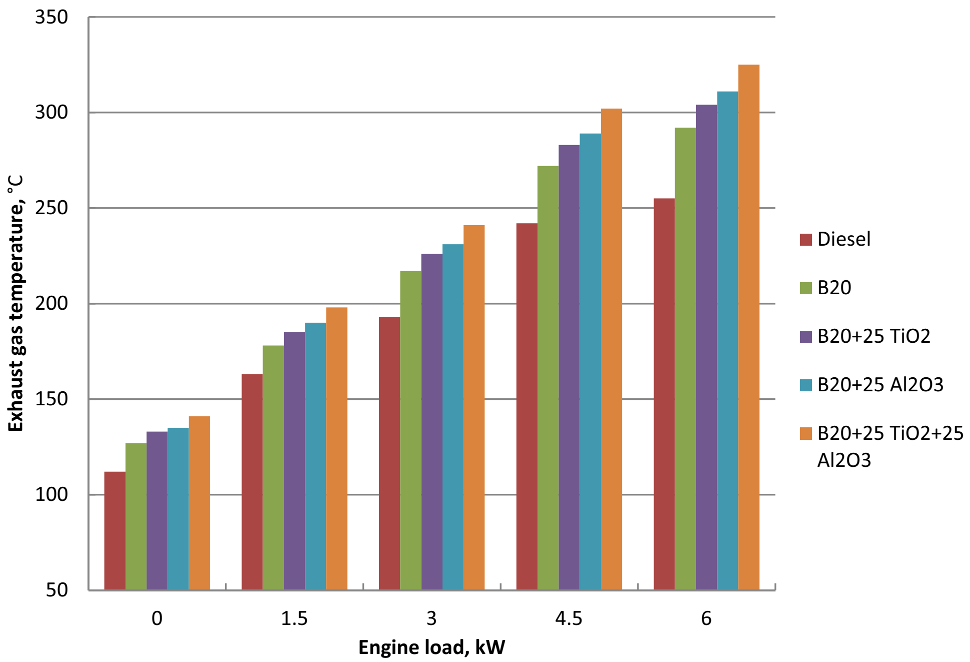

Figure 10. EGT of nano materials blended with B20.

meet the higher output power demand, the exhaust gas temperature rises with engine load. The small nanoparticle dispersion shortens the igniting delay, increasing the exhaust's enthalpy[24]. A greater cylinder temperature was the outcome of the reduction in ignition time due to the homogeneity impact of nanoparticles. The temperature of the exhaust was increased by nanoparticles mixing with biodiesel. As a result of improved combustion, improved engine thermal efficiency, and enthalpy loss in the exhaust was decreased due to tha addition of nano particle[42]. Hybrid nano additives of aluiminum and titanium oxides improve the thermal, physical and chemical properties. WCO biodiesel blends with nano additions B20 + 25 TiO_2, B20 + 25 Al_2O_3, and B20 + 25 TiO_2 + 25 Al_2O_3 achieve EGT increases up to 5, 7, and 12%, respectively related to biodiesel blend at 100% of engine load.

Cylinder pressure

Figure 11 shows the changes in cylinder pressure as a function of crank angle for all the fuels. Lower cylinder pressure is associated with biodiesel due to the lower calorific value, higher density and viscosity about diesel oil. Atomization and vaporization problems of biodiesel produced the lower cylinder pressure. Higher peak cylinder pressure is correlated with the maximum rate of pressure increase, which may be explained by the significant amount of fuel consumed during the premixed combustion phase. Premixed combustion involves burning a large percentage of the fuel, which raises the pressure inside the cylinder and causes it to rise quickly. This occurrence is a sign of quick and effective combustion processes, which are frequently linked to the addition of nanoparticles[14]. Moreover, nano additives are essential for improving the characteristics of biodiesel combustion, mostly because of their catalytic actions and the increased surface area to volume ratio[21]. Nano additives were added to biodiesel blends to improve their properties, primarily by reducing physical delay and evaporation time. Nanoparticles play a critical role in improving micro-explosion, air–fuel mixing, and thermal characteristics while also reducing fuel consumption. Together, these elements encourage the premixed combustion phase, which raises the maximum cylinder pressure and enhances evaporation rates, heat transfer, and thermal conductivity[43]. Hybrid nano additives of aluminum and titanium oxides improve the thermal, physical and chemical properties.The maximum cylinder pressures rise for B20 + 25 Al_2O_3, B20 + 25 $TiO2_3$, and B20 + 25 Al_2O_3 + 25 TiO_2 were 1.3%, 2%, and 2.5%, respectively.

Heat release rate (HRR)

The Heat Release Rate (HRR) of nanoparticle-enhanced biodiesel blends at various crank angles under full load is shown in Fig. 12. As compared to crude diesel, heat release rate is lowered by the atomization and vaporization difficulties biodiesel mixtures due to higher viscosity amd lower calorific value. Addition of nanoparticles to these mixtures increases the HRR by improving the catalytic reactivity. Moreover, the enhanced thermal characteristics, heat transfer, and the availability of high surface area to volume ratio were shown for biodiesel with nano additives[44]. A greater heat release rate is the end consequence of combustion processes progressing considerably as more fuel is used during the premixed combustion phase. Additionally, owing to the enhanced fuel–air mixing and combustion characteristics brought about by nanoparticles, less fuel is consumed[21]. The inclusion of nanoparticles has a noteworthy impact of oxidizing carbon deposits, which further reduces fuel use. Reactive surfaces on nanoscale particles improve their catalytic potential[23]. The parameters of combustion and fuel air mixing were enhanced by the nanoparticles addition. Hybrid nano additives of aluiminum and titanium oxides improve the thermal, physical and chemical properties.When 25 ppm of Al_2O_3, TiO_2 and hybrid additions were mixed with B20, respectively, the maximum HRR values increases were 1.3%, 2.2%, and 3.3% relative to biodiesel blended at peak load.

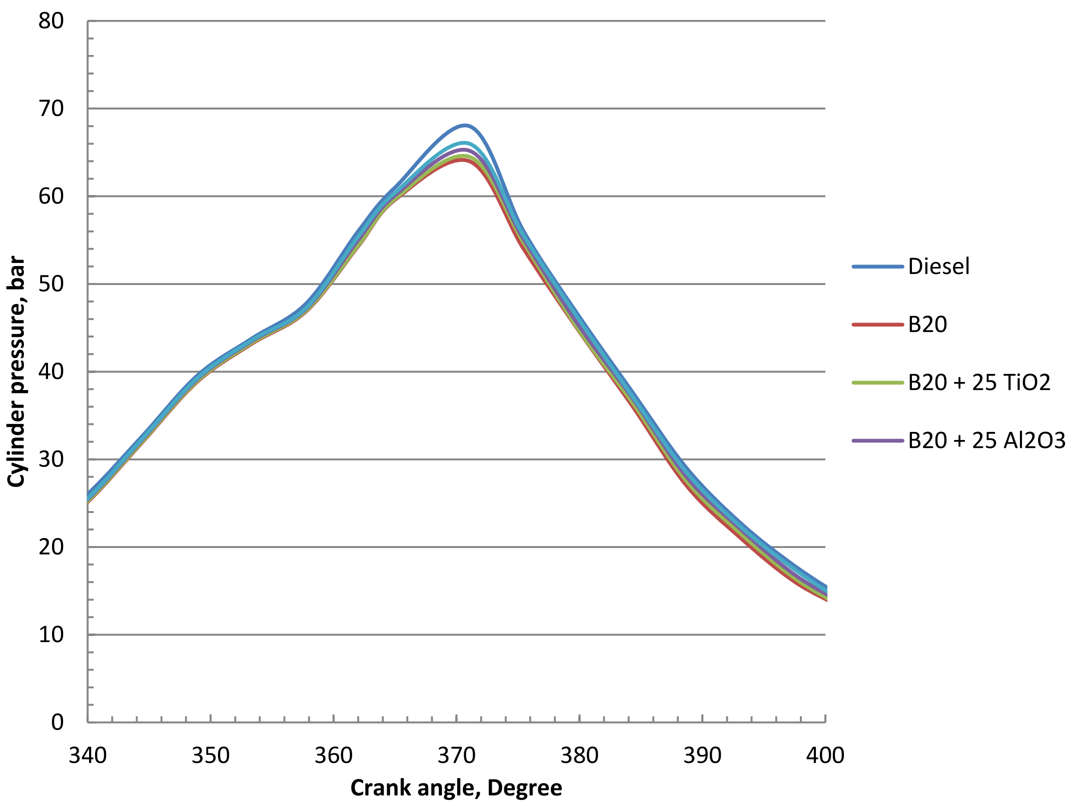

Figure 11. Cylinder pressure against crank angle variation for B20 with nano additives.

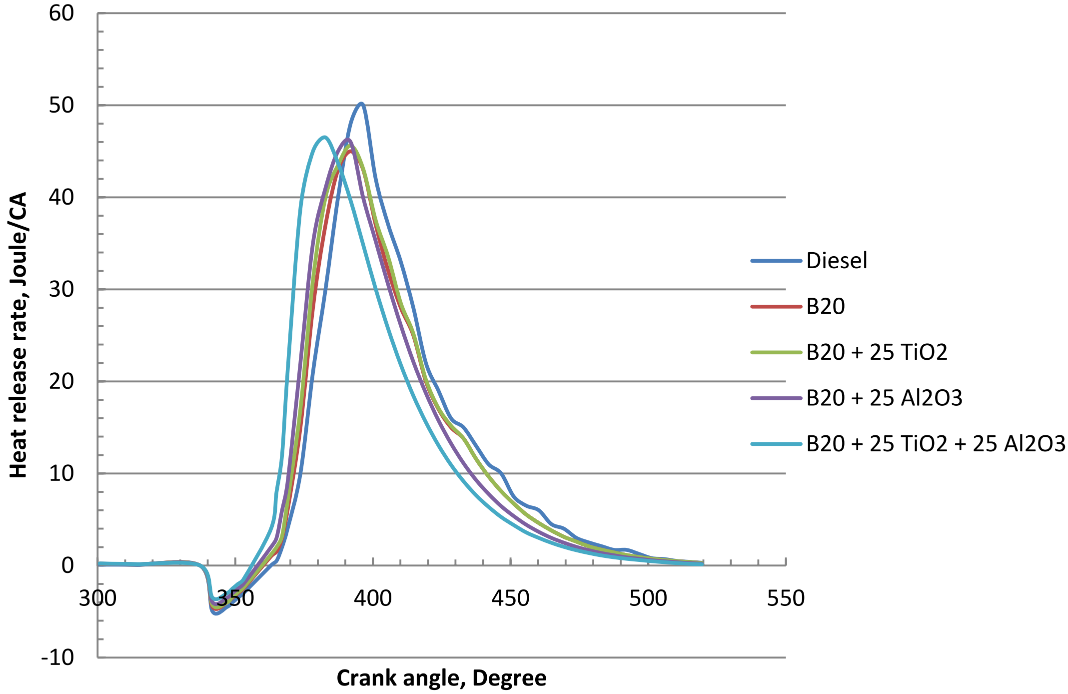

Figure 12. HRR of methyl ester with various nano materials at different crank angles.

Ignition delay

The effect of nano materials inclusion on the ignition delay period is shown in Fig. 13. The amount of time that passes between the start of fuel injection and the start of combustion is known as the ignition delay. The decrease in ignition delay with increasing engine load is one noteworthy trend that has been seen. Ignition delay was decreased for biodiesel about pure diesel due to the higher cetane number[21]. The reduction of igniting delay is facilitated by the concentration of nanoparticles. This decrease is explained by the air–fuel mixture's greater homogeneity, higher catalytic activity, and improved surface area to volume ratio, all of which work together to

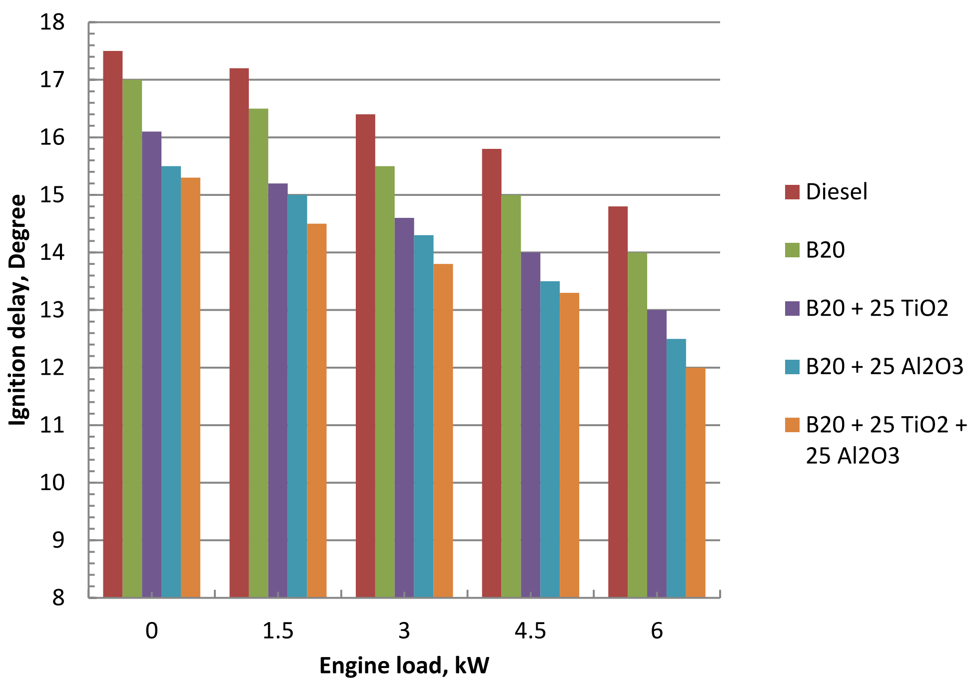

Figure 13. Ignition delay for biodiesel with nano additives at different loads.

improve burning chracteristics and combustion efficiency. Premixed combustion uses more fuel, which causes the pressure within the cylinder to rise quickly. This phenomenon suggests that the combustion processes linked to the inclusion of nanoparticles are both efficient and fast. Hybrid nano additives of aluiminum and titanium oxides improve the thermal, physical and chemical properties[23]. It is clear from comparing these findings to the baseline reference case of biodiesel blend that the maximum ignition delay reductions for B20 + 25 Al_2O_3, B20 + TiO_2 and B20 + TiO_2 + Al_2O_3 were 7%, 10%, and 14%, respectively.

Burning analysis (CA50)
The combustion process may be shown by using the location of the CA50, which characterizes the energy released during combustion. The combustion phasing can also be ascertained by looking at the crank angle position at which 50% of the injected fuel was utilized. The location of CA50 for tested fuels at various engine loads is shown in Fig. 14. Because of the larger volumes of injected fuel mixture, the areas of CA50 for fuels grow with engine loads; however, other variables including turbulence in mixture formation, shorter ignition delay time, and improved injection timing may also be at play. Due to the fast rate of mixture evaporation, increase in surface-to-volume ratio, high oxygen content of nanoparticles, and expected improvement in spray characteristics, when using B20 in different proportions, delay the combustion phasing or CA50 sites. Diesel oil's ignition delay was lowered by adding biodiesel, although this had a negative impact on the reaction rate and combustion properties. Its reduced ignition time may be attributed to the greater cetane number, increased oil viscosity, and inadequate air–fuel mixing. Diesel oil had higher ignition delays and combustion periods than biodiesel. At full load, the degrees for CA50 were 484.5, 484, 483.5, 482.5, and 482 CA, respectively (Fig. 14).

Comparative analysis
Table 2 compares emissions and performance CI engine burning B20 with TiO_2, Al_2O_3 and hybrid nano.

Conclusion
Biodiesel was created by converting waste cooking oil. Physical and chemical characteristics of methyl esters complied with ASTM requirements. Diesel oil was blended with biodiesel at a volume ratio of 20%. A titanium dioxide (TiO_2) and alumina (Al_2O_3) fueled diesel engine's performance and emissions were evaluated experimentally. WCO biodiesel blend (B20) has hybrid titanium dioxide and alumina nanoparticles added at 25 mg/l dose. At steady state conditions with load variation at 1500 rpm engine speed, all parameters were assessed. Conclusions that were addressed were as follows:

- When B20 was combined with nanomaterials such as TiO_2, Al_2O_3, and hybrid nano, the corresponding decreases in brake-specific fuel consumption were 4, 6, and 11%, respectively. However, as compared to a biodiesel blend, the largest gains in thermal efficiency were 4.5, 6.5, and 12%, respectively, at maximum load.

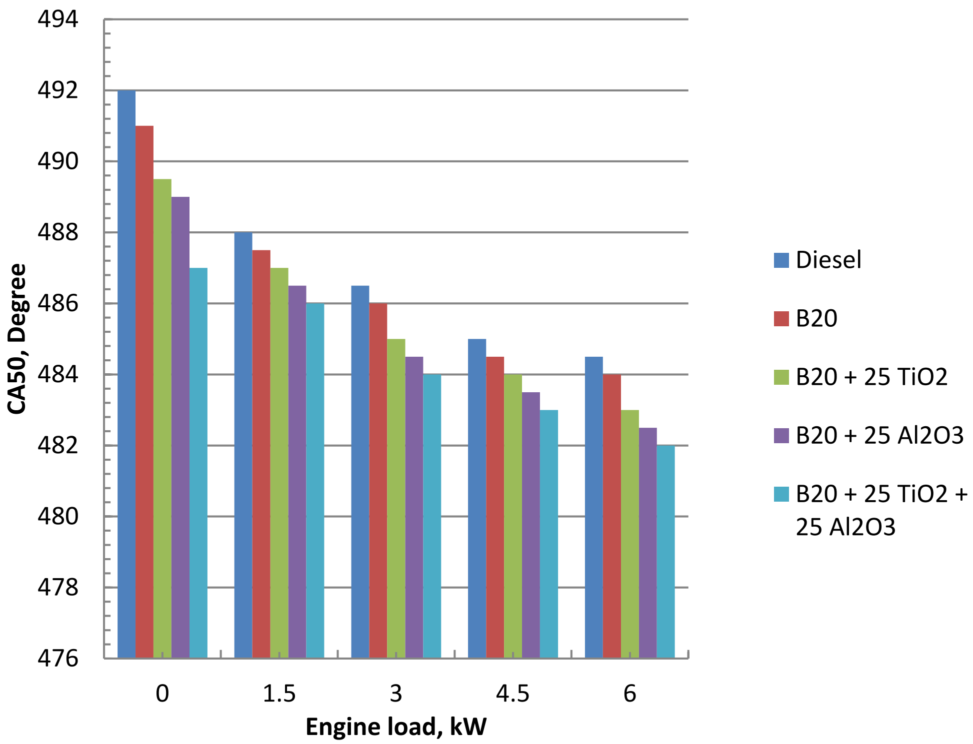

Figure 14. CA50 of biodiesel with various nano materials at different loads.

Relative change (%)	B20 + 25 TiO_2 (%)	B20 + Al_2O_3 (%)	B20 + 25 TiO_2 + 25 Al_2O_3 (%)
Specific fuel consumption	− 4	− 6	− 11
Thermal efficiency	+ 4.5	+ 6.5	+ 12.5
Exhaust gas temperature	+ 5	+ 7	+ 12
HC emission	− 7	− 13	− 20
Carbon monoxide emission	− 6	− 12	− 16
Smoke concentration	− 8	− 15	− 21
NO_x concentration	+ 7	+ 15	+ 23
Peak cylinder pressure, bar	+ 1.3	+ 2	+ 2.5
Peak heat release rate, Joule/CA	+ 1.3	+ 2.2	+ 3.3
Ignition delay	− 7	− 10	− 14

Table 2. Relative variations in performance and emissionssaboutmethyl estermixture B20 at full load ((+) indicates of increase and (−) of decrease).

At 100% of output power, the waste cooking oil methyl ester blends including nanoparticles B20 + 25TiO_2, B20 + 25 Al_2O_3, and B20 + 25TiO_2 + 25 Al_2O_3 exhibited greater increases in EGT up to 5, 7 and 12%, respectively, than B20.

- When TiO_2, Al_2O_3, and hybrid nanoparticles were introduced to biodiesel blends with 100% engine load, HC emissions were reduced by 7, 13, and 20% but CO emissions were reduced by 11, 24, and 30%.
- For B20 + 25TiO_2, B20 + 25 Al_2O_3, and B20 + 25TiO_2 + 25 Al_2O_3, the largest increases in NOx emission at maximum engine load were up to 7, 15, and 23%, respectively. Up to 8, 15, and 21% less smoke was released, correspondingly, which were the largest reductions.
- The maximum cylinder pressures rise for B20 + 25 Al_2O_3, B20 + 25 TiO_2, and B20 + 25 Al_2O_3 + 25 TiO_2 were 1.3%, 2%, and 2.5%, respectively but the maximum HRR values increases by 1.3%, 2.2%, and 3.3%, respectively. the maximum ignition delay reductions for B20 + 25 Al_2O_3, B20 + TiO_2 and B20 + TiO_2 + Al_2O_3 were 7%, 10%, and 14%, respectively. At full load, the degrees for CA50 were 484.5, 484, 483.5, 482.5, and 482 CA, respectively.
- While pure biodiesel may be used in diesel engines, its higher density, lower cetane number, and lower calorific value prevent it from fully substituting regular diesel. Using of biodiesel in cold climate leads to problems in injection system and fuel filter. Addition of nano additives solves these problems, improves engine performance and reduces exhaust emissions. Fuel consumptions with high costs were significantly reduced by using nano additives such as alumina, TiO_2, and hybrid nano additives. Nanomaterials are used in small percentages with biodiesel. The cost difference between using nanomaterials with biodiesel and conventional fuel is compensated by the decrease in harmful emissions, fuel consumption and thermal efficiency improvement. Nanoparticles comprise a smaller portion of the fuel cost. Utilizing the suggested nano-based fuel has favorable environmental effects that meet the requirements of the Sustainable Development Goals (SDGs). Combination of biodiesel with low concentration of nanoparticles demonstrated lower fuel consumption, environmental, and financial aspects for the practical use in engines. In cold climate, this application promotes the usage of pure biodiesel.
- The recommended dosage of 25 ppm alumina and 25 ppm TiO_2 achieved a noticeable improvement in diesel engine emission, combustion and performance about WCO biodiesel mixture B20. When alumina and TiO_2 were added at a concentration of 25 ppm, WCO blend B20 shows the highest engine performance, combustion characteristics, and emissions reductions when compared to biodiesel blend. This study supports the relevance of hybrid nano additives in improving B20 thermal conductivity, evaporation rate, catalytic reactivity, and heat transfer rate. Therefore, it is highly recommended to utilize waste cooking oil biodiesel blend B20 with 25 ppm of nano alumina and titanium oxide as alternative fuel in diesel engine.

Data availability
The data presented in this study are available on request from the corresponding author.

Received: 12 May 2024; Accepted: 12 August 2024
Published online: 22 August 2024

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Acknowledgements
This work was supported and funded by the Deanship of Scientific Research at Imam Mohammad Ibn Saud Islamic University (IMSIU) (Grant number IMSIU-RG23039).

Author contributions
Conceptualization, M.S.G. and H.M.A.H.; methodology, M.H.N. and A.K.H; software, M.B.B.H; validation, M.B.B.H.; formal analysis, M.B.B.H. and M.S.G.; investigation, R.A.; resources, R.A.; data curation, H.M.A.H. and M.H.N; writing—original draft preparation, M.B.B.H, M.S.G. and H.M.A.H; writing—review and editing, M.B.B.H. and A.K.H; visualization, M.H.N.; supervision, M.B.B.H.; project administration, M.B.B.H.; funding acquisition, R.A. All authors have read and agreed to the published version of the manuscript."

Competing interests
The authors declare no competing interests.

Additional information
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ARTICLES FOR FACULTY MEMBERS

COMPARATIVE ANALYSIS OF WASTE COOKING OIL BIODIESEL MIXED WITH NANOPARTICLE ADDITIVES ON PHYSICOCHEMICAL PROPERTIES AND DIESEL ENGINE PERFORMANCE

Impact of carbon nanotubes and graphene oxide nanomaterials on the performance and emissions of diesel engine fueled with diesel/biodiesel blend / Elkelawy, M., El Shenawy, E. S. A., Bastawissi, H. A. E., & Shams, M. M.

Processes
Volume 11 Issue 11 (2023) 3204 Pages 1-19
https://doi.org/10.3390/pr11113204
(Database: MDPI)

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Article

Impact of Carbon Nanotubes and Graphene Oxide Nanomaterials on the Performance and Emissions of Diesel Engine Fueled with Diesel/Biodiesel Blend

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Abstract: Biodiesel produced from waste cooked oil (WCO) resources mixed with various nanoparticle additives and used as a fuel blend in diesel engine combustion is a hopeful research trend. All previous studies indicate that alternative fuels can provide better fuel properties with enhanced engine combustion, performance, and lower emissions than fossil diesel fuel. This study uses three fuel blends to compare the diesel engine's combustion, performance, and emissions attributes at different loading values. Pure diesel fuel, B40, which is a blend of 40% WCO biodiesel and 60% diesel fuel, and mixtures of 40% WCO biodiesel, 56% diesel, and 4% toluene with carbon nanotubes (B40-CNTs) or graphene oxide nano-additive (B40-GO) at three concentrations of 50, 100, and 150 ppm were used. The results show enhancements in the diesel engine attribute values using B40-CNTs and B40-GO blends at different concentrations and engine load values better than the diesel engine attribute result values using B0 or B40 without nanoparticle additives. The combustion, performance, and emission attribute showed improvements using nanoparticles due to the increase in the evaporation rate, the oxygen rate, the surface area to volume ratio, and the thermal properties of the mixture. The highest in-cylinder peak pressure is recorded at 61 bar in B40 with 150 PPM of GO nanoparticles. The brake thermal efficiency records 43.6%, with the highest percentage found using B40-150GO at the maximum engine load value. The NOx emissions are dropped from 1240 PPM using pure diesel fuel to 884 PPM using B40 with 150 PPM of GO nanoparticles at the maximum engine load due to the lower combustion temperatures and duration.

Keywords: diesel engine; waste cooking oil biodiesel; carbon nanotubes; graphene oxide nanoparticles

Citation: Elkelawy, M.; El Shenawy, E.S.A.; Bastawissi, H.A.-E.; Shams, M.M. Impact of Carbon Nanotubes and Graphene Oxide Nanomaterials on the Performance and Emissions of Diesel Engine Fueled with Diesel/Biodiesel Blend. *Processes* **2023**, *11*, 3204. https://doi.org/10.3390/pr11113204

Academic Editor: Miguel Ladero Galán

Received: 2 September 2023
Revised: 21 October 2023
Accepted: 31 October 2023
Published: 9 November 2023

1. Introduction

Nowadays, the massive consumption of fossil fuels in internal combustion engines can lead to fossil fuel depletion. The combustion of fossil fuels produces harmful exhaust gases that can change the climate and deteriorate the health of humans [1]. Diesel fuel can be wholly or partially substituted with biodiesel fuel from various resources in diesel engines, which is a green fuel with good combustion properties, including high burning ability and oxygenation [2,3].

Biodiesel can be produced cheaply using modernized technologies from various resources such as edible oil and nonedible and animal fat [4]. Note that direct oil from biodiesel resources cannot be applied to diesel engines as a fuel before converting to biodiesel fuels due to their high density, viscosity, and water content values [5]. The high viscosity can cause gum for the combustion chamber and injection components. The water content can cause corrosion and wear to the engine components [6].

Biodiesel from waste cooking oil can be produced using multiple manufacturing techniques such as pyrolysis, dilution, transesterification, and micro-emulsion [7]. Dilution can be achieved by mixing WCO at a maximum allowable percentage of 20% with fossil diesel fuel. Dilution for WCO can prevent engine damage causes [8]. Pyrolysis is an anaerobic decomposition of the oil by heating without oxygen [9]. The micro-emulsion is a colloidal dispersion of fat combined with methanol or ethanol as a solvent to reduce viscosity and increase spraying quality [10]. Transesterification converts biodiesel resources to fatty acid methyl ester (FAME) and glycerol using alcohol like methanol and a catalyst [11]. There are four types of catalysts: acid, base, nano-catalyst, and enzyme [12]. Base catalysts have several benefits, such as availability, less energy requirement, fewer corrosion issues for engine components, and faster action than acid catalysts [13].

In a recent study [14], Cyclohexane was added by volume at 5, 10, and 15% as a flammable liquid to WCO biodiesel and diesel fuel in three blends: B60:D35C5, B60D30C10, and B60D25C15. The results showed that the engine performance and emission attributes improved if fuel blends were used compared to fossil diesel fuel. In addition, by increasing the injection pressure from 150 bars to 250 bars, the UHC, CO, and BSFC decreased. An experimental study was conducted using a single-cylinder diesel engine to compare the differences between two combustion modes, blend, add fuel combustion, and RCCI combustion. The blended fuel was biodiesel/n-butanol at various EGR rates, various timings of injection, and various loads of the engine. The optimum EGR percentage was 30%. The blended fuel mode maintained high BTE and low emissions but with high NOx [15,16]. In addition, the advanced technology suggestions for improving the combustion and emissions characteristics were applied in conventional diesel engines [17,18]. The PPC engine concept was applied using an oxygenated and high-octane rating fuel such as methanol with different fuel injection strategies. In addition, the emissions reductions from using a low-carbon fuel such as alcohol reached 10% in some conditions compared with conventional engines.

Nanoparticles are the main elements in nanotechnology. Nanoparticles have a range of sizes from 1 nm to nearly 100 nm and have many shapes: cylindrical, spherical, and flat [19]. They can be crystalline or amorphous with zero, one, two, and three dimensions [20]. Nanoparticles can be classified according to their physical and chemical properties as organic, metal, ceramic, semiconductor polymeric, lipid, carbon-based, or composite nanoparticles [21]. The organic type is used mainly in medicine [22,23]. Metal nanoparticles and their oxides have good specifications for combustion in compression ignition engines due to their oxygen content, which can reduce harmful emissions and increase the surface area to volume ratio to increase the evaporation rate of the mixture [24–27].

Nanoparticles can be prevented from crumbling in the base fuel by using solvent and surfactant to increase the dissolving and guarantee the stability of the blend. Nanoparticles can be characterized and inspected through tests like X-ray diffraction (XRD), Brunauer–Emmett–Teller (BET), scanning electron microscopy (SEM), and transmittance electron microscope (TEM) tests. The nanoparticle production methods include the top-down and bottom-up production processes [28]. The top-down approach is a damaged technique for the most significant molecules that are transformed into small ones and converted to nanoparticles [29,30]. Moreover, a bottom-up process is a reverse approach for building up nanoparticles via spinning and atomic condensation.

The effect of using CeO_2 nanoparticles dispersed in biodiesel on the elemental carbon (EC), organic carbon (OC), size distribution, combustion, and emissions of the CRDI diesel engine is explored [31]. The diesel engine operated without a diesel particulate filter to prove that the emissions depend on the filter. The results indicated that adding CeO_2 nanoparticles to the biodiesel improved the in-cylinder pressure and the heat release rate. Using B15 with CeO_2 at 20 PPM, the Co and UHC significantly decreased, but NO_x emission increased compared to pure diesel. It was also observed that the B0 and B0C20 fuels produced particles with diameters more significant than the diameters of B10C20 and B15C20. The EC soot was higher than the OC for all fuels. The influence of CeO_2 nanoparticles on dual fuel and varied loads of diesel engines was studied. The CeO_2 nanoparticles were dispersed in methanol at 25 ppm and 100 ppm concentrations (MCN).

The diesel engine was operated in three modes: The first was direct injection mode. The second mode was injecting the methanol in the intake manifold, and the diesel fuel was directly injected. The third mode injects the MCN in the intake manifold and injects the diesel fuel directly. It was observed that there was an increase in the peak in-cylinder pressure and the peak heat release rate using the MCN mode. The BTE and the BSFC were enhanced using the MCN compared to methanol mode. Most of the emissions were reduced using the MCN mode [32]. This paper [33] investigated the characteristics of the direct-injection diesel engine. Pure diesel fuel (D), WCO biodiesel (B), n-butanol (But), and titanium dioxide (TiO_2) nanoparticles were used. The test fuels were D100, B20, B20+ TiO_2, B20But10, and B20But10+TiO_2. Adding TiO_2 increased the brake power and torque compared to using TiO_2 nanoparticles. Adding n-butanol and TiO_2 to the test fuels improved the peak in-cylinder pressure and the peak heat release rate compared to pure diesel. The CO, UHC, and smoke opacity emissions were reduced, and the NO_X emissions were reduced using n-butanol.

Carbon nanotubes (CNTs) are one of the significant nanoparticles. CNTs are described as nonmetal nanoparticles. CNTs have properties better than metal nanoparticles, such as high thermal conductivity [34]. CNTs can be used as a catalyst to nanofuels, improving the attributes of diesel engines by increasing the surface area to volume ratio, and thus the cetane number of the fuel [35]. The BTE of the diesel engine can be enhanced by adding CNTs due to the high chemical reactivity [36]. CNTs added to the diesel-water emulsion can produce better BTE than diesel-water only. Using CNTs in diesel engines can increase the peak in-cylinder pressure and shorten the combustion duration [37]. The peak heat release rate increases by dosing CNTs compared to base fuel only due to the high surface area to volume ratio, evaporation rate, and chemical reactivity [38].

CNTs have effective influences on the emissions produced by the diesel engine. CO emissions decreased with CNTs due to complete combustion, resulting from good blended fuel atomization and high surface area to volume ratio [39]. Also, the UHC emissions decreased due to combustion completion [40]. The reductions in NOx emissions depend on the fuel type, the combustion duration, and the combustion temperatures. Low soot emissions are also observed using CNTs in diesel engines because of the high surface area to volume ratio and complete combustion.

Multiwalled carbon nanotubes (MWCNTs) were used with C. Inophyllum biodiesel and diesel blend (CIB20) to investigate the characteristics of diesel engines [41]. The MWCNTs were dispersed in the mix at 20, 40, 60, and 80 ppm concentrations. The results showed that the combination with MWCNTs at 60 ppm gave the highest percentage of BTE. All emissions were reduced with MWCNT compared to using CIB20 alone. Silicon dioxide (SiO_2) nanoparticles were used with methanol in diesel engine operation. The test fuels are diesel, diesel fuel with methanol, and finally, methanol diesel fuel with SiO_2 nanoparticles (MSN). The MSN fuel was injected into the intake manifold. It was observed that the peak in-cylinder pressure and heat release rate are increased in addition to enhancements in the BTE [42]. Nitrogen-doped multiwalled carbon nanotubes (N-doped MWCNTs) were used to enhance the attributes of the diesel engine. The MWCNTs were used as a reference for comparing with N-doped MWCNTs. The results showed enhancements in the engine attributes using N-doped MWCNTs [43].

Graphene oxide (GO) nanoparticles can be used in various applications, such as heat transfers. As nanoparticle additives, GO nanoparticles are used in diesel engine combustion due to their energy density, high thermal conductivity, and environmentally friendly [44,45]. GO nanoparticles can complete the combustion process due to the increased surface area to volume ratio, high chemical reactivity, and the existence of oxygen atoms [46]. GO nanoparticles were dispersed in biodiesel at B0, B10, and B20, and the GO concentrations were 30, 60, and 90 ppm, distributed via ultra-sonication [43]. The attributes of the diesel engine were investigated, and it was observed that GO nanoparticles enhanced the BTE and torque and reduced the BSFC. Also, reductions in CO and UHC emissions were observed, while increased CO_2 and NO_x emissions were reported.

Three nanoparticle additives GO, TiO_2, and GO with TiO_2, were used to study the characteristics of a cylinder diesel engine [47]. There was a reduction in BSFC of 12%

using diesel with TiO_2 fuel compared to pure diesel. The in-cylinder peak pressures using nanoparticle additive fuels were higher than those using pure diesel. Using TiO_2 and GO-TiO_2 with diesel fuel reduced the NOx emissions formation and increased the CO emissions. In another study [48], GO nanoparticles at varying doses of 30, 60, and 90 PPM were added to the Oenothera lamarchiana biodiesel and diesel fuel (B20) blend to investigate the attributes of diesel engines. The results showed that the brake power, exhaust gas temperature, and CO_2 and NOx emissions increased while the UHC and CO emissions were reduced. Single-walled carbon nanotubes, graphene oxide, and cerium oxide were used to investigate the characteristics of diesel engines at different loads [37]. A reduction in the combustion duration of 10.3%, the combustion advancing by 18.5%, an improvement in the BSFC of 15.2%, and a decrease in CO and UHC of 23.4% and 24.1%, respectively, were observed using single-walled CNTs at 25 PPM concentration.

In preparing the nanofuels, the dispersion of nanoparticles in the base fuel is one of the drawbacks. The method of nanoparticle distribution inside the original fuel is essential for enhancing the surface changes of nanoparticles due to the repulsion forces between all nanoparticles. Electrostatic dispersion is one method that can be attempted by coating the nanoparticles with a dispersing agent or surfactant [49,50]. The nanoparticle's surface is covered with the surfactant. Some changes are generated, producing repulsive forces between the nanoparticles in the base fuel. The surfactant amount must be maintained to act as the suitable coating, prevent repulsion, and compensate for the attraction forces of van der Waals. The type of surfactant can be classified into ionic surfactants and cationic surfactants [51,52].

The present study uses toluene (T) as a surfactant for dispersing GO or CNT nanoparticles in the fuel. Toluene was experimented with three percentages of the blend volume: 2%T, 4%T, and 6%T. It is observed that the ideal volume percentage is 4%T due to the stability and homogeneity of the blend and its ability to prevent the repulsion forces between the nanoparticles as much as possible.

The recent research aims to study the influence of nanoparticles dispersed in different blends of WCO biodiesel and diesel fuel on the combustion, performance, and emission attributes of single-cylinder, constant-speed diesel engines at varying loads. The nanoparticle types are CNTs or GO nanoparticles dispersed individually using toluene at 4% by volume in 56% fossil diesel fuel and 40% WCO biodiesel. The tested fuels are pure diesel (B0), a blend of WCO biodiesel at 40% and 60% diesel fuel (B40), and B40 with 50, 100, and 150 PPM of CNTs or GO nanoparticles.

2. The Procedure and the Experimental Setup

2.1. The Experimental Setup

A single-cylinder diesel engine test bench performs all the scheduled experiments. The tested engine is assembled with all the necessary equipment to measure the engine attributes. The test engine schematic diagram is presented in Figure 1. However, the whole system is pictured as shown in Figure 2. In addition, the tested engine specifications are displayed in Table 1. The engine is connected to an "ATE-160 LC" hydraulic dynamometer using a coupling to load the diesel engine and calculate the brake power at four specific loads. The hydraulic dynamometer's technical specifications are listed in Table 2. The diesel engine is supplied with Kistler 6125C01U20, an in-cylinder pressure transducer, to measure the in-cylinder pressure. The in-cylinder pressure transducer is connected to the charge amplifier and data acquisition system. The data acquisition is triggered with an optical crank angle encoder and is correlated with the top dead center (TDC) signal using a software application.

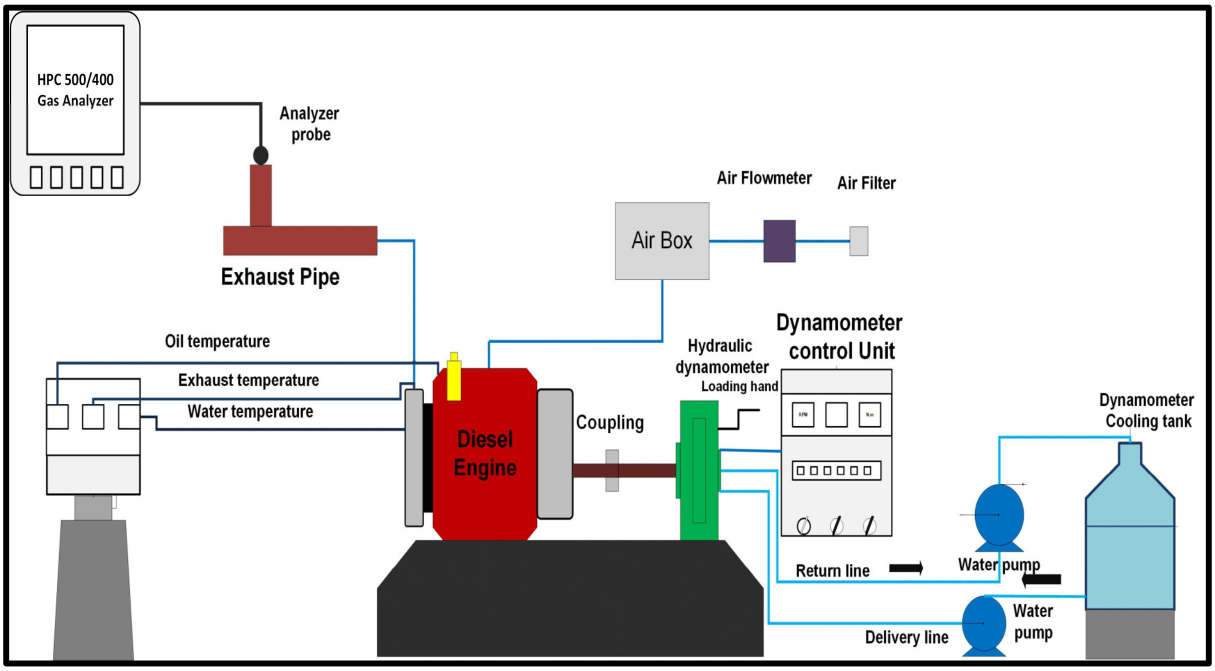


Figure 1. The test rig diagram.

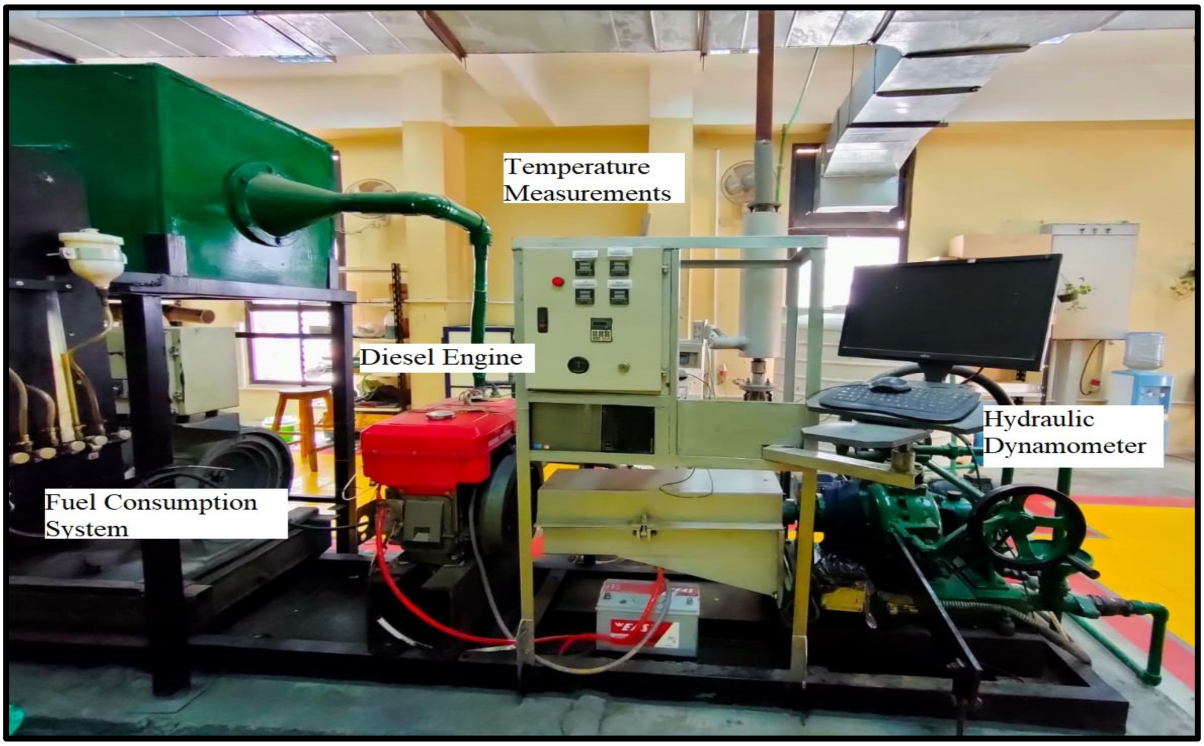


Figure 2. Photographic image of test bench equipment.

Table 1. The technical specifications of the ZS1115 diesel engine.

Parameter	Description
Model	ZS1115NM
Displacement	1.194
Bore × stroke	115 × 115 (mm)
Power rated	16.2/2200/min (kw/r/min)
Consumption of the fuel	≤242.1 (g/kW·h)
Cooling system	Condenser>
Starting method	Electric starting>
Lubrication system	Pressure/splash>
Net weight	185 (kg)
Compression ratio	17>

Table 2. "ATE-160 LC" hydraulic dynamometer technical data.

Dynamometer Trade Name	ATE-160 LC
Load cell capacity	(0–1050) (N·m)
Weight sensor	Load cell
Length of calibration lever arm	0.7645 m
Type of absorption	Water/Hydraulic
Dynamometer with engine connecting	Using half coupling

2.2. The Diesel Fuel and WCO Biodiesel Manufacturing

The specifications for the pure diesel fuel and WCO biodiesel are given in Table 3. The specifications of waste cooked oil biodiesel-diesel blend at 40% with 100 PPM of CNT or GO nano-additives are shown in Table 4. Waste cooked oil must be treated before being used as a biodiesel fuel. In this study, WCO is converted to biodiesel using a transesterification process. Transesterification is an approach to convert vegetable oil resources to fatty acid methyl ester (FAME) and glycerol. The transesterification approach has three steps, as shown in Figure 3: reaction, separation, and washing. The process was attempted by placing six liters of waste cooking oil with 1.2 L of methanol and 54 g of NaOH as a catalyst. Afterward, the mixing and heating of the ingredients are performed for an hour using a mixer rotating at a speed of 450 rpm and heated at 65 °C. In the separation process, the mixtures are left for one day to separate the biodiesel fuel from the glycerol. Finally, the washing process is attempted by feeding hot water at 100 °C with the biodiesel. After an hour, the WCO biodiesel will separate from the water and, by opening the bottom valve, the washing water gets out from the washing tank; the final product of WCO biodiesel fuel is then obtained.

2.3. The Carbon Nanotubes and Graphene Oxide Nanoparticles

Two nanoparticle additives used in this study are CNTs and GO nanoparticles purchased from NanoTech Egypt CO, City of 6 October, Al Giza, Egypt. CNTs or GO nanoparticle additives used in the experiments are dispersed at 50, 100, and 150 PPM concentrations. The CNTs are inspected using transmittance electron microscope (TEM), as indicated in Figure 4, for size and structure inspection. Thermal gravimetric analysis (TGA) is used to inspect the thermal decomposition of the CNTs, as shown in Figure 5.

Table 3. Specifications of diesel and waste cooking oil biodiesel.

Specification	Diesel	WCO Biodiesel
Calorific value	42.10 MJ/kg	39.51 MJ/kg
Density	830 kg/m^3	875 kg/m^3
Cetane number	55	52
Flashpoint	45 °C	158 °C
Kinematic viscosity(cSt)@ 25 °C	3.14	5.13
Specific gravity	0.85	0.88
Auto ignition temperature	263 °C	273 °C
Cloud point	0 °C	6 °C
Oxygen content	0 (wt.%)	9.414 (wt.%)
Water content	0.05 (vol. %)	0.05 (vol. %)

Table 4. Specifications of diesel and waste cooking oil biodiesel with nano-additives.

Specification	B40 + 100 CNT	B40 + 100 GO
Calorific value	43.73 MJ/kg	44.4 MJ/kg
Density	846 kg/m^3	834 kg/m^3
Cetane number	55.8	56.1
Kinematic viscosity(cSt)@ 25 °C	5.07	5.02

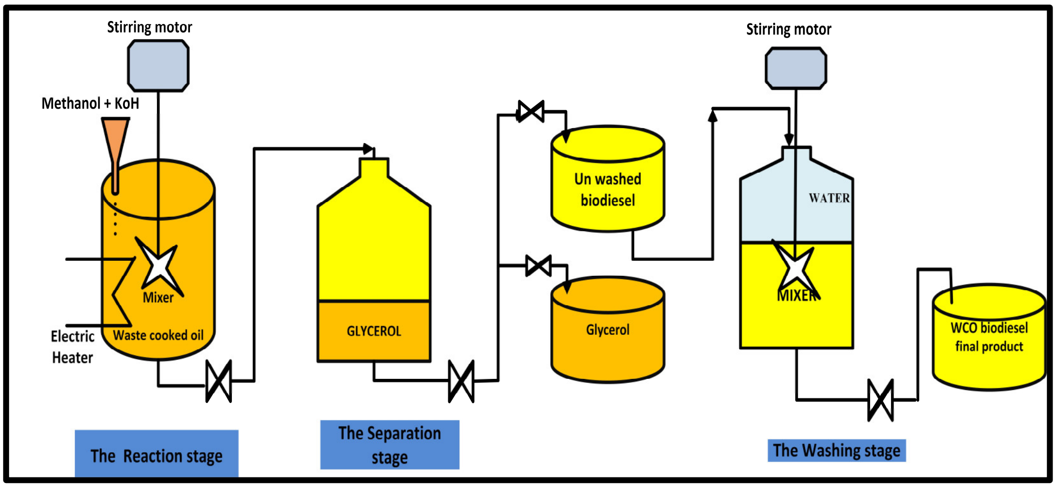


Figure 3. Schematic diagram of WCO biodiesel production.

The GO nanoparticles are inspected using transmittance electron microscope (TEM) for size and structure inspection, as indicated in Figure 6. X-ray diffraction (XRD) is used to study the crystallographic structures. Surface-enhanced Raman spectroscopy (SERS) uses a Lab RAM HR 800 Laser Raman analyzer to inspect the surface properties. The properties of carbon nanotubes (CNTs) and graphene oxide (GO) nanoparticles are indicated in Table 5.

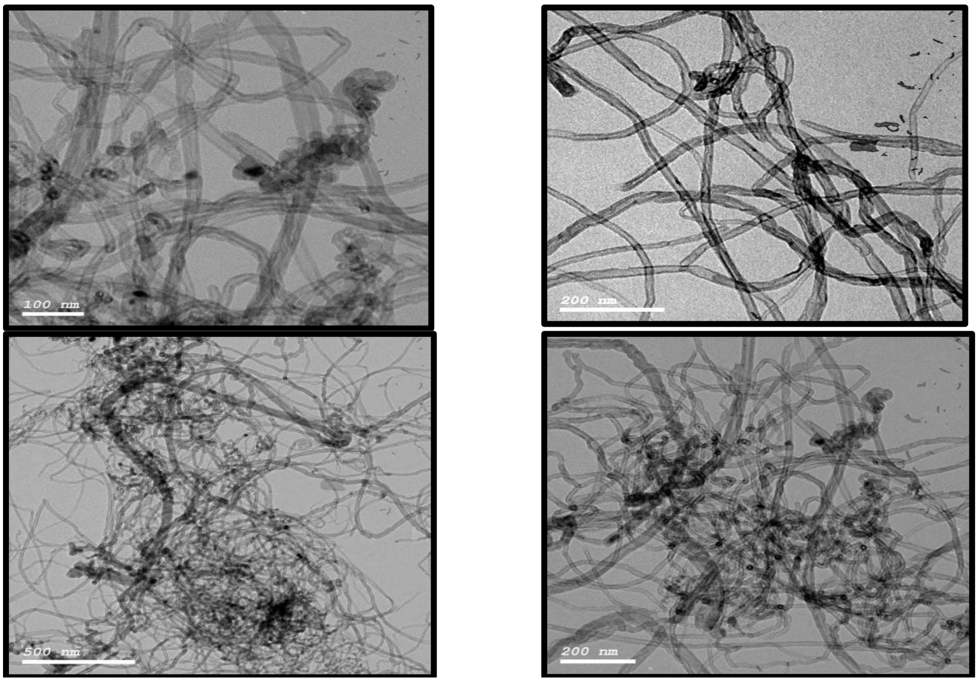


Figure 4. TEM micrograph for the CNTs.

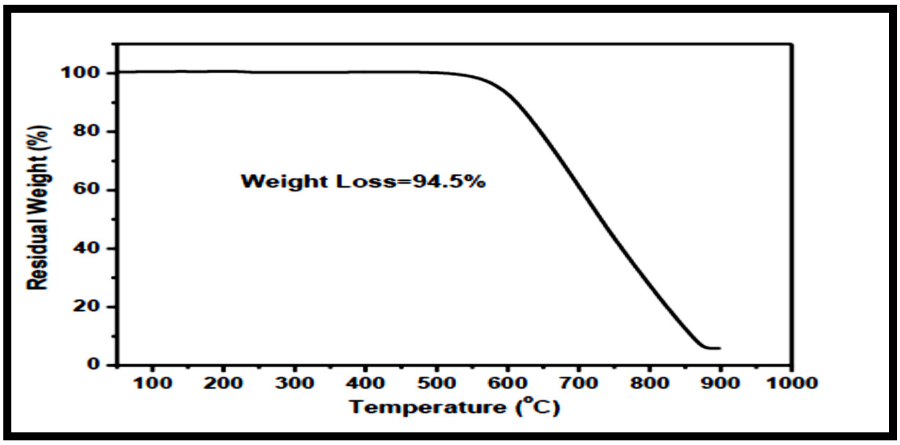


Figure 5. TGA thermo-gram of CNTs.

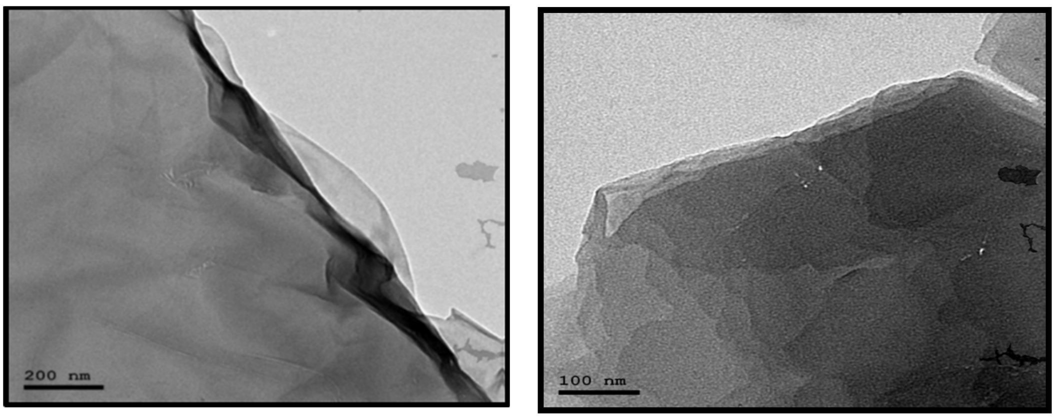


Figure 6. Transmittance electron microscopy for GO nanoparticles.

Table 5. Carbon nanotubes and graphene oxide specifications.

Specification	CNTs	GO
Color	Black	Brown black
Form	Powder	Powder
Ability of Solubility	Dispersed in water	Dispersed in water
Average Size	(L: >660 nm) and (D: 15 ± 7 nm)	Microns in length and a few nanometers in thickness
Purity	94.5%	-------------
Shape (TEM)	Tubular-like shape	Sheets
Expiration Date	10/2023	11/2023

2.4. The Uncertainty Test

The produced temperatures in the experiments are measured using K-type thermocouples, and the data are viewed using a data logger. The thermocouples are placed to measure the cooling water temperatures, lubrication oil, and exhaust gases. Exhaust emissions such as oxygen (O_2), nitrogen oxides (NOx), carbon monoxide (CO), carbon dioxide (CO_2), and un-burned hydrocarbon (UHC) emissions are measured using a Gas board 5020 analyzer. The smoke opacity is calculated using an AVL 415 S smoke meter. The errors are caused by factors like equipment error, measurements, the surroundings, and the measurement methods. All attributes are measured providing the diesel engine's stability and the uncertainties are calculated using the square root method and are listed in Table 6.

$$\text{The uncertainity} = \sqrt{\left[(3)^2 + (0.5)^2 + (1)^2 + (1)^2 + (1)^2 + (0.4)^2\right]} = \pm 3.522$$

Table 6. The uncertainty of the measuring equipment and performance.

Equipment	Uncertainty
Exhaust gas analyzer	±0.5%
Smoke meter	±3%
In-cylinder pressure transducer	±1%
In-cylinder pressure transmitter	±1 Kpa
Temperature transmitter	±1 deg.
Brake thermal efficiency	±0.4%

3. Results and Discussions

The present study investigates the effects of using pure diesel, a blend of WCO biodiesel with diesel fuel (B40), and combining CNTs or GO in B40 at various concentrations. The CNTs or GO concentrations are 50, 100, and 150 PPM. The experiments are carried out at different engine load values (0, 2, 4, 6, and 8 kW) at a constant engine speed of 1400 rpm. The diesel engine's combustion, performance, and emission attributes prove the benefits of using two different types of nanoparticles in addition to the waste cooked oil biodiesel in enhancing the characteristics of the diesel engine over and above the reduction in all emissions compared with the pure fossil diesel fuel.

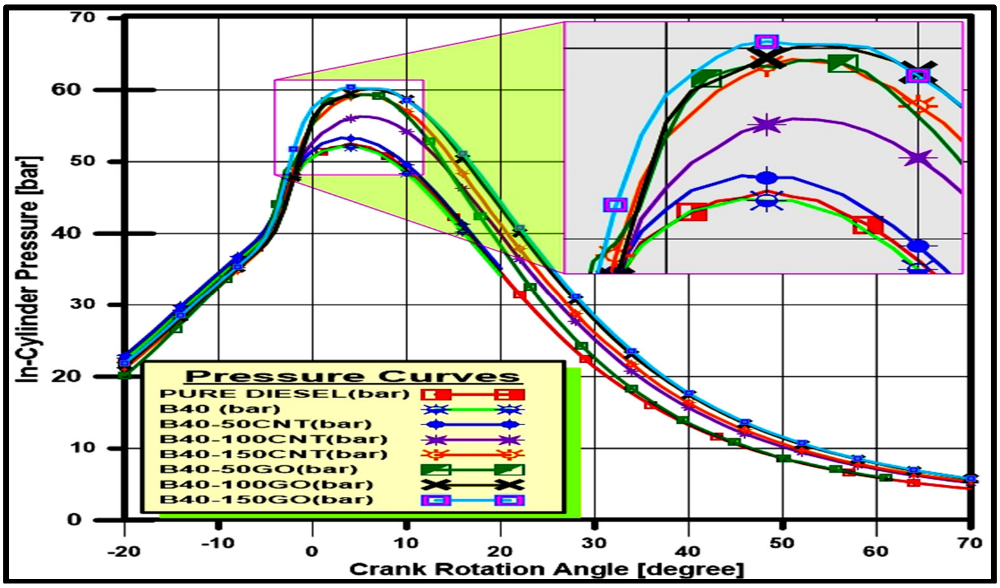
3.1. Combustion Attributes

The influence of different nano-additives on pure diesel, B40, and B40 with various concentrations of GO nanoparticles or CNTs on diesel engine combustion is studied. Figure 7a illustrates the variations in the in-cylinder pressure for the tested fuels with varying crank angles at a constant diesel engine load of 4 kW. In contrast, Figure 7b shows the in-cylinder heat release rate at the tested conditions. From the graph, it is observed that the peak in-cylinder pressures are recorded when using B40 with different concentrations of GO nanoparticles in comparison to the other fuels; the enhancement made in the combustion process was due to the high surface area to volume ratio and the high evaporation rate of the fuel droplets inside the combustion chamber which advances the ignition delay (ID) period and completes the combustion process in the controlled combustion phase. The highest in-cylinder peak pressure was recorded using B40 at 150 PPM of GO nanoparticles. Also, Figure 7b illustrates the relationship between the heat release rates (HRR) and varying the crank angle at constant load in the diesel engine. The graph shows HRRs are recorded using GO nanoparticles at different concentrations compared with the other fuels, and the highest value for the peak HRR occurred with B40 added by 150 PPM of GO nanoparticles. This phenomenon is observed due to GO nanoparticles that improve the premixed phase combustion, reducing the blended fuel's auto-ignition. However, the higher air-fuel utilization due to the micro explosion of the fuel droplets will dramatically increase the evaporation rate and shorten the combustion duration. However, because of the advancement of the reaction surface area and the increasing heat transfer rate of the fuel droplets by adding nanoparticles, it is easier to start the primary stage of combustion.

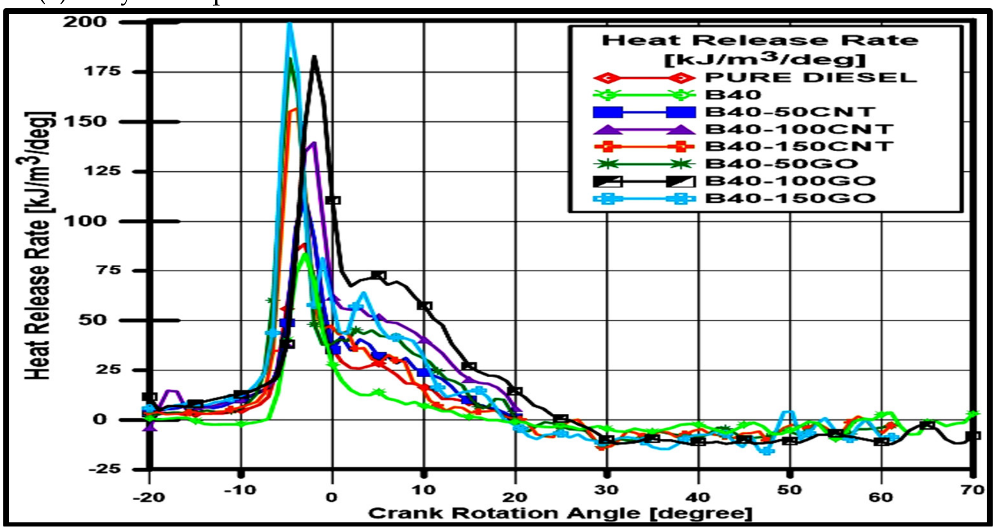
The combustion progression can be expressed by the combustion energy released, which is characterized by the location of the CA50. The combustion phasing can also be known by the crank angle position when 50% of the injected fuel was burned. The CA50 location is a significant factor through which we can predict the enhancement of the engine brake thermal efficiency and reduce all emissions. However, Figure 8 shows the location of CA50 at different engine loads for B0, B40, and B40 with various concentrations of CNTs or GO nanoparticles. From the graph, the areas of CA50 for fuels increase with an increase in the engine loads due to the rise in the amounts of the injected fuel mixture, although the turbulence in the mixture formation, the reduction in the ignition delay period, and the advances in the injection timing also have an impact. The locations of the CA50 in the case of using B40 with different concentrations of CNTs or GO nanoparticles were advanced compared to B40 or B0 at any specified engine loads. This is due to the enhancement in the fuel blend's thermal and physical properties using CNTs or GO nanoparticles. As mentioned, the high evaporation rate for the mixtures, the increase in the surface-to-volume ratio, the high oxygen content for the GO nanoparticles, and the predicted improvement for the spray characteristics will promote the combustion phasing or CA50 locations advancement when using CNTs or GO nanoparticles.

3.2. Performance Attributes

The influences of using pure diesel (B0), B40, and B40 at different concentrations of CNTs and GO nanoparticles on the engine performance were studied. Figure 9 shows the variation of BSFC for all the tested fuel blends at other engine loads and fixed speeds of 1400 RPM. It is noted that at the same engine load, by converting the fuel from B0 to B40, the BSFC increased due to increased WCO kinematic viscosity. This will reduce the spray characteristics inside the engine cylinder. By adding CNTs or GO nanoparticles to B40, the BSFC gradually decreased by increasing the concentrations due to the high evaporation rate of the fuel droplets and the increase in the surface area to volume ratio for B40-CNTs or B40-GO. With engine load increasing, the BSFC decreased, and the effect of using B40-GO can be compared with B40-CNT at varying concentrations due to oxygen atoms in the GO nanoparticles.



(**a**) In-cylinder pressure data at different nano-additives



(**b**) In-cylinder heat release rate data at different nano-additives

Figure 7. Effect of different nano additives on (**a**) in-cylinder pressure and (**b**) heat release rate relationships with crank rotation angle at 4 kW.

The BTE is the ability to convert the energy of combustion into mechanical work. Figure 10 indicates the influence of the fuel blends with different engine loads on the BTE. The BTE depends on the fuel properties like evaporation rate and chemical reactivity. It is observed from Figure 10 that at the same engine load, the BTE using B40 decreased compared to pure diesel. When CNTs or GO nanoparticles are added to B40 at different concentrations, the BTE percentages are increased compared to B0 and B40 due to the high evaporation rate, high oxygen content, advances in the ignition delay period and the increase in the surface area to volume ratio for B40-CNTs or B40-GO. By increasing the engine load, the BTE increased, and note that the effect of using B40-GO with different concentrations shows better results than that of B40-CNTs owing to the oxygen atoms in the GO nanoparticles.

The exhaust gas temperature (EGT) values are displayed in Figure 11. It is noted that by increasing the engine load values, the EGT values increase. EGTs for B0 have values higher than those of B40. Using nanoparticle fuels at different concentrations produces lower EGTs than B0 and B40 blends due to the decreased combustion duration and the advances in the ignition delay period. It is interesting to note that the B40-GO blends at different concentrations give lower EGTs than B40-CNT. The previous research and results supported the present results [53].

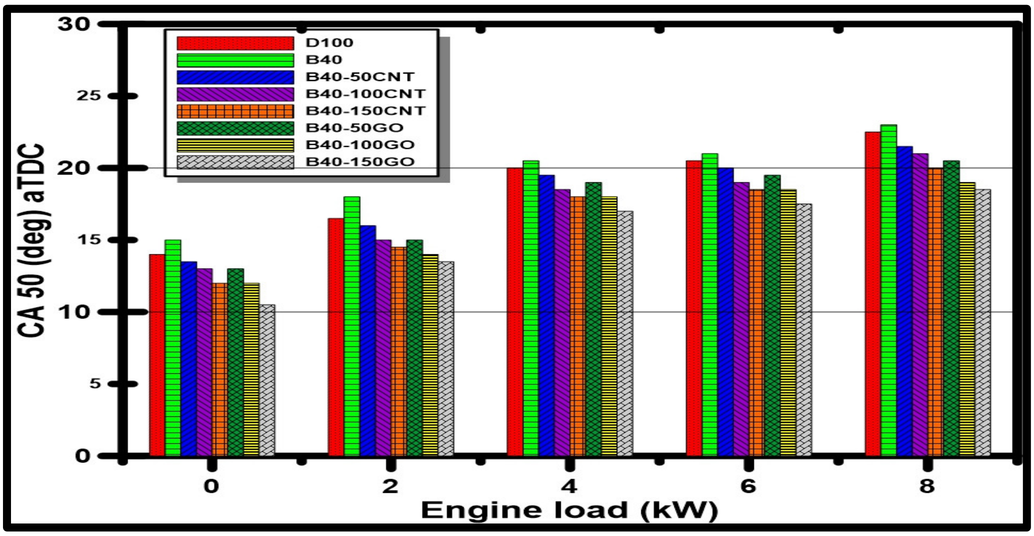


Figure 8. The relationship between the location of CA50 values and engine load.

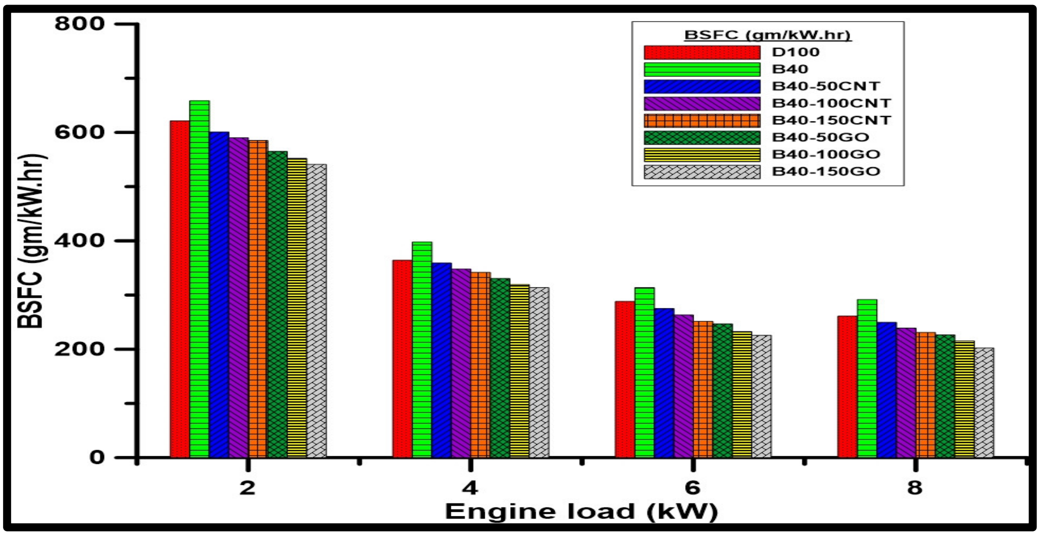


Figure 9. The relationship between BSFC values and engine load.

3.3. Emission Attributes

The influence of applying the fuel blends of B0, B40, B40-CNTs, and B40-GO on CO_2 emission is shown in Figure 12. The main variables influencing CO_2 emission are the temperature of combustion and the presence of oxygen atoms in the fuel blends. It is important to remember that the CO_2 level increases with completion of the combustion process inside the engine cylinder. As seen in Figure 12, the level of CO_2 increases with the increase in engine load due to the high combustion temperature and more combustion completion. The value of CO_2 using B40 is lower than that of B0 at the same engine load due to the reduction in evaporation rate for the fuel droplets inside the engine cylinder and the late ignition delay period of B40 compared to B0. Using B40-CNTs or B40-GO fuels at various concentrations will increase the combustion phasing and temperatures, increasing the CO_2 levels. Also, using B40-GO at different concentrations gives high CO_2 levels due to the existence of oxygen atoms and high evaporation rates in B40-GO, which increase the combustion temperatures.

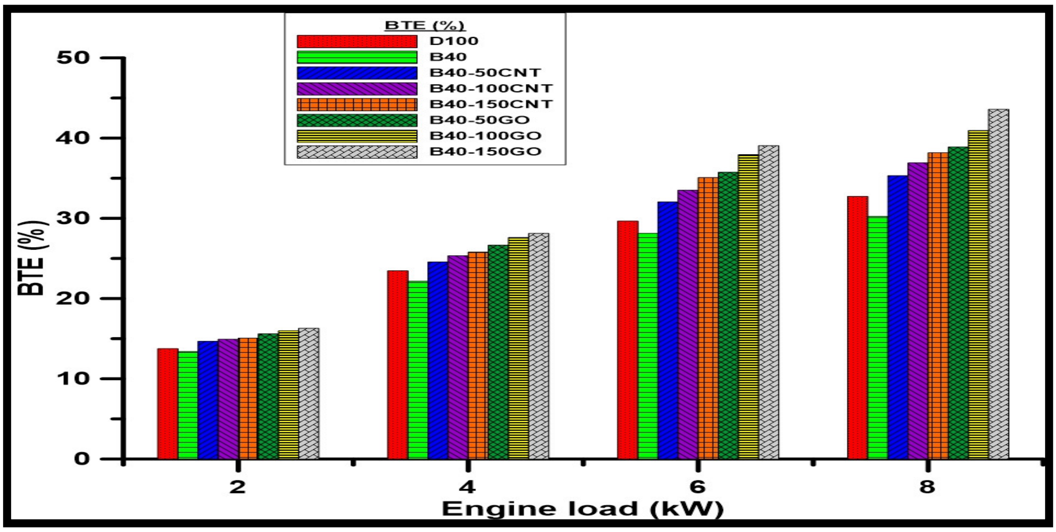


Figure 10. The relationship between BTE percentages and engine load.

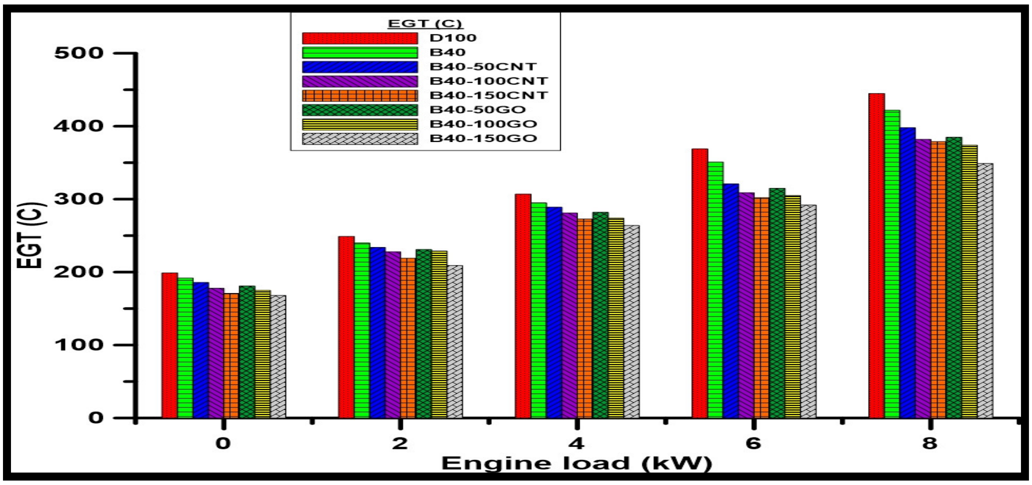


Figure 11. The relationship between EGT values and engine load.

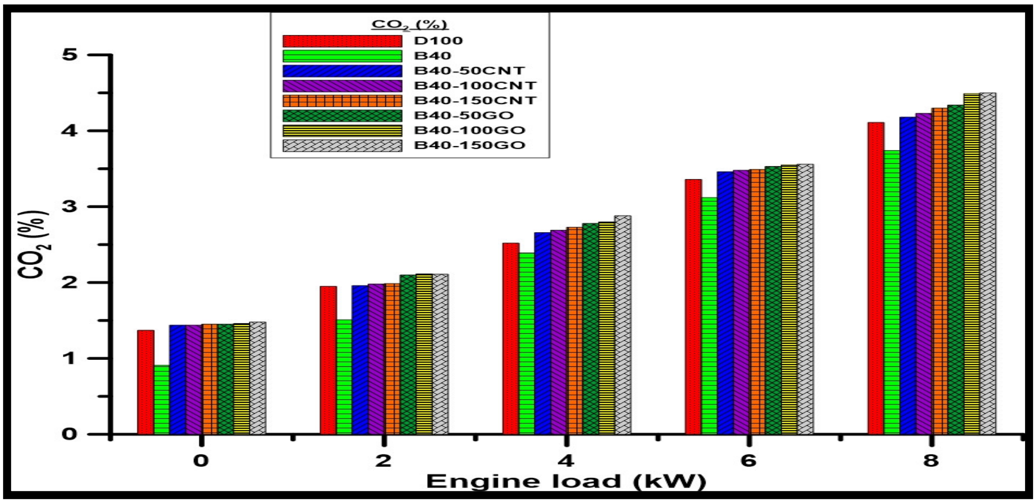


Figure 12. The relationship between CO_2 percentages and engine load.

NOx emissions, which include NO, N_2O_2, and NO_2, have catastrophic effects on the environment and human beings. Several factors, such as fuel mixture properties, engine loads, combustion temperatures, and combustion duration, affect NOx emissions.

Figure 13 shows that the NOx emissions increase by increasing the engine load. However, with the use of B0, more NOx emissions are produced compared with B40 due to the high combustion temperatures of B0. The NOx emissions decrease once the nanoparticles are added due to the lowered combustion duration, which dramatically reduces the residence time of combustion, and the high thermal conductivity of the nanoparticles, representing as a heat sink and decreasing combustion temperatures [54].

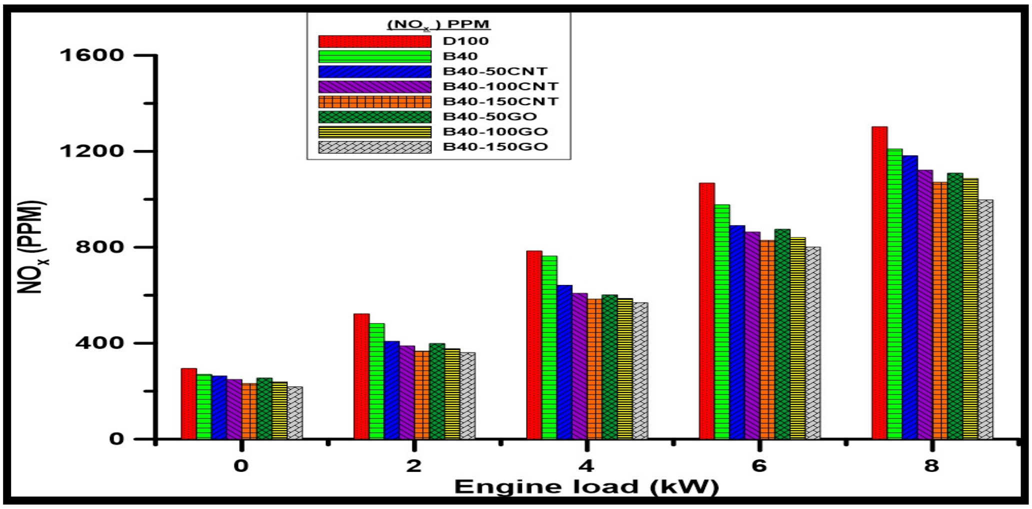


Figure 13. The relationship between NOx emissions and engine load.

Unburned hydrocarbon (UHC) emissions are formed partly due to the lack of evaporation of the fuel and incomplete combustion. Figure 14 shows the influence of the fuel blends on UHC emissions at different engine loads at a fixed speed of 1400 RPM. It can be seen that UHC emissions increase with an increase in the engine load due to expanding the charge richness. By using B40 fuel, the UHC emissions were reduced again compared with B0 because of the existing oxygen content in WCO biodiesel, thus facilitating more complete combustion. Moreover, using nanoparticles decreases UHC emissions due to the high surface-to-volume ratio and enhancement made in the fuel droplets inside the engine. The UHC emissions decrease using B40-GO nanoparticles more than using B40-CNTs because of the increased oxygen content in the B40-GO nanoparticle blends [55].

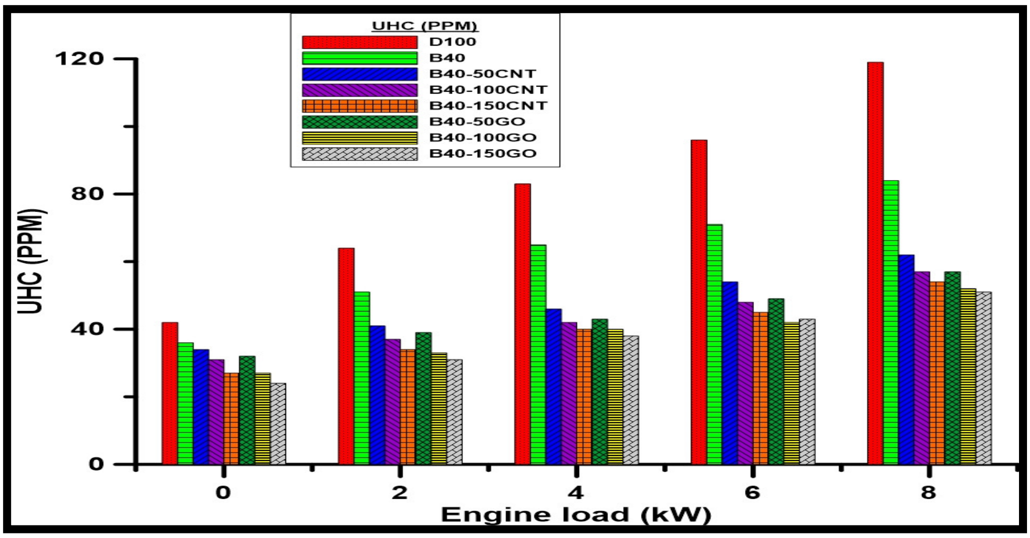


Figure 14. The relationship between UHC emissions and engine load.

The smoke opacity emission percentage decreases as a result of the complete combustion. Figure 15 shows the influence of the fuel quality on the smoke opacity emission percentage. It can be seen that the smoke opacity percentage increases with increasing the engine load. At the same load value, using B40 fuel, an oxygenated fuel, reduces the smoke opacity percentage emission compared with B0 because of the existing oxygen content in WCO biodiesel. Moreover, using nanoparticles decreases the smoke opacity percentage emission due to the high surface-to-volume ratio, which increases the chemical reactivity. The smoke opacity percentage emission decreases with the use of B40-GO nanoparticles compared with the help of B40-CNTs because of the high oxygen content in the B40-GO nanoparticle blends, and quicker completion of the combustion.

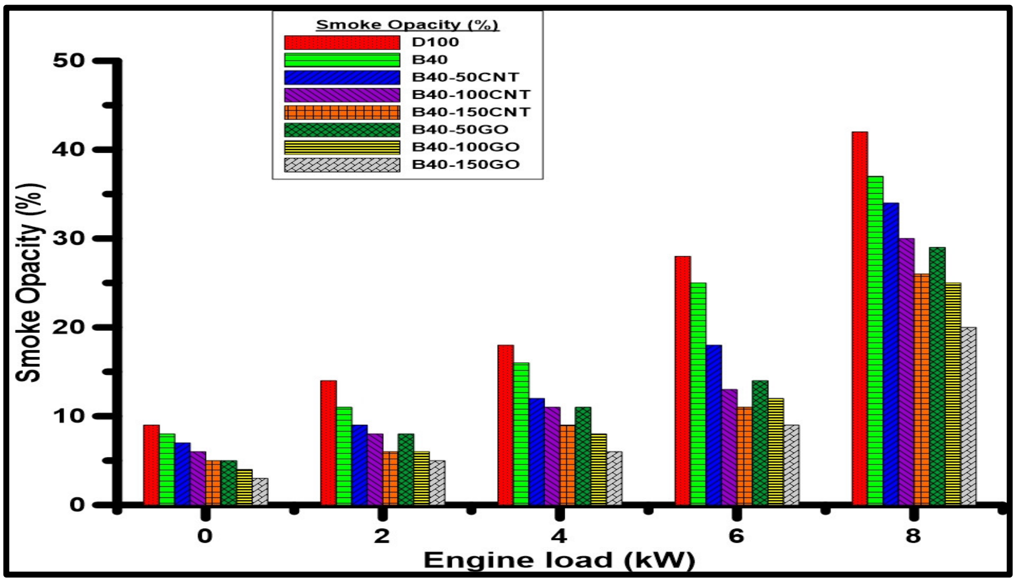


Figure 15. The relationship between smoke opacity emissions and engine load.

4. Cost Analysis

The cost of using CNTs or GO nanoparticles at various concentrations in diesel engine combustion to investigate the combustion, performance, and emission attributes can be analyzed as follows: The cost of one kg of B40 can cost 1.5 USD. The price of one gram of CNTs or GO nanoparticles is 33.5 USD. The concentrations of nanoparticles are 0.050 g, 0.100 g, or 0.150 g for one kg of 40% WCO biodiesel-diesel blend so can cost 3.175 USD, 4.85 USD, or 6.525 USD, respectively. The total cost for using B40 with 150 PPM of CNTs or GO nanoparticles at the maximum load (8 kW) according to the calculated BSFC is 1.5021 USD and 1.320 USD, respectively. The cost of using B40 only without nanoparticles at the total load (8 kW), according to the BSFC, is 0.437 USD. Therefore, the total cost of fuel is increased by adding nanoparticles because the nanoparticles are purchased commercially, which is so expensive. Still, the price will be lower if the nanoparticles are produced for mass production. Therefore, adding nanoparticles in diesel engine combustion has high utilities in conditions using low concentrations of nanoparticles in addition to lower produced emissions and lower BSFC. However, the total cost for B40 and 150 PPM of CNTs at 8 kW maximum engine load for one hour of the engine operation can be calculated as follow:

$$The\ total\ cost\ of\ B40\ +\ 150\text{PPM}\ CNTs =$$
$$(total\ cost\ of\ one\ gm\ of\ B40\ and\ 150\text{PPM}\ CNTs) \times BSFC =$$
$$\left(\frac{6.525}{1000}\right) \times 230.22 = 1.5021\ \text{USD}$$

Also, the total cost for B40 and 150 PPM of GO at 8 kW maximum engine load for one-hour operation is calculated as follows:

$$The\ total\ cost\ of\ B40 + 150\text{PPM}\ GO =$$
$$(total\ cost\ of\ one\ gm\ of\ B40\ and\ 150\text{PPM}\ GO) \times BSFC =$$
$$\left(\frac{6.525}{1000}\right) \times 202.35 = 1.320\ \text{USD}$$

Finally, the total cost of B40 only at 8 kW maximum engine load is performed as follows:

$$The\ \ total\ cost\ of\ B40 =$$
$$(total\ price\ of\ one\ gm\ of\ B40) \times BSFC =$$
$$\left(\frac{1.5}{1000}\right) \times 291.78 = 0.437\ \text{USD}$$

5. Conclusions and Future Work

A comprehensive study on the influence of using pure diesel (B0), B40, B40-CNTs, and B40-GO at three concentrations of 50, 100, and 150 ppm on the diesel engine attributes is investigated. From the results of the experiments, the conclusions are as follows:

1. The peak in-cylinder pressures are increased using different concentrations of nanoparticles due to the high surface area to volume ratio and the high evaporation rate.
2. The BSFC and BTE of B40-CNTs and B40-GO improved gradually with increasing nanoparticle concentrations and engine load compared to pure diesel (B0 and B40). Nanoparticle fuels also enhance exhaust gas temperatures (EGTs) due to the higher surface area to volume ratio oxygen content and the lowered combustion duration, which reduced the EGTs compared to B0 and B40.
3. The percentages of CO_2 levels increased with the increasing engine loads and with the use of nanoparticle fuels. B40-GO gives the highest CO_2 levels at different concentrations due to its high oxygen content, facilitating more complete combustion. Due to their high cetane number and oxygen content, NOx emissions values are also low for the B40-CNTs and B40-GO nanoparticle fuels. Furthermore, the UHC emissions are significantly reduced using B40-CNTs and B40-GO nanoparticle fuels due to the increased surface area to volume ratio, increased evaporation, and more complete combustion.

The suggestions for future studies are to increase the concentrations of nanoparticles, use different types of nanoparticles, use different types of biodiesel, raise the percentage of biodiesel-diesel blends, use error bars in the Section 3, and use the response surface methodology (RSM) to examine numerous factors affecting the response variables of diesel engine combustion, performance, and emission attributes.

Author Contributions: H.A.-E.B., M.E., E.S.A.E.S. and M.M.S. suggested and planned the laboratory work. M.M.S. and M.E. carried out the experiments. All authors wrote, analyzed, discussed the results, and performed the final paper. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Tanta University Research Fund, grant code: tu: 02-19-01.

Data Availability Statement: All data used to support the findings of this study are included within the article.

Conflicts of Interest: The authors have no relevant financial or non-financial interests to disclose.

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COMPARATIVE ANALYSIS OF WASTE COOKING OIL BIODIESEL MIXED WITH NANOPARTICLE ADDITIVES ON PHYSICOCHEMICAL PROPERTIES AND DIESEL ENGINE PERFORMANCE

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Propulsion and Power Research
Volume 11 Issue 2 (2022) 3204 Pages 209–223
https://doi.org/10.1016/J.JPPR.2022.04.004
(Database: ScienceDirect)

Propulsion and Power Research 2022;11(2):209–223

http://ppr.buaa.edu.cn/

Propulsion and Power Research

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ORIGINAL ARTICLE

Impact of different nano additives on performance, combustion, emissions and exergetic analysis of a diesel engine using waste cooking oil biodiesel

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Received 17 August 2021; accepted 19 April 2022
Available online 27 June 2022

KEYWORDS

Waste cooking oil (WCO);
Nano additives;
Engine performance;
Exergy;
Combustion characteristics;
Emissions

Abstract Biodiesel is derived from waste cooking oil (WCO) by transesterification. Methyl ester was prepared by mixing diesel and biodiesel oils as 20% by volume. Nano particles as TiO_2, Al_2O_3 and CNTs were blended with biodiesel blend at different concentrations of 25, 50, and 100 mg/l to enhance the physicochemical fuel characteristics to obtain clean and efficient combustion performance. An experimental setup was incorporated into a diesel engine to investigate the influence of these nano-materials on engine performance, exergy analysis, combustion characteristics and emissions using WCO biodiesel-diesel mixture. Enriching methyl ester mixture with 100 ppm titanium, alumina and CNTs (B20T100, B20A100 and B20C100) increased the thermal efficiency by 4%, 6% and 11.5%, respectively compared to B20. Biodiesel blending with nano additives B20T100, B20A100 and B20C100 decreased the emissions of CO (11%, 24% and 30%, respectively), HC (8%, 17% and 25%, respectively) and smoke (10%, 13% and 19%, respectively) compared to B20. However, the noticeable increase of NO_x was estimated by 5%, 12% and 27% for B20T100, B20A100 and B20C100, respectively. Finally, the results showed the rise in peak cylinder pressure by 5%, 9% and

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Peer review under responsibility of Propulsion and Power Research.

Production and Hosting by Elsevier on behalf of KeAi

https://doi.org/10.1016/j.jppr.2022.04.004

11% and increase in heat release rate by 4%, 8% and 13% for B20T100, B20A100 and B20C100, respectively. The fuel exergy of B20T100, B20A100 and B20C100 are lower than biodiesel blend B20 by 6.5%, 16% and 23% but the exergetic efficiency are increased by 7%, 19% and 30% at full load about B20.

Nomenclature

B20A25	blending 25 ppm of Al_2O_3 with B20
B20A50	blending 50 ppm of Al_2O_3 with B20
B20A100	blending 100 ppm of Al_2O_3 with B20
B20C25	blending 25 ppm of CNT with B20
B20C50	blending 50 ppm of CNT with B20
B20C100	blending 100 ppm of CNT with B20
B20T25	blending 25 ppm of nano TiO_2 with B20
B20T50	blending 50 ppm of TiO_2 with B20
B20T100	blending 100 ppm of TiO_2 with B20
BSFC	brake specific fuel consumption (unit: kg/(kW·hr))
CNTs	carbon nano tubes particles
CO	carbon mono oxide emission (unit: %)
D100	diesel oil
Ex_{exh}	exergy rate in exhaust (unit: kW)
Ex_{air}	exergy rate in air (unit: kW)
Ex_f	exergy rate in fuel (unit: kW)
Ex_W	exergy rate in work (unit: kW)
HC	unburned hydrocarbon emission (unit: ppm)
ID	ignition delay (unit: degree)
NO_x	nitrogen oxides (unit: ppm)
T_{exh}	exhaust gas temperature (unit: °C)
TE	thermal efficiency (unit: %)
TiO_2	titanium oxide nano particles
P_{cy}	instantaneous in-cylinder pressure (unit: bar)
HRR	heat release rate (unit: J/deg)
WCO	waste cooking oil biodiesel fuel
SI	sustainability index

1. Introduction

Biodiesel is considered as a substitute fuel because of its sustainability, zero-sulfur, and less pollution emitted. The barrier of methyl ester widespread is its higher price compared to regular diesel fuel. Cheapness of waste cooking oil (WCO) feedstock makes it the best effective source of biodiesel fuel. Nano particles were added to improve the engine performance and emissions. Cylinder pressure of biodiesel blended with nano additive was higher than B20 because of the rapid vaporization and lower ignition delay. Introduction of nano TiO_2 in biodiesel led to the decrease of NO_x emission by 22.57% about pure biodiesel. The decrease in smoke emission was 16.25% for blending biodiesel blend with 25 ppm nano titanium oxide concentration [1]. Introduction of nano TiO_2 of 25 ppm mass concentration incremented the brake thermal efficiency by 24.94% about alumina with the same concentration. The decreases in ignition delay were 5.47% and 0.99%, respectively about pure fuel for mixing of nano TiO_2 and Al_2O_3, respectively. In-cylinder pressure was increased for nano TiO_2 about Al_2O_3 nano particles addition [2]. Blending of TiO_2 nano particle with palm biodiesel led to the increase of thermal efficiency compared to pure biodiesel. There were improvements in combustion characteristics and emissions levels with the nano additive inclusion [3]. Nano titanium oxide was blended with Tamanu biodiesel mixture B30 in different concentrations as 25, 50 and 100 ppm. There is a positive impact on HC, CO and smoke emissions about B30 because of the improved properties [4,5].

The smoke emission was declined by the introduction of nano titanium oxide in biodiesel blend [6]. There were decreases in CO, HC and smoke emissions for nano TiO_2 concentrations of 100 and 200 ppm about crude diesel. Inclusion of TiO_2 nanofluid in methyl ester led to the emissions reductions because of the catalytic effect, improved thermal conductivity and enhanced oxidation capability [7]. Biodiesel of Acacia concinna by 40% by vol% was blended with diesel oil and TiO_2 nanoparticles in different concentrations doses. The optimum value of 150 mg/L of TiO_2 was obtained because of the specific fuel consumption, smoke and HC concentrations reductions by 18.42%, 38% and 20%, respectively about pure fuel [8]. The maximum brake thermal efficiency improvement was 26.39% under the effect of 1 g/L of nano Al_2O_3 with B20 [9,10]. Alumina nanoparticle of 30 mg/L concentration was blended to biodiesel blend B20 of poultry litter oil to examine the combustion characteristics and performance related to diesel fuel. The nano aluminum oxide content of oxygen led to the greater fuel consumed in premixed combustion and leading to the better combustion. The emissions reduction under the influence of nano additives was because of the higher surface area to volume ratio and catalytic reactivity in combustion process [11].

The surfactant was used to maintain the stability and homogeneity of dissolved nano materials in the fuel for 12 weeks. The stability of nano Al_2O_3 was investigated using UVs spectroscopy. The surfactant of 1:4 ratio was blended to achieve the higher absorption. The increase of nanoparticles concentration up to 60 ppm led to the engine performance reduction and stability problems in comparison to B20 biodiesel blend. NO_x concentrations were increased because of the higher adiabatic flame temperature, cetane number and oxygen content. Alumina concentrations of 30, 60, and 90 ppm were introduced in the base fuel [12,13]. Nano Al_2O_3 dose of 30 mg/L achieved the highest emissions reduction and engine performance improvement [14,15]. Mixing of alumina nano particles with diesterol fuel led to the increase of cylinder pressure about pure fuel due to the ignition delay improvement. Cylinder temperature reduction lowered the emission of NO_x up to 50% compared to the fuel without nanoparticles. Nano additive concentration of 75 mg/L improved the engine performance [16]. Tamarind biodiesel blend (TSME 20) was mixed with Al_2O_3 nano particles at different concentrations by an ultrasonicator. The nano particles homogeneity in the fuel was characterized by XRD and SEM methods. Introduction of alumina to TSME biodiesel could be a good substitute to diesel oil [17].

The nano particles oxidation and reduced ignition delay led to the emissions reductions [18]. The oxygen content and higher surface area of alumina nano particles in soybean biodiesel led to the improved combustion. Improved heat transfer rate and enhanced atomization rate due to the nano particles addition improved the engine performance [19]. The combustion start advancing with Al_2O_3 addition led to the enhancement in combustion characteristics [20]. Addition of nano particles has an effect on the fuel physicochemical properties. The best stability was shown at pH = 7.7 for nano Al_2O_3 [21]. Alumina oxide nano particles were introduced with jatropha biodiesel concentrations of 10, 30 and 60 ppm [22,23]. Nano particles of 10−15 nm size with different concentrations from 10 to 50 mg/L were blended with biodiesel blend with ultrasonicator. Inclusion of MWCNTs led to the performance enhancement and emissions decrease at a concentration of 30 mg/L. At nano additive dose of 50 mg/L, improved combustion characteristics were achieved [24]. Carbon nano materials introduction to the tested fuels advanced the combustion start [25].

Mixing methyl ester with CNT enhanced the BTE about biodiesel due to the secondary atomization, air-fuel mixing improvement and micro-explosion [26]. The reduction in emissions was reduced due to the micro-explosion of nano materials [27]. Inclusion of MWCNTs to jatropha biodiesel blend JME40B accelerated the combustion. Carbon deposits were eliminated for more than one month after nano particles preparation [28,29]. Nano particles concentration of 40 mg/L achieved the improved engine performance and emissions reductions [30]. Fuel vaporization and homogeneity were enhanced [31−34]. Secondary atomization and micro-explosion reduced the exhaust emissions under the impact of CNT additive [35]. The nanofluid stability is important parameter to reduce the sedimentation.

The UVs analysis proved that the good stability after 30 days [36]. The considerable enhancement in thermal conductivity of the nanofluids in all concentrations about diesel oil was shown [37]. The better combustion characteristics were proved compared to biodiesel blend under the effect of nano additives [38−40]. Carbon nanotubes were used as fuel borne nano particle additives in methyl ester mixtures. CNTs doses of 25, 50 and 100 ppm were included in the biodiesel blends under high speed agitation followed by ultrasonication [41,42].

Authors of Refs. [43] added 100 ppm nano particles of Al_2O_3 and TiO_2 nanoparticles to diesel and B10 blends. D90B10 and D90B10 Al_2O_3 have the exergy efficiencies of 25.57% and 28.12%, respectively. The greatest and lowest sustainability index values for D90B10 Al_2O_3 were 1.391 and 1.344, respectively [43]. Titanium oxide nanoparticles of three sizes (28, 45, and 200 nm) are introduced to canola biodiesel (C10) at mass fraction of 100 ppm. Specific fuel consumption was reduced by 16.91% for C10 + 28 nm TiO_2, 12.97% for C10 + 45 nm TiO_2, and 10.24% for C10 + 200 nm TiO_2. The energy and exergy efficiency values for C10 + 200 nm test fuel were the lowest, but the greatest for C10 + 28 nm TiO_2. The use of nanoparticles boosts the specific exergy of test fuels. The particle size of nanomaterials has a significant impact on the engine performance. Nanoparticles with tiny particle sizes should be favored for the improved energy and exergy performance [44]. Al_2O_3 is added to castor biodiesel B20 in three concentrations: 25, 50, and 100 ppm. The addition of 25 ppm Al_2O_3 to B20 decreased the specific fuel consumption by 14.86%. For 25, 50, and 100 ppm, the opacity of smoke is reduced by 5.2%, 12% and 17.0%, respectively. The maximum NO_x reductions for 25, 50, and 100 ppm Al_2O_3 was 11%, 4.89%, and 4.32%, respectively [45]. Spirulina microalgae biodiesel was produced and tested with inclusion of Al_2O_3 nano particles at different blends [46]. B15 and B30 biodiesel blends containing 75 ppm Al_2O_3 were used. Blending biodiesel with nano particles about base fuel resulted in higher thermal efficiency and lower fuel consumption [46]. When nanoparticle additives such as Al_2O_3 and TiO_2 are employed, NO_x emissions are reduced. Increased doses of nanoparticles were used to reduce the smoke emissions. Because of the catalytic activity, high surface-to-volume ratio, and enhanced fuel-air mixing, the inclusion of nano particles reduced the CO and HC emissions [47]. The addition of nano materials (Al_2O_3 and TiO_2) to diesel fuel enhances the combustion and decreases the pollutants. When adding mass fractions of 25, 50, 100, and 150 ppm of nano Al_2O_3 and TiO_2 to diesel fuel, the cylinder's maximum pressure was increased. The addition of nano TiO_2 and Al_2O_3 improved the thermal efficiency by 24.25 and 20.45%, respectively. The addition of 25 ppm nano Al_2O_3 and TiO_2 boosted the maximum cylinder pressure to 63.2 and 60.4 bar, respectively [2].

Several studies have been conducted on the influence of biodiesel blends with inclusion of nano additives on either performance, combustion or emission characteristics of engines. But, combining many types of nano particles (Al_2O_3, TiO_2 and CNTs) with a broad range of concentration variations (25, 50 and 100 ppm) for different biodiesel blends and comparing with regular diesel in one study has not been investigated elsewhere. Moreover, there is a literature gap on studying theses comprehensive effects on waste cooking oil, which is unique and novel. The use of the three nanoparticles types is to obtain the combined effect of these nanoparticles as stability, geometrical structure, catalytic reactivity and improved thermal properties. The optimized nano additive dose was assessed from testing broad band of concentrations to obtain the best engine combustion performance with the lowest emissions. Addition of nano additives enhances the physicochemical properties, evaporation, thermal properties, heat transfer and increases the surface area to volume ratio. Fewer studies had been done on the exergy analysis of a diesel engine burning nanoparticle biodiesel blends. Three different nano additives as CNT, Al_2O_3 and TiO_2 were considered in different particle size. Nano additives are added to the tested fuel to improve the cold flow properties of biodiesel, enhance combustion efficiency and reduce the harmful emissions. Concentration band of additives was considered and varied from 25 to 100 ppm because the higher concentrations create soot suppression. Vaporization, atomization problems and improper fuel-air mixture associated with the operation of biodiesel operation are diminished by the inclusion of nano particles which enhance the physicochemical properties of biodiesel. Biodiesel was derived from economical waste cooking oil. Disposal of waste cooking oil led to the environmental problems and water resources pollution. Specific fuel consumption, thermal efficiency, heat released rate, emissions of HC, CO and NO_x, ignition quality, in-cylinder pressure and exhaust temperature are examined and compared with regular biodiesel blend.

2. Material and methods

2.1. Production of biodiesel

High viscosity of waste cooking oil (WCO) makes it is using directly in diesel engines. Transesterification separates the methyl ester from the oil. WCO was purified and the moisture was eliminated by the oil preheating to 110 °C [48]. The oil was placed in a flask supported with magnetic stirrer, condenser and thermometer. Potassium hydroxide (KOH) was used as a catalyst of 1.5% by weight and was dissolved in methanol alcohol of 1:9 molar ratio to produce methoxide [49]. The oil and methoxide blend were stirred well for 90 min at a temperature of 60 °C to get the glycerin and methyl ester. In the separating funnel, the mixture was remained to settle for 24 h to separate the ester from glycerin. Warm water was used to eliminate the impurities, unreacted methanol and catalyst. A rotary evaporator was used to remove the water and dry the biodiesel. Diesel oil was mixed with methyl ester in 20% by volume as B20. The biodiesel blends properties were evaluated in comparison to diesel oil as shown in Table 1.

2.2. Preparation of tested fuels

Carbon nanotubes (CNTs), titanium oxide (TiO_2) and alumina (Al_2O_3) were used as additives to biodiesel blend. Nanotech egypt provided the nano materials and its specifications were displayed in Table 2. Scanning Electron Microscope (SEM) (Model: Quanta FEG250) and Transmission Electron Microscope (TEM) (Model: JOEL JEM-2100) were used to investigate the internal structure of nano additives. SEM and TEM images are shown in Figure 1. TEM photos show the spherical appearance with the average diameters of 10 and 35 nm for alumina and titanium oxide, respectively. The particles of large clusters are shown in SEM images. The tubular shape is of 20 nm diameter and 660 nm length as in CNTs. The nano additives were dispersed uniformly in biodiesel mixture by ultrasonication.

The average particle size of TiO_2, Al_2O_3 and CNTs are 35, 10 and 20 nm, respectively. Homogenous distribution of nano additives in the fuel was checked continuously. An ultrasonicator of capacity 160 W and frequency of 40 kHz

Table 1 Properties of WCO biodiesel and its blends with nano-additives.

Properties	Method	Biodiesel WCO	Diesel	B20	B20T100	B20A100	B20C100
Density @15 °C	ASTM D-4052	883	835	840	843	842	841.5
Kinematic viscosity, cSt, @40 °C	ASTM D-445	5.1	3.5	3.7	3.9	3.84	3.75
Flash point/°C	ASTM D-93	120	72	78	82	85	87
Cetane number	ASTM D-13	52	49	50	51	51	51
Calorific value/(MJ/kg)	ASTM D-224	39.5	42	40.5	40.8	41	41.2

Table 2 Nano particles properties.

Properties	TiO_2	Al_2O_3	CNTs
Supplier		Nanotech Company, Egypt	
Color	White	White	Black
Form		Powder	
Solubility		Dispersed in water	
Bulk density/(gm/cm^3)	0.24	3.95	1.35
Avg. size (TEM)	35 ± 5 nm	10 ± 2 nm	(W: 20 ± 5 nm) and (L: > 660 nm)
Shape	Spherical	Spherical	Tubular

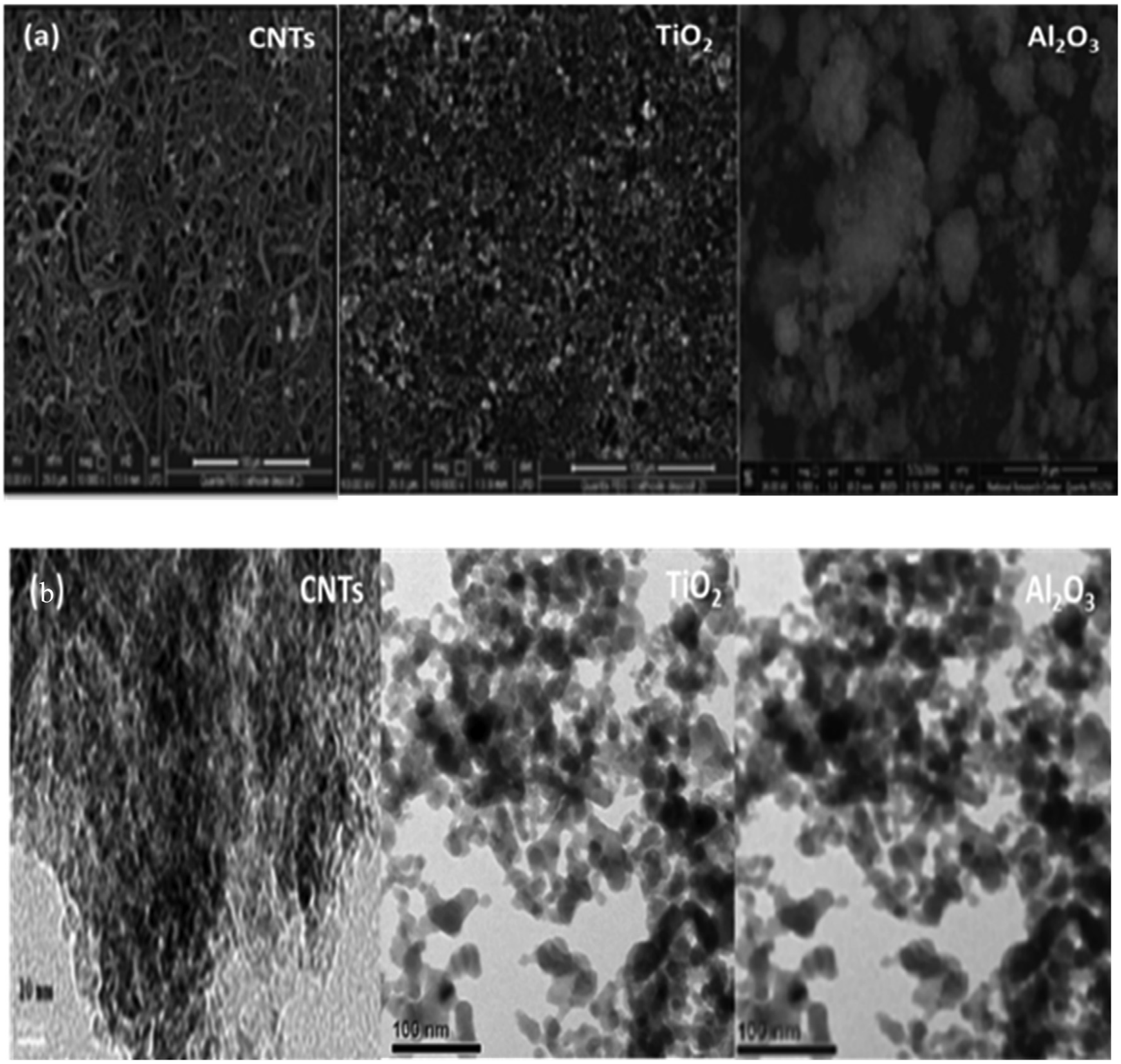

Figure 1 Micrographs of the used nanomaterials: (a) SEM images and (b) TEM images.

produced the uniform suspension of the nanoparticles at a fixed agitation time of 30 min. Ultrasonication is used for the dispersion of nanoparticles in the base fuel and prevents the agglomeration of nanoparticles. The stability was enhanced by using Span 80 and Tween 80 surfactants. This preparation does not lead to the accumulation and precipitation of nano additives.

The homogenous distribution of additives in the fuel was achieved by agitation of 30 min continuously. Nano materials concentrations of 25, 50, and 100 mg per liter of biodiesel blend were prepared. Prepared tested fuels were observed for a time of 21 days to show the sedimentation and stability. Blended TiO_2 nano particles with biodiesel blend were named as: B20T25, B20T50 and B20T100 for 25, 50, and 100 mg/L, respectively. Blends of CNTs concentrations with biodiesel are B20C25, B20C50 and B20C100 but alumina doses with B20 are named as: B20A25, B20A50 and B20A100 for 20, 50, and 100 mg/L, respectively. Chemical and physical properties of nano materials are shown in Table 2.

2.3. *Setup test rig*

Table 3 shows the specifications of the tested engine. Experimental set up schematic diagram was displayed in Figure 2. Test engine was directly connected to AC generator (Model: Meccalte, U.K.) of 10.5 kW maximum output power to show the engine brake output power. A sharp

Table 3 Engine specifications.

Parameters	Specifications
Model	DEUTZ F1L511
Number of cylinders	1
Cooling type	Air cooled
Stroke/mm	105
Bore/mm	100
Compression ratio	17.5:1
Fuel injection advance angle	24° BTDC
Rated output power/kW	5.775 at 1500 rpm
Injector opening pressure/bar	220

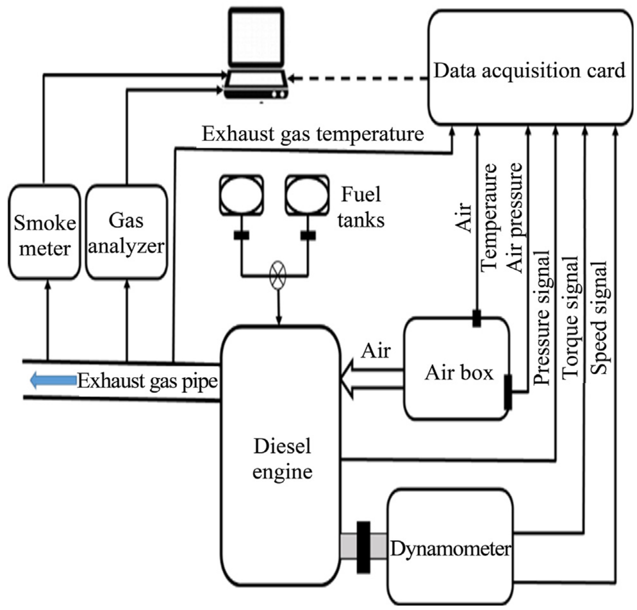

Figure 2 Experimental setup schematic diagram.

edged orifice attached to the air box was used to evaluate the intake air flow rate. Calibrated thermocouples of K type were used to measure the exhaust and intake air temperatures. HC, NO_x, CO emissions were measured using gas analyzer (Model: MRU DELTA 1600-V, Germany). Smoke emission was evaluated by a smoke meter (Model: OPA, France). Piezoelectric pressure transducer (Kistler, model 601A) measured the cylinder pressure (250 bar range, accuracy of 1.118% and sensitivity of 16.5 pc/bar) and its signal was transmitted to a charge amplifier (Nexus, 2692-A-0S4). The piping resonance and signal lag were minimized by mounting the transducer as flush in the cylinder head. The position of the piston was evaluated using a proximity switch (LM12-3004NA) on the engine output shaft measured. The pressure signals were averaged over 120 cycles. The sensors data was transmitted by acquisition card (NI-USB-6210) using LABVIEW software. Engine load was varied until 100% at 1500 rpm engine speed during all tests. First, the engine was warmed up by using pure diesel oil. Then, the methyl ester blend with nano additives fuels was used. The repeatability errors were minimized by doing all measurements three times. Table 4 shows the instrumentation specifications with their uncertainties. The overall uncertainty was evaluated and has a maximum value of 3.33%.

All tests were carried out by varying the load from zero to full load at constant rated speed of 1500 rpm throughout the experiment. First, the engine was warmed up without loading using pure diesel fuel until obtaining a constant exhaust temperature. Then, tested fuel line was switched and engine load was regulated. Finally readings were recorded after reaching the steady state condition. All tests were carried out three times for repeatability errors. The details of the instrumentation adopted in the present investigation with their uncertainties are presented in Table 4. The overall uncertainty of the experiment was calculated and found to have a maximum value of 3.33%.

2.4. Exergy and sustainability assessment

Exergy conservation of the system as shown below

$$\sum \dot{E}x_{in} = \sum \dot{E}x_{out} + \sum \dot{E}x_{des} \tag{1}$$

Applying the general exergy conservation to the engine system as follows:

$$\sum \dot{E}x_{air} + \sum \dot{E}x_{fuel} = \sum \dot{E}x_{work} + \sum \dot{E}x_{exh} + \sum \dot{E}x_{losses} + \sum \dot{E}x_{des} \tag{2}$$

$\sum \dot{E}x_{air}$, $\sum \dot{E}x_{fuel}$, $\sum \dot{E}x_{work}$, $\sum \dot{E}x_{exh}$, $\sum \dot{E}x_{losses}$ and $\sum \dot{E}x_{des}$ denote the exergy of inlet air and fuel, output work, outlet exhaust and losses respectively.

Evaluation of each term can be estimated as follows [50]:

$$\sum \dot{E}x_{air} = \dot{m}_{air} c_{p,air}\left[(T_{air} - T_o) - T_o \ln\left(\frac{T_{air}}{T_o}\right)\right] \tag{3}$$

$$\sum \dot{E}x_{fuel} = \dot{m}_f \, H_u \, \varepsilon_{fuel} \tag{4}$$

$$\varepsilon_{fuel} = 1.0401 + 0.1728\frac{H}{C} + 0.0432\frac{O}{C} + 0.2169\frac{S}{C}\left[1 - 2.169\frac{H}{C}\right] \tag{5}$$

$\frac{H}{C}$, $\frac{O}{C}$ and $\frac{S}{C}$ are mass fractions of hydrogen, carbon, oxygen and sulfur for the tested fuels. H_u expresses the lower heating value of the tested fuel. $_{fuel}$ denotes the chemical exergy factor, which is higher than one. This justifies why is the exergy rate of fuel is greater than its input heating value.

Table 4 Accuracy and maximum uncertainty of various parameters.

Instrument		Range	Accuracy	Uncertainty
Load indicator		250–5000 W	±10 W	±0.2
Thermocouples		0–1300 K	±1 °C	±0.15
Exhaust gas analyzer	NO	1–5000 ppm	±12	±0.2
	HC	0–20000 ppm	±12	±0.2
	CO	0–10%	±0.06	±0.2
Pressure transducer		0–250 bar	±1	±2

$$\dot{E}x_{work} = BP = T\omega \quad (6)$$

$$\sum \dot{E}x_{exh} = \sum_{i=1}^{n} \dot{m}_i(\dot{E}x_{m,i} + Ex_{ch,i}) \quad (7)$$

$\dot{E}x_{m,i}$ and $\dot{E}x_{ch,i}$ are thermophyiscal and chemical exergies of the exhaust of each species.

$$\dot{E}x_{m,i} = c_{p,i}\left[(T_{exh} - T_o) - T_o \ln\left(\frac{T_{exh}}{T_o}\right)\right] \quad (8)$$

$$\dot{E}x_{ch,i} = \overline{R}\left[T_o \ln\left(\frac{y_i}{y_{env,i}}\right)\right] \quad (9)$$

$\overline{R}$ is the universal gas constant (8.314 kJ/(kmol·K)), T_0 is the ambient temperature (K). y_i and $y_{env,i}$, show the molar fractions of the exhaust and environment components respectively.

$$\sum \dot{E}x_{losses} = \dot{Q}_{lost}\left(1 - \frac{T_0}{T_{cw}}\right) \quad (10)$$

The exergy efficiency of the engine using biodiesel can be estimated as follows [2]:

$$\psi = \frac{\dot{E}x_{work}}{\dot{E}x_{air} + \dot{E}x_{fuel}} \quad (11)$$

The sustainability index assesses the economic and environmental impacts of using new trends of fuels. There is a direct nexus between the sustainability index and exergy efficiency as both terms express the environmental and economical benefits gained by implementing sustainable systems. Evaluating sustainable index can be expressed as follows [51]:

$$SI = \frac{1}{1 - \psi} \quad (12)$$

3. Results and discussions

3.1. Brake specific fuel consumption (BSFC)

Figure 3 displays the effect of nano CNTs, TiO_2 and Al_2O_3 addition to waste cooking oil biodiesel (B20) on BSFC at different engine loads. A typical trend of BSFC versus engine load is depicted for all types of tested fuels. BSFC of nano additives blended with biodiesel were lower than WCO biodiesel and neat diesel due to the great role of nanoparticles in advancing the physical fuel properties. The catalytic activity induced by adding nano particles rises the surface/volume ratio and promotes the combustion characteristics and leads to the less fuel consumption. Nano particles addition reduced the physical delay, evaporation time of the fuel and enhanced the properties of fuel related to diesel oil. The secondary atomization of oxide nanoparticle is improved and supports efficient burning rate of fuel. BSFC of CNT at 100 ppm slightly approaches the same value of regular diesel at different loads. The maximum decreases in BSFC of B20T100, B20A100 and B20C100 were 4.5%, 7% and 12% respectively compared to pure methyl ester mixture at full engine load. Results are confirmed as in Refs. [11,15,24].

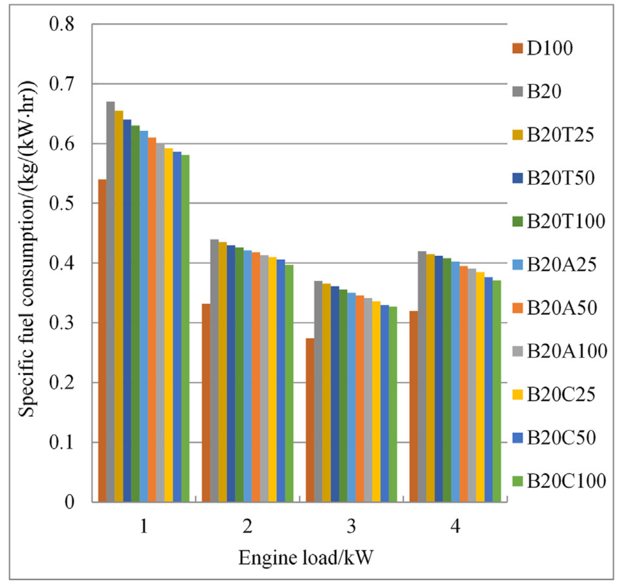

Figure 3 Brake specific fuel consumption of nano additives blended with WCO biodiesel.

3.2. Thermal efficiency (TE)

Brake thermal efficiency of diesel, WCO biodiesel blend with additives at different loads are given in Figure 4. It

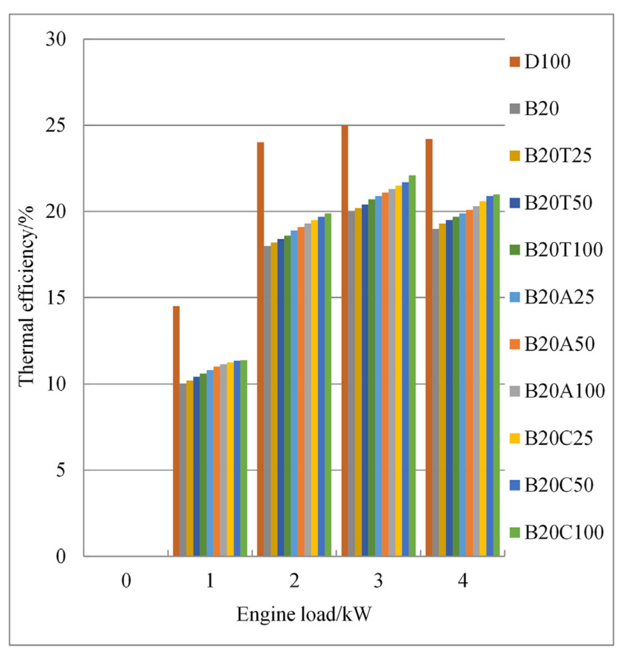

Figure 4 Influence of nano particles blended with methyl ester on the thermal efficiency.

shows that addition of nano particles on biodiesel increases the TE about methyl ester blend. This can be justified as the result of the surface to the volume ratio increase associated with the nano particles catalytic activity which enhances the reaction kinetics and leads to the heat released rate improvement. The nano particles addition promotes the injected fuel dispersion and fuel droplet burning. This leads to obtain better fuel air mixing and hence an efficient combustion characteristics. The carbon deposits oxidation and less fuel consumption are shown under the impact of nanoparticles. Blending of biodiesel blend with nano particles B20T100, B20A100 and B20C100 produced the maximum increases in thermal efficiency up to 4%, 6% and 11.5% respectively at 100% of engine load compared to crude methyl ester mixture. These findings are in great agreement with literature [11,25].

3.3. Exhaust gas temperature (T_{exh})

Exhaust gas temperature of neat diesel, waste cooking biodiesel blend versus different engine loads with nano materials is investigated in Figure 5. Increase of T_{exh} is proportional to the load that needs more burning fuel to meet the output power increase. Inclusion of nano particles to B20 rises the exhaust gas temperature at the engine exit. The fine dispersion supported by addition on nano particles enhances the ignition quality of biodiesel and increases the burning rate which has a direct effect on increasing the exhaust enthalpy at engine exit. The decrease of ignition delay brings high cylinder temperature under the effect of nano particles homogenization. Waste cooking oil biodiesel blend with nano particle B20T100, B20A100 and B20C100 at 100% of the engine load showed the higher increases in the exhaust gas temperature up to 5%, 12% and 20% respectively about methyl ester mixture, which agrees with literature [11,30,32].

3.4. Cylinder pressure (P_{cy})

The cylinder pressure variation with crank angle for all tested fuels at full load is shown in Figure 6. Higher peak cylinder pressure and maximum rate of pressure rise correspond to the large amount of fuel burned in premixed combustion. P_{cy} of biodiesel blend is lower than diesel oil because of the less fuel consumption in premixed combustion stage and short ignition delay. Short ignition delay and higher cetane number were due to the addition of nano particles and this led to the higher burning rate. The combustion characteristics are improved due to the catalytic effect and higher surface area of nano additives. The improvements in evaporation rate, thermal conductivity and heat release rate as the result of nano particles addition which led to the higher peak cylinder pressure. The higher fuel burning in premixed combustion phase is the main cause of higher peak cylinder pressure. The decrease of ignition delay is due to the earlier appearance of P_{max} and combustion advance. Figure 7 shows the peak cylinder pressure under the effect of nano particles at different load. Cylinder pressure of CNT at 100 ppm slightly approaches the same value of regular diesel at different loads. The increases in the peak cylinder pressures for B20T100, B20A100 and B20C100 about B20 were 5%, 9% and 11%, respectively at full load. The findings are agreed with references [11,25,30].

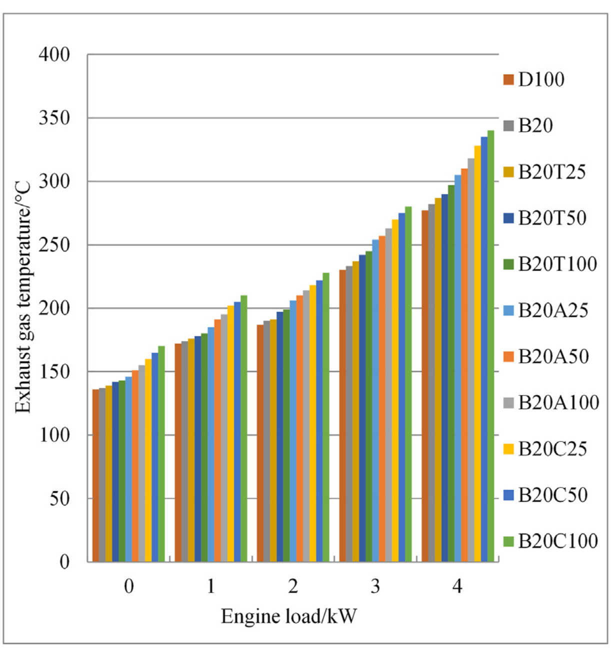

Figure 5 Influence of nano additives addition on exhaust gas temperature.

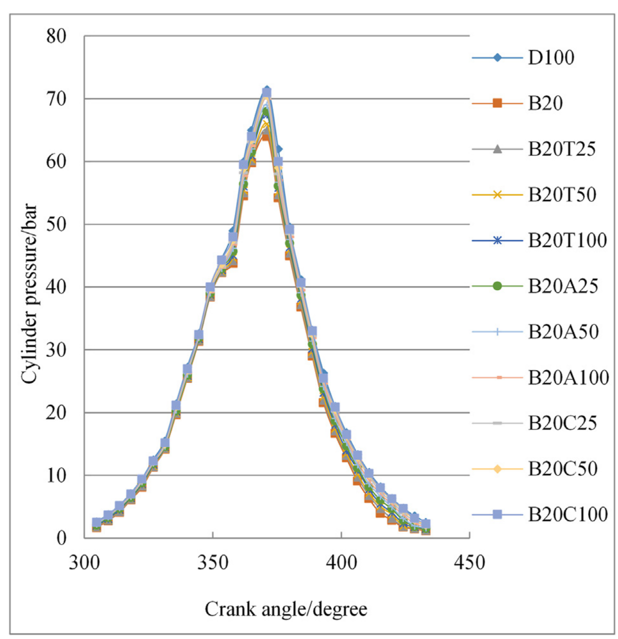

Figure 6 Cylinder pressure of all tested fuels for biodiesel blends at full load.

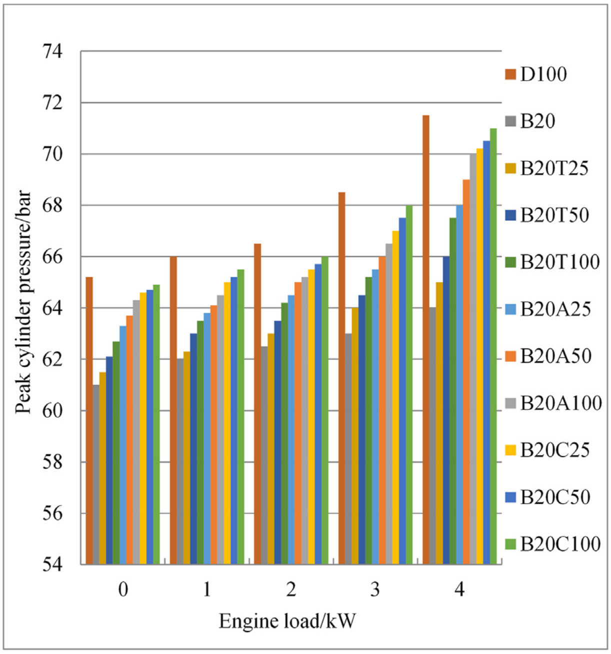

Figure 7 Peak cylinder pressure of biodiesel blend with nano-additives at different loads.

3.5. *Heat release rate (HRR)*

HRR distributions of methyl ester blend with nano additives at crank angle variation at full load are shown in Figure 8. Heat release rate and in-cylinder pressure of biodiesel blend are lower than diesel oil due to the less fuel consumption in premixed combustion accompanied with the short ignition delay.

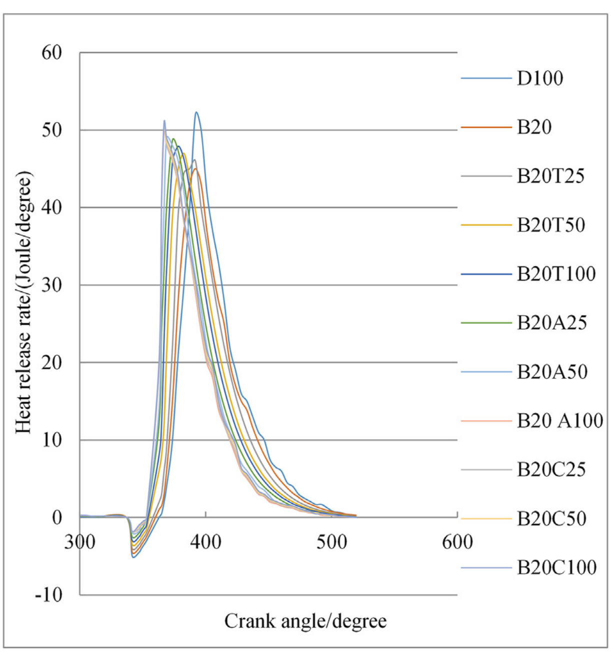

Figure 8 HRR of biodiesel blend with nano-additives at full load.

The atomization and vaporization problems of biodiesel blends lowered the heat released rate compared to crude diesel. Addition of nano particles led to the improvement of catalytic reactivity and HRR. This promotes the fuel penetration and ignition properties. Thermal properties enhancement and high surface area to volume ratio activate the reaction rate of blended biodiesel. The more fuel in the premixed combustion plays a great role in the combustion advance which results in higher heat release rate. Thus increasing the nano particles dosing level in methyl ester fuel tends to increase the heat release rate. The increases in peak HRR values for B20T100, B20A100 and B20C100 are 4%, 8% and 13%, respectively about B20 at full load, which confirms with references [25,30,32].

3.6. *Ignition delay (ID)*

Start of combustion can be detected experimentally as the zero value of heat release rate and the minimum cumulative heat release. Variations of ignition delay period for the different nano additives concentrations are displayed in Figure 9. The engine load increase leads to the ignition delay decrease. Nanoparticles addition produces the ignition delay decrease. Improved air-fuel mixture homogeneity, catalytic activity and surface area/volume ratio led to the heat released rate improvement. The maximum decreases in ignition delay for B20T100, B20A100 and B20C100 were 11%, 23% and 31%, respectively related to crude methyl ester mixture at full load. These findings are in great agreement with references [15,30,32].

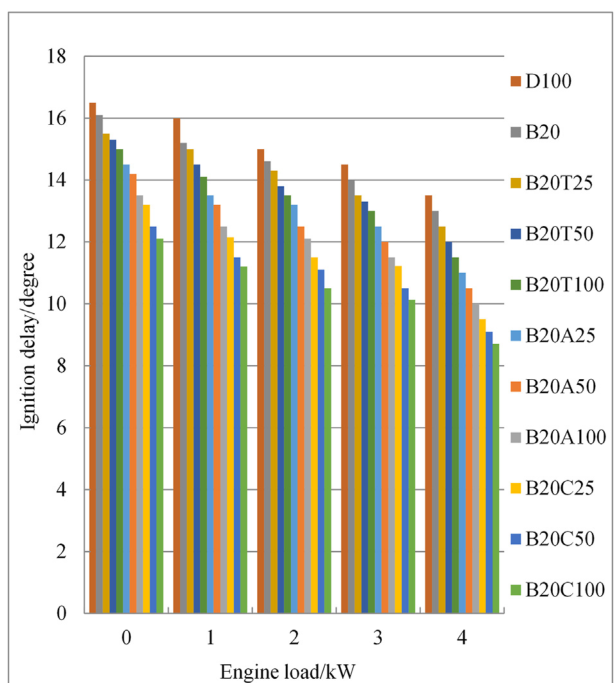

Figure 9 Influence of nano additives biodiesel blends on ignition delay.

3.7. CO emission

CO emissions trends versus the engine load for crude diesel/biodiesel blend with nano particles are indicated in Figure 10. CO increases with the engine load due to the rich combustion that takes place at higher loads. Biodiesel is oxygenated fuel and emits lower CO emission than diesel oil. Air-fuel mixing and combustion efficiency are improved under the effect of biodiesel blend. Adding nano particles promotes the atomization and vaporization processes of biodiesel with better fuel dispersion that supports air-fuel mixing strength to develop the greater reduction in CO emission. Larger surface contact area of nanoparticles leads to the chemical reactivity and ignition characteristics improvement. The sharp drop in fuel homogeneity leads to the more breakup during the fuel injection under the effect of nanoparticles addition. The oxygen content in nano titanium and alumina also helps to the combustion improvement and CO emission reduction. Inclusion of nano particle to biodiesel blend B20T100, B20A100 and B20C100 achieved the maximum reductions in CO emissions up to 12%, 24% and 31%, respectively at 100% of engine load related to biodiesel blend, which is confirmed with references [15,30,32].

3.8. HC emission

Hydrocarbon emissions variable engine load of biodiesel blend with nano particles are described Figure 11. HC trends are similar to CO, where HC emissions are increased from lower to higher loads due to the relatively less available oxygen and higher fuel consumption at high loading. The oxygen content and short ignition delay of biodiesel produced the reduction of HC emission related to regular diesel. Introduction of nano particles to methyl ester mixture results in the more fuel-air homogeneity and vaporization enhancement. The nano particles smaller size promotes the secondary fuel atomization. Thus enhances the mixing of reactants and guarantees the combustion completeness. Existence of oxygen and higher catalytic activity improve the combustion and reduce the production of unburned hydrocarbons. Fuel oxidation improvement and lower carbon combustion activation temperature were shown under the addition of nano particle. The highest decrease in HC emissions with nano particle of B20T100, B20A100 and B20C100 were about 8%, 17% and 25%, respectively at 100% of engine load compared to neat biodiesel mixture. These results are in great compliance with references [15,25,30].

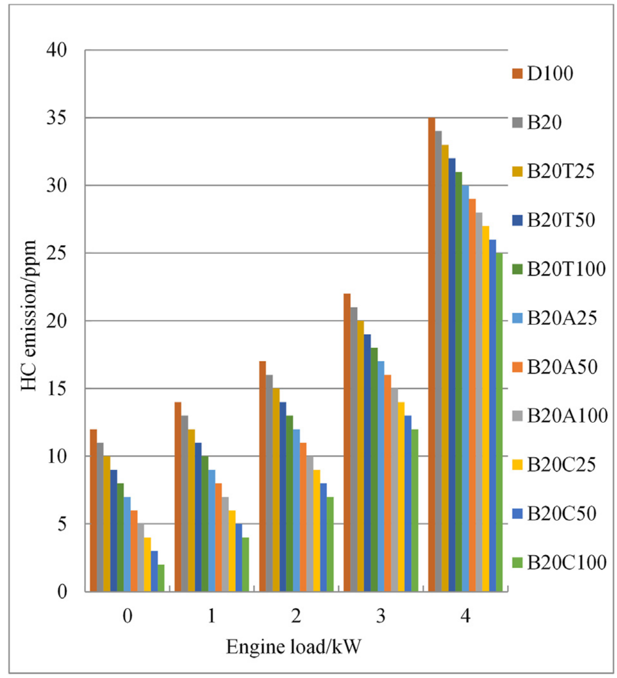

Figure 11 Influence of nano additives addition to biodiesel on HC emission.

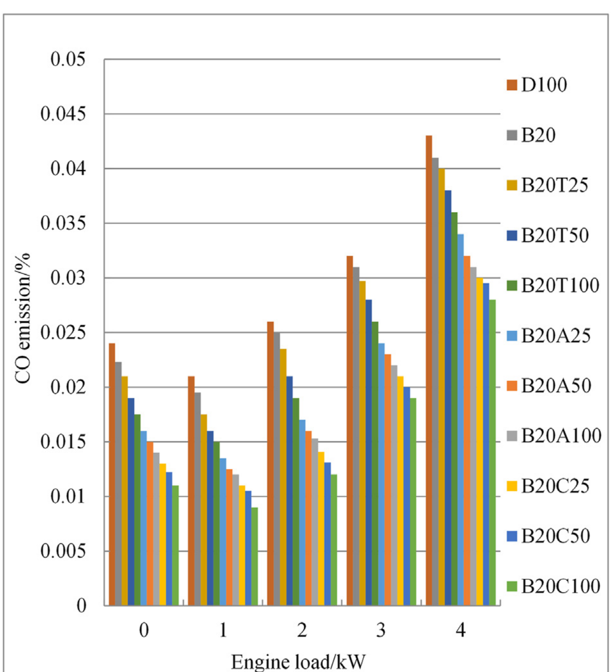

Figure 10 Influence of nano materials blended with biodiesel on CO emission.

3.9. NO_x emission

Figure 12 presents the nano particles addition effect on NO_x emissions. Nitrogen oxide emission of methyl ester is greater than crude diesel. Higher cylinder and adiabatic flame temperatures lead to the increase of NO_x emissions with the engine load. NO_x formation is affected by the oxygen availability, ignition delay and cylinder combustion temperatures. Biodiesel achieves the higher NO_x emission than diesel oil due to its physiochemical properties which influences on the cylinder temperature and hence the reaction kinetics of NO_x formation. With thorough comparison between Figures 5 and 12, it is depicted that both trends of

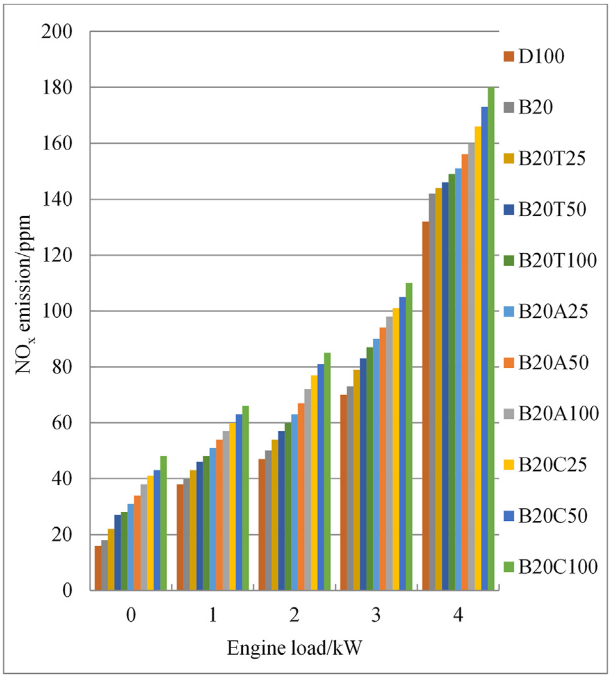

Figure 12 Impact of nano particles addition to biodiesel on NO_x emission.

exhaust temperature and NO_x are similar for all fuels at various engine loads which confirms the direct dependence between NO_x and exhaust gas temperature. This noticeable observation justifies that inclusion of nano particles improves the ignition quality of biodiesel and consequently increases the heat release rate along with exhaust gas temperature and hence produces the higher NO_x as well.

The highest increases in NO_x emission were up to 5%, 12% and 27%, respectively at full engine load for B20T100, B20A100 and B20C100 about methyl ester mixture. These results are confirmed with references [15,24,25,30].

3.10. Smoke emission

Smoke emissions values at the engine load range of all fuels are investigated in Figure 13. The smoke emission increases with the engine load increase because of the fuel consumption rise and rich fuel-air mixture. The deviation in smoke emissions of biodiesel blend about crude diesel is due to the oxygen existence that results in combustion enhancement. More burned fuel in the combustion diffusion stage and ignition delay reduction lead to the decrease in smoke emission. The reduction in smoke emission is due to the higher surface area/volume ratio, surface activity and ignition characteristics improvement under the impact of nano additives inclusion. Waste cooking methyl ester mixture with nano additives B20T100, B20A100 and B20C100 attains the smoke reductions up to 10%, 13% and 19%, respectively at full engine load compared to B20. These results are agreed with the literature [15,30,32].

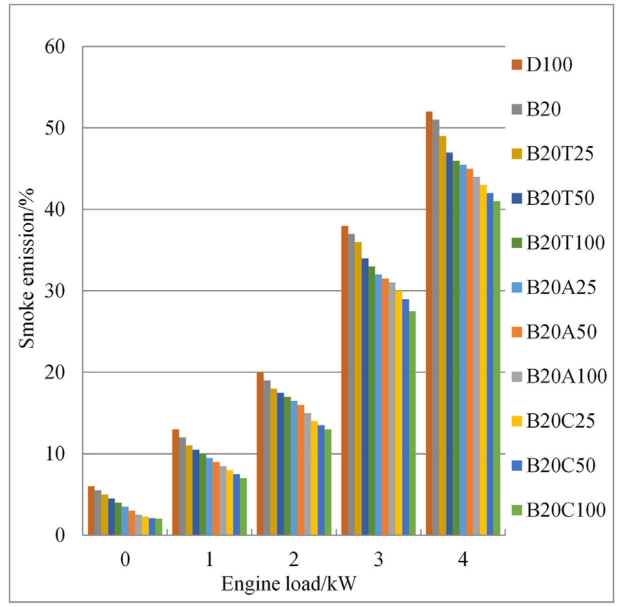

Figure 13 Effect of nano materials addition to biodiesel on smoke emission.

3.11. Fuel exergy rate

The fuel exergy can be used to describe the qualitative heat input to the engine that will be turned into useful work. The fuel exergy of different nano additives concentrations is displayed in Figure 14. The fuel exergy increases with the load increase for all blends because of the increments in fuel consumption at higher loads. The exergy of diesel is lower than all tested fuels at all engine loads. The fuel exergy of B20T100, B20A100 and B20C100 are lower than biodiesel

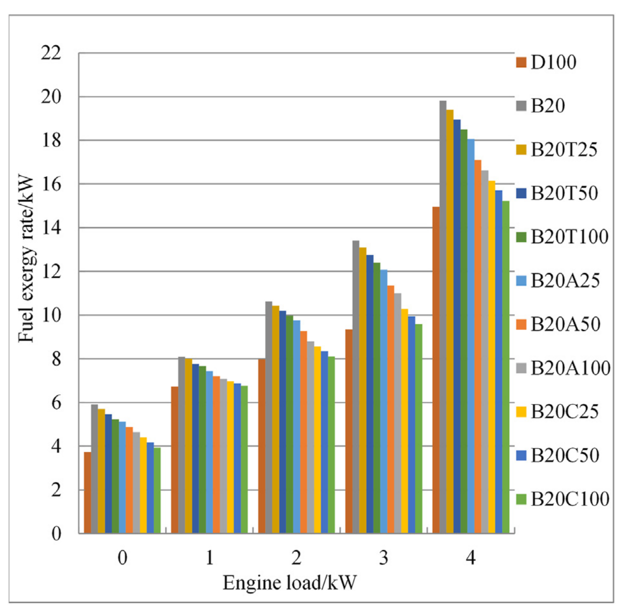

Figure 14 Influence of nano additives on fuel exergy rate.

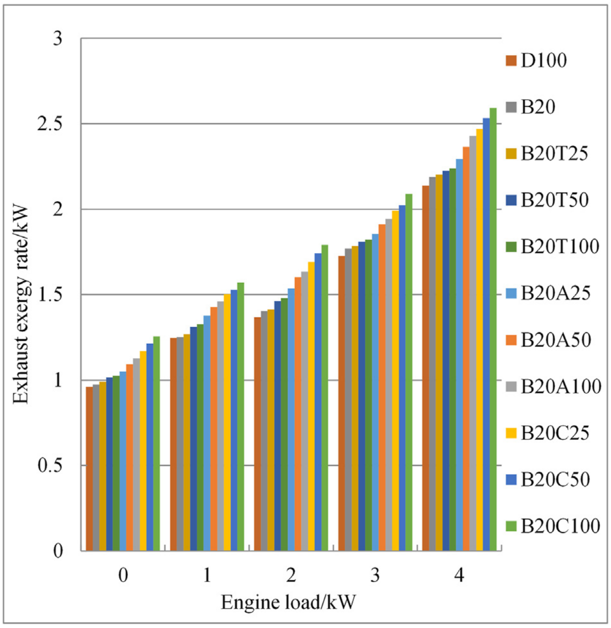

Figure 15 Effect of nano additives on exhaust exergy rate.

blend B20 by 6.5%, 16% and 23% at high load. Biodiesel with nano additives have lower specific chemical energy but higher fuel consumptions than diesel oil [50].

3.12. Exhaust exergy

The exhaust exergy rate increases with the increase of engine load as shown in Figure 15 because the combustion gas temperature was increased due to the increment in fuel injection rate with the engine load increase. The exhaust exergy of a diesel engine burning diesel oil is the lowest about all fuels due to the exhaust heat loss decrease. The exhaust exergy of B20T100, B20A100 and B20C100 are increased by 2.3%, 11% and 18% about B20 because of higher exhaust gas temperature and pressure resulted of inclusion of nano additives as presented in Figures 5—7. These results were agreed with references [50,51].

3.13. Exergetic efficiency

The exergetic efficiency of combination of biodiesel and nano additives against the engine load is illustrated in Figure 16. The exergetic efficiencies of all fuel blends are improved with the load increase. Compared to diesel oil, exergetic efficiency of all fuels are lower due to the lower power output, higher calorific value and higher fuel consumption. The exergetic efficiency of B20T100, B20A100 and B20C100 are increased by 7%, 19% and 30% at high load about B20. The exergetic efficiency is improved with the increase of nano additive concentration into fuel mixture because of the combustion efficiency improvement [47]. It can be depicted that adding 100 ppm of CNT in B20 keeps its exergetic efficiency approaching the same value of

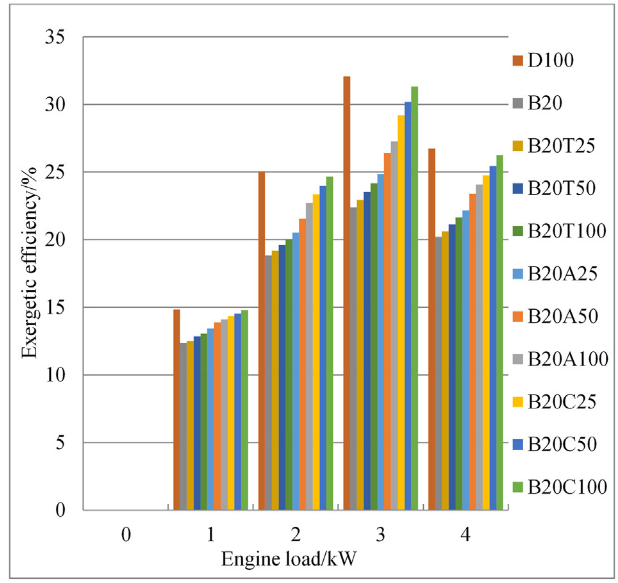

Figure 16 Exergetic efficiency of nano additives blended with biodiesel.

regular diesel at all tested loads. The findings were confirmed with literature [51,52].

3.14. Sustainability index (SI)

Figure 17 represents the effects of biodiesel blend with nano additives at different engine loads on the sustainability index. The sustainability index of a diesel engine was is in the range up to 1.5 and decreased as engine load elevated. Sustainability increased with the improvement in exergetic efficiency. Diesel oil achieves the best exergetic-sustainable

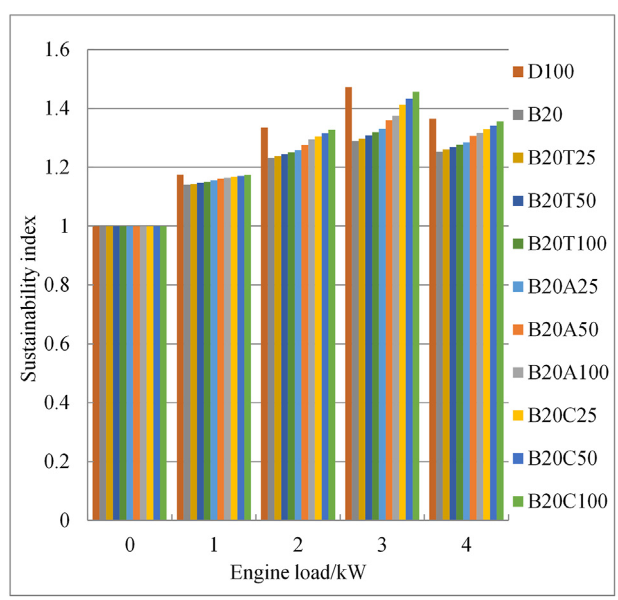

Figure 17 Effect of nano materials inclusion to biodiesel on sustainability index.

Table 5 Relative change in comparative analysis at full load about biodiesel blend ((+) indicates of increase and (−) of decrease).

Relative change	B20T100	B20A100	B20C100
Peak cylinder pressure	+5%	+9%	+11%
Peak HRR	+4%	+8%	+13%
Ignition delay	−11%	−23%	−31%
Specific fuel consumption	−4.5%	−7%	−12%
Thermal efficiency	+4%	+6%	+11.5%
Exhaust gas temperature	+5%	+12%	+20%
CO emission	−11%	−24%	−30%
HC emission	−8%	−17%	−25%
NO_x emission	+5%	+12%	+27%
Smoke emission	−10%	−13%	−19%
Fuel exergy rate	−6.5%	−16%	−23%
Exhaust exergy rate	+2.3%	+11%	+18%
Exergetic efficiency	+7%	+19%	+30%
Sustainability index	+2.5%	+5.5%	+9%

fuel about all fuels. The sustainability is enhanced with the increase of nano additive concentration into the fuel mixture because of the combustion improvement. The sustainability index of B20T100, B20A100 and B20C100 are increased by 2.5%, 5.5% and 9% at high load about B20 [50–52].

4. Comparative analysis

Engine emissions, performance, exergy analysis and combustion characteristics of B20T100, B20A100 and B20C100 comparable to B20 are shown in Table 5.

5. Conclusions

Biodiesel was derived from WCO and was mixed with diesel oil in 20% volume percentage. Different nano additives as Al_2O_3, TiO_2 and CNTs were introduced to methyl ester mixture in concentrations of 25, 50 and 100 mg/L. Properties of Biodiesel with nano particles blends are evaluated and agreed with ASTM standards of National Research Center & Egyptian Petroleum Institute. Performance, exhaust emissions, exergy analysis and combustion characteristics of waste cooking biodiesel blended with nano additives are investigated. Summary of the main conclusions are stated below:

- The maximum decreases in brake specific fuel consumption of B20T100, B20A100 and B20C100 are 4.5%, 7% and 12%, respectively but the maximum increases in thermal efficiency are up to 4%, 6% and 11.5%, respectively at full load, compared to crude biodiesel mixture.
- Waste cooking oil biodiesel blend with nano particles B20T100, B20A100 and B20C100 at 100% of the engine load showed the higher increases in the exhaust gas temperature up to 5%, 12% and 20%, respectively compared to B20.
- The increases in the peak cylinder pressures for B20T100, B20A100 and B20C100 are 5%, 9% and 11%, respectively, in addition the increases in peak HRR values for B20T100, B20A100 and B20C100 are 4%, 8% and 13%, respectively compared to B20 at full load. The maximum decreases in ignition delay for B20T100, B20A100 and B20C100 are 11%, 23% and 31%, respectively with respect to biodiesel blend at full load.
- Inclusion of nano particle to biodiesel blend B20T100, B20A100 and B20C100 achieved the maximum reductions in CO emissions up to 11%, 24% and 30%, respectively and the highest decrease in HC emissions are up to 8%, 17% and 25%, respectively at 100% of engine load related to neat biodiesel mixture.
- The highest increases in NO_x emission for B20T100, B20A100 and B20C100 are up to 5%, 12% and 27% respectively, whereas the highest reductions in smoke emissions are up to 10%, 13% and 19%, respectively at full engine load compared to B20.
- The fuel exergy of B20T100, B20A100 and B20C100 are lower than biodiesel blend B20 by 6.5%, 16% and 23% at high load. The increases in exhaust exergy of B20T100, B20A100 and B20C100 are 2.3%, 11% and 18% about B20 because of the improved combustion quality and fuel ignition of diesel oil about all biodiesel blend with additives.
- The exergetic efficiency are increased by 7%, 19% and 30% but the increases in the sustainability index are increased by 2.5%, 5.5% and 9% for B20T100, B20A100 and B20C100, respectively at high load about B20.
- Inclusion of CNTs in WCO biodiesel achieves the best enhancements in engine performance, combustion characteristics and emissions reductions among all tested nano particles. This finding justifies the great role of CNTs addition in enhancement of thermal conductivity, evaporation rate, catalytic reactivity and heat transfer rate of B20. Addition of 100 ppm of CNTs to B20 gives nearly the same performance of regular diesel at different engine loads. Therefore, waste cooking oil biodiesel blend B20 with nano CNTs concentration of 100 ppm is

highly recommended to operate in a broad range of diesel engines applications.

Acknowledgements

This work was carried out in the Heat Engine Laboratory of National Research Centre (NRC), El Dokki, Egypt. Authors greatly appreciate NRC for its endless support to produce the present work.

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ARTICLES FOR FACULTY MEMBERS

COMPARATIVE ANALYSIS OF WASTE COOKING OIL BIODIESEL MIXED WITH NANOPARTICLE ADDITIVES ON PHYSICOCHEMICAL PROPERTIES AND DIESEL ENGINE PERFORMANCE

Impact of nanoparticle-based fuel additives on biodiesel combustion: An analysis of fuel properties, engine performance, emissions, and combustion characteristics / Mofijur, M., Ahmed, S. F., Ahmed, B., Mehnaz, T., Mehejabin, F., Shome, S., Almomani, F., Chowdhury, A. A., Kalam, M. A., Badruddin, I. A., & Kamangar, S.

Energy Conversion and Management: X
Volume 21 (2024) 100515 Pages 1-24
https://doi.org/10.1016/J.ECMX.2023.100515
(Database: ScienceDirect)

Energy Conversion and Management: X 21 (2024) 100515

Contents lists available at ScienceDirect

Energy Conversion and Management: X

journal homepage: www.sciencedirect.com/journal/energy-conversion-and-management-x

Impact of nanoparticle-based fuel additives on biodiesel combustion: An analysis of fuel properties, engine performance, emissions, and combustion characteristics

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ARTICLE INFO

Keywords:
Nanoparticles
Nanoadditives
Engine performance
Engine combustion
Biodiesel Combustion

ABSTRACT

Nanoparticles (NPs) are becoming increasingly crucial in academic as well as industrial applications. Nanoparticles' addition to biodiesel shortens the time it takes for the fuel to ignite, allowing combustion to begin earlier and reducing the amount of heat released and the pressure in the cylinders under full load. Recent review studies have focused on nanoparticle additives used in biodiesel and diesel engines, performance, combustion behavior, and emission properties of biodiesel-powered diesel engines, and stability and combustion characteristics of metal nanoparticles (NPs) and their additive impact on compression ignition engines powered by biodiesel and diesel. However, nanoparticle effects on either biodiesel properties, engine performance, emissions, or combustion have not been comprehensively investigated in these studies. This paper addresses this gap by focusing on cost-effective and sustainable strategies for the development of fuel additives for biodiesel combustion. The literature has demonstrated that the incorporation of NP mixes ($CeO_2 + Al_2O_3$) with biodiesel fuel improved the overall performance, emission characteristics, and combustion efficiency of the engine. For instance, the addition of TiO_2 nanoparticles reduced smoke emission by 32.98 %, carbon monoxide (CO) by 30 % and unburned hydrocarbons (HC) by 28.68 %. Emissions of nitrogen oxide (NO_x), CO, HC, and smoke were reduced by 30 %, 60 %, 44 %, and 38 %, respectively, while brake power (Bp) and brake thermal efficiency (BTE) went up by 12 %. This study will show advances and potential areas for nanoparticle-enhanced biodiesel engine improvement, leading to cost-effective and sustainable renewable energy solutions.

Introduction

Biodiesel is an excellent alternative fuel source that is produced using a number of processes, the most common of which is the esterification of vegetable oils, animal fats, and waste oils with a catalyst [80]. One of its main advantages is that, when used as an engine fuel, it requires almost no engine modifications. Biodiesel releases significantly less carbon monoxide (CO) and carbon dioxide (CO_2) compared to petroleum-based diesel (PBD). Biofuels help to reduce atmospheric CO_2 depletion since burning biomass emits CO_2 which is absorbed by plants for their growth. Biodiesel produces nearly no CO emissions because of the abundance of oxygen molecules in the fuel [101]. There are significant amounts of saturated fatty acids and their esters in biodiesel, which are susceptible to crystallization into wax at low temperatures. The use of biodiesel in cold climates is severely constrained by its poor cold-flow characteristics, as wax/crystal formation impedes the fuel's free movement through pipes and filters, thereby affecting engine performance. There are different methods for enhancing the cold flow properties of biodiesel, including transesterification using branched-chain alcohol, winterization, altering the fatty acid profiles of the fuel, mixing biodiesel with petroleum-based fuel, and adding additives [101]. In general, adding

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https://doi.org/10.1016/j.ecmx.2023.100515
Received 21 September 2023; Received in revised form 30 November 2023; Accepted 16 December 2023
Available online 17 December 2023

Nomenclature

Acronyms

Al_2O_3	Aluminium Oxide
ASTM	American Society for Testing and Materials
BSFC	Brake-specific fuel consumption
BTE	Brake thermal efficiency
$C_{18}H_{34}O_2$	Oleic Acid
CeO_2	Cerium Oxide
CeO_2	Cerium Dioxide
CI	Compression Ignition
CNT	Carbon Nanotube
Co_3O_4	Cobalt-Oxide
CuO	Copper Oxide
CVD	Chemical Vapor Deposition
DI	Direct Injection
DMC	Dimethyl Carbonate
DME	Dimethyl Ether
DMF	Dimethylfuran
DWS	Diesel-water system
EDX	Energy Dispersive X-ray Spectroscopy
EGR	Exhausted gas recirculation
ESC	European Stationary Cycle
$Fe(C_5H_5)_2$	Ferrocene
$Fe(C_5H_5)_2$	Ferrocene
FE-SEM	Field Emission Scanning Electron Microscopy
FE-SEM	Field Emission Scanning Electron Microscopy
FR-IR	Fourier Transform Infrared Spectroscopy
GNPs	Graphene Nanoplatelet
GO	Graphene Oxide
IDP	Ignition Delay Period
La_2O_3	Lanthanum Oxide
MgO	Magnesium Oxide
Mn_2O_3	Manganese Oxide
MoO_3	Molybdenum Trioxide
NED	New European Driving Cycle
PBD	Petroleum-Based Diesel
ppm	Parts Per Million
rpm	Revolutions Per Minute
SCR	Selective Catalytic Reduction
SDS	Sodium Dodecyl Sulphate
SEM	Scanning Electron Microscopy
TEM	Transmission Electron Microscopy
TiO_2	Titanium Oxide
UHC	Unburnt hydrocarbon
UV	Ultraviolet
WCO	Waste cooking oil
XRD	X-ray Diffraction
ZnO	Zinc Oxide
ZrO	Zirconium Oxide

PBD to biodiesel improves its fundamental fuel characteristics, particularly its low-temperature performance [67].

Being one of the most popular and unmatched renewable fuels, biodiesel improves the immaculateness and durability of compression ignition (CI) engines. By adding nanoparticles to an emulsion fuel, Vigneswaran et al. [133] intended to improve the engine characteristics of a single-cylinder diesel powertrain. For emulsion fuels, titanium dioxide (TiO_2) was chosen and adopted for photocatalysis. The current study speculates the effects of a diesel-water system (DWS) emulsion fuel and TiO_2 nanoparticle (NP) on the combustion, exhaust, and engine characteristics of a single-cylinder diesel fuel engine. When TiO_2 was first created, a mechanical method called sol–gel was used, and the resulting NPs were between 55 and 5 nm in size. Using a mechanical agitator, emulsion fuel (DWS produced with 10 % water + 0.2 % surfactant + 89.8 % diesel) was combined with TiO_2 at levels of 30, 60, and 90 ppm to create homogeneous fuels that were referred to as DWT1, DWT2, and DWT3, respectively. Fuel characteristics were assessed in accordance with ASTM standards. Additionally, the manufactured fuels were tested in a mono-cylinder diesel engine, and the importance of the results, as well as the observations made at low, part, and full load situations, were reviewed. The results were compared to those of diesel fuel and emulsified fuel (DWS). According to the findings, the brake thermal efficiency (BTE) for DWT3 fuel increased at full loads by 5.65 % to be on par with diesel and by 2.76 % to be on par with DWS fuel. For the DWT3 fuel, CO, smoke emission, and unburned hydrocarbon (HC) were reduced by 30 %, 32.98 %, and 28.68 %, respectively. Overall, TiO_2-incorporated fuel was found to be a useful alternative to conventional diesel engines. Again, Mei et al. [84] compared two common nanomaterials—nano-MoO_3 and CNT (non-metal with great heat conductivity)—as additives for clean diesel. Appropriate physical and chemical dispersion techniques were used to prepare CNT-diesel and MoO_3-diesel nanofuels. The exhaust emission and combustion characteristics of the nanofuels and neat diesel were compared through experiments in a solitary-cylinder common rail diesel engine. Results revealed that compared to neat diesel, CNT-diesel and MoO_3-diesel performed better in terms of fuel efficiency, emissions, and combustion. The high heat conductivity, surface deficiencies, and excellent catalytic oxidizing function of MoO_3 and CNT may be responsible for these results. Additionally, it was determined that CNT-diesel was more promising than MoO_3-diesel since it appears to generate more advantages in reducing emissions and increasing combustion efficiency.

A literature search was conducted using the keywords nanoparticles, biodiesel, fuel additive, combustion, performance enhancement, exhaust engine, engine emission, etc. Mourdikoudis et al. [86] reviewed and provided a concise summary of the current understanding of the application, developments, benefits, and drawbacks of numerous experimental approaches that are available for the characterization of nanoparticles. The various characterization approaches were categorised based on the approach's concept/group, the information it provides, and the materials it is intended for. The approaches' key features were shown comparatively to the property being researched in each instance, as well as their fundamental principles of operation and several application examples. Sekoai et al. [108] critically analysed the many published research studies on improving the process yields of biofuel production processes such as the generation of biohydrogen, biogas, biodiesel, and bioethanol. They also classified the various kinds of nanomaterials (e.g., nanotubes, nanofibers, metallic) used in these bioprocesses. Additionally, they assessed how immobilized nanoparticles affect biofuels like biodiesel as well as how well and efficiently they might reduce inhibitory chemicals in specific situations. There was a brief section about the variables that affected the performance of nanoparticles during the manufacture of biofuels. The review ended with recommendations for enhancements and other lines of inquiry for these nanoparticle-based bioprocesses. Fatt et al. [34] summarized significant studies on the exhaust emission and engine performance of diesel engines powered by biodiesel blends and presented the findings of those studies. The engine performance tests revealed that biodiesel blends had lower torque, braking power, and thermal efficiency than diesel fuel, but they also consumed more fuel specifically for brakes and heated exhaust gases. When compared to diesel fuel, the engine emissions from biodiesel blends were found to be higher in CO_2 and NO but surprisingly lower in CO.

Using a variety of biodiesel blends, Abu-Zaid [3] analysed the effects on diesel engine performance under varying loads. The efficiency of diesel engines was tested to determine the impact of using different biodiesel blends derived from palm, sunflower, and corn oils. The engine was run at a set speed and variable load. Brake thermal power, torque, brake-specific fuel consumption (BSFC), BTE, exhaust emission, and fuel consumption were the primary factors that were determined. According to the engine test results, all the biodiesel blends resulted in lower exhaust temperature, lower BFSC, and higher brake thermal efficiency than pure diesel. This suggested that using biodiesel blends as an engine fuel is more cost-effective than using pure diesel. Even in the field of energy generation, green innovation is a vital aspect to ensure sustainability. With this in view, Gour and Jain [45] discussed approaches to integrate metallic nanoparticles as an attempt to utilize green techniques to combine NPs. Plant metabolites and other natural chemicals are used in green techniques to orchestrate NPs for medicinal and other uses.

Over recent years, apart from its application in piston engines, biodiesel has seen increasing utilization in swirl combustion systems. Swirl combustion, characterized by the introduction of a swirling motion to the air or fuel entering the combustion chamber, significantly enhances air–fuel mixing, leading to faster combustion rates and improved combustion efficiency [22]. Biodiesel's inherent properties, such as higher viscosity and density compared to conventional diesel, can influence the swirling flow patterns, impacting the combustion characteristics [10]. In a pivotal study by Prabhakaran et al. [96], the authors investigated the effects of biodiesel blends on swirl-induced combustion processes. They reported an optimal swirl ratio, where biodiesel blends outperformed pure diesel in terms of combustion efficiency and reduced pollutant emissions. Another significant contribution by Masoud et al. [82] focused on the stability of the swirling flames when using biodiesel. Their findings highlighted that certain biodiesel concentrations could enhance flame stability, particularly at higher swirl numbers. Reddy et al. [103] presented a comprehensive analysis of biodiesel's impact on the turbulence characteristics of swirl flows. They noted that biodiesel's properties led to more pronounced vortex breakdown phenomena, which in turn affected the overall combustion efficiency and emission profiles. Furthermore, a recent review by Bari et al. [13] synthesized the latest advancements in biodiesel usage within swirl combustion systems, emphasizing its potential benefits and challenges, particularly concerning emissions and engine wear.

A number of review studies have been carried out in recent years, with a focus on nanoparticle additives used in biodiesel and diesel engines [72], performance, combustion behavior, and emission properties of diesel engines powered by biodiesel including CeO_2 [51], and stability and combustion characteristics of metal NPs and their additive impact on compression ignition engines powered by biodiesel and diesel [106]. However, these studies did not assess the impact of nanoparticles on biodiesel properties, engine performance, engine emissions, or engine combustion. The present study thus introduces several innovative elements to the biodiesel research landscape. This research differs from previous work by adopting a multifaceted approach, simultaneously exploring the impacts of nanoparticle-based fuel additives on fuel properties, engine performance, emissions, and combustion characteristics. This holistic view offers a more integrative understanding of nanoparticle influences on biodiesel usage in engines. We particularly focus on novel nanoparticle mixes like $CeO_2 + Al_2O_3$ and TiO_2, observing significant improvements in emissions and efficiency. These findings not only contribute substantially to the field by enhancing the performance of biofuels but also emphasize the cost-effective and sustainable development of these additives. Thus, this research bridges crucial gaps, presenting new perspectives and innovative solutions for efficient and sustainable renewable energy applications. By situating the current study within this broader context of existing research and highlighting its unique contributions, we underscore the necessity and innovation brought forward in this manuscript, paving the way for future advancements in the field.

The structure of this paper offers a comprehensive exploration of the role of nanoparticles in biodiesel-enhanced engine systems. Post-introduction, Section 2 provides a detailed overview of various nanoparticles, their synthesis, properties, and applications. Section 3 delves into how nanoparticles influence biodiesel properties, while Section 4 assesses their impact on engine performance. Section 5 evaluates the implications of nanoparticle additives on engine emissions, emphasizing their environmental ramifications. Section 6 deepens the analysis by examining the effects of nanoparticles on the combustion dynamics of the engine. The paper concludes with insights and directions for future research in Section 7.

Nanoparticles

Over the last decade, there has been rising interest in nanomaterials and nanoscience. Nanoscience studies the synthesis and engineering of nanoparticles. Nanomaterials have been largely employed for their enhanced physiochemical properties. The size of the nanoparticles ranges from 1 to 100 nm. The different surface effects and quantum effects of nanomaterials give them leverage over other materials [59]. Over the years, the thermal, mechanical, optical, electronic, and magnetic properties of nanomaterials have been explored [8]. Their unique size, structure, and properties allow various applications.

Types of nanoparticles

Nanoparticles are classified into four main categories: organic-based nanoparticles, inorganic-based nanoparticles, carbon-based nanoparticles, and composite-based nanoparticles. Each of these nanoparticle types can be employed in various fields.

Organic-based nanoparticles

Organic-based nanoparticles are mainly employed in the biomedical field. They consist of polymeric-based nanoparticles and lipid-based nanoparticles. The polymeric nanoparticles have both nanospheres and nanocapsules with morphological distinctions. The polymeric core absorbs the active compounds on the surface or entraps them within [144]. Polymeric nanoparticles can be readily functionalized; hence, they are widely used for drug delivery. Lipid-based nanoparticles are also used in clinical applications. The spherical diameters of lipid nanoparticles are less than 1,000 nm [71]. The core of lipid nanoparticles is made of lipids and a matrix comprised of dissolvable lipophilic compounds. Additionally, the lipid nanoparticles inhibit the oxidation, decomposition, and degradation of the active compound, thus proving to be an effective nanocarrier in the clinical field.

Inorganic-based nanoparticles

Inorganic-based nanoparticles are commonly metal, metal oxide, semi-conductors, and ceramic nanoparticles. Examples of metal-based nanoparticles are gold, silver, copper, aluminium, and lead, while metal oxide nanoparticles are copper oxides, zinc oxide, and cerium oxide (CeO_2). Metal and metal oxide nanoparticles exhibit varying physiochemical characteristics, leading to their employment in different applications, for example, the localized surface plasmon resonance (LSPR) of metal nanoparticle optoelectrical properties. Metal nanoparticles have a broad absorption spectrum which is a favourable electromagnetic property. On the other hand, semiconductor nanoparticles have characteristics of both metals and non-metals, therefore, they are utilized across various sectors. The semiconductor nanoparticles exhibit superior optical properties and wide band gaps [59,104]. Furthermore, the properties of these nanoparticles can be altered significantly which leads to their application in catalysis and optoelectronics.

Carbon-based nanoparticles

This category of nanoparticles is composed only of carbon atoms. Carbon-based nanoparticles such as graphene, fullerene, and carbon nanotubes (CNTs) are the subject of fundamental research and can be employed in several applications. The carbon atoms are arranged in various shapes such as hexagonal and pentagonal. The high thermal resistance and electrical conductivity make this class of nanoparticles highly efficient. The demand for carbon quantum dots is rising due to their high quantum yield and modifiable photoluminescence properties [77]. Carbon-based nanoparticles have low toxicity and high absorption and are cost-effective. Additionally, the wide range of structural diversity and surface chemistry allows for their application in imaging and biosensor development.

Composite-based nanoparticles

Composite-based nanomaterials are a combination of different types of nanomaterials. Of the several phases of nanocomposites, one of the phases has dimensions of less than 100 nm or is repetitive between phases. These nanomaterials have metal–organic frameworks which allow them to have a set of properties that gives them leverage over other nanoparticles. Nanocomposites derived using a metal–organic framework were studied for electromagnetic wave absorption. Doping Co/C with nickel led to a synergistic effect between bimetallic components and the hollow structure of the novel composite. The enhanced impedance matching considerably increased the electromagnetic wave absorption [134]. Nanocomposite-based nanomaterials can be used to enhance the output of synergetic interactions between different composites [64].

Synthesis of nanoparticles

Nanoparticle synthesis involves diverse methods aimed at optimizing efficiency and performance, broadly categorized as top-down and bottom-up approaches (Fig. 1). Top-down methods, including lithography, physical, and chemical deposition, involve the reduction of larger structures into nanoparticles. On the other hand, bottom-up approaches, such as sol–gel, green synthesis, and biochemical synthesis, focus on building nanoparticles from smaller components (Khan Ibrahim, 2017). Among the top-down approaches, chemical and physical vapor deposition stands out for its scalability. In this method, precursor molecules are converted into a gaseous form and deposited onto a substrate, resulting in thin film deposition that yields nanoparticles with high uniformity and improved quality [123]. Despite these advantages, challenges such as low cost-effectiveness and poor yield are associated with this process. The selection of the synthesis method is crucial, considering factors like scalability, cost, and the desired properties of the nanoparticles for specific applications.

Lithographic methods are various types such as optical lithography, electron beam lithography, photo-lithography, and nanoimprint lithography [56]. In the fabrication of oxide patterns, photolithography is often employed, involving the creation of sacrificial layers and subsequent pattern transfer through etching or vapour-phase deposition [93]. In electron beam lithography, a substrate modified with an electron-sensitive material is exposed to an electron beam, causing alterations in substrate properties contingent upon the energy deposition [7]. Nanoimprint lithography utilizes a nanostructured stamp pressed into a resist polymer, enabling the transfer of the nanostructure onto the polymer surface [107]. These lithographic methods play a crucial role in enhancing the magnetic and optical properties of nanomaterials, offering precise control over the structural characteristics of nanoparticles for tailored applications in various fields.

The sol–gel technique involves two crucial components: sol and gel. The sol phase arises from the suspension of solid particles in liquids, while the gel phase results from dissolving a solid macromolecule in a solvent. The synthesis process commences with the dispersion of a precursor liquid, typically a metal alkoxide, into the primary solution through agitation, such as shaking and stirring. Subsequently, various separation techniques are employed to isolate the final solution, ultimately yielding the gel as the end product. This method stands out for its cost-effectiveness and the ability to maintain a minimum reaction temperature, facilitating precise control over the chemical composition of the resulting nanoparticles [16]. Another noteworthy bottom-up approach is the polyol synthesis method employed in the production of metal-based nanoparticles. Polyols serve dual roles as reducing agents and solvents, as highlighted by Favier et al. [35]. The unique properties of polyols make them versatile in the creation of high-quality nanoparticles, encompassing metallic, oxide, and semiconductor nanoparticles. The polyol synthesis method allows for tailoring the properties of the nanoparticles, contributing to their enhanced functionality in various applications.

The pursuit of eco-friendly alternatives has driven active research in the field of green synthesis of nanoparticles. Conventional physical and chemical methods often generate harmful by-products and consume significant energy, contributing to environmental concerns. According to Can [19], the integration of biomolecules as reductants offers a sustainable alternative to traditional chemical compounds. Amino acids, polyphenols, proteins, and their derivatives have proven effective in this regard, providing a cost-effective and efficient means for nanoparticle

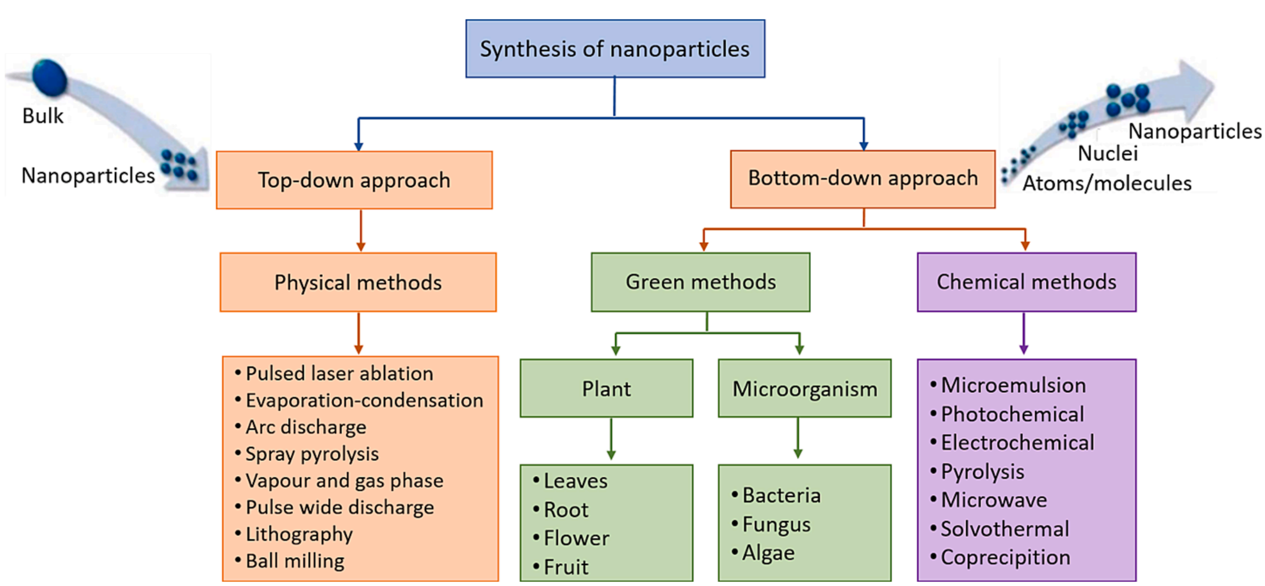

Fig. 1. Methods of synthesising nanoparticles, modified from Ahmed et al. [9].

synthesis. The adoption of biomolecules not only mitigates toxicity and pollution associated with conventional methods but also aligns with the broader goal of sustainable and environmentally conscious nanotechnology. However, challenges such as the extraction of raw materials and extended processing times must be addressed to realize the full potential of green synthesis, especially in the context of large-scale implementation. Balancing the environmental benefits with practical considerations remains a crucial aspect in advancing the application of green synthesis methods for nanoparticle production.

Properties of nanoparticles

Providing depth and breadth to our knowledge of nanomaterials is the comparison of their physicochemical properties, which include mechanical, magnetic, thermal, electrical, and optical properties. Nanoparticles possess distinct mechanical characteristics, including heightened strength and modified elasticity, as a result of their diminished size and expanded surface area [135], which in fact affects their structural integrity. These properties include increased strength and changed elasticity. At the nanoscale, the magnetic properties of nanoparticles become more noticeable, which opens up new possibilities for targeted drug delivery and magnetic resonance imaging. Nanoelectronics and energy storage rely heavily on nanoparticle thermal characteristics, such as thermal conductivity and heat dissipation. Nanoparticles exhibit substantial modifications in their electrical and optical characteristics, as quantum phenomena exert an influence on conductivity and give rise to new optical phenomena. The complex interaction of properties at the nanoscale allows for the development of sophisticated materials for various uses. It also emphasizes the significance of comprehending and utilizing the unique physicochemical traits of nanoparticles in the constantly changing field of nanotechnology.

Mechanical properties

Nanoparticles exhibit distinct mechanical properties compared to bulk materials, and these properties are highly influenced by their size, shape, and composition. The relationship between nanoparticle size and mechanical properties is a well-explored phenomenon. As highlighted by Wu et al. [135], the surface-to-volume ratio of nanoparticles increases with decreasing size. This increase in surface area provides a platform for various modifications, enabling significant enhancements in mechanical properties. Their study emphasized the importance of this large surface area, serving as a canvas for engineering nanoparticles to achieve desired mechanical characteristics. Inorganic and organic materials, the building blocks of nanoparticles, inherently possess different mechanical properties due to their unique compositions. The challenge arises when both types of nanoparticles exhibit poor mechanical characteristics. However, this limitation can be effectively addressed through strategic addition and modification of nanoparticles. Ferrag et al. [39] investigated the influence of size and shape on the mechanical properties of nanoparticles, highlighting the potential for tailoring these properties based on specific applications. The incorporation of nanoparticles into polymer matrices has been a focus of research to enhance mechanical properties. Bui et al. [17] conducted a study demonstrating that the presence of nano-SiO_2 in a polymer matrix resulted in improved adhesion and abrasion resistance. This finding underscores the transformative impact of introducing nanoparticles into new compounds to achieve desirable mechanical properties. It not only broadens the applications of nanoparticles but also showcases their potential to enhance the performance of composite materials.

Magnetic properties

Understanding the magnetic properties of nanoparticles is crucial for their application as fuel additives, particularly in the context of biodiesel combustion. The magnetic traits of nanoparticles are induced during their formation, a phenomenon driven by uneven electron dispersion. These magnetic characteristics are further influenced by the presence of magnetic atoms or the number of electron pairs within the nanoparticle. The synthesis process of nanoparticles plays a pivotal role in determining their magnetic properties. Research by Fayazzadeh et al. [38], delves into the hydrothermal synthesis of cobalt ferrite nanoparticles, revealing a profound impact on saturation magnetization and coercivity. This underscores the significance of the synthesis method in tailoring the magnetic behavior of nanoparticles for specific applications, such as combustion enhancement in biodiesel. Unlike bulk materials, the magnetic properties of nanoparticles are highly influenced by their size and shape [73]. Superparamagnetism, a fascinating size-dependent trait of nanoparticles, becomes evident as their size decreases. The reduction in size concurrently decreases magnetic anisotropy energy, leading to the flipping of magnetic moments. This size-dependent magnetic behavior has implications for the interaction of nanoparticles with fuel components in biodiesel combustion.

Thermal properties

The large surface area of NPs allows direct and effective heat transfer due to the presence of a higher number of electrons. The nanoparticles can be modified to enhance their thermal characteristics. Nomai & Schlarb [90] assessed the effect of nanoparticle size on the thermal properties of polycarbonate, providing insights into how the manipulation of nanoparticle dimensions influences heat-related characteristics. Their study revealed that increasing the size of SiO_2 nanoparticles resulted in improved thermal properties of polycarbonate. This improvement was attributed to the increased interaction between the larger nanoparticles and the polycarbonate chain, demonstrating the potential for tailoring thermal behavior through nanoparticle size adjustment. Maaza et al. [81] explored the impact of aluminum oxide (Al_2O_3) NPs on thermal stability, a critical factor in the context of biodiesel combustion. Through thermogravimetric analysis, the study demonstrated that the addition of Al_2O_3 NPs contributed to high thermal stability. This enhanced stability was attributed to the hindrance of free radical movement by the presence of Al_2O_3 nanoparticles. Importantly, this hindrance led to delayed carbonization of the hybrid material (PANI-derived@ Al_2O_3), providing valuable insights into how nanoparticle-induced changes in thermal stability can impact combustion kinetics. The volume of dispersed nanoparticles, in addition to size, mass, and the number of atoms, plays a crucial role in influencing thermal properties.

Electrical and optical properties

Size-dependent optical properties and a substantial UV–visible extinction band distinguish noble metal NPs from bulk metals. When the input photon frequency remains fixed in phase with the collective excitation of the conduction electrons, a locally focused surface-plasma resonance is generated. The electronic and optical characteristics of NPs are influenced by their size, shape, and surrounding dielectric environment. The results of UV–Vis and PL analysis of barium oxide nanoparticles suggest a high potential for nanoparticles in the optoelectronic and photonic systems [11].

Like other property enhancements, the electrical properties of the nanoparticles can be improved through modification. According to the study conducted by Abutalib & Rajeh [4], the synergetic interaction of nanoparticles and the polymer matrix enhanced the dielectric properties and electrical conductivity of the nanoparticles. Raising the nanofiller content increased the AC electrical conductivity. A decrease in the intensity peak of pure blends was reported due to the dispersion of nanoparticles in the polymer mix and the interaction of Ag/TiO_2 nanoparticles with the blend. Similarly, in a study by Hassan et al. [48], different ratios of barium titanate nanoparticles were added to cellulose nanofibers (CNF) to examine their effect on electrical properties. The study concluded that doping CNF with nanoparticles effectively increases the dielectric constant.

Applications of nanoparticles

Nanoparticles are widely employed for efficient drug delivery in a microenvironment. The nanostructured systems allow access to critical areas of living organisms with the help of nanocarriers. According to Lombardo et al., [78] organic and inorganic nanomaterials are mainly employed to exploit their biocompatibility and further detect disease-related conditions. Better transport and higher precision in drug delivery promise more efficient treatment of affected tissues. Additionally, some nanoparticles also display antibacterial properties which extend their application in the clinical sector. Silver nanoparticles are widely known for their antibacterial characteristics. The release of silver ions from nanoparticles works as an effective mechanism for eliminating microbes. Adherence of silver nanoparticles to the cell wall and the cell membrane makes them an efficient bacterial inhibitor [138]. The thickness of bacterial cell walls can influence the inhibition activity of the nanoparticles, which can then exhibit different disruption intensities for gram-negative and gram-positive bacteria [85].

Nanoparticles also play an essential role in tissue engineering. Magnetic nanoparticles and semiconductors like iron oxide have found applications in the biomedical sector. According to Lu et al., [79], iron oxide nanoparticles can be employed to synthesize scaffolds, improving attachment and promoting stem cell differentiation. Nanoparticles' high deliverability and stability have been utilized for in situ remediation [18]. Organic chemicals are retained in the soil and groundwater for an extended period, thus, removing these contaminants is essential for minimizing their threat to the environment. Similarly, nano zero-valent can be employed for the remediation of heavy metal-polluted sites [75]. The adsorption properties of nanoparticles make them an efficient choice for remediation at a large scale.

Nanoparticles can be used as additives for performance enhancement. Tang et al., [121] synthesized black phosphorus with silver nanoparticles as a lubricant additive for poly-alpha-olefin (PAO6) based oil. The result exhibited anti-wear properties and significantly reduced friction. The enhanced lubricating performance for steel/steel contact increases the potential for future application. Nanoparticles have also been increasingly used as additives for biodiesel blends. With high economic viability and low toxicity, biodiesel has been proven to be an efficient alternative to fossil fuels. According to Bitire et al. [15] the incorporation of copper oxide nanoadditives into biodiesel significantly improved emission properties and engine performance. The CuO nanoparticles work as an oxidizing agent to minimize CO and HC emissions.

Effect of nanoparticles on biodiesel properties

As we continue our search for cleaner, more efficient energy sources, one new frontier is understanding how nanoparticles affect biodiesel's properties. Due to their distinct physical and chemical attributes, nanoparticles possess the capacity to substantially modify the properties of biodiesel. These attributes may include viscosity, emission profiles, and combustion efficiency. This field of study investigates the complex relationship between biodiesel and nanoparticles to capitalize on the benefits provided by additives at the nanoscale. The incorporation of nanoparticles into biodiesel formulations has a positive impact on combustion properties, fuel stability, and emission reduction. As a result, this advancement will contribute to biofuel generation that is both efficient and cleaner. The issues in the renewable energy industry might be better understood and solved through this interdisciplinary study, which could lead to new developments that help achieve goals for sustainability.

Biodiesel is a great alternative fuel since it lowers carbon emissions and thus improves the environment. There are different types of nanoparticles based on size, shape, and structure, such as organic and inorganic nanoparticles, bionanoparticles, and ceramic nanoparticles. These categories include bionanoparticles, ceramic nanoparticles, and organic and inorganic nanoparticles. Organic nanomaterials are categorized as carbon, metal, or metal oxide-based, whereas inorganic nanomaterials are further classified into metal oxide NPs and metal NPs [9,56]. Currently, both organic and inorganic nanoparticles, as well as nanomaterials, are mostly in use as additives in biodiesel. Nanoparticle use in a variety of industries, including energy, medicine, and nutrition, has increased significantly in recent years. Indeed, in India and China, metal particles like gold have been utilized extensively for medicinal and Ayurvedic remedies since ancient times [57]. Metal nanoparticle application in biomedicine and related fields is constantly growing on a global scale. Due to their distinctive features, metal nanoparticles, nanostructures, and nanomaterial production are currently the focus of research. Applications are vastly enhanced by improvements in the pour, flash, and fire point, as well as other standards depending on the type of nanoparticle.

An examination of the nanoparticles of AlO(OH) in biodiesel found a large decrease in NO_x emissions and a significant decrease in fuel usage, as reported by Devarajan et al. [26]. These metal-based additives are added to biodiesel in the form of powder and act as a catalyst to reduce NO_x emissions and improve engine combustion. As the alumina nanoparticles aid the lowering of gas temperature, a maximum reduction in smoke and NO_x emission of 18.4 % and 12.4 %, respectively, was obtained for BD100A when compared to BD100 (Appavu & Venkata Ramanan, 2020; [99]). Another similar study [102] focused on how different additives, such as antioxidants and nanoparticles, affect the way biodiesel performs in engines and how its emissions react. According to the experimental findings, the combination of CeO_2 nanoparticles in diesel and fuel boosted BTE by 6 % and reduced NO_x emissions by up to 30 % at high loads. The implementation of this technology can establish optimum development in engine performance and emissions.

Adding magnesium oxide (MgO) and CeO_2 NPs to waste cooking oil (WCO) biodiesel has been shown to improve separation, especially when compared to pure diesel [1]. This improves the compression ignition (CI) of VCR one-cylinder engines' performance characteristics. MgO and CeO_2 NPs were combined with the various WCO biodiesel-diesel mixes of 40 %, 60 %, and 20 % (B60, B20, and B40) employing an ultrasonicator. Later, the experimental results show that adding MgO and CeO_2 NPs to various mixtures of WCO biodiesel, as opposed to clean diesel, improved the VCR engine performance parameters. Moreover, this study looked at how WCO biodiesel's nanoparticle dispersion affected the thermal performance traits of VCR engines.

Another study [87] tested the lubricity of diesel–biodiesel fuel and found that the fuel with nanoparticle TiO_2 B30 (30 % biodiesel and 70 % diesel) performed the best, with the smallest worn scar diameter and the lowest friction coefficient of any of the samples tested. The frictional coefficient is increased for all other fuel samples due to the presence of fatty acids, oxygen, and a small amount of free fatty acids. Also, the wear and friction coefficient of fuel samples containing ethanol were extremely high compared to fuels using other additives. The fuel samples with nanoparticle blends had the best tribological behaviour of all the fuel types examined. The study conducted by Nouri et al. [91] demonstrated that the incorporation of ZnO nanoparticles as an additive in biodiesel resulted in enhanced BTE and reduced BSFC values. The ignition delay of these compounds minimized burning. So, by adding the nanoparticles, the BTE increases and the BSFC decreases. Furthermore, the results of the most recent research on the impacts of nanoparticles on the properties of biodiesel were largely promising, which leads us to the conclusion that the future role and usage of nanoparticle additions in biodiesel is recommended.

Effect of nanoparticles on engine performance

Research suggests that nanoparticles have a significant positive effect on engine performance and exhaust gas temperatures. To optimize the air–fuel mixture, the nanomaterials disseminated into the diesel–biodiesel proved capable of removing obstructions and atomization.

Additionally, each of these nanoparticles raises the surface area/volume, which improves combustion and reduces fuel usage [37]. NPs also have an impact on exhaust gas temperature and engine power. According to Hoseini et al. [52], adding graphene oxide (GO) nanomaterials to diesel–biodiesel increased the engine braking power significantly. This was due to GO NPs having a greater surface area to volume ratio, which raises the heat transfer coefficient and leads to greater peak in-cylinder pressures and quicker heat delivery rates. According to [40], adding nanoparticles to jatropha biodiesel and its blends decreased the temperature of exhaust gases by up to 27 %. This could be a result of the nanoparticles' enhanced fuel–air mixture and in-cylinder combustion properties, which increase engine performance.

The most advantageous method for improving engine characteristics is thought to be fuel formulation techniques. The density and volume of the micron-sized particles cause them to aggregate and gather in bunches at the bottom of the fuel. Hence, it is extremely difficult to disperse them uniformly throughout liquid fuel. Venu & Madhavan [127,128] explored the impact of nanoadditives on the different properties of diesel engines running on ternary mixes of biodiesel-ethanol–diesel fuels. They claimed that adding nanoadditives to the tertiary blend enhanced the diesel engine's performance metrics. However, they also observed increased particulate matter production when using fuels combined with nanoparticles.

The performance, combustion, and emission characteristics of the fuel blend samples were assessed by Kalaimurugan et al. [62] using experimentally determined standards including cloud point, viscosity, calorific value, density, and pour point. No modifications were made to the engines. Engine performance was evaluated using parameters including BTE, BSFC, exhaust emission of HC, NO_x, CO, and smoke opacity. The incorporation of a biodiesel blend containing CuO_2 NPs into a diesel-powered engine resulted in enhanced combustion, a significant enhancement in performance attributes, and a reduction in exhaust emissions. However, a thorough investigation of the potential health and environmental consequences caused by the integration of CuO_2 NPs into diesel-powered engines is of the utmost importance in light of the growing concerns about nanoparticle exposure.

Brake power

Brake power can be simply defined as the capacity of an engine. It is one of the prominent engine performance parameters that can be enhanced by the addition of nanomaterials. By incorporating some nanoparticles into the base fuel, the properties related to combustion are improved and the exhaust emissions are decreased, which in turn improves the overall engine performance [115]. One such nanoparticle is Al_2O_3, the addition of which generates heat within diesel-ethanol fuel and thereby enhances the combustion properties [113]. Researchers have investigated the variation of brake power with brake thermal efficiency at various load percentages for various fuel blends to find the optimum condition for combustion engine performance. Brake power can regulate other engine performance metrics such as BSFC, BTE, and emission of nitric oxide (NO_x). The majority of researchers claim that utilizing biodiesel instead of diesel fuel during combustion in a diesel engine results in lower brake power and thermal efficiency, and higher exhaust gas temperatures [34].

Prabu [97] conducted an experiment in which three fuel series—biodiesel-diesel-nanoparticles (B20A30C30), biodiesel-diesel (B20), and biodiesel-nanoparticles—were used in a single-cylinder direct injection (DI) diesel fuel engine to study the engine's performance, combustion, and emission characteristics (B100A30C30). Using ultrasonication, NPs, including CeO_2 and Al_2O_3, were combined with the fuel mixtures to achieve uniform suspension. Results reported that the performance, combustion, and emission characteristics of the diesel engine improved as a result of the increased surface area/volume ratio properties of the NPs, which also increased the degree of chemical reactivity and mixing during combustion [32]. When compared to B100, the engine's braking power and thermal efficiency for the nanoparticle-disseminated fuel (B20A30C30) showed a pronounced increase of 12 %, followed by reductions in NO emission of 30 %, CO emission of 60 %, HC emission of 44 %, and smoke emission of 38 %.

The use of 100 % biodiesel has been found to effectively increase the brake power of engines [3]. The author experimented to ascertain how the use of various biodiesel blends made from palm, sunflower, and corn oils may affect the performance metrics of diesel engines. The results demonstrated a correlation between brake power and engine load. The relationship between brake power and engine load was shown to be directly proportional, meaning the brake power increased when the load was increased and vice-versa. This parameter is crucial because it demonstrates the engine's ability to turn fuel into brake power, indicating how well the engine performs. These results were supported by Devarajan et al. [25] who used silver oxide (AgO) as nanoparticles embedded in pure diesel. An additional improvement in the ignition was seen after adding AgO nanoadditives to biodiesel combined with palm stearin.

Brake-specific fuel consumption

The ratio between the rates of consumption to output braking power is called brake-specific fuel consumption (BSFC) [25]. It measures the fuel usage and consumption per unit of time and power and evaluates engine fuel efficiency [80]. The comparison between BSFC and engine load is a key factor in determining how well an engine performs. BSFC often declines with an increase in load. The key variables that affect how much BSFC a diesel engine needs are density, calorific value, viscosity, and volumetric efficiency of fuel injection [101]. Diesel-biodiesel typically has a higher BSFC value than diesel, primarily because when the engine production is constant, biodiesel fuel has a lower calorific value than diesel, requiring the consumption of more fuel to retain the same power and energy.

Chen et al. [21], and Dhahad and Chaichan [27] discovered that a promising strategy for raising the engine's BSFC was to incorporate nanomaterials into the fuel. A lower BSFC value is recommended for engine operation. The BSFC serves as a measuring scale for determining the engine's effectiveness in converting the fuel heat energy into the necessary brake power [60]. The authors assessed the effect of using various biodiesel blends made from sunflower, palm, and corn oils on the performance of diesel engines while determining various parameters, one of which was BSFC. The results demonstrated that fuel consumption typically increases with increasing engine load. This is due to the increased demand for fuel. Regular diesel had higher values than all biodiesel. This is because their calorific values are lower than those of pure diesel.

Brake thermal efficiency

Brake thermal efficiency (BTE) is a crucial engine performance metric that denotes the proportion of heat provided by the fuel to the energy that is produced by the engine [80]. BTE is influenced by fuel usage and heating value (HV). Nanoparticle encapsulation in biodiesel blends prompts secondary atomization after the micro-explosion that occurs while mixing fuels, promoting full combustion, and boosting BTE. This happens due to a decrease in physical delay, a high evaporation rate, a sustained flame for a longer period, and the higher flame temperature of the nanoparticles, all of which improve the thermal efficiency of the brakes. Additionally, nanoparticles such as TiO_2 and Al_2O_3 boost the mixture velocity and penetration depth in the cylinder by reducing the ignition delay and improving combustion and BTE [118]. Incorporating nanoadditives derived from metal oxides into diesel engines has the potential to shorten the ignition delay and combustion time of biodiesel blends, while simultaneously increasing the cylinder pressure and net heat release rate, leading to a corresponding increase in BTE [58], as depicted in Fig. 2.

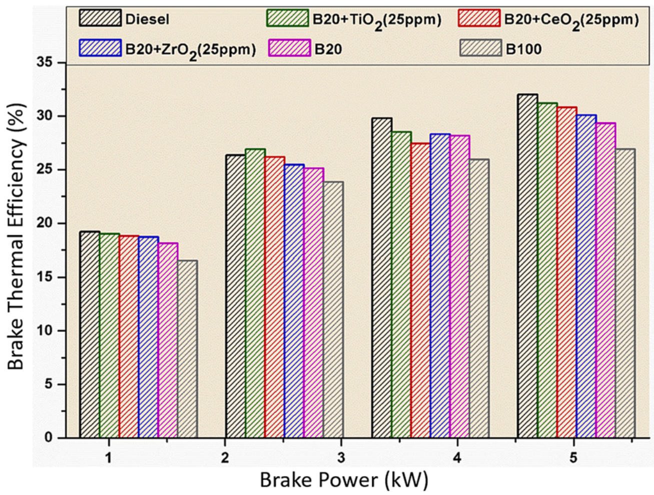

Fig. 2. BTE variation in relation to brake power across various fuel blends, reprinted with permission of Elsevier from Janakiraman et al. [58].

Some researchers investigated how biodiesel with TiO_2 nanoparticles affected an engine's operation and they found that the BTE improved along with a reduction in CO and HC, and in NO_x emissions. For instance, El-Seesy et al. [32] examined the effects of adding nanoparticles to biodiesel and diesel engines and discovered that doing so improved BTE and decreased exhaust gas emissions. On the contrary, blends with CeO_2 have reportedly slightly enhanced BTE with diesel ethanol fuel [118]. However, higher BTE and lower emissions can be accomplished simultaneously with improved diesel fuel start of injection (SOI) [139]. Additionally, a direct correlation exists between BTE and exhausted gas recirculation (EGR).

Although EGR reduces cylinder oxygen saturation, it is nevertheless used to control combustion temperatures, as reported by Yilmaz [137]. This results in less BTE, a longer delay period (ID), and increased soot formation. BTE improves and carbon-based emissions decline with the addition of hydrogen. To achieve complete combustion and greater temperature efficiency, diesel–biodiesel blends can have their heat, radiation, and mass-transferring performance improved using nanoparticles. According to Lv et al. [80], nanoparticle-added fuel has higher BTE, as also supported by Ranjan et al. [101] in their experiment. The effects of blending mahua methyl ester (MME) with silicon dioxide nanoparticles were investigated in a study by Nutakki and Gugulothu [92]. The combinations employed in the experiment were: MME20 + SIO40, MME20 + SIO120, and MME20 + SIO80. The experimental outcomes demonstrated that the BTE of MME blended with SiO_2 shows a slight increase, but the BSFC shows a downward trend compared to other blends previously evaluated. Further, the study demonstrated a decrease in the release of smoke, HC (unburned hydrocarbons), and CO compared to regular diesel. The silicon dioxide (SiO_2) blended with MME produced the highest level of NO_x emissions of all the mixes. When SiO_2 was combined with biodiesel, the engine's overall performance was improved, and this combination also helped the engine emit fewer harmful emissions.

Diesel fuel was blended with ZnO at concentrations of 250, 500 and 1000 ppm in an experiment conducted by [100]. In addition to diesel fuel, the engine characteristics of the prepared fuels were evaluated using a standard bench-scale engine. All experiments were conducted at engine velocities varying from 2000 rpm to 3000 rpm, while maintaining a constant engine load and utilizing advanced injection timing. The results obtained from these experiments demonstrated that fuels supplemented with ZnO nanoparticles produced greater brake thermal efficiency and cylinder pressure in comparison to diesel fuel. Fuels containing ZnO nanoadditives exhibited lower brake-specific fuel consumption and emission gas temperatures compared to diesel fuel. To offer a greater understanding of the practical consequences of utilizing ZnO nanoadditives in diesel engines, a more thorough investigation of possible side effects, including engine longevity, wear and tear, and nanoparticle stability under various operating conditions, is required.

Summary and analysis of findings on nanoparticles' effect on engine performance

The impact of nanoparticles on engine performance and associated metrics like brake power, brake-specific fuel consumption (BSFC), and brake thermal efficiency (BTE) is profound and multi-dimensional. Nanoparticles, due to their unique properties such as high surface area-to-volume ratio, significantly influence the combustion process, fuel efficiency, and emission reduction in engines. The addition of nanoparticles like Al_2O_3 and CeO_2 to fuel blends such as biodiesel-diesel-nanoparticle mixtures has been observed to enhance brake power. This enhancement is primarily attributed to improved combustion properties and higher chemical reactivity offered by nanoparticles. Nanoparticles affect BSFC, which is a critical measure of fuel efficiency. Although biodiesel typically shows a higher BSFC compared to diesel due to its lower calorific value, the incorporation of nanoparticles can improve the fuel's calorific profile, reducing the BSFC and implying better fuel efficiency. The incorporation of nanoparticles also positively impacts BTE. Nanoparticles like TiO_2 and Al_2O_3 improve combustion efficiency by facilitating finer atomization of fuel, leading to more complete burning. This not only enhances BTE but also reduces harmful emissions.

There is a critical balance between enhancing fuel efficiency and controlling emissions. While nanoparticles generally improve engine performance and efficiency, their impact on emissions is varied. For example, SiO_2 nanoparticles, when blended with biodiesel, can reduce emissions but might increase NO_x levels. Different nanoparticles have distinct effects on engine performance. For example, CeO_2 is reported to marginally enhance BTE with diesel-ethanol fuel, while TiO_2 significantly improves BTE along with a reduction in emissions. The use of 100 % biodiesel increases brake power but might lead to higher emissions of particulate matter. Diesel, on the other hand, generally shows lower BSFC and better BTE but is less environmentally friendly.

The integration of nanoparticles in engine fuels is a compelling avenue for enhancing engine efficiency and reducing emissions. However, the type of nanoparticle used, the base fuel, and the engine's design and operating conditions significantly influence the outcomes. Each nanoparticle type brings specific benefits and challenges. There is a need for more comprehensive studies focusing on finding the optimal balance between nanoparticle type, fuel mixture, and engine conditions to maximize both performance and environmental benefits. Additionally, it's important to address and mitigate any potential negative impacts, especially on emissions, to harness the full potential of nanoparticle-enhanced fuels. As this field evolves, focusing on sustainable, green synthesis methods for nanoparticles could further amplify the environmental benefits of this technology.

Effect of nanoparticles on engine emission

In the last few decades, the advancement of biodiesel engines has attracted great attention from the transportation and power generation industries. Biodiesel engines provide many advantages including a high-quality thermal brake system, a high compression process, and low fuel consumption. However, biodiesel engines emit large amounts of CO, smoke, CO_2, NO_x, HC and so on which eventually limits their efficiency [63,140]. However, the addition of nanoparticles can improve fuel properties that can decrease exhaust emissions and enhance the performance of biodiesel engines [47]. Since nanoparticles have a high surface-weight ratio, they exhibit some unique properties such as good oxidizing capability, and catalytic and thermal activity. Through this, nanoparticles can improve combustion behaviour and eventually help to reduce the emission of pollutants in biofuel [63]. For instance, an experimental investigation conducted by Demir et al. [24] demonstrated that the incorporation of graphene into a diesel engine led to improved thermal efficiency and decreased emissions.

The addition of CNTs and graphene nanosheets in a dosage of 100 ppm (parts per million) can reduce smoke contamination by 28 % and 54 %, CO by 27 % and 47 %, NO_x by 22 % and 44 %, and HC by 28 % and 52 % for B20CNT100 and B20CNS100 biodiesel, respectively [41]. Another study showed that turnery fuel with alumina nano addition (20 ppm) can lower the emission of smoke, HC, CO, and NO_x by 6.48 %, 5.69 %, 11.24 %, and 9.39 %, respectively, performing better than neat turnery fuel [130]. Thus, the use of nanoparticles decreases noxious gas emissions which ultimately contributes to rectifying pollution problems and helps to improve the performance of biodiesel in different sectors.

Carbon monoxide

The generation of carbon monoxide (CO) is mainly correlated to a deficient fuel combustion process. When the combustion process cannot take place properly, some of the carbon atoms cannot be oxidized effectively. As a result, they cannot be transformed into CO_2 at the end of the reaction which eventually leads to the formation of CO in the biodiesel [111]. CO emissions from a CRDI diesel engine operating in steady-state mode were analyzed by Yusuf et al. [141] in relation to diesel fuel blends containing hybrid nanoparticles (Al_2O_3 + TiO_2). Utilizing the ultra-sonification method, experiments were conducted with fuel mixtures containing the hybrid nanoparticles at concentrations of 20, 40 and 60 ppm. An increase in the concentration of hybrid NPs from 20 to 60 ppm is accompanied by a gradual reduction in CO emissions (Fig. 3). This is primarily due to the increased number of oxygen atoms in nanofuel, which assists in combustion promotion. Furthermore, the decrease in CO concentration can be attributed to the diminished heat dissipation of the coolant.

There are several factors such as shortage of oxygen, period of ignition delay, temperature, LCA (low carbon activation), spray penetration, and timing of ignition which are primarily responsible for the inadequate combustion process and subsequent CO formation [117,119]. According to several studies [21,70,98,106,124], nanoparticles have a substantial impact on biofuel in the timing of chemical reactions, which further shortens the IDP (ignition delay period) and causes a reduction in the diesel engine's emission characteristics. Therefore, many researchers have started to use different nanoparticles, including CeO_2, TiO_2, and Al_2O_3, to reduce the emission of CO in biodiesel [42,118].

The efficiency, combustion, and contamination behaviour of non-edible vegetable biodiesel engines were investigated by Ranjan et al. (2018b) in a study that examined the impacts of MgO (magnesium oxide) at concentrations of 20, 30, 40, and 50 ppm. The glycine-nitrate combustion method was used to manufacture MgO and the XRD (x-ray diffraction) method was used to characterize the resulting nanoparticles. MgO blended biodiesel can decrease CO emissions by an average of 15.71 % compared to fuel without MgO additives. Prabu, [97] used Al_2O_3 and CeO_2 nanoparticles as nanoadditives in a study to explore the combustion and emission characteristics of *Jatropha curcas* biodiesel in a four-stroke DI diesel engine. SEM (scanning electron microscopy), and XRD were used to analyse different parameters such as morphology and the crystalline phase of nanoparticles. Al_2O_3 and CeO_2 showed the potential to reduce the emission of CO by 60 % owing to their higher surface-volume ratio, exhibiting strong thermal, oxidative, and catalytic activity which can facilitate the evaporation and diffusion of the reaction. Thus, the incorporation of these nanoparticles can improve the combustion process which can then easily convert CO to CO_2 and reduce CO emissions [14,143].

The effect of manganese oxide (Mn_2O_3) and cobalt oxide (Co_3O_4) in concentrations of 25 and 50 ppm in B20 blended biodiesel (20 % waste frying oil biodiesel + 80 % diesel) on CO emissions was investigated by [83]. The incorporation of Mn_2O_3 and Co_3O_4 exhibited excellent combustion and oxidative behaviour which resulted in a lower period of ignition delay after the reaction. Thus, the use of Mn_2O_3 and Co_3O_4 is a sustainable solution for a considerable reduction in the contamination of CO. Another study carried out by Pandian et al. [94] evaluated the emission effect of TiO_2 mixed with neat mahua oil biodiesel at 100 and 200 ppm. They used the traditional transesterification process to obtain

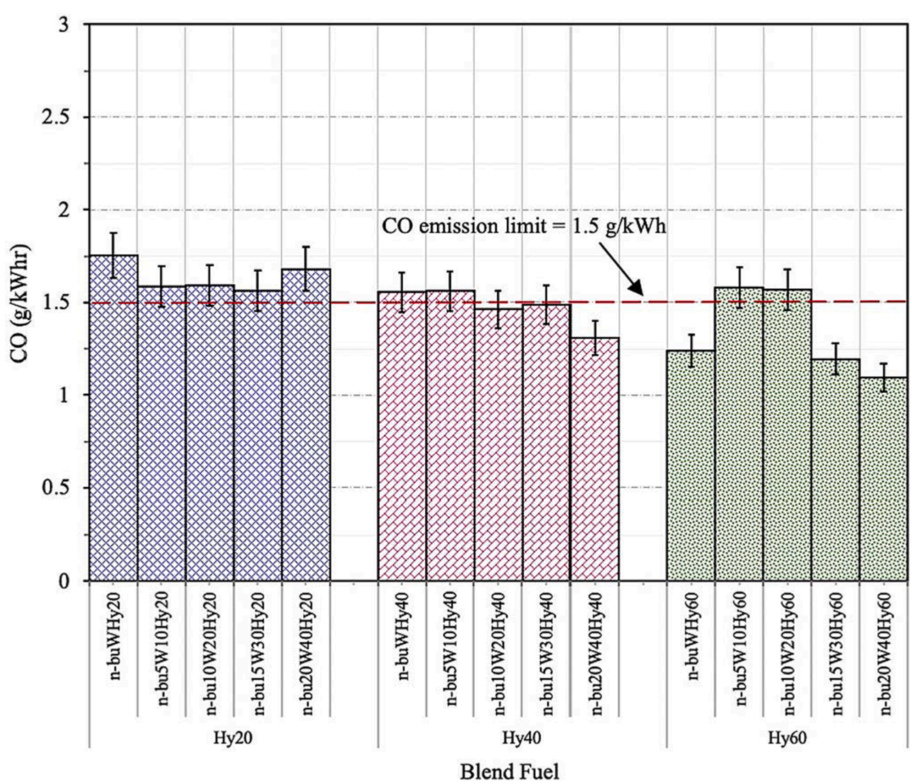

Fig. 3. Variation in CO emissions across various test fuels incorporating hybrid nanoparticles, reprinted with permission of Elsevier from Yusuf et al. [141].

mahua biodiesel and XRD to synthesize TiO_2 nanoparticles. The complete blending operation was carried out using an ultrasonicator with a frequency ranging between 60 and 100 kHz. The result shows that a total reduction of up to 9.3 % of CO emissions was obtained at 200 ppm of TiO_2 compared to neat mahua biodiesel. Radhakrishnan et al. [99] examined the effect of alumina oxide additive in a biodiesel engine fuelled with cashew nut shell biodiesel. The biosynthesis of alumina was carried out in this experiment utilizing the sol–gel method in an engine known as a “single-cylinder four-stroke”. The result revealed that using alumina oxide in BD100A biofuel can reduce CO emissions by up to 10.1 %. It is worth noting that a lower range of CO emissions is formed at lower engine loads. This could be due to a reduction in fuel consumption and the lean fuel mixture used in biodiesel engines.

Likewise, using graphene oxide (GO) nanoparticles in an Ailanthus altissima biodiesel engine also reduces CO output [53]. GO was blended with Ailanthus altissima biodiesel at concentrations of 30, 60, and 90 ppm by means of an ultrasonicator. It was discovered that the addition of GO can lower CO emissions from biodiesel engines by around 7 % to 20 %. Furthermore, increasing the doses of the GO in Ailanthus altissima biodiesel B10G30, B10G60, and B10G90 can improve the mitigation of CO emissions by 4.84 %, 10.48 %, and 18.55 %, respectively. A similar result was also cited by Soudagar et al. [115] when GO was used as an additive in a CI (compression ignition) engine fuelled with dairy scum oil biodiesel. According to the findings, the high viscosity of the biodiesel was one of the primary factors for increasing CO emissions. However, the increase of SDS (sodium dodecyl sulphate) surfactant concentration played a crucial role in reducing the viscosity which eventually helped to suppress CO emissions by 38.62 % for DSOME2040. The findings of the above research contradict the result of another study when working with CNTs and nano-MoO_3 in neat biodiesel (Mei et al., 2019b). These two nanoadditives were prepared using the physio-chemical dispersion method. The result of this study showed that CNTs and nano-MoO_3 can exhibit fantastic thermal conductivity and catalytic oxidation properties which can accelerate the burning process and result in a dramatic decrease in CO emissions.

Hydrocarbon emissions

Like CO, hydrocarbon (HC) is mainly produced by the inefficient combustion of fossil fuels. The insufficient content of oxygen prevents proper combustion and results in HC formation in the combustor. Besides that, the air–fuel ratio, improper design, and induction system of the combustion chamber are also equally responsible for HC emissions [28]. Different types of fuels such as petrol and diesel are usually ejected from the engine in an unburned condition and cause HC pollution, which raises the risk to the public’s health [12,111]. In one study, it was found that the interaction of gaseous HC in sunlight results in photochemical smog, which causes a substantial risk to the human respiratory system [55]. In such conditions, using nanoparticles in biofuel could be one of the best solutions for lowering HC emissions in biofuel. The inclusion of nanoparticles in biofuel can play a significant role as an oxidizing catalyst and speed up flammability inside the cylinder. Thus, it can lower the carbon activation temperature and lead to complete combustion which can eventually prevent HC emissions in the diesel engine [106].

The addition of aluminium oxide also contributes to the significant reduction of HC emissions. A study conducted by Kumar Nema & Singh, [70] used Al_2O_3 as a nanoadditive to examine how effective this nanoparticle was in reducing the emission of HC in the CI engine. The goal of this research was to compare the effectiveness of the nanoadditive in two different types of biodiesel, soybean methyl ester and rapeseed methyl ester. This study revealed that the use of Al_2O_3 can achieve a reduction in HC emissions by approximately 62 % at 50 % load. Since this nanoadditive can act as an oxygen buffer, it performs better at reducing HC emissions compared to the biodiesel blend. A similar finding was also highlighted by Dhana Raju et al., [28], where the incorporation of alumina oxide with TSME (tamarind seed methyl ester) showed a positive impact on the combustion process at different concentrations. After conducting a comprehensive analysis, it was found that the tamarind seed methyl ester blend has a stimulatory effect on HC emissions. Since tamarind seed methyl ester has excessive oxygen content in its structure, it can oxidize the HC. Adding a total of 60 ppm of alumina oxide maximized the reduction of HC emissions by 24–68 %. This result indicates that adding Al_2O_3 can undoubtedly minimize HC emissions.

The carbon nanotube is another nanoparticle that is frequently used to reduce exhaust emissions of HC in biodiesel. The influence of MWCNTs (multi-walled CNTs) on WCO (waste cooking oil) biodiesel was reviewed by Soudagar et al., [116]. The authors used concentrations of 30, 60, and 90 ppm of this nanoparticle in B5 and B10 WCO biodiesel. The blend of CNTs with B10 fuel was found to be more effective at 90 ppm where HC emissions were reduced by 44.98 %. A further study conducted by Ghanbari et al. [44] looked at the impact of CNTs and Ag (nano-silver) on the operation, exhaust emissions, and combustion behaviour of CI engines running on a blend of neat diesel and diesel–biodiesel. The experiment was run on a 4-stroke diesel engine. The transesterification and blending of nanoparticles and biodiesel were carried out using an ultrasonic processor with a frequency of 24 kHz. Additionally, two types of microscopic techniques such as SEM (scanning electron microscopy) and TEM (transmission electron microscopy) were used to characterize the nanoparticles. The result suggests that CNTs120BD nanoparticles caused an increase in HC emissions of 14.21 %, while Ag120BD can suppress HC emissions by about 28.56 %. This could be attributed to the fact that CNTs have a carbon atom in their structure which led to an increase in the level of HC emissions.

Since metal oxide has some versatile physio-chemical properties, its use could be another sustainable solution to reducing HC emissions. Ganesan et al. [42] conducted a study where they looked at the impact of different concentrations of CeO_2 on biodiesel engine emissions. Following the solvothermal method, CeO_2 was synthesized, and different microscopic techniques were employed to characterize the nanoparticle. After conducting a comprehensive analysis, it was found that the addition of CeO_2 in concentrations of 10, 20 and 30 ppm can reduce HC emissions by up to 4.2 % in BD20 at all loads (palm oil methyl ester + diesel blends) compared to neat BD20. In another investigation [115], HC emissions were inhibited using GO blended with diary scum oil biodiesel. The authors wanted to observe whether the integration of GO has any impact on the exhaust emission of biofuel. The nanoparticles were prepared using the CVD (chemical vapor deposition) synthesis method and all GO parameters were analysed using SEM, EDX (energy-dispersive x-ray spectroscopy) UV-spectrometry (ultra-visible spectrometry) and XRD. The results show GO is one of the most effective nanoadditives by achieving a reduction in HC emissions of around 21.68 % for DSOME2040 biodiesel.

Magnesium oxide (MgO) is another nanoparticle that demonstrates excellent efficiency in the reduction of HC emissions. For instance, Arunprasad et al., [12] conducted a study where MgO nanoparticles were integrated with *Chlorella vulgaris* algae biodiesel as a nanoadditive. A single-cylinder four-stroke CI engine was used to complete the engine test. Furthermore, different nanoparticle characteristics like size, distribution, shape, and elements were analysed using SEM, TEM and EDX techniques. B20MgO showed the potential to reduce HC emissions with a 27.9 % efficiency at a concentration of 100 ppm compared to B20. This study also revealed that since the biodiesel blended with MgO can extend the ID (ignition delay), fuel explosion, and rate of heat escape, it can easily improve the combustion process which eventually contributes to reducing HC emission levels. Even though nanoadditives can lower HC emissions, sometimes integrating nanoparticles can have a negative effect on that reduction.

In an experimental study, Venu & Madhavan [129], compared the performance and emission properties of four different types of bent fuel by using ZrO_2 (zirconium oxide), TiO_2, and DEE (diethyl ether). The fuels used in this study were BE (80 % biodiesel + 20 % ethanol), BE-DEE (80 % biodiesel + 20 % ethanol + 50 ml DEE), BE-Ti (80 % biodiesel + 20 % ethanol + 25 ppm TiO_2) and BE-Zr (80 % biodiesel + 20 % ethanol + 25 ppm ZrO_2). A stationary Kirloskar engine fuelled by diesel was used to conduct the experiments. After a comprehensive analysis, this study noted that the biofuels blended with TiO_2 and ZrO_2 nanoparticles can increase HC emissions compared to BE fuel. Since DDE can increase the rate of heat release, it may be one of the most important variables in increasing biofuel emissions.

Nitrogen oxide emissions

Another exhaust pollutant is nitrogen oxide (NO_x), which is usually comprised of two types of chemical elements: nitric oxide (NO) and nitrogen dioxide (NO_2) [118]. The two factors of greater combustion temperature and longer reaction residence time are the main contributors to the production of NO_x emissions [118]. Due to the higher combustion temperature (>1,800 k), NO_x formation is higher in a diesel engine than in other engines (Ranjan et al., 2018b). Additionally, there are also some other parameters like oxygen content, fuel properties, and flame temperature which also affect the generation of NO_x emissions [97,106]. The free nitrogen atoms mix with oxygen in the presence of high oxidative fuel at high temperatures and produce NO_x. Since biodiesel has a good amount of oxygen content, the use of this fuel can result in higher NO_x emissions in the environment [106,119].

Many researchers ([44,50,53,83]; Mei et al., 2019b; [6]) have started to use different nanoadditives, including metal-based additives, metal oxide and non-metal oxide additives, to reduce NO_x emissions in biofuel. The study conducted by Ağbulut et al. [6] revealed that the utilization of metal-oxide nanoparticles (B10Al_2O_3, B10TiO_2, B10SiO_2) in test fuel results in reduced emissions in comparison to the reference diesel of D100 (Fig. 4). Some of studies claimed that sometimes the adoption of biofuel blends and nanoadditives can result in an increment in NO_x emissions. For instance, Hoseini et al. [53] observed that GO blended with biodiesel can increase NO_x emissions by around 5–8 % in biodiesel engines whereas Ghanbari et al., [44] found a 25.32 % rise in the magnitude of NO_x contamination. This could be due to the higher concentration of nanoparticles where the emissions of NO_x from biodiesel-nanoparticle blends increase with the increase in nanoparticle concentration. Additionally, they also attributed their result to the flame temperature of combustion and stoichiometry combustion process. However, some researchers also claim that a biodiesel-nanoadditive blend has a positive impact on the reduction of NO_x emissions.

Vedagiri et al. [124] carried out a study with CeO_2 and ZnO (zinc oxide) nanoadditives in grapeseed oil biodiesel at a concentration of 100 ppm. This study aimed to evaluate the effect of nanoparticles on the productivity, emission, and combustion characteristics of grapeseed oil biodiesel in CI engines. A SCR (selective catalytic reduction) device and a non-SCR system were used to improve NO_x reduction. Further, the nanoparticles were characterized utilizing FTIR spectroscopy (Fourier-transform infrared spectroscopy). The engine test was conducted on a single-cylinder engine. NO_x emissions were found to reduce by 4.19 % and 13.13 % for CeO_2 and ZnO, respectively. Additionally, the use of the SCR system reduced the total emissions for CeO_2 by 74.16 % for ZnO by 80.06 %. This result agrees with another study conducted by Praveena et al., [98] where the author mixed two types of metal oxides, including CeO_2 and ZnO (zinc oxide), with grapeseed oil methyl ester to observe the combustion and emission behaviour of a compression ignition (CI) engine. This work's primary objective was to use vineyard biowaste as a sustainable substrate for CI engines. The characterization of nanoparticles was performed using SEM and FTIR techniques. They identified that adding CeO_2 and ZnO to the fuel improves the BTE (brake thermal efficiency) and lowers emission levels. Since the water particles in nanoemulsion have a faster evaporation rate, the integration of these nanoblends can reduce NO_x emissions by 10 %.

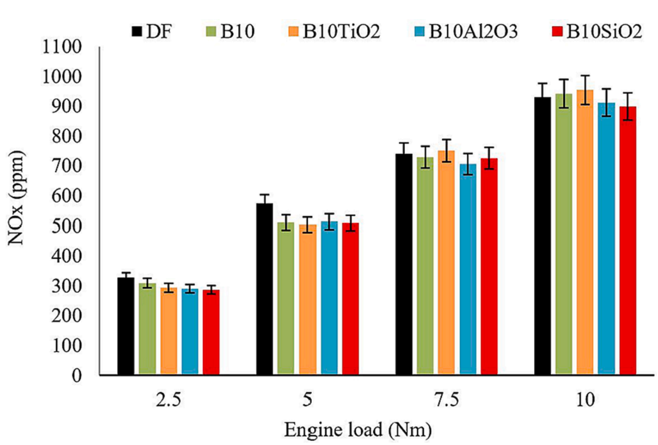

Fig. 4. Fluctuations in NO_x emissions occur as a result of different test fuels and engine loads, reprinted with permission of Elsevier from Ağbulut et al. [6].

The functionality and effluence features of biodiesel engines were also examined in another study by El-Seesy et al. [32] where graphene nanoplatelets (GNPs) were added to JB20 (20 % Jatropha methyl ester + 80 % diesel) at concentrations of 25, 50, 75, and 100 mg/L of JB20. The levels of contamination were determined using a gas analyser. Jatropha oil was analysed using an FT-IR spectrometer, whereas the various characteristics of the nanoadditive were examined using SEM and TEM methods. Since the combustion process for GNP-JB20 is shorter, NO_x emissions were claimed to be lower at various speeds. For instance, at an engine speed of 2,000 rpm, NO_x emissions were reduced by 55 %, while at 2,500 ppm they were reduced by 40 %. Similar results were found by Prabu [97] where the performance and emission characteristics of a DI (direct injection) engine were evaluated using nanoadditives. In this study, two types of nanoparticles (Al_2O_3 and CeO_2) were used. Using an ultrasonicator, each of these nanoparticles was blended with fuel at 30 ppm. The combination of Al_2O_3 and CeO_2 nanoadditives showed excellent efficiency in reducing noxious gas emissions. The total emissions reduction obtained for B20A30C30 (biodiesel-biodiesel-nanoparticles) fuel was 30 %.

The effects of nanoadditives on urea-SCR-equipped biodiesel engines were investigated in a study by Mehregan & Moghiman [83]. The study also looked at how urea-SCR technology and blended biodiesel additives affect the functional efficiency and discharge capabilities of a diesel engine. Mn_2O_3 (manganese oxide) and Co_3O_4 (cobalt oxide) were combined as nanocatalysts with the fuel at concentrations of 25 and 50 ppm, respectively. In comparison to manganese oxide, adding 50 ppm of cobalt oxide showed excellent performance in emission behaviour. For Co_3O_4, the reduction in NO_x emissions was measured at 40 %, whereas for Mn_2O_3, the emissions were reduced by 14 %.

Soudagar et al., [116] conducted a study where magnetic ferrofluid was combined with MEMO (methyl esters of mustard oil) to examine the latter's impact on the performance and emission behaviour of diesel engines. The biodiesel engine's speed was steady for the duration of the experiment. This study demonstrated that increasing the proportion of magnetic ferrofluid in a combustion mixture results in a greater quantity of heat produced at higher combustion temperatures, which helps to shorten the ID (ignition delay) time and reduce NO_x emissions. By adding 1 % of magnetic ferrofluid (by volume) to MEMO, this study observed a total reduction in NO_x emissions of 7.74 %. Nevertheless, the results presented here conflict with those of a different study by Srinivasan et al. [118] where the authors used Al_2O_3 and TiO_2 nanoparticles with neat biodiesel at 25 and 50 ppm to evaluate the impact on the function, combustion, and exhaust emission behaviour of a CI engine. A sol–gel method was employed to synthesize the nanoparticles. The results demonstrated that the incorporation of aluminium oxide and titanium oxide in a blended biodiesel revealed a negative impact on the reduction of NO_x and an increase in NO_x emissions of 21 %. A similar result was also found in a study cited by Heydari-Maleney et al., [50] when using CNTs as an additive to diesohol-B2fuels (diesel + ethanol) at concentrations of 20, 60, and 100 ppm. The results of this study showed that the incorporation of CNTs increases NO_x emissions by 12.22 %. This might be explained by a shortage of oxygen causing an incomplete reaction and ultimately increasing the NO_x output.

Particulate matter emissions

Particulate matter emissions are another sort of emission with a negative impact on biodiesel performance. The main components of particulate matter are different types of metallic materials, soot, and solid and liquid volatile organic compounds (VOC) [116,131]. The generation of particulate matter (PM) follows a complex mechanical process in which the combustion process plays a significant role. The emission of particulate matter occurs in the biodiesel engine due to the lack of sufficient oxygen in heterogeneous combustion (Venu and Madhavan, 2017b). Other factors such as heat, fuel properties, oxygen concentration, residence time, and fuel pressure also make equal contributions to increasing the emission of PM from biofuel [76]. In most cases, unburned byproducts are carbonized and dehydrated at high temperatures in an O_2-poor environment to produce PM. Hence, the presence of nuclei and a high load facilitates the generation of particulate matter, whereas higher oxygen content and a longer period of residence time cause a reduction in PM emissions [143].

Several studies ([28]; Venu and Madhavan, 2017b; [143]) were conducted to find a sustainable solution to reducing the emission of PM. It was found that since nanoparticles exhibit a higher surface area and excellent catalytic activities, the use of nanoparticles has been proven to be one of the most effective ways to alleviate PM emissions. According to a study, the presence of a higher content of oxygen in nanoparticles makes a crucial contribution to PM emissions reduction [116]. A comparative experiment was undertaken using MCNTs (multi-wall CNTs) and CeO_2 nanopowders of a 25 and 50 nm size, respectively, where authors aimed to test the influence of the nanoadditive on the combustion and emission behaviour of biodiesel engines [143]. An ultrasonication device was employed to combine the nanoadditive with biodiesel. The study was performed in a four-stroke diesel engine operated using the ESC (European Stationary Cycle) technique. Due to a better spray system and lower combustion process, the blend of CNTs-biodiesel achieved a reduction in PM emissions of around 5.5 % compared to neat diesel fuel. This indicates that the use of CNTs can effect a reduction in PM emissions. Furthermore, CeO_2 incorporated in the fuel can oxidize the particulate matter and is also capable of consuming HC before it becomes particulate matter. Thus, the use of CeO_2 also has a positive impact by reducing PM emissions.

Like MWCNTs and CeO_2, Al_2O_3 also behaved as an effective additive in another study by Fayad & Dhahad [36], where authors incorporated Al_2O_3 into a butanol-diesel blend (B20) in different concentrations of 30, 50, and 100 mg/l to examine the performance, combustion, and emission behaviour of a diesel engine. The blending of B20 and the Al_2O_3 nanoadditive reduced the contamination of particulate matter by 30.5 % at a 3.5 bar engine load. Although this study encountered some difficulties in creating the mix of nanofluids because of the van der Waals interaction, it ultimately recommended that the concentration of nanoparticles should be increased to 100 mg/l to improve productivity and the combustion process in biodiesel engines.

The effectiveness of Al_2O_3 and oleic acid ($C_{18}H_{34}O_2$) in reducing the contamination of different exhaust gases and particulate matter was measured by Karthikeyan et al. [66]. The authors integrated the nanoparticles *Kappaphycus alvarezii brown* algae biodiesel concentrations of 10, 20 and 50 ppm to observe how the nanoadditives react with third-generation biofuel and minimize the outflow of pollutants from the engine. This study synthesized the nanomaterials using a sol–gel method. The results showed that the combination of nanoadditives has a significant capability to reduce PM emissions with an efficiency of 14.8 %, 20.3 % and 25.6 % at 10, 20 and 50 ppm, respectively. Due to the higher oxidant content of the biodiesel blend and the high temperature of the cylinder, emissions were reduced with an increase in the concentration of the nanoadditives. Although the blended biofuel showed a significant result at 50 ppm, this improvement also caused a rise in the production of NO_x emissions in the biodiesel engine.

Biodiesel particulate matter emissions were also studied by Verma et al., [132], who looked at the impact of biodiesel alcohol and nanoadditive blends. They assessed different oxygenated additives such as DME (dimethyl ether), DMF (2,5-dimethylfuran), DMC (dimethyl carbonate), triacetin and so on. After doing a comprehensive analysis, this study concluded that the absorption of triacetin can dramatically eliminate the emissions of PM. The findings achieved from the above studies revealed consistent trends with those reported by Dobrzyńska et al. [30]. The authors utilized two types of nanoparticles such as CeO_2 and ferrocene ($Fe(C_5H_5)_2$) as nanocatalysts with the aim of exploring the effect of nanoadditives in reducing the emission of harmful components into the environment. Different emissions were measured using a chassis dynamometer and the NED (New European Driving) Cycle. The significant efficiency of CeO_2 in reducing emissions means it can be used to reduce PM emissions by as much as 7 %.

Carbon dioxide emissions

Carbon dioxide (CO_2) is one of the fundamental components of greenhouse gases which play a significant role in causing global warming. It has a disastrous effect on the atmosphere causing severe health problems in humans. However, the effect of CO_2 emissions is comparatively less harmful than the release of CO. Since photosynthesis is a vital process for plants and CO_2 is one of the most essential components for photosynthesis, plants may effectively remove a significant amount of CO_2 from the atmosphere (Ranjan et al., 2018b; [136]). Thus, photosynthesis not only lessens the harmful effects of CO_2 on the environment but also protects people from a variety of health issues.

The emission of CO_2 is mainly caused by the perfect flammable process where the presence of a higher amount of oxygen burns down the fuel and produces water and CO_2 at the end of the reaction [120]. Further, fuel properties, engine speed, the ratio of C/H, fuel pressure, the density of the mixture, and the starting point of injection contribute equally to the generation of CO_2 [70,126]. In these circumstances, many researchers have conducted studies on how to minimize the risk of CO_2 in diesel engines. Saxena et al. [106]examined that since biodiesel has a low amount of carbon content compared to diesel, the use of biodiesel could result in lower CO_2 emissions into the atmosphere. Additionally, some investigators also reported that adding various nanoparticles to biodiesel may be one of the best solutions for lowering CO_2 emissions [32,31,55,74,88].

The effects of Al_2O_3, MWCNTs, and SiO_2 nanoadditives on diesel combustion were investigated by Chen et al. [21] at 25, 50, and 100 ppm concentrations in a diesel engine. Three nanoparticles were compared for their performance in terms of engine functionality, emission, and combustion. Different bioelectronic devices, for instance FESEM, SEM, EDX, and UV–Vis spectrophotometer (ultraviolet visible spectrophotometer), were used to analyse the characteristics and stability of the nanoparticles. The engine test was run on a YANMAR TF120M engine at a speed of 1,800 rpm. Although the silicon blend biofuel indicated a modest reduction in CO_2 emissions, the other two blends exhibited no noticeable effects at a low biofuel volume. However, all the blends exhibited an increase in emissions with an increase in engine load.

Even though CNTs blends are reported to have better BSFC, BTE and NO_x emissions reduction rates in diesel engines, the stability issues of this blend need to be resolved before they can be considered as a potential remedy in the future. Similarly, Shanmugam et al., [110] used CeO_2 with Citrus medica (citron) peel oil biodiesel in another study. The focus of this research was to find alternative fuel sources that might potentially increase biodiesel engine performance and reduce biofuel emissions by employing nanoadditives. To carry out the experiment, the engine was coated with a thermal barrier coating (TBC) system using the APS (air plasma spray) process. The whole study was undertaken in a CI (compression ignition) engine with and without TBC. The results show that CeO_2 makes a remarkable contribution to reducing CO_2 emissions in CI engines. This may be accounted for by the fact that the addition of CeO_2 served as an oxidizing agent, improving the oxidation process, and ultimately reducing CO_2 emissions.

Two recent studies conducted by El-Seesy examined the impact of GO on the behaviour of diesel engines [32,31]. In the first study, GO, GNPs, and CNTs were integrated with biodiesel, whereas only graphene oxide was integrated in the second study. In both cases, the authors mixed Jatropha methyl ester biodiesel with nanoparticles using the ultrasonication process and used some bio-electronic techniques including TEM, FTIR, and XRD to ascertain the different parameters of the nanoadditives. Both studies revealed that GO is highly efficient in reducing CO_2 emissions. The findings of the aforementioned research support those of another comparative study conducted by Characteristics [20] where graphene oxide (GO) nanoparticles and n-Butanol fuel additives were mixed with *Nigella sativa* biodiesel. The objective was to improve the *Nigella sativa* biodiesel properties using nanoadditives (NSME25) and discover if the blended fuel performs better and emits fewer pollutants when used in CRDI (common rail direct injection) engines. The mixtures of nanofluids were prepared using the sonication process. Along with nanoadditives, SDBS (sodium dodecyl benzene sulphonate) surfactant was also applied in this experiment. The graphene oxide was synthesized using XRD, SEM, EDX, and TEM, respectively, to ascertain the morphology as well as the crystallization feature of the GO. The results indicate that when graphene oxide was added to *Nigella sativa* biodiesel, it showed excellent efficiency in decreasing the contamination of CO_2 compared to B20 fuel.

Sometimes the addition of nanoparticles in biodiesel blends may lead to an improved combustion process which eventually increases CO_2 emissions in biodiesel [106]. In a recent experiment by Deepak et al. [23], the CNTs were used with Calophyllum inophyllum biodiesel to make a comparison between the performance obtained from biodiesel-diesel blended fuel with biodiesel in a CI engine. The results indicated that since CNTs have a high surface-volume ratio, using them can speed up the heat transmission process which ultimately leads to complete combustion. As a result, when the engine load increases, CO_2 emissions also increase. Likewise, Vellaiyan [125] found a profound effect of CNTs on the increment of CO_2 emissions in biofuel. In this study, the author incorporated CNTs as a nanoadditive with soybean biodiesel to investigate whether nanoadditives have a positive impact on diesel engine performance. The comprehensive analysis from this study revealed that the inclusion of CNTs had a significant impact on emission behaviour, where the CNTs were found to generate a 12.1 % increase in CO_2 emissions at 100 ppm.

A consistent result was also reported in another study by Karthikeyan et al., [65] where the authors used lanthanum oxide (La_2O_3) to assess the impact of NPs on the exhaust effluence behaviour of the CRDI engine with microalgae biodiesel at concentrations of 50, 75, and 100 ppm. The nanoadditive blend was produced by the ultrasonication method. The engine test was conducted in a single-cylinder four-stroke CRDI diesel engine. The experimental observation demonstrated that due to the higher content of carbon atoms, CO_2 emissions were higher in the nanoadditive blended biofuel than in B20 biodiesel. Additionally, it was discovered that the emissions increased as engine loads rose, with a total increase of around 10 % detected at maximum load.

Smoke emissions

Smoke emissions refer to an unwanted end product of the combustion process in a diesel engine. The primary cause of smoke emissions is an improper hydrocarbon fuel burning process [136]. Smoke opacity is used to quantify the concentration of soot in the emissions. Smoke is mainly generated in the fuel-rich region of the engine and the amount present is influenced by oxidation and soot generation [28]. Therefore, when the engine operates at full load, it causes the smoke's opacity to be more unpredictable [115]. For instance, due to the high air–fuel ratio and fuel consumption, smoke emission opacity was reported to increase and decrease with variations in engine load. Again, an increase in oxygen content causes a decrease in emissions [2,41]. This could be attributed to the presence of a high O_2 content which can lead to complete combustion, ultimately reducing smoke emissions [54]. In addition, rapid vaporization, a shorter explosive delay, and a shorter flame propagation phase also significantly reduce smoke emission opacity [41].

A study by Thangavelu S & Arthanarisamy [122] investigated the potential of the nanoadditive CeO_2 on the combustion behaviour, emission characteristics and functionality of a direct injection (DI) compression ignition (CI) engine using tyre pyrolysis oil. The volumetric blends of tyre oil and diesel fuel used were 5 %, 10 %, 15 % and 20 %. The emission characteristics of the biodiesel and smoke opacity were measured using different experimental equipment including a thermocouple, gas analyser, smoke meter, and gas thermometer. After undertaking an insightful analysis, this study detected a 7.7 % reduction in smoke opacity in comparison to traditional biodiesel. Furthermore, the use of B5D85 + CeO_2 (5 % tyre pyrolysis oil + 85 % diesel + 100 ppm nanoadditive) fuel showed better performance and lower emission characteristics. Hence, this fuel is considered as one of the most effective diesels for CI engines.

Arunprasad et al., [12] carried out a study to examine the impact of MgO in diesel engines fuelled by *Chlorella vulgaris* algae biodiesel. With the help of the transesterification process, methyl ester was collected from the *Chlorella vulgaris* algae biodiesel. The morphology of the nanoparticles was observed by SEM, TEM and EDX. The findings of this investigation showed that the incorporation of nanoadditive can lower smoke opacity by 1.9 % and 3.7 % at concentrations of 50 and 100 ppm, respectively. This indicates that the amount of smoke emissions is inversely related to the level of nanoparticles where the emissions were found to decrease as the concentration of nanoadditives increased.

The influence of diesel engines was also explored in a study by Janakiraman et al. [58] where novel Garcinia gummi-gutta biodiesel was used with three different nanoparticles, namely, CeO_2, TiO_2 and ZrO_2. This study aimed to investigate the feasibility of Garcinia gummi-gutta biodiesel when integrated with different nanoparticles. Nanoadditives were blended with B20 (20 % Garcinia gummi-gutta biodiesel + 80 % diesel) at a concentration of 25 ppm by means of ultrasonication. The Sol-gel method, SEM, TEM and XRD analysis were employed to synthesize and characterize the nanoparticles. In comparison to diesel, the blend of TiO_2 and B20 showed around 16.25 % better efficiency in reducing smoke opacity and other exhaust emissions. The Garcinia gummi-gutta biodiesel and nanoadditive blend can thus be considered a sustainable alternative fuel for CI engines. The result of this investigation was found to be consistent with those of a recent study by Vigneswaran et al. [133] where TiO_2 was used as a nanoadditive in an unmodified diesel engine. The purpose was to determine whether adding a nanoadditive to a water-in-diesel emulsion fuel could alter the engine's performance in any way. A sol–gel system and FTIR techniques were used to synthesize and characterize the nanoparticles. Using a mechanical agitator, homogeneous fuels, termed DWT_1, DWT_2, and DWT_3, were prepared by combining emulsion fuel (DWS), which is made up of 10 % water, 89.8 % diesel, and 0.2 % surfactant, with TiO_2 at concentrations of 30, 60 and 90 ppm. The addition of TiO_2 resulted in a 32.98 % reduction in smoke emissions which indicates that the use of TiO_2 blended emulsion fuel is highly efficient in the diesel engine.

Nonmetal oxide is another nanoadditive that plays a signification role in decreasing smoke emission opacity. Sivathanu & Valai Anantham, [114] researched how MWCNTs could improve the function, emissions, and combustion characteristics of diesel engines using waste fishing net oil. Waste fishing net oil was synthesized using the pyrolysis process. The morphology of the nanoparticles, including size, shape, and surface area, were determined using various nanotechnologies, for example, FE-SEM (field emission scanning electron microscopy) and TEM. The fuel properties were evaluated as per the ASTM (American Society for Testing and Materials) standard. A significant reduction of 14.81 % in smoke opacity was reported at 100 % engine load. This result agrees well with a recent study by Perumal & Ilangkumaran [95] who employed copper oxide (CuO) as a nanoadditive to pongamia methyl ester biodiesel in a biodiesel engine with the aim of observing the influence of this nanoadditive on the engine's performance, emissions, and combustion characteristics. The biodiesel was prepared using a number of consecutive methods, for instance, pyrolysis, microemulsification, dilution, and transesterification. Furthermore, a sol–gel process was employed to blend the nanoparticles with pongamia oil. A considerable reduction was found in smoke opacity when the emissions decreased by approximately 12.8 %. Table 1 provides a summary of the performance of various nanoadditives in reducing engine emissions.

Summary and analysis of findings on nanoparticles' effect on engine emission

The analysis of carbon monoxide (CO) and hydrocarbon (HC) emissions in biodiesel engines, particularly with the incorporation of various nanoparticles, reveals a complex interplay of factors influencing combustion efficiency and exhaust characteristics. The formation of CO is linked to deficient combustion, influenced by factors like oxygen shortage, ignition delay, temperature, and spray characteristics. Nanoparticles, such as CeO_2, TiO_2, Al_2O_3, MgO, and graphene oxide, have shown promise in reducing CO emissions through their catalytic and combustion-enhancing properties. However, the effectiveness varies, and the choice of nanoparticle influences combustion dynamics. Similarly, HC emissions, a result of incomplete combustion, can be mitigated with nanoparticle additives like Al_2O_3, CNTs, Ag, CeO_2, and MgO.

While some studies suggest that nanoadditives, such as CeO_2 and ZnO, can effectively reduce NO_x emissions, others caution about potential increases, emphasizing the importance of dosage control. The role of nanoadditives, including Al_2O_3, CeO_2, and MWCNTs, in mitigating PM emissions is discussed, showcasing the potential for higher surface area and catalytic activity. The examination of CO_2 emissions underscores the complex relationship between biodiesel composition, nanoparticle types (e.g., graphene oxide), and combustion efficiency. However, the nuanced discussion acknowledges instances where nanoadditives may inadvertently lead to elevated CO_2 emissions. The study also delves into smoke opacity reduction, citing nanoadditives like CeO_2 and MgO as effective in decreasing smoke emissions. The role of nanoparticles in enhancing combustion and reducing emissions is evident, but the specific nanoparticle characteristics, concentrations, and biodiesel blends play crucial roles. Comparative studies reveal varied impacts, highlighting the need for careful selection and application of nanoparticles in biodiesel engines. The intricate relationship between nanoparticle properties and combustion behavior necessitates a nuanced approach for optimal emission reduction in biodiesel engines.

Effect of nanoparticles on engine combustion

Using nanoparticle additions improves engine power, torque, and combustion characteristics while lowering BSFC and results in lower smoke, CO, and HC emissions [89]. First, nanoparticles are added to the diesel fuel. This improves the diesel fuel's physical qualities like the cetane number, which rises from 51.6 to 54.3 for Al_2O_3 at 150 ppm (Ranjan et al., 2018b). Also, during the process, reducing the delay time results in more heat being released during the diffusion combustion stage and less during the premix combustion stage. In the premix combustion stage, the heat release decreases for both nanoparticles, especially at 25 ppm, as compared to filtered diesel. Moreover, compared to natural diesel, the heat released during filtration combustion was reduced for both fuels. Using alumna nanoparticles as an additive with diesel–biodiesel blends has many advantages, including the fact that with a minor modification to engine design, alumina nanoparticles can be used as an alternative fuel to help reduce air pollution in urban areas, enhancing the Clean Air Act and reducing diesel engine emissions [43].

The effect of nanoparticles might vary depending on factors such as engine design. For instance, research by Hussain et al. (2020) showed the effects of hybrid diesel–biodiesel fuels made from soybeans integrated with 3 % zinc oxide nanoparticles with a cerium coating (Ce-ZnO) on the ignition parameters of an individual diesel engine. The brake thermal efficiency (BTE) and heat release rate (HRR) increased with the 50 ppm Ce-ZnO blend. In comparison to SBME25 fuel operation, the Ce-ZnO nanoparticle additive in SBME25 (SBME25Ce-ZnO50) produced less CO, smoke, and HC which dropped 30 %, 18.7 %, and 21.5 %, respectively. The study also revealed that Ce-ZnO at 50 ppm is an excellent choice for enhancing the emissions and combustions of the diesel engine. Thus, nanoparticle blended fuel shows superior combustion performance compared to the other test fuels included in the studies [105]. Nanoparticles that remain after engine combustion are expelled around the surroundings, causing severe toxicity and atmospheric pollution which is harmful to human health. Furthermore, typical combustion characteristics of nanoadditive blended biodiesel engines for diesel are converted to a number of mixed results (climate change, ecosystem quality, human health, and resource damage) in order to determine the most environmentally friendly blends [80].

Exhaust gas temperature

Exhaust systems have a variety of distinctive parts and designs and are used to release exhaust gases into the environment. CO_2 and water vapor, the two principal combustion byproducts, are present in high concentrations in the exhaust gas. In ethanol-fueled diesel engines for all operating modes, it is known that the temperature of the exhaust gas increases as the engine load increases which in turn is brought on by the increase in total energy at a high engine load after significant fuel depletion [131]. Research by Venu et al. [131] concentrated on exhaust gas recirculation (EGR) combined with 25 ppm TiO_2 nanoparticles (PBN) in B30 (70 % diesel, 30 % palm biodiesel). The experimental results show that the synergistic effect of nanoparticles, biodiesel, and exhaust gas temperature (EGR) is successful in enhancing performance while reducing exhaust emissions [131]. Further, the study uncovered that the exhaust gas temperatures decreased as the EGR% increased. Throttling the intake airflow ended in a 42° C increase in exhaust gas temperature as an outcome of reduced cylinder charge but at a cost of a 7.2 % increase in fuel consumption and a minor increase in NO_x emissions. Engine operating conditions such as speed, fuel–air ratio, etc. can affect the exhaust gas temperature in an engine as well as the amount of energy the turbine extracts. Various technologies need to be evaluated to determine the most effective one, taking into account the engine's performance, emission, and combustion characteristics.

Evaluation of fuel combustion and exhaust emissions using a variety of combustion controls was the focus of a recent study [46]. Experiments were carried out on a powerful single-cylinder diesel engine subjected to a normal rail pressure of 2.2 bar and a modest load indicating mean effectiveness. Among the many technologies investigated in the study, the combination of belated internal exhaust gas recirculation (iEGR) and intake valve closure (LIVC) was found to be the most efficient method, with an increased temperature of 62 °C in the exhaust gas and fuel consumption of 4.6 %. External EGR and reduced fuel injection pressure were ineffective at increasing exhaust gas temperature. It also included different comparisons of the combustion emissions in different models. Aside from this, the model was used for more experiments on LIVC and specific HC, NO_x, and CO exhaust emissions.

A method was presented by Dittrich et al. [29] for synthesizing nanoparticles with a productivity of the catalytically relevant size fraction < 10 nm exceeding 1 g/h. This was achieved by optimizing the fragmentation and ablation conditions, and implementing an in-process size tuning strategy. It was found that laser-generated catalysts

Table 1
The effectiveness of various nanoadditives in engine emissions.

Nanoparticle	Technique/technology/method	Biodiesel type	Emission types	References
MgO	Glycine-nitrate combustion method, XRD	Waste cooking oil biodiesel	CO and smoke emissions declined; NO emissions increased	Ranjan et al., [101]
GO	Ultraviolet–visible spectrometry, CVD (chemical vapor deposition), EDX, SEM	Diesel-biodiesel fuel	CO, smoke, NO_x, and HC emissions decreased by 38.66 %, 24.88 %, 5.62, and 21.68 %, respectively.	Soudagar et al., [115]
Al_2O_3	Sol-gel method, single-cylinder four-stroke diesel engine,	Turnery fuel	A total of 11.24 %, 9.39 %, 5.69 %, and 6.48 % reduction was found for CO, NO_x, HC, and smoke emissions, respectively.	Venu et al., [130]
CNTs and MoO_3 (molybdenum trioxide)	186FA DI diesel engine, FE-SEM (field emission scanning electron microscopy)	Neat diesel	NO_x emissions were reduced by 4.1 %, 8.9 %, 2.3 % and 5.2 % for CNT_{50}, CNT_{100}, Mo_{50} and Mo_{100}, respectively; HC emissions were decreased by 2.7 %, 11.4 %, 1.8 % and 7.5 % for CNT_{50}, CNT_{100}, Mo_{50} and Mo_{100}, respectively; reductions of 10.1 %, 15.2 %, 4.5 % and 8.3 % were found for CNT_{50}, CNT_{100}, Mo_{50} and Mo_{100}, respectively.	Mei et al., [84]
CuO (copper oxide)	SEM, XRD	Pongamia methyl ester biodiesel	Around 12.8 %, 9.8 % and 29 % of the reduction was obtained for smoke, NO_x, and CO emission, respectively.	Perumal & Ilangkumaran, [95]
Magnetite ferrofluid	Transesterification	Methyl esters of mustard oil	HC, CO, and NO_x emissions decreased by 5.8 %, 2.66 % and 7.74 %, respectively.	Yuvarajan & Ramanan, [142]
CeO_2, Al_2O_3	X-ray diffraction, SEM, XRD	Biodiesel	A 30 % reduction was observed in NO_x emissions whereas CO emissions were reduced by 60 %. Furthermore, a reduction of 44 % and 38 % was found for hydrocarbon and smoke emissions.	Prabu, [97]
Al_2O_3, TiO_2	Sol-gel method, SEM	Neat biodiesel	Approximately 44 %, 28 %, and 44 % reduction efficiencies were obtained for CO, HC, and smoke, respectively, whereas an increase in NO_x emissions of around 21 % was achieved.	Srinivasan et al., [118]
ZnO, TiO_2 and Al_2O_3	Sol-gel method, XRD, SEM and FT-IR	lemongrass biodiesel	Reductions of 17 %, 39 % and 5 %in CO emissions was found for B3050TiO_2, B3050ZnO and B3050Al_2O_3, respectively; reductions in HC of around 3.3 %, 32.5 % and 1 % was achieved for B3050TiO_2, B3050ZnO and B3050Al_2O_3, respectively.	Sunil Kumar et al., [119]
GNPs	TEM, SEM	Jatropha biodiesel-diesel	Reductions of 40 % in NO_x, 60 % for CO, and 50 % in unburned HC were achieved.	El-Seesy et al., [32]
GO	Ultrasonication, TEM, SEM	*Ailanthus altissima* biodiesel	CO and UHC emissions reduced in the range of 7–20 % and 15–28 %, respectively, whereas CO_2 and NO_x emissions increased by approximately 6–10 % and 5–8 %, respectively.	Hoseini et al., [53]
CNTs	Ultrasonication	Diesohol-B2fuels	Around 5.47 %, 31.72 %, and 6.96 % reductions were achieved in CO, unburned HC, and soot emissions whereas a 12.22 % increase was achieved in NO emissions.	Heydari-Maleney et al., [50]
ZnO, CeO_2	SEM, FTIR	Grapeseed oil methyl ester	HC, NO_x, and CO emissions were reduced by 13 %, 10.8 % and 4.6 %, respectively.	Praveena et al., [98]
Al_2O_3	Ultrasonication	Soybean methyl ester and rapeseed methyl ester blend biodiesel	HC emissions were reduced by 62 % and HC reduced by 12 %.	Kumar Nema & Singh, [70]
CeO_2 and ZnO	SCR system, FTIR	Grapeseed oil biodiesel	NO_x emissions reductions of 4.19 % and 13.13 % were achieved for CeO_2 and ZnO, respectively.	Vedagiri et al., [124]
TiO_2	XRD	Neat biodiesel	CO, HC, NO_x, and smoke emissions were reduced by 9.3, 5.8, 6.6, and 2.7 %, respectively	Pandian et al., [94]
Mn_2O_3, Co_3O_4	SCR system	Urea-SCR-equipped diesel engine	A considerable reduction was found in NO_x and CO emissions.	Mehregan & Moghiman, [83]
Alumina oxide	Sol-gel method	cashew nut shell biodiesel	Reductions of around 16.1 %, 10.23 %, 7.4 %, and 5.3 % were found in smoke, NO_x, HC, and CO emissions, respectively.	Radhakrishnan et al., [99]
Alumina oxide and multi-walled CNTs	SEM, XRD	Tamarind seed methyl ester	The contamination of CO reduced by 15–51 %, unburned HC emission decreased by 24–68 %, whereas NO_x emissions decreased by 7–9 %.	Dhana Raju et al., [28]
CNTs	Review	Waste cooking oil	HC emissions were reduced by 44.98 %.	Soudagar et al., [116]
CNTs and silver particles	Ultrasonication, transesterification, SEM, TEM	Neat diesel	The incorporation of silver nanoparticles reduced HC emissions by 28.56 %. A 25.17 % reduction was achieved in CO emissions whereas CO_2 and NO_x emissions were increased by 17.03 % and 25.32 %, respectively.	Ghanbari et al., [44]
CeO_2	Solvothermal method, SEM, TEM	Palm biodiesel	NO_x, CO, HC, and smoke emissions decreased significantly.	Ganesan et al., [42]
MgO	SEM. TEM and EDX	*Chlorella vulgaris* algae biodiesel	HC emissions reduced by 27.9 %.	Arunprasad et al., [12]
TiO_2, ZrO, diethyl ether	Stationary diesel-powered Kirloskar engine	Biodiesel-ethanol	HC and CO emissions increased whereas NO_x and smoke emissions reduced.	Venu & Madhavan, [129]
CNTs, CeO_2	Ultrasonication, European Stationary Cycle	Standard diesel	Reductions of 20 %, 22.6 %, 21 % and 5.5 % were obtained in CO, HC, and NO_x emissions and particulate numbers.	Zhang et al., [143]
Al_2O_3	SEM	Butanol-diesel	CO, HC, NOX, and PM emissions decreased by 42.71 %, 37.46 %, 12.37 % and 30.5 %, respectively.	Fayad & Dhahad [36]

(*continued on next page*)

Table 1 (*continued*)

Nanoparticle	Technique/technology/method	Biodiesel type	Emission types	References
Al_2O_3, $C_{18}H_{34}O_2$	Sol-gel method	Kappaphycus *alvarezil brown* algae biodiesel	Particulate matter emissions decreased by 14.8 %, 20.3 % and 25.6 % at 10, 20 and 50 ppm, respectively, whereas the NO_x emissions increased.	Karthikeyan et al. [66]
CeO_2 and $(Fe(C_5H_5)_2)$	NED Cycle and chassis dynamometer	Standard European diesel fuel	NO_x emissions increased by 2–4 % CO, HC, and PM emissions were reduced.	Dobrzyńska et al. [30]
Multiwall CNTs, SiO_2 andAl_2O_3	FESEM, SEM, EDX, UV–Vis spectrophotometer	Diesel	Silicon blends showed a remarkable contribution to reducing CO and CO_2 emissions.	Chen et al., [21]
CeO_2	Thermal barrier coating system	Citrus medica (citron) peel oil biodiesel	CO, NO_x, and CO_2 emissions decreased.	Shanmugam et al. [110]
CNTs	Ultrasonication, esterification	Calophyllum inophyllum	NOx emissions were reduced by 30.95 % with the addition of CNTs whereas CO_2 emissions were increased.	Deepak et al. [23]
CNTs	Transesterification, emulsification	soybean biodiesel	NO_x and smoke emissions were low whereas CO and HC emissions were high; CO_2 emissions improved by 12.1 %.	Vellaiyan [125]
Lanthanum oxide	Ultrasonication	Microalgae-biodiesel	CO_2 emissions were high.	Karthikeyan et al. [65]
CeO_2	k-type thermocouple, AVL DI-gas analyser, AVL 437C smoke meter,	Tyre pyrolysis oil	HC, smoke, and CO emissions were reduced by 3 %, 7.7 %, and 1.33 %, respectively.	Thangavelu S & Arthanarisamy (2020)
MgO	SEM, TEM, EDX, transesterification	*Chlorella vulgaris* algae biodiesel	HC, CO, and smoke emissions were reduced.	Arunprasad et al. [12]
CeO_2, ZrO_2 and TiO_2	Ultrasonication, sol–gel method, SEM, TEM and XRD	Garcinia gummi-gutta biodiesel	Smoke emissions were reduced by 16.25 %.	Janakiraman et al. [58]

exhibited comparable efficiency in converting CO to the reference, whereas they demonstrated enhanced activity in the oxidation of NO. By reorienting the laser beam's focal plane into the liquid layer just above the ablation target by 1 mm, both the mass yield and absolute productivity of the fraction consisting of nanoparticles smaller than 10 nm were substantially enhanced. To create industrial catalysts such as those required to treat exhaust fumes, a motivator based on laser synthesis resembles a fixed alternative to alloys made of chemical nanoparticle formations. The use of lasers to create catalysts appears to be promising. To demonstrate this potential, however, further analysis is necessary, commencing with a comprehensive examination of the catalyst's defect before proceeding to future research on aging. The cause of the upper conversion and resistance percentage may be connected to the reported greater flexural strains discovered in Pd nanoparticles produced by lasers.

The study by Afzal et al. [5] focused on creating chemiresistor-type gas sensors for identifying NO_2 gas at 600 °C. The sensing element used in these sensors was made of $ZnFe_2O_4$ nanoparticles created using an increased-energy ball milling process and annealing at different temperatures between 600 °C and 1,000 °C. The impact of a normalizing temperature on the shape, gas-sensing, and crystal structure capabilities of the $ZnFe_2O_4$ nanoparticles was investigated. Fig. 5 specifically displays 3D micrographs and surface profiles that reveal the sensitive element's $ZnFe_2O_4$ nanoparticles' surface morphology, roughness, and topography after annealing at 600 °C, 800 °C, and 1,000 °C. $ZnFe_2O_4$ nanoparticles, therefore, exhibit excellent potential for high-temperature exhaust gas detection.

Cylinder pressure

Nanoparticles can be added to biodiesel to accelerate early ignition of combustion and reduce ignition delay, which lowers the pressure in the cylinder and the rate of heat release under full load [97]. Air is pushed through the fuel injectors to introduce fuel into the combustion chamber and compression takes place. This is how internal combustion happens within the engine body leading to cylinder pressure. Dhahad et al. [27] investigated the outcomes of adding nanoscale Al_2O_3 and TiO_2 to diesel fuel to enhance fuel combustion quality and reduce

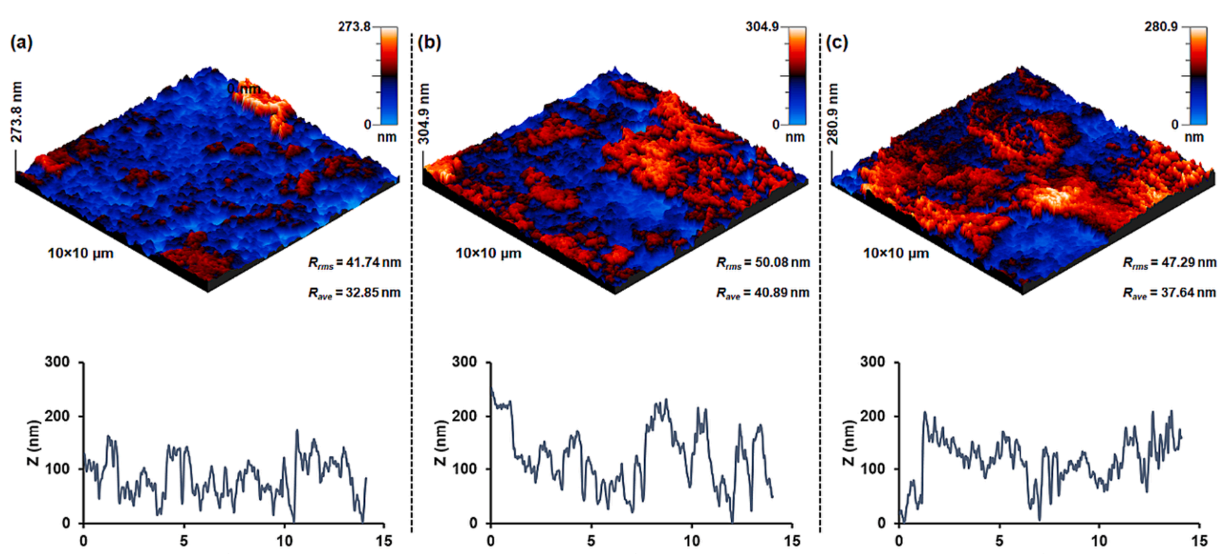

Fig. 5. 3D micrographs with surface profiles illustrating the roughness of surface morphology, and topography of sensitive element–$ZnFe_2O_4$ NPs processed at (a) 600 °C, (b) 800 °C, and (c) 1000 °C [5].

emissions. The nanoparticles were introduced to Iraqi diesel during the process in four large fractions of 25, 50, 100, and 150 ppm. During the experiments, the addition of the nanomaterials dramatically changed the combustion and increased the cylinder pressure. The braking thermal efficiency of conventional diesel improved by 18.9 %, while nano-Al_2O_3 and nano-TiO_2 blends improved by 24.25 % and 20.45 %, respectively. The cylinder's highest stress under total load conditions was 62 bar; following the inclusion of 25 ppm of nano-Al_2O_3 and nano-TiO_2, the pressure climbed to 63.2 and 60.4 bar, respectively. Finally, the ignition delay duration also decreased significantly by 5.47 % and 0.99 % for the nano-Al_2O_3 and nano-TiO_2 blends, respectively. The TiO_2 nanoparticles performed better than the Al_2O_3 nanoparticles across all loads in terms of the cylinder pressure just before combustion begins.

The properties of graphene's performance and emission characteristics in nano-biodiesel were tested in a study by Paramashivaiah et al. (2018) using an individual-cylinder, direct injection, automated, water-cooled, four-stroke diesel engine. Graphene nanoparticles were added in various quantities to blends of Simarouba diesel and biodiesel. To create graphene in these nano-biodiesels, graphene was dispersed in a Simarouba methyl ester (SME) blend with diesel. It has been noted that a 40 ppm graphene concentration produces the highest peak pressure. The in-cylinder combustion properties are improved by graphene nanoparticle dosing, which decreases the combustion duration and improves cylinder pressure. This dosing significantly decreased the combustion time and very slightly increased the highest cylinder pressure under every operational load. The use of SME20 containing 40 ppm graphene (SME2040) led to a reduction of CO emissions by 42.855, unburned hydrocarbon (HC) emissions by 9.14 %, and NO_x emissions by 12.71 %. Overall, all the outcomes show that Simarouba could well be employed in CI engines to enhance performance and control emissions without engine modification.

Neochloris oleoabundans biodiesel-diesel gasoline blends with CuO_2 nanoparticles are discussed by Kalaimurugan et al. [61]. CuO_2 NPs were utilized at concentrations of 50, 25, 75, and 100, ppm in combination with clean fuel and 20 % *Neochloris oleoabundans* algal oil (B20). The study was conducted in an air-cooled, one-cylinder engine without modifications coupled to an electronic dynamometer, with the injection pressure and timing left at the original, engine-appropriate standards. The standard B20 generated a lower cylinder pressure. This could potentially be caused by the introduction of fuels that enhance the ignition properties of CuO_2 nanoparticles and increase the surface area at a volume-to-volume ratio, resulting in quicker combustion and reduced peak pressure. In the findings, the CuO_2 nanoadditive fuel blends show a minor advancement in ignition compared to standard B20, with CuO_2 nanoadditive fuels showing the highest cylinder pressure and a quicker start to burning in addition to shorter ignition delays.

A compression combustion engine running on a blend of biodiesel and diesel fuel with used cooking oil enriched with nanomaterials made of iron-doped CeO_2 was the focus of the research conducted by Hawi et al. [49]. The main goal of the study was to lessen toxic emissions, such as soot and NO_x, from engines run on diesel. Both cerium and CeO_2 containing 10 % and 20 % iron, respectively, were added as nanoparticles. Experiments were undertaken with reference diesel D100 and biodiesel-diesel blends of 70 % diesel by volume (B30) and 30 % cooking oil methyl ester waste (WCOME) at consistent engine speeds of 2,000 rpm and varied massive amounts starting from 0 to 12 nm. In comparison to D100, it was discovered that the B30 fuel blends with the nanoadditives generated a higher cylinder pressure, with the maximum pressure increasing by as much as 3.5 % as an outcome of the nanomaterials' improved combustion processes. Additionally, unburned hydrocarbon emissions showed no significant change, while NO_x emissions decreased by up to 15.7 %. For B30, CO emissions decreased by up to 24.6 %, and for B30 with nano-additives, they were reduced by up to 15.4 %.

Heat release rate (HRR)

The percentage of heat released is like that of power, which is produced using the energy released by the combustion. The maximum amount of steam is released in the process of the engine's complete combustion. Elkelawy et al. [33] discovered that due to the higher release of heat during the mixed combustion phase at high loads, exhaust gas recirculation (EGR) of up to 15 % produces increased performance. At the rated output power, the charge dilution slows down the reaction and reduces the heat release rate. Experimental analysis was carried out by Ahmed I El-Seesy et al. [32] to determine the ideal intensity of Al_2O_3 NPs in a Jojoba biodiesel-diesel gasoline mix (JB20D) to achieve best-in-class exhaust emissions and engine presentation. This study's findings showed that, in contrast to pure diesel oil, JB20D slightly decreased engine performance while improving emission factors in every engine-tested operating situation. However, the best emission characteristics were attained at a concentration of 20 mg/l, with notable reductions of 80 % for CO emissions, 70 % for NO_x emissions, 35 % for smoke emission opacity, and 60 % for UHC (unburnt hydrocarbons) emissions. The density of Al_2O_3 in JB20D blends significantly helped in enhancing engine performance.

Kolekar et al. [69] introduced the combustion time coefficient (CTC), a novel metric established to quantify the timing of combustion and patterns of heat release to assess how combustion affects efficiency parameters and to analyse the influence of combustion [69]. CTC is utilized in conjunction with a steam discharge rate the HRR-balanced coefficient (HBC), a coefficient associated with the HRR. The experimental investigation of reactivity-controlled compression ignition (RCCI) methods for biogas diesel dual-fuel engines used ignition indicators. In RCCI combustion, there are two steps to the heat release process. Low-temperature heat release (LTHR) is the term used to describe the first step, and high-temperature heat release (HTHR) describes the second. The maximum value of the low heat release (LHR) falls when the high heat release (HHR) maximum value increases. A one-cylinder compression ignition (CI) engine with different compression ratios and dual fuel was used for the experiments. Biogas energy shares were measured for RCCI at 0 %, 40 %, 20 %, 60 %, and 80 % at the different compression ratios of 18, 17, 16, and 15, respectively. According to the findings, while NO_x emissions increased, BTE, CO, and HC emissions were positively impacted by an increase in CTC and a decrease in HBC. In order to lower emissions and improve engine performance, the optimal CTC and HBC ranges were determined for light and heavy loads, respectively.

The effects of CuO_2 nanostructures used in *Neochloris oleoabundans* algae biodiesel in CI engines were studied by Kalaimurugan et al. [61]. CuO_2 nanoparticles were added to each mixture of B20 in concentrations of 50, 25, 75, and 100 ppm during a procedure that prepared the nano blends individually using B20 made from methyl ester from *Neochloris oleoabundans* algae. The engine combustion was also studied along with the calorific index, cloud point, viscosity, density, and discharge point. The authors used a Kirloskar four-stroke diesel engine and an electrical resistance dynamometer as the load. They recommended against using the engine as a test engine due to its ease of modification. The study showed that CuO_2 nanoparticles at a concentration of 100 ppm could be employed as fuel additives for biodiesel to enhance engine performance and ignition qualities as well as lower exhaust pollutants for diesel engines. The results demonstrated that using a biodiesel mix with CuO_2 nanoparticles in a diesel-fueled engine achieves better combustion than B20 fuel.

Ignition delay

Knowledge of the radiation absorption efficiency of fine particles is crucial for estimating the combustion delays of energetic ingredients containing inclusions of highly absorbing compounds. It is particularly important to understand this when metal nanomaterial explosives are heated using a laser. Ağbulut et al. [6] examined the effects of different metal-oxide-based nanoparticle blends on single-cylinder diesel engine energy consumption, performance, ignition, vibration, and noise factors. Various fuels were examined, including reference diesel (D100), WCOME (10 vol%), and B10 with different percentages of titanium oxide mass ($B10TiO_2$), 100 ppm of aluminium oxide ($B10Al_2O_3$), and separately silicon oxide ($B10SiO_2$) into the B10. During the experiments, many equations were used to calculate the system's overall thermal efficiency, level of uncertainty, and fuel consumption related to BTE, as well as crank angle, in-cylinder stress, and engine speed. The research revealed that the high oxygen concentration in the metal oxide nanoparticles improves combustion. According to the literature, long-term tests could be used in future studies to examine how different nanoparticles affect engine wear. However, the nanoparticle concentrations were not modified, although the authors advise this should be undertaken in the future to improve the understanding of the best type of nanoparticle for this context.

The burning of various particle loadings in semi-droplets of nanoemulsions consisting of Bakken crude and nanomaterials was documented in a study by Singh et al. [112] using CCD (charge-coupled device) and CMOS (complementary metal-oxide semiconductor) cameras. The post-processing of the images produced from studying the impact of carbon-based nanoparticles on crude oil droplets produced data on the total combustion time, and for the different crude suspensions, researchers calculated the flame stand-off ratio (FSR), burning rate, and ignition delay. Data were produced after post-processing the resulting photos on the total burning time, combustion duration, and burning rate, and for the various crude suspensions, the flame stand-off ratio (FSR). At the particle's highest combustion rate, improvements of 31.1 % and 39.5 % were achieved with loadings of 0.5 wt% acetylene black nanoparticles and 0.5 wt% MWCNTs, respectively. The findings also included particle amounts of 1.0 % w/w MWNT and 0.5 % w/w AB, and the highest average ignition delay increases of 14.5 % and 13.8 % were recorded due to lower vapor pressure. This study is anticipated to attract more attention to the utilization of MWNT and AB nanoparticles in splashes of oil to improve ISB efficiency.

Kim et al. [68] explored how to modify the combustion and ignition characteristics of nanoenergetic materials by introducing carbon black nanoparticles. Since the heat transfer capabilities of these nanoparticles are very good, the combustion delay duration of the examined energy materials was monotonically reduced as the CB NP application increased. The study used spoil explosion tests that showed that changing the CB NP content of the nEM matrix may be used to influence the diameter of the created crater. CB NPs cause a backlash in Al/CuO composite powders. The combustion delay time in nEMs constructed from Al/CuO NPs was found to decrease monotonically due to the CB NPs' improved thermal conductivity. Use of carbon black NP additives as a capacity control medium for nEM ignition components. This can have a major effect on the flow of steam and, by extension, on thermochemical reactions.

The effects of cobalt-chromium NPs in homogeneous charge compression ignition engines running on citronella oil were investigated by Senthur et al. [109]. Using clean diesel, CBD 5 % (5 % citronella + 95 % diesel), CBD 15 % (15 % citronella + 85 % diesel), and CBD 20 % (20 % citronella + 80 % diesel) are all biodiesels containing citronella, and various performance parameters of the HCCI engine, including fuel use particular to BSFC and BTE ignition pressure and HRR, and unburning, were examined. The heat conduction, ratio of ground area to volume, and the rate of heat transmission inside the oil layers were all improved by the inclusion of nanoparticles. The outcome revealed that the CBD 15 % fuel outperformed the other citronella biodiesel-blended fuels. Due to the limited combustion postponement and increased the fuel's cetane rating, the brake thermal efficiency and HRR rose by 5.49 % and 6.8 %, correspondingly, when using CBD 15 % + C30 fuel. Based on the overall findings of the experiments, the CBD 15 % + C30 test fuel produced superior BSFC and BTE efficiency and efficiently decreased NO_x, CO, UBHC and smoke emissions. It would be a suitable substitute fuel for HCCI engines under all extreme circumstances. Table 2 summarizes the impact of various nanoparticles on internal combustion engine performance.

Summary and analysis of findings on nanoparticles' effect on engine combustion

The addition of nanoparticles to diesel fuel demonstrates improvements in physical qualities like cetane number, contributing to enhanced combustion efficiency. Studies with different types of nanoparticles, such as aluminum oxide (Al_2O_3) and zinc oxide (Ce-ZnO), highlight their positive effects on engine parameters like brake thermal efficiency and heat release rate. The examination of exhaust gas temperature reveals the complex interplay between nanoparticles, biodiesel blends, and exhaust gas recirculation (EGR), showing potential synergies for performance enhancement and emissions reduction. Furthermore, investigations into cylinder pressure, ignition delay, and heat release rate shed light on the intricate relationships between nanoparticle dosages, fuel blends, and combustion characteristics. The studies also consider the environmental implications, emphasizing the importance of responsible research for minimizing toxicity and pollution. While challenges like potential nanoparticle residues and variations in engine designs are acknowledged, the comprehensive analysis and synthesis of findings contribute to a deeper understanding of the intricate dynamics involved in nanoparticle-fueled biodiesel combustion.

Conclusions and further research

A major step forward in improving combustion characteristics, lowering emissions, and increasing fuel efficiency has been the incorporation of nanoparticle-based fuel additives into biodiesel combustion. To improve biodiesel's combustion dynamics and fuel characteristics, this innovation incorporates nanoparticles that have been rigorously developed. Catalysts or combustion enhancers, the nanoparticles allow for more thorough and efficient combustion of fuel. The chemical and physical attributes of biodiesel can be enhanced using certain additives, leading to enhanced engine performance, lower emissions, and enhanced combustion characteristics. This study differs from prior research by employing a comprehensive approach, concurrently investigating the effects of fuel additives containing nanoparticles on biodiesel properties, engine performance, emissions, and combustion characteristics.

By incorporating nanoparticles, biodiesel gains enhanced viscosity, surface tension, and thermal stability. Biodiesel viscosity can be lowered and its thermal stability increased by adding alumina nanoparticles, for instance; these two properties have been associated with a decrease in engine fouling and an increase in engine performance. Also, by enhancing fuel combustion efficiency and decreasing pollutants, nanoparticle additions could improve engine performance. Fuel atomization and combustion may be enhanced using nanoparticles because of their larger surface area. This can lead to a cleaner, more efficient combustion process, lowering the emission of harmful substances like particulate matter and NO_x from the engine. When copper oxide nanoparticles are added to biodiesel, for instance, NO_x emissions are lowered and fuel economy is increased. Combustion properties like ignition delay and combustion duration can be enhanced by adding nanoparticles. Fuels that have had their reactivity improved by these additions often have a shorter ignition delay and burn faster. Especially in low-temperature combustion environments, this may increase engine performance and reduce emissions. Iron oxide nanoparticles, for instance, have been added to biodiesel to decrease ignition latency and increase combustion efficiency. NPs' effectiveness as fuel additives can vary widely depending on their size and concentration.

Prospects and recommendations for future development:

Table 2
Effects of different nanoparticles on engine combustion.

Nanomaterial	Study	Method	Outcomes	Remarks
TiO_2	Venu et al. [131]	Exhaust gas recirculation (EGR)	Due to the reduced cylinder charge, increasing the intake airflow resulted in a 42 °C increase in the exhaust gas temperature, albeit at the expense of 7.2 % greater fuel consumption and a small increase in NO_x emissions.	Increased emissions result in pollution.
HC, NO_x, and CO	Guan et al. [46]	The combination of belated internal exhaust gas recirculation (iEGR) and intake valve closure (LIVC)	With the least negative impact on fuel consumption, exhaust gas from an internal combustion engine was enhanced by raising its temperature by 62 °C and reducing emissions from the engine. Exhaust gas temperature was not increased by the reduced fuel injection force or external EGR.	Inefficient EGR in raising the temperature of exhaust gases.
Pd	Dittrich et al. [29]	Using multiple laser beam planes, we may produce nanoparticles with a catalytically significant size area of 10 nm at a rate of > 1 g/h.	Nanoparticles less than 10 nm in size were created by a laser beam which can be used to make industrial catalysts, such as those needed to cure exhaust emissions. When numerous planes of the laser beam were moved inside the moisture layer immediately above (1 mm) the target, the production of nanoparticles was significantly increased.	Further analytical research on aging and a more comprehensive examination of the catalyst defect prior to and after future analytical investigations are required to validate this prediction.
$ZnFe_2O_4$	Afzal et al. [5]	A ball milling procedure with increased energy followed by various melting temperatures between 600 °C and 1,000 °C	NO_2 gas identification using chemiresistor-type gas sensors at 600 °C. Scanning electron microscope photographs of $ZnFe_2O_4$ nanoparticles, 3D micrographs, and surface profiles show the surface morphology, roughness, and topography of the sensitive element.	Exhibits excellent potential for high-temperature exhaust gas detection.
Al_2O_3, TiO_2	Dhahad et al., [27]	Four large fractions measured at 25, 50, 100, and 150 ppm	For the first time, nano-Al_2O_3 and nano-TiO_2 were introduced to a diesel engine to boost its thermal efficiency during braking and fuel efficiency. The addition of the nanomaterials Al_2O_3 and TiO_2 also significantly reduced the ignition delay duration by 5.47 % and 0.99 %, respectively.	In terms of the cylinder pressure shortly before combustion starts, TiO_2 nanoparticles outperformed Al_2O_3 nanoparticles.
Graphene	Paramashivaiah et al. (2018)	A single-cylinder, direct-injection, automated, water-cooled, four-stroke diesel engine was used to test nanobiodiesel; graphene was dispersed in a Simarouba methyl ester (SME) blend with diesel	The SME2040 variant, which contains 40 ppm graphene, increased BTE by 9.14 %, decreased unburned HC by 15.38 %, lowered CO emissions by 12.71 %, and cut NO_x emissions by 42.855 ppm.	Simarouba could be used in CI engines without engine modification to improve performance and emissions.
CeO_2	Kalaimurugan et al., [61]	An air-cooled, single-cylinder engine with an electronic dynamometer with injection pressure and timing kept at their original, engine-appropriate levels	Showed a modest improvement in ignition over B20, with CeO_2 nanoadditive fuels having the highest cylinder pressure, quickest start to burning, and shortest ignition delays.	Early combustion and reduced peak pressure are both results of the introduced fuels.
iron-doped CeO_2	Hawi et al., [49]	Experiments were conducted using reference diesel (D100) and biodiesel-diesel blends consisting of 30 % cooking oil methyl ester waste (WCOME) and 70 % cooking oil by volume (B30) at constant engine speeds of 2,000 rpm.	As a result of the B30 fuel blend's enhanced combustion processes and the higher cylinder pressure of those fuels compared to D100, their maximum pressure increased by as much as 3.5 %.	Fuel extension did not noticeably emphasize HC emissions, and the nanoadditives were shown to reduce CO emissions by up to 24.6 % for B30 and 15.4 % for B30 compared to D100.
Al_2O_3	Ahmed I El-Seesy et al. [32]	Experimental study; recirculation of exhaust gases (EGR).	In every engine-tested operating condition, JB20D slightly reduced engine performance compared to pure diesel oil while increasing the emission parameters. Al_2O_3's density in JB20D blends greatly contributed to improving engine performance.	Despite the best mechanical performance and engine ignition parameters being reached at a dosage of 40 mg/l, the highest rates of pressure increase (dp/dmax) and gross heat discharge (dQg/dmax) were 4.5 %, and 4 %, respectively.
CO, NO_x, HC	Kolekar et al. [69]	Combustion time coefficient (CTC)	Although NO_x emissions increased, the observed increase in CTC and decrease in HBC have a favourable impact on BTE, CO, and HC emissions.	CTC and HBC concentrations for lower- and higher-load conditions are increased, emissions are reduced, and engine performance is improved.
NiO	Srinidhi et al. (2018)	Nickel oxide nanoparticles were added to the NBE25 blend in concentrations of 25, 75, 50, and 100 ppm.	In comparison to 23°bTDC, the average reduction in fuel consumption for the brakes was 6.91 %, 7.13 %, 5.29 %, and 7.86 %. The use of NiO particles in the primary fuel, which greatly reduced the emissions of HC and CO, was another advantage of this study. Emissions of CO_2 were considerably reduced.	Recent advancements in the presence of nanoparticles and the timing of fuel infusion have improved engine performance and reduced emissions.

(continued on next page)

Table 2 (*continued*)

Nanomaterial	Study	Method	Outcomes	Remarks
CuO_2	Kalaimurugan et al. [61]	Employing B20, an algal methyl ester produced from *Neochloris oleoabundans*, to prepare the nano mixes one at a time; engine combustion was also studied.	Employing a biodiesel mixture containing CuO2 nanoparticles in a diesel-fueled engine leads to better combustion than B20 fuel.	When utilized in diesel engines, CuO2 nanoparticles at a concentration of 100 ppm could be added to biodiesel to improve its performance and ignition characteristics while also reducing the amount of exhaust pollutants.
$B10SiO_2$, $B10TiO_2$, $B10Al_2O_3$	Ağbulut et al. [6]	A variety of equations were used to calculate the system's total thermal efficiency, degree of uncertainty, fuel consumption related to the BTE, crank angle, in-cylinder stress, and engine speed.	The increased oxygen content of the metal oxide nanoparticles enhances combustion.	Although it is suggested that they do so in the future to improve observation of the ideal type of nanoparticle, the scientists did not change the concentrations of the nanoparticles.
Bakken crude	Singh et al. [112]	The flame stand-off ratio (FSR), burning rate, and ignition delay for the various crude suspensions were estimated after analysis of the effect of carbon-based nanoparticles on crude oil droplets to obtain data on the overall combustion time.	The maximum particle loadings of 0.5 wt% acetylene black nanoparticles and 0.5 wt% MWCNTs improved combustion rates by 31.1 % and 39.5 %, respectively. The biggest average ignition delay increases of 14.5 % and 13.8 % were observed, along with particle quantities of 1.0 % w/w MWNT and 0.5 % w/w AB.	This work is anticipated to attract more attention to the utilization of MWNT and AB nanoparticles in splashes of oil to improve ISB efficiency.
CB NP-based additives	Kim et al. [68]	Soil explosion tests were used as a medium for regulating ignition and explosion.	The nEMs constructed from Al/CuO NPs saw a monotonic decrease in the combustion delay time.	The steam transport and thermochemical reactions between nEM components can be significantly impacted using CB NP-based additives as a capacity control medium for nEM component ignition.
Cobalt-chromium	Senthur et al. [109]	Nanoparticles were introduced into homogenous charge compression ignition engines that ran on citronella oil.	The test fuel generated from CBD 15 % + C30 showed excellent BSFC and BTE efficiency and effectively reduced smoke, NO_x, CO, and UBHC emissions. It would be an acceptable replacement for the HCCI fuel engine in all extreme cases.	When using CBD 15 % + C30 gasoline, brake thermal efficiency and HRR increased by 5.49 % and 6.8 %, respectively, because of limited combustion postponement and enhanced cetane rating of the fuel.

i) To maximize performance gains while avoiding potential side effects, future studies should determine the optimum size and concentration of nanoparticles.
ii) Nanoparticles have been found to enhance short-term engine performance, but their long-term implications on engine longevity are little understood. The long-term impacts of nanoparticles on engine wear and tear, including their impact on engine components like fuel injectors and pumps, should be investigated in future studies.
iii) Many nanoparticles have been researched as potential fuel additives, but many more are yet to be explored. Evaluation of nanoparticle performance, including synergistic effects when mixed with other additives, should be a primary focus of future research.
iv) Researchers could investigate the influence of various nanoparticle compositions, sizes, and shapes on the process of biodiesel combustion. Optimizing these factors has the potential to enhance combustion efficiency and minimize emissions.
v) It is important to evaluate the economic viability of integrating additives based on nanoparticles into the production of biodiesel and subsequent engine utilization. When considering the viability of such technologies, cost-effectiveness is a crucial determinant.
vi) Undertaking a thorough lifecycle analysis would enable an assessment of the environmental effects associated with fuel additives based on nanoparticles, encompassing their manufacturing, utilization, and eventual disposal.
vii) The regulatory considerations of nanoadditives should be addressed in future research. Emission requirements and safety policies must be evaluated thoroughly.
viii) It is recommended to investigate the potential for integrating nanoadditives with alternative renewable energy sources, including advanced biofuels or hydrogen, in order to advance the development of energy systems that are both sustainable and efficient.

Funding

Open Access funding provided by the Qatar National Library.

CRediT authorship contribution statement

M. Mofijur: Conceptualization, Writing – original draft. **Shams Forruque Ahmed:** Methodology, Writing – original draft, Supervision. **Bushra Ahmed:** Formal analysis, Writing – original draft. **Tabassum Mehnaz:** Software, Writing – original draft. **Fatema Mehejabin:** Writing – original draft. **Sristi Shome:** Writing – original draft. **Fares Almomani:** Methodology, Writing – review & editing. **Ashfaque Ahmed Chowdhury:** Formal Analysis, Writing – review & editing. **M.A. Kalam:** Resources, Writing – review & editing. **Irfan Anjum Badruddin:** Supervision, Writing – review & editing. **Sarfaraz Kamangar:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgment

The authors extend their appreciation to the Deanship of Scientific Research at King Khalid University for funding this work through the large group Research Project under grant number RGP.2 /303/44.

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ARTICLES FOR FACULTY MEMBERS

COMPARATIVE ANALYSIS OF WASTE COOKING OIL BIODIESEL MIXED WITH NANOPARTICLE ADDITIVES ON PHYSICOCHEMICAL PROPERTIES AND DIESEL ENGINE PERFORMANCE

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Arabian Journal for Science and Engineering   **(2024) Pages 1-16**   **https://doi.org/10.1007/s13369-024-09643-w**   **(Database: Springer Nature)**

Arabian Journal for Science and Engineering
https://doi.org/10.1007/s13369-024-09643-w

RESEARCH ARTICLE-MECHANICAL ENGINEERING

Impact of Nano-TiO_2 Combination with Biodiesel on Diesel Engine Performance and Emissions Under Fuel Magnetism Conditioning

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Received: 28 May 2024 / Accepted: 26 September 2024

Abstract

Problems of atomization, spray, and lower output power are due to the biodiesel's higher viscosity. All of these aim to encourage fuel magnetism and nanoparticles addition to reduce fuel consumption. Waste cooking oil was converted to methyl ester by transesterification. To make methyl ester blend, diesel and biodiesel were mixed at volume ratio of 20%. TiO_2 nanoparticles were added to biodiesel blend B20 at doses of 25 and 50 mg/L. TEM and XRD were used to characterize the nanomaterials. A magnetic coil was placed before the fuel injector to apply a magnetic field on the line of fuel. South pole of the magnetic field is located near to the fuel line, whereas the north pole is located further away. To examine the impact of these nanomaterials with fuel magnetism on engine performance and emissions using WCO biodiesel mixture, an experimental test rig was built connected to diesel engine. During testing, diesel engine operates at 1500 rpm with load variation. The average increases in BTE were 1, 1.5, 3.5, 5.5, and 6.5% but the decreases in BSFC were 1.2, 2, 4, 5, and 6% for B20 + magnet, B20 + 25 TiO_2, B20 + 25 TiO_2 + magnet, B20 + 50 TiO_2, and B20 + 50 TiO_2 + magnet, respectively, at engine load range. The average drops in CO, NO_x, and HC concentrations were 16, 22, and 33%, respectively, at load range for B20 + 50 TiO_2 + magnet. To improve engine performance and reduce emissions, biodiesel blend B20 from waste cooking oil with nanoTiO_2 concentration of 50 ppm under magnetic field effect was recommended as a substitute fuel in diesel engine.

Keywords Biodiesel · NanoTiO_2 · Electromagnetic coil · Performance · Emissions

Abbreviations

BSFC	Brake specific fuel consumption, kg/kW hr
BTE	Brake thermal efficiency, %
B20	Blending biodiesel of 20% and diesel oil by 80% by volume
B100	Pure waste cooking biodiesel
B20 + magnet	Biodiesel blend with magnet
B20 + 25 TiO_2	Blending of 25 ppm TiO_2 with biodiesel blend
B20 + 25 TiO_2 + magnet	Mixing of 25 ppm TiO_2 with B20 using magnet
B20 + 25 TiO_2	Mixing of 25 ppm TiO_2 with biodiesel blend
B20 + 25 TiO_2 + magnet	Blending of 50 ppm TiO_2 with B20 using magnet
CO	Carbon mono-oxide emission, %
D100	Diesel oil
EGT	Exhaust gas temperature, °C
HC	Unburned hydrocarbons, ppm
NO_x	Nitrogen oxides emissions, ppm
TiO_2	Nano titanium oxide
WCO	Waste cooking oil

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1 Introduction

It is possible to replace fossil diesel with biodiesel. Nonetheless, the worldwide food scarcity is becoming a growing issue due to the biodiesel growth and might result in a food

Published online: 18 October 2024

catastrophe. A lot of attention is presently being paid to alternative non-food feedstocks, such as used cooking oils, in order to minimize utilizing food resources for fuel [1]. Transesterification was used to turn used cooking oil into biodiesel. Blends of biodiesel made from used cooking oil have poorer thermal efficiency than diesel oil. Blends of biodiesel have lower CO and HC concentrations than regular diesel. Diesel fuel had lower nitrogen oxides emissions than methyl ester blends [2]. Four mass fractions of nano titanium oxide nanoparticles were blended with Iraqi diesel as 25, 50, 100, and 150 ppm. Thermal efficiency of diesel was enhanced from 18.9 to 24.25% with the introduction of nano TiO_2 [3]. Addition of TiO_2 boosted the engine power and torque by 9.74 and 10.20%, respectively, but the specific fuel consumption was declined by 28.3% [4]. To improve the stability of blends, the ultrasonication procedure is used to stir the nanoparticles. Nanoparticle addition does not appear to have a significant impact on density, kinematic viscosity, flash point, or cetane number. At 21% absorption rate after 240 hrs of sedimentation, the nanoparticles of TiO_2 demonstrated greater stability. BSFC of diesel engine using the nanoparticles TiO_2 is 22% lower than other mixtures [5].

Using a mechanical agitator, homogeneous fuels (DWT1, DWT2, and DWT3) were created by mixing TiO_2 at concentrations of 30, 60, and 90 ppm with an emulsion fuel made of 10% water, 89.8% diesel, and 0.2% surfactant. BTE of DWT3 and DWT2 fuel rose by 5.65% and 2.76%, respectively, as related to diesel and DWS fuels. With using DWT3 fuel compared with diesel fuel, carbon monoxide, unburned hydrocarbon, and smoke emission were reduced by 30%, 28.68%, and 32.98%, respectively. Nevertheless, as compared to diesel and DWS fuel, DWT3 fuel's nitrogen oxide (NOx) emission was increased from 16.26 to 39.68% [6, 7]. Biodiesel of 200 ppm nanotitanium oxide was found to be the ideal ratio for WFME biodiesel and diesel [8]. In order to improve the thermal efficiency while producing the less emissions, nanoparticles like TiO_2 were sonicated with the mixtures at a rate of 50 ppm. Blend B30TH was determined to have a maximum thermal efficiency of 29.5% [9, 10]. Using an ultrasonicator to agitate the particles and ensure the stability of the blends with titanium oxide nanoparticles at concentrations of 25, 50, 75, and 100 ppm, nanoparticles were blended with methyl ester-diesel mixtures in 15–20 min [11]. Acacia Concinna biodiesel and diesel were blended together to create the modified nanofluid (MNF) fuels, which were then combined with titanium dioxide nanoparticles in different proportions. TiO_2 doping rate of 150 mg/litre is the best combination at an engine load of 82.37%. With somewhat higher NOx emissions than diesel, BTE, BSFC, HC, and smoke emissions were all improved by 3.25, 18.42, 38, and 20%, respectively [12, 13].

Titanium dioxide reduced specific fuel consumption by 5.16% and enhanced thermal efficiency by 29.65% at a dose of 100 ppm added to hemp seed oil biodiesel. When nano titanium dioxide was added, hydrocarbon emissions were decreased by 12.07% at 50 ppm and CO concentration were reduced by 40.15% at 75 ppm. Nitrogen oxide emissions rose by an average of 27% as a result of nano titanium dioxide inclusion. Optimal engine load and titanium dioxide ratio were 2000 W and 75 ppm, respectively. The largest increases were 27.94%, 1081.51 g/kWh, 0.057%, 40.293 ppm, 257.3742 ppm, and 0.7064% for thermal efficiency, specific fuel consumption, CO, HC, NOx, and smoke concentrations [14]. Using the B20 blend, nano additive were added at 25 ppm dose and mixed for 30 min in a magnetic stirrer before being subjected to 10 min of ultrasonication. The most significant decreases in pollutants were generated by B20 with 25 ppm TiO_2 [15]. TiO_2 nanoparticles made by Anatase were mixed with diesel oil to show the engine emissions and performance. The numerical and forecasting findings closely matched the outcomes of the experiment [16]. EGT was increased when 30% palm biodiesel/70% diesel was blended with 25 ppm of TiO_2 nanoparticles, CO, HC emissions, and BSFC were declined [17]. Thermal efficiency was enhanced by 3.1% using B2040TiO_2 fuel. Compared to B20, inclusion of TiO_2 nanoparticles increased nitrogen oxides and reduced HC and CO emissions [18, 19]. BTE was increased by 12, 11, 06, 9.48, 4.87, and 0.48%, respectively, when B20But30TiO_2 (100 ppm), B20But30TiO_2 (75 ppm), B20But30TiO_2 (50 ppm), and B20But30 were compared to diesel oil at full load [20]. Engine BTE was boosted by the addition of TiO_2 nanomaterials of 150 ppm to pig fat biodiesel mixture B20. BSFC values for 50 and 100 ppm concentrations were lower, while the nitrogen oxide concentration for 200 ppm blend was lower than other mixtures. Carbon emissions have marginally were decreased when the concentration of nanoadditive was increased [21, 22].

The vital alternative technique to enhance the combustion parameters of IC engines is the magnetic fuel treatment. Physical fuel treatment is a low-cost and simple installation option. Depending on the operating circumstances and the coil design, the decrease in engine emissions was 50% or more and the reduction in fuel consumption was up to 15.5% [23]. Low magnetic intensity electromagnetic coil was powered by DC source of little or no power consumption [23]. Thermal efficiency was increased and specific fuel consumption was dropped as the magnetic field intensity rose. The fuel consumption decrease of 15% was achieved as the result of magnetic field's influence. At idle speed, there were up to 7, 30, and 40% less CO, NO, and CH_4 emissions [24]. With a field intensity of 9000 Gauss, there is a fuel decrease rate up to 1%. CO and HC percentages were reduced by 30% and 40%, respectively, while CO_2 percentage rose by up to 10%. Under the impact of the magnetic field, the infrared and ultraviolet light absorption spectrum revealed the change in physical and chemical characteristics of the fuel molecules structure. The fuel's surface tension was reduced due to the magnetic field effect [25]. The way that oxygen and hydrocarbon molecules interact changes as the result of fuel's magnetic properties. Magnetic fields with strengths of 1000, 2000, 3000, and 4000 gauss had all been applied to the tested fuel. The maximum specific fuel consumption decrease with 4000-gauss magnetized fuel was 2.3% [26].

Hydrocarbon fuel molecules were ionized, declustered for improved atomization, and mixed with oxygen to facilitate combustion, which the increases in fuel combustion efficiency by magnetic field application. Using a permanent magnet of 3000 Gauss field strength, the influence of CuO nanoadditives on engine emissions and performance was studied. By aligning and orienting hydrocarbon molecules for better fuel atomization, which leads to the improved fuel's characteristics and better engine emission. Treatment of CuO nanofuel with magnetic field resulted in 6% drop in BSFC and reductions of 19 and 13% for NO_x and CO_2 concentrations, respectively [27]. The particles of fuel were reduced in size by the use of permanent magnet of 7000 Gauss field strength, and it has been demonstrated that declumping the hydrocarbon fuel molecules improves the fuel's atomization. This ensures that the fuel vigorously reacts with oxygen to produce complete and more improved combustion. When compared to fuel without a magnetic conditioning, magnetic fuel conditioning produced the declines in HC, CO, NO_x, and CO_2 emissions of 18, 11, 10, and 10%, respectively. Diesel engine emissions were lowered, and combustion was enhanced due to the magnetic fuel treatment [28]. The magnet effect improved the fuel economy by the increase of thermal efficiency and the fuel consumption reduction [29].

Magnetic field application reduced the fuel consumption by 22%. For used cooking oil and diesel oils, the combustion efficiency rose by 12% and 8%, respectively. For diesel and used cooking oil, there were decreases in CO_2 of 28 and 31%, HC of 29 and 25%, and CO of 30 and 37% in the magnetic field, respectively. The fuel magnet was demonstrated to increase the nitrogen oxide emission by 40 and 48% and oxygen concentration by 21 and 12%, respectively, for diesel and used cooking oil [30]. Around 21.3% less carbon dioxide was released, while fuel usage was dropped by 4.89% using magnetic conditioner [31]. Permanent magnet field of 4000 Gauss was used along the volume percentages of 10 and 20% WCO methyl ester before the fuel injector. Thermal efficiencies of crude diesel and biodiesel mixtures B10 and B20 were increased by 2, 4, and 11%, respectively, by applying the magnetic field. Diesel oil and the biodiesel mixtures B10 and B20 both experienced reductions in CO emissions of 3, 3.5, and 4%, respectively, when exposed to a magnetic field. Diesel, B10, and B20 fuels showed reductions in HC emissions of 6, 11, and 8%, respectively. The impact of fuel magnet was demonstrated to reduce nitrogen oxides concentrations by 3, 1.5, and 2% for diesel and B10 and B20 blends, respectively [32]. By allowing increased access to oxygen molecules, HC molecules are able to participate more actively in combustion when the magnetic field is applied. With a stronger magnetic field, there is an increase in fuel economy and decreases in exhaust emissions. Maximum fuel efficiency improvement is 9.36%. CO_2 concentration was increased but CO and HC emissions were decreased by 12% and 72.84%, respectively [33]. The fuel savings from 7 to 11% are still less than diesel oil because WCO biodiesel has a higher viscosity than diesel oil and prevents clumping under magnetic field enough to break down the molecules and improve combustion. CO and NOx emissions were decreased by 13–53% and 7–21%, respectively [27, 34].

Hydrogen in fuel exists in two isomeric forms as ortho and para, which produce opposing nucleus spins. Hydrogen in its ortho state is more effective for burning than hydrogen in its para state. By applying a high magnetic field to the fuel line, the ortho state is created [35–37]. The performance of engines was enhanced by varying the permanent magnet strength. The hydrocarbon fuel's viscosity was reduced with the magnetism application. Declustering of the hydrocarbon fuel molecules improved the atomization, fuel–air mixing, thermal efficiency, and reduced the unburned fuel [38, 39]. Engines with improved fuel efficiency and lower fuel consumption achieve complete combustion and lower CO_2 emissions [40]. Fuel molecule is made up of many atoms; each of which has a nucleus and electrons orbiting around it. The molecules of fuel cannot align themselves and do not actively interact with oxygen molecules during combustion if there is no magnetic field effect. Molecules exert less force on one each another. The molecules move as a result of the magnetic field and have positive and negative electrical charges. During combustion, the fuel molecules were repositioned and interlocked with oxygen. Clusters of hydrocarbon molecules are found in nature. The greatest space is obtained for the molecules of oxygen to mix with the fuel molecules if the permanent magnetic device is powerful enough to dislodge the clusters [41]. B25 fuel was mixed of 50, 100, and 150 ppm doses of TiO_2 nanoparticles. The increase in nanoparticle concentration results in the greater improvement in engine performance. When compared to B25 fuel without nanoparticles, TiO_2 nanoparticles at 150 ppm enhance the brake thermal efficiency by 3.67% and decrease the brake specific fuel consumption by 3.21% on average. TiO_2 nanoparticles addition reduces CO emissions and smoke opacity by up to 31.89% and 24.56%, respectively. NO emission was increased for B25 to 30.58% but nanofuels emit less NO emission than diesel fuel [42]. Biodiesel's low volatility, high viscosity, and poor cold flow characteristics prevent it from being used in diesel engines at large mixing ratios or pure. One workable way to get rid of biodiesel's drawbacks is to combine it with high-volatility, lowviscosity biofuel. Biodiesel fuels containing acetate exhibit improved kinematic viscosity and cold filter plugging point temperature. Compared to diesel fuel, acetate-added biodiesel fuels had from 24.01 to 32.29% higher brake specific fuel consumption. In contrast to plain biodiesel, their advantageous combustion properties can boost engine thermal efficiency by 3.58% [43].

Several research investigations had been conducted to study and further clarify the impacts of adding nano-TiO_2 to methyl ester mixed fuels on diesel engine emissions and performance as can be seen from the review of the literature that was done above. It was revealed that no studies on the operation and emissions of diesel engines employing WCO biodiesel–diesel blends with titanium oxide nanoparticles and the fuel magnetism effect have been published. WCO disposal causes issues in the network of landfills and water sources. The research paper aims to recover energy from waste cooking oil and use it as a substitute fuel in CI engines. The goal of the work is to demonstrate how much magnetism and how much nanoparticle concentration can be used to increase engine efficiency and reduce exhaust emissions. Fuel magnetic conditioning increases the thermal efficiency and reduces the fuel consumption by promoting better fuel burning. Because of its large surface area, robust metal support contact, and chemical stability, titanium dioxide has demonstrated a great deal of promise as a heterogeneous catalyst. TiO_2 NP usage may also be advantageous. A number of variables, including surfactant, ultrasonication, particle size, concentration, and solution chemistry, affect on the stability of nanofluid. Small doses as 25 and 50 ppm are recommended to ensure homogenous dispersion and stability [44, 45]. The use of nanoadditions to improve the cold properties of biodiesel is encouraged by its drawbacks and incompatibility in cold climate. High viscosity of biodiesel about diesel oil leads to the atomization and vaporization problems in fuel. Titanium oxide nanoparticles introduction enhances the atomization, vaporization, and thermal properties. Nanoadditives enhance heat transfer, catalytic reactivity, and surface/area volume ration about base fuel. The influence of biodiesel with nanoparticles under the magnetic effect is discussed in the study in order to boost the engine performance and decrease exhaust pollutants. Fuel magnetization improves atomization through declustering and ionization under, combining oxygen with fuel molecules, and boosted combustion efficiency. Therefore, the current experimental investigation investigates the effects of TiO_2 nanoparticle addition with magnetic field on the performance and emission characteristics of diesel engines using a combination of biodiesel and diesel. WCO biodiesel was combined of 20% with diesel oil. Biodiesel mixture B20 was combined with titanium dioxide nanoparticles at 25 and 50 ppm.

Table 3 Properties of titanium dioxide nanoparticles

Properties	Value
Average particle size	24.8 nm
Melting point	1843 °C
Appearance	White powder
Density	3900 kg/m^3
Boiling point	2972 °C

2 Materials and Methods

2.1 Biodiesel Production

High viscosity of used cooking oil prevents from direct utilization in diesel engines. Waste cooking oil is a mixture of used oils as palm, castor, and corn. WCO was gathered from hotels and restaurants. In order to remove the deposits and humidity, the oil was heated to 100 °C. After that, the oil was added to a flask that was held steady by a thermometer, condenser, and magnetic stirrer. Potassium hydroxide (KOH) of 1.5% by weight was dissolved in methanol molar ratio of 1:9 producing methoxide. In transesterification procedure, the methoxide and oil blend was rapidly stirred for 90 min at a temperature of 65 °C to form methyl ester and glycerin. The produced solution was kept in the separating funnel for a whole day in order to separate the glycerin from the ester. Warm water was used to get rid of contaminants, catalyst, and unreacted methanol. The produced biodiesel was dried using rotary evaporator to get rid of the water. Biodiesel blend of 20% was used as its properties are near to diesel oil. B20 is created by mixing methyl ester of 20% by volume with diesel oil. Table 1 compares the properties of the biodiesel blends to those of diesel oil. Biodiesel agrees with ASTM 6751 and EN 14214 standards as shown in Table 2 [44].

2.2 Blending Biodiesel with Nanomaterial

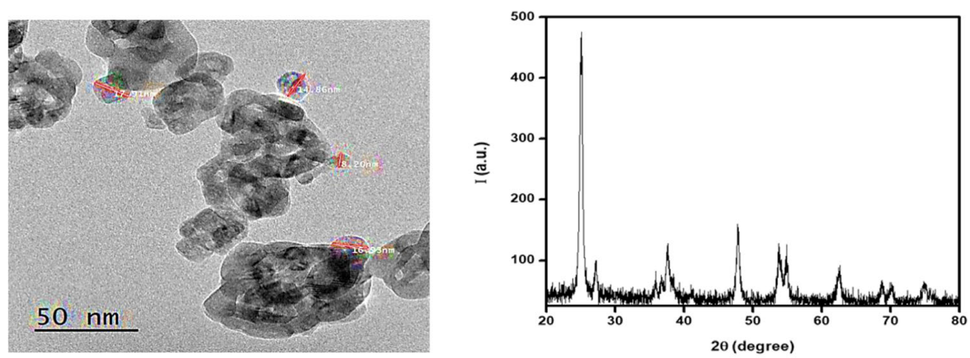
Titanium oxide nanoparticles (TiO_2) were dispersed in 20% WCO biodiesel blend (B20) under homogenous dispersion and stability conditions. To obtain fuel blends of nanomaterials and disperse the nanoparticle clusters, a digital homogenizer was employed. To increase the stability of the fuel blend, nanoparticle blends were held in an ultrasonicator for 30 min at a frequency of 24 kHz with a cooling bath. TiO_2 particles were purchased from SIGMA-ALDRICH Co., USA. Properties of nanoparticles are shown in Table 3. The sample is uniform in size. To capture TEM images, a transmission electronic microscope (TEM) MODEL JEOL-JEM-2100 is employed as in Fig. 1. The high-resolution image produced by the microscope allows one to clearly see the sample's uniform distribution. Nanoparticles of 25 and

Table 1 WCO biodiesel blends characteristics

Fuel properties	Unit	Biodiesel (B100)	Diesel oil (D100)	B20	B20 + 25 TiO_2	B20 + 50 TiO_2	Standard ASTM
Density at 15 °C	kg/m^3	878	830	849	852	855	D1298
Kinematic viscosity at 40 °C	mm^2/s	4.2	2.73	3.1	3.3	3.4	D445
Flash point	°C	148	58	79	–	–	D92
Centane number	–	52	49	51	–	–	D6751
Pour point	°C	− 7	−33	− 21	–	–	D2500
Lower heating value	MJ/kg	39.8	42.7	41.9	42	42.1	D240

Table 2 ASTM D6751 and EN 14242 standards of biodiesel [43]

Fuel properties	Biodiesel (B100)	Standard ASTM 6751	Standard EN 14242
Density at 15 °C, kg/m^3	878	870–900	860–900
Kinematic viscosity at 40 °C, mm^2/s	4.2	1.9–6	3.5–5
Flash point, °C	148	130–191	120 min
Centane number	52	47 min	51 min
Pour point, °C	− 7	−15–10	–
Lower heating value, MJ/kg	39.8	35 MJ/kg	–



(a) Images of TEM
(b) XRD of Titanium dioxide nano particles

Fig. 1 TEM and XRD images of nanoadditives: **a** images of TEM and **b** XRD of titanium dioxide nanoparticles

50 mg/L (25 and 50 ppm) were added to biodiesel blend as B20 + 25 TiO_2 and B20 + 50 TiO_2, respectively. Figure 1 shows the pattern of XRD analysis plot for TiO_2 nanoparticles, with the peak appearing at $2\Theta = 25$ as the nanomaterials begin to crystallize (Table 3).

The increased surface area exposes more of the material to the environment, which can significantly accelerate the catalytic reactivity and oxidation in chemical reactions of nanomaterials [46]. Improved reactivity and increased surface area in nanostructured materials have led to the development of better catalysts. The surface area of spherical shape nanoadditive is calculated as (3/r) where r is the radius of nanoadditive particle. Decrease of particle radius leads to the increase of surface area about base fuel [45, 47]. Introduction of nanoadditives as solid non-vaporizing particles into the cylinder leads to the enhancements of heat transfer and thermal properties within engine cylinder. Nanoadditives work in the combustion as a catalyst. It improves the surface area and catalytic reactivity of the reaction. It improves the reaction chemical kinetics and rate of reaction. All these lead to the improvements in vaporization, heat transfer, and thermal properties. Thermal conductivity and specific heat were improved about base fuel [10, 14, 15].

2.3 Magnetic Field Application

For optimal alignment and impact, a magnetic coil should be positioned before the injector on the input pipe or housing as shown in Fig. 2. The fuel was magnetized before it entered the engine cylinder using magnetic coil. To guarantee that magnetism occurs, an electric magnetic coil was used. The magnet that creates the magnetic field has its south pole close

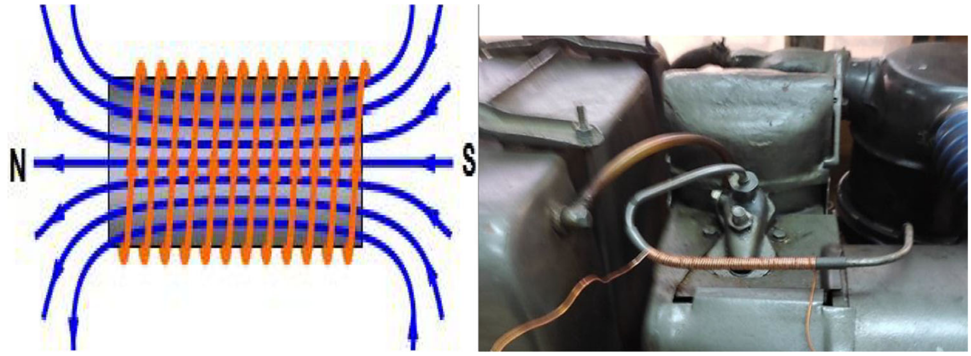


Fig. 2 Installation of magnetic coil

Table 4 Specifications of electromagnetic coil

Specifications	Value
Materials	copper
Coil input voltage	12 VDC
Number of wire turns (N)	75
Maximum current (A)	7
Actual current (A)	2.5
Type of current	DC
Length of coil (cm)	25
Position	Direct before fuel injector

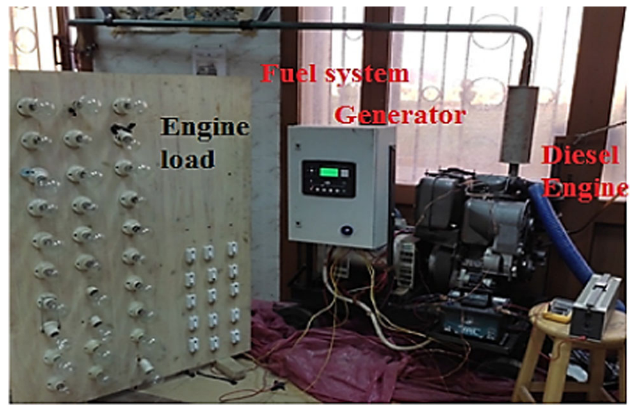


Fig. 3 Test rig photographic view

to the fuel line and its north pole farther away. As the magnetic field is applied, solenoid coils are frequently utilized. The electromagnetic coil specifications are shown in Table 4. Biodiesel blend with nanoadditives of 25 and 50 mg/litreL (25 and 50 ppm) and magnet was used as B20 + 25 TiO_2 + magnet and B20 + 50 TiO_2 + magnet, respectively.

$$\text{Magnetic flux density} = \mu_0\mu_r \ \text{NI/L} = 3 \ \text{MTesla}$$

2.4 Experimental Test Rig

Photographic view of the experimental rig is shown in Fig. 3. Figure 4 depicts the schematic layout of the experimental setup employed in this study, and Table 5 lists the test engine's parameters. This engine is a small utility engine that had been modified for research purposes. AC generator with a maximum output power of 10.5 kW (Model: Meccalte, U.K.) was connected to the tested engine. A sharp-edged orifice was adapted to the air box to monitor the intake air flow rate. The fuel flow rate is calculated as the time required consuming a fixed measured fuel volume of 25 cm^3. K type calibrated thermocouples are used to evaluate the temperatures of exhaust gases and intake air. German-made MRU DELTA 1600-V gas analyzer was used to measure the concentrations of HC, NOx, and CO. The tests were carried out with different loads of 0.9, 1.8, 2.7, 3.6, and 4.5 kW while the engine was operating at 1500 rpm. The engine was warmed up without load until it reached a constant exhaust temperature using only pure diesel fuel. After switching the fuel line that was being tested, the engine load was then managed. Readings were eventually recorded after it reached to the stable state. Each test was measured three times to check for repeatability errors. Specific operational aspects and procedures such as equipment selection, climatic conditions, and instrument calibration are the source of errors and uncertainties in the experiments. To measure the overall uncertainty of the experimental tests, error analysis was employed. Every test was run three times to guarantee the accuracy and consistency of the findings. The calibration process for all equipments was carried out before carrying out the investigation. The engine's BSFC, BTE, and T_{exh} performance parameters as well as CO, CO_2, O_2, HC, and NOx emissions were noted. Ambient and exhaust temperatures thermocouples have an uncertainty of ± 0.15, a temperature range of 0–1300 K, and an accuracy of ± 1 °C. The load has an uncertainty of ± 0.2, a precision of ± 10 W, and a range of 250–5000 W. The exhaust gas ranges include 0-NO (1–5000 ppm), HC (0–20000 ppm), CO (0–10%), and CO_2 (0–10%), and ± 12, ± 12, ± 0.06 and ± 0.05 for accuracy, ± 0.2, ± 0.2, ± 0.2 and ± 0.2 for uncertainty, respectively. Calculations showed that the experiment's overall uncertainty

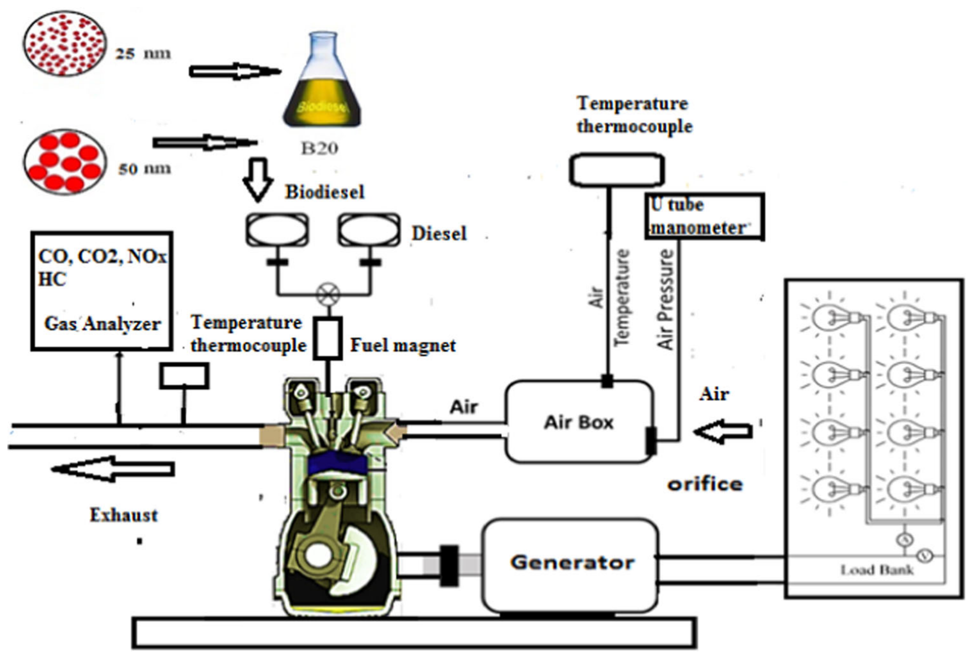


Fig. 4 Schematic diagram of test rig

Table 5 Engine specifications

Engine model	DEUTZ F1L511
Engine type	four stroke, air cooling,naturally aspirated
Cylinder number	1
Bore × Stroke	100 mm × 105 mm
Max power at designed speed (kW)	7.7
Compression ratio	17.5:1
Injection pressure, bar	175
Number of nozzle holes	1
Injection timing	24° BTDC

could only be 3.33%.

$$W_R = \left[\left(\frac{\partial R}{\partial x_1} w_1 \right)^2 + \left(\frac{\partial R}{\partial x_2} w_2 \right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n} w_n \right)^2 \right]^{1/2} \tag{1}$$

W_R is the test rig's total uncertainty. The parameters R and x denote the independent and dependent measurements, respectively.

3 Results and Discussions

3.1 Brake Specific Fuel Consumption (BSFC)

Figure 5 indicates how the BSFC for biodiesel mixture adapted with magnet and nanoparticles varies with output power. BSFC is inversely related to engine load for all fuels. Biodiesel blend showed the highest specific fuel consumption than crude diesel because the lower calorific value. Titanium oxide nanoparticles enhance the atomization process and combustion properties. Addition of nanoparticles decline becomes more dramatic with increasing nanoparticle concentrations. Because more oxygen is available from titanium oxide nanoparticles to complete chemical processes, there is a particular decrease in fuel consumption. The surface/volume ratio increases due to the catalytic activity brought on by the use of nanoparticles, which enhances the combustion properties and decreases fuel consumption. The inclusion of nanoparticles improved fuel attributes linked to diesel oil and decreased physical delay and fuel evaporation time. Nanoparticle oxide secondary atomization promotes the fuel burning at an efficient rate. Fuel efficiency is increased by ionizing, declustering for better atomization, and mixing hydrocarbon fuel molecules with oxygen to assist burning. During combustion, fuel molecules may align and engage in active interaction with oxygen molecules [24, 25]. The magnetic field causes the molecules to move, and they also have positive and negative electrical charges. The average decreases in BSFC for B20 + magnet, B20 + 25 TiO_2, B20 + 25 TiO_2 + magnet, B20 + 50 TiO_2, and B20 + 50 TiO_2 + magnet were 1.2, 2, 4, 5 and 6%, respectively, at load range.

3.2 Brake Thermal Efficiency (BTE)

Figure 6 displays the thermal efficiencies for biodiesel with nanomaterials and fuel magnetism. Because of lower calorific value, greater viscosity, and larger molecular weight,

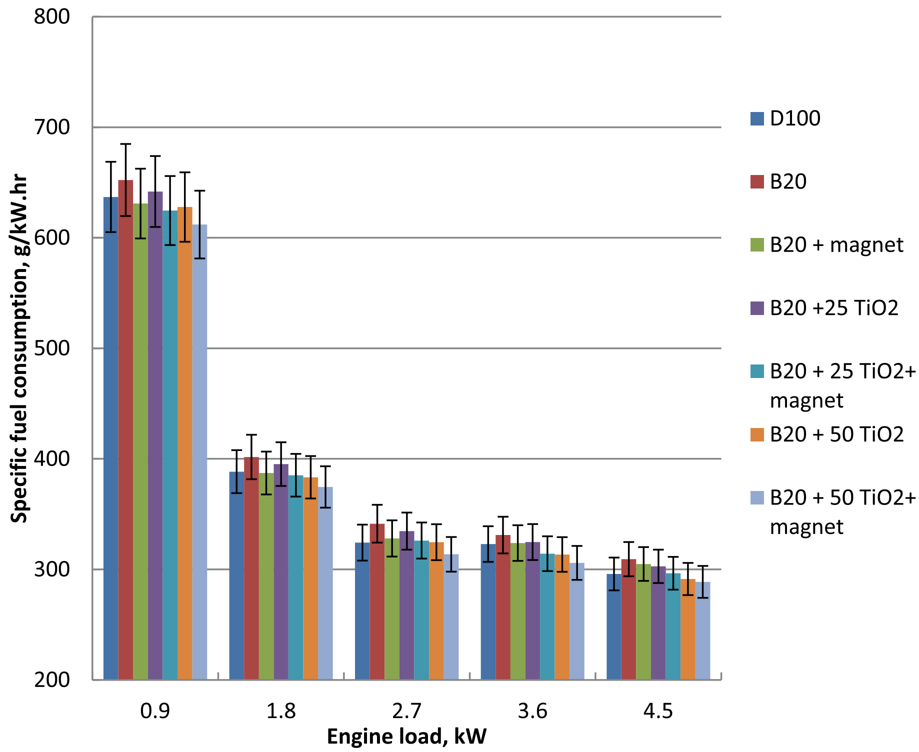


Fig. 5 Effect of tested fuels on specific fuel consumption

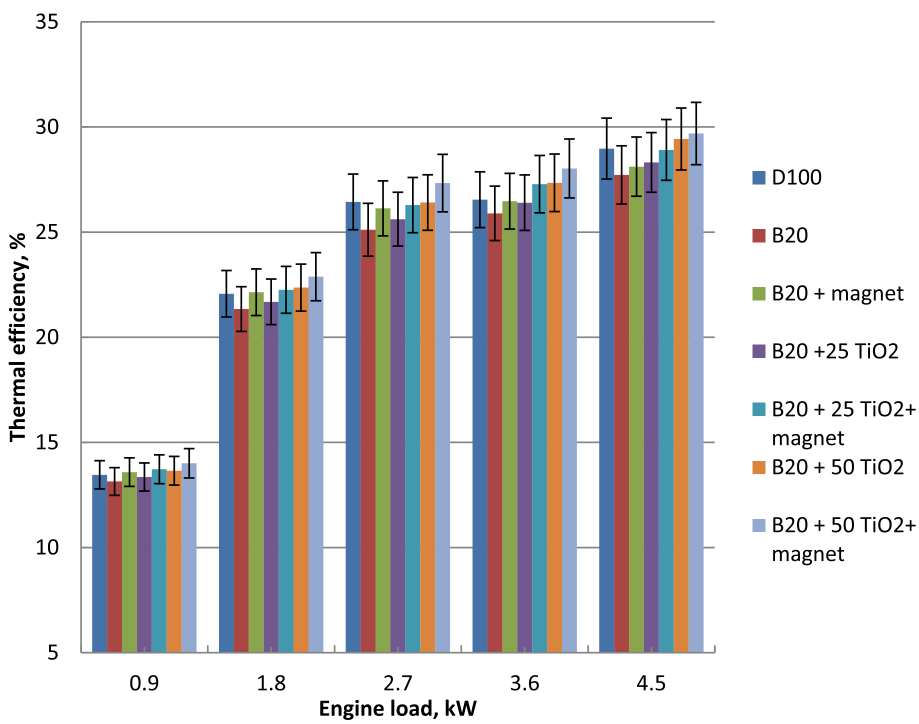


Fig. 6 Thermal efficiency of B20 with nanomaterials and magnetism

biodiesel blends had the lowest BTE values reported. BTE rises as engine load increases. The BTE rises when titanium oxide nanoparticles are added to biodiesel blends, and this increase is essentially consistent dependent of the nanoparticle concentration in the biodiesel blends. This rise may be ascribed to the quick evaporation, which led to the improvement in combustion efficiency. This can be explained by the surface to volume ratio improvement brought on by the catalytic activity of nanoparticles, which improves the reaction kinetics and increases the rate at which heat is emitted. The inclusion of nanoparticles encourages the spread of fuel droplets after injection. This results in efficient combustion and improved fuel air mixing. Under the nanomaterials influence, the deposits of carbon are oxidized and fuel consumption is decreased. The fuel molecules were repositioned during burning and interlocked with oxygen due to the fuel magnetism. The oxygen molecules have the space to combine with the fuel molecules. Ionization, declustering for improved atomization, and combining hydrocarbon fuel molecules with oxygen to improve the combustion efficiency. The magnetic effect does not affect on the temperature of fuel. By speeding up the atomization process of the spray and accelerating the pace at which the droplets disintegrate owing to the decrease in the fuel's surface tension and viscosity [23, 24]. The magnetic field aids in better mixture formation. When the links between hydrocarbon chains are broken by magnetization, the atomization or injection process produces finer droplets due to the reductions in density and surface tension [25–27]. Spray droplets with a large surface area per volume were created to interact with the oxidizer. The average increases in BTE for B20 + magnet, B20 + 25 TiO_2, B20 + 25 TiO_2 + magnet, B20 + 50 TiO_2, and B20 + 50 TiO_2 + magnet were 1, 1.5, 3.5, 5.5, and 6.5%, respectively, at load range.

3.3 Exhaust Gas Temperature (EGT)

In Fig. 7, the relationship between the exhaust gas temperature of methyl ester blend doped with nanomaterials under magnetic field and various engine loads is examined. The increase of engine load is associated with the fuel consumption increase. EGT is proportional to the engine load. EGT increases as the load increases. EGT is increased by adding nanoparticles to B20. The uniform dispersion is aided by the use of nanoparticles which improves the biodiesel's ignition delay and speeds up the burning process, which directly affects the engine's exhaust enthalpy. Homogenization of nanoparticles increased the cylinder temperature due to the reduction of ignition delay. In order to promote combustion, the particles should be split into smaller finer particles. The fuel is helped to be ionized by the magnet effect. Hydrocarbon molecules shift their orientation in the direction opposite to the magnetic field as they pass through the magnetic field. As a result, the molecules' intermolecular interaction lessens and their molecule structure changes. The magnetic field reduces the viscosity and surface tension of the fuel. The combustion and thermal efficiency were raised by magnetic field due to the improved fuel–air mixing and fuel atomization. The average declines in exhaust gas temperature for 20% biodiesel with magnet, 25 ppm, 25 ppm + magnet, 50 ppm, and 50 ppm + magnet were 3, 4.5, 5, 5.5, and 6%, respectively, at load range.

3.4 Carbon Monoxide (CO) Emission

Figure 8 shows how carbon monoxide emission for a biodiesel mixture with a nanoaddition and magnetism varies with engine load. The fuel–air mixture's strength has an effect on CO emissions. A higher combustion temperature with increased engine loads is the cause of the decrease in CO emissions. At low load and engine start, the fuel–air mixture is rich and there is an increase in fuel consumption. Increase of load to 75%, the fuel–air mixture changes to lean mixture and there is a decrease in fuel consumption. From 75% output power to full load, there is an increase in fuel consumption and richness of fuel–air mixture. Compared to diesel oil, biodiesel releases less carbon monoxide because it has been oxygenated. The impact of the biodiesel blend results in better homogeneity of fuel/air blending and combustion efficiency. By incorporating nanoparticles, the atomization and vaporization of methyl ester are enhanced, resulting in leaner air–fuel mixing and larger CO emission decrease. Chemical reactivity and ignition properties improve as nanoparticle surface contact area increase. Under the influence of nanoparticles inclusion, the decline in fuel homogeneity causes increased breakdown during fuel injection. The oxygen concentration of nanotitanium contributes to the improved combustion and lower CO emission levels. Combustion was more effective when the fuel lines were exposed to a magnetic field. Intermolecular tensions were decreased, fuel molecules realigned, making it simpler for them to the oxygen interlock and resulting in the combustion improvement. Fuel molecules clusters may be shown. The viscosity is reduced, the molecules are dispersed, the clusters are broken up by magnetism, and there is more space due to the oxygen presence. Under the magnetic effect, produced fuel–air better blending and enhanced fuel atomization decrease the CO concentration. B20 + magnet, B20 + 25 TiO_2, B20 + 25 TiO_2 + magnet, B20 + 50 TiO_2, and B20 + 50 TiO_2 + magnet had the average drops in CO emissions as 5, 7, 10, 12, and 15%, respectively, at load range.

3.5 Oxides of Nitrogen (NOx)

The impact of fuel magnetism and nanoparticles on NOx emissions is shown in Fig. 9. Methyl ester emits more

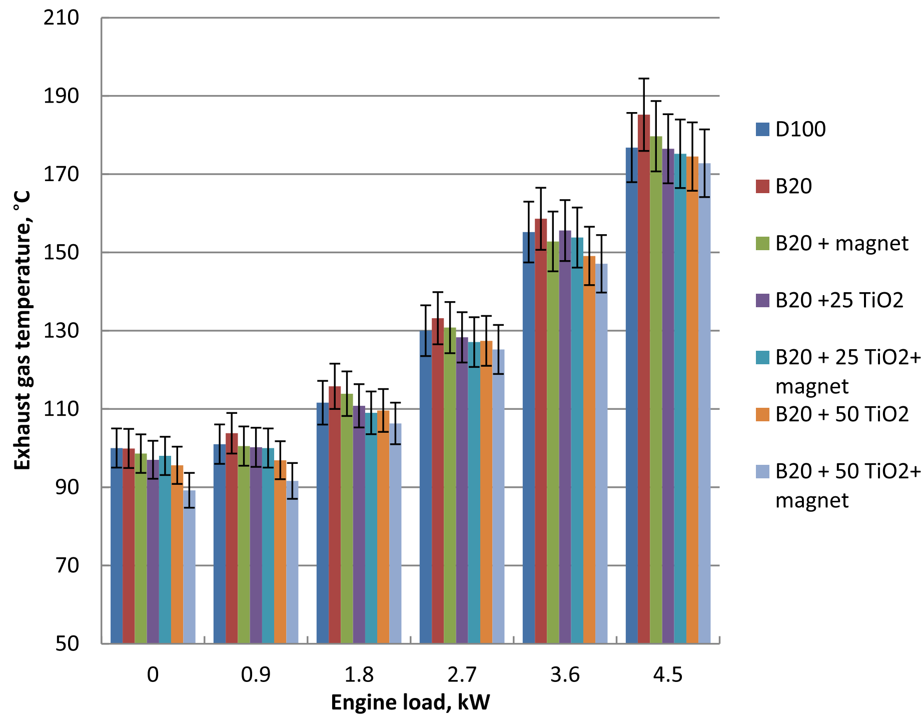


Fig. 7 Exhaust gas temperature of methyl ester with nanomaterials and magnetism

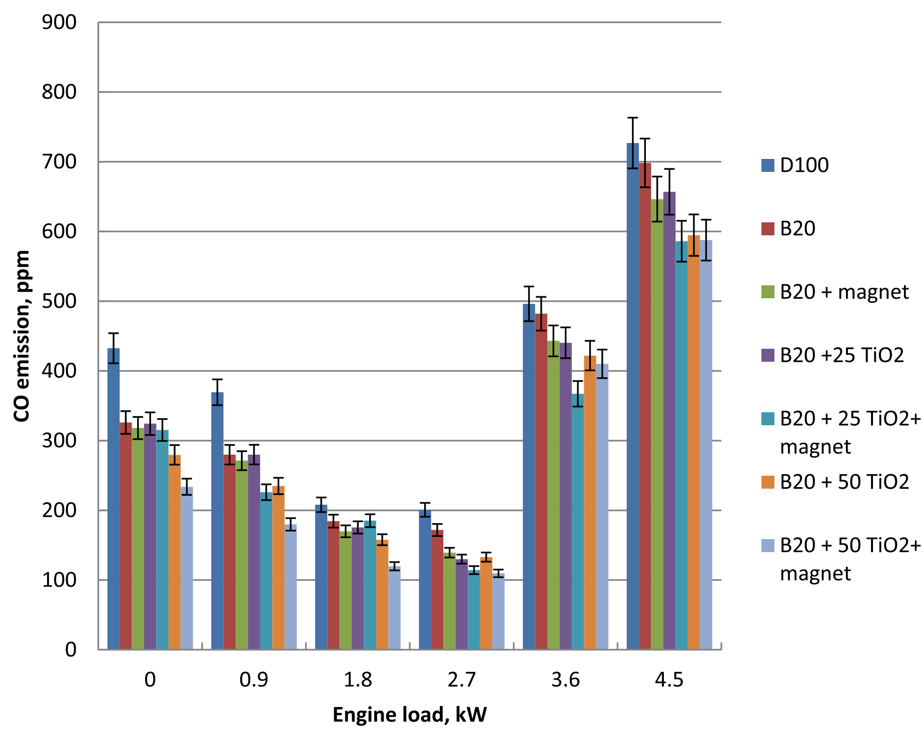


Fig. 8 Impact of magnetism and nanoparticles with biodiesel blend on CO emission

nitrogen oxide than regular diesel. When the engine load increases, higher cylinder and adiabatic flame temperatures cause the rise in NOx concentrations. Biodiesel mixtures emit more NOx than diesel oil. The oxygen content in biodiesel aids in complete combustion and increases the cylinder temperature. Higher cylinder pressure and higher adiabatic flame temperature were the result of shorter ignition delay and enhanced percentage of biodiesel that was being burned premixed. The catalytic action of TiO_2 nanoparticles, which encourages the heterogeneous combustion and lessens the breakdown of hydrocarbon molecules, is most likely to the decrease in the likelihood of thermal NOx generation. Inclusion of nanoparticles leads to the heat transfer rate enhancement; exhaust gas temperature decreases

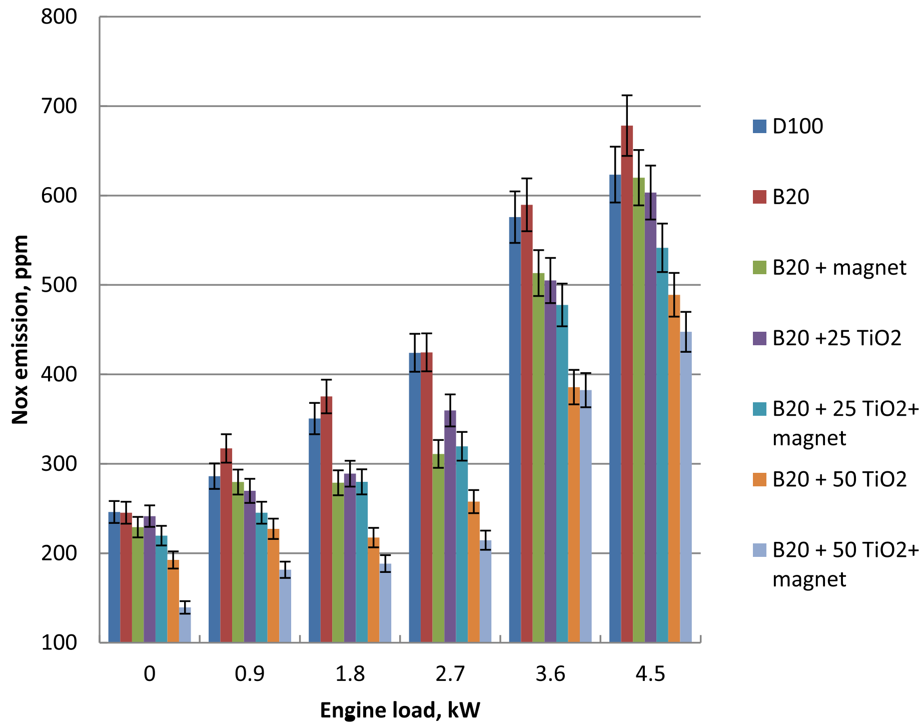


Fig. 9 Impact of nanomaterials and magnetism inclusion on NO_x emission

and ignition delay improvement. Using a magnet lowered the emitted NOx concentration. During combustion, fuel molecules are repositioned and interlocked with oxygen. Fuel magnetism increases the oxygen receptivity, resulting in a leaner combustion that lowers the cylinder temperature and NOx emission. Under the influence of a magnetic field, ionization makes it possible for molecules to bind and link with negative oxygen, leading to complete combustion. The average reductions in NO_x emissions for B20 + magnet, B20 + 25 TiO_2, B20 + 25 TiO_2 + magnet, B20 + 50 TiO_2, and B20 + 50 TiO_2 + magnet were 7.5, 9, 17, 20, and 26%, respectively, at load range.

3.6 Hydrocarbons Emissions (HC)

Figure 10 depicts the hydrocarbon emissions of a biodiesel mixture containing nanoparticles with magnetism at various engine loads. Similar to CO trends, HC emissions rise with the load increase because there is comparatively less oxygen available at higher loads and more fuel is used. The biodiesel's oxygen content and quick ignition time resulted in a decrease in HC emission when compared to pure diesel. Homogeneity of fuel and air combination is increased and vaporization is enhanced when nanomaterials are added to methyl ester mixture. Subsequent fuel atomization is encouraged by the nanoparticles' lower size. This improves the reactants mixing and ensures full combustion. Higher catalytic activity and the presence of oxygen lead to the combustion enhancement and hydrocarbons decline. Fuel oxidation improvements, enhanced surface area, and decreased activation temperature for carbon combustion were seen with the use of nanoparticles. Fuel magnetism disperses molecules, breaks up clusters, reduces viscosity, and creates the most space possible for the molecules of oxygen to mix with the fuel. Carbon buildup in the combustion chamber and fuel injectors is removed by the ionization of the fuel while being affected by the magnetic field. Ionization improves the fuel atomization, fuel–air mixing, and produced less HC emissions by causing more complete combustion under the influence of magnetic field. B20 + magnet, B20 + 25 TiO_2, B20 + 25 TiO_2 + magnet, B20 + 50 TiO_2, and B20 + 50 TiO_2 + magnet had the average declines in HC emissions as 8, 12, 17, 21, and 32%, respectively, at the engine load range.

3.7 Carbon Dioxide Emissions

The carbon dioxide content indicates the chance of full burning. Figure 11 displays the CO_2 concentrations for each of the tested fuels. The higher engine load leads to an increase in fuel consumption, which raises the CO_2 levels. Because of the higher carbon content and greater availability of oxygen in the biodiesel mixture related to diesel, CO_2 concentration is higher. Because of the uniformity of air and fuel blending, the oxygen concentration, the enhanced fuel atomization, and vaporization, combustion takes place more thoroughly and produces more carbon dioxide emissions. Carbon dioxide emissions were more when the nanoparticles were utilized.

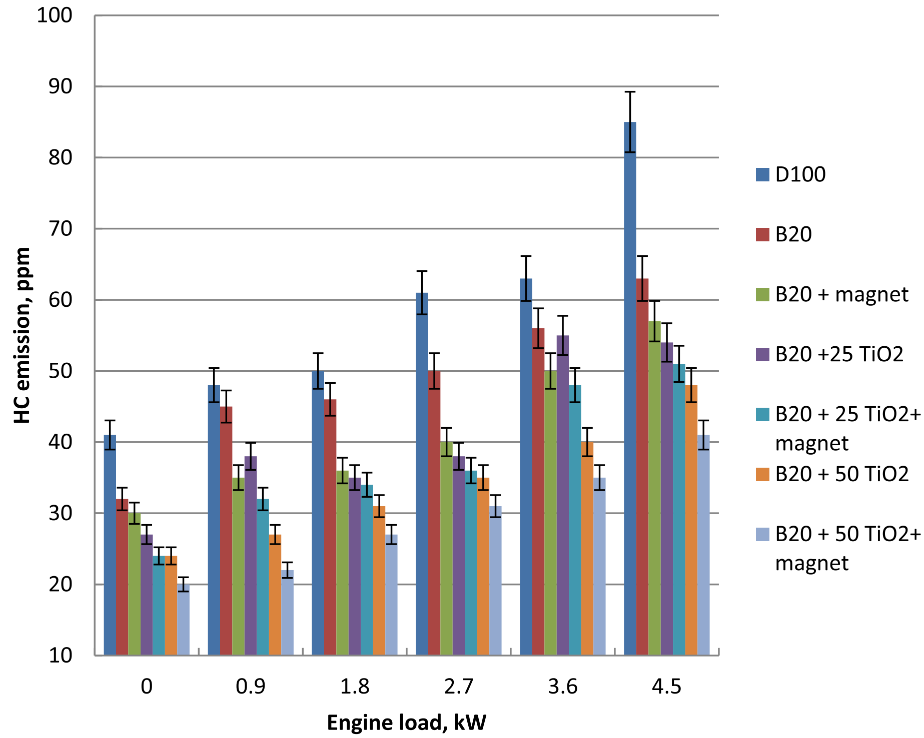


Fig. 10 Effect of nano-TiO_2 and magnetism inclusion on hydrocarbons emission

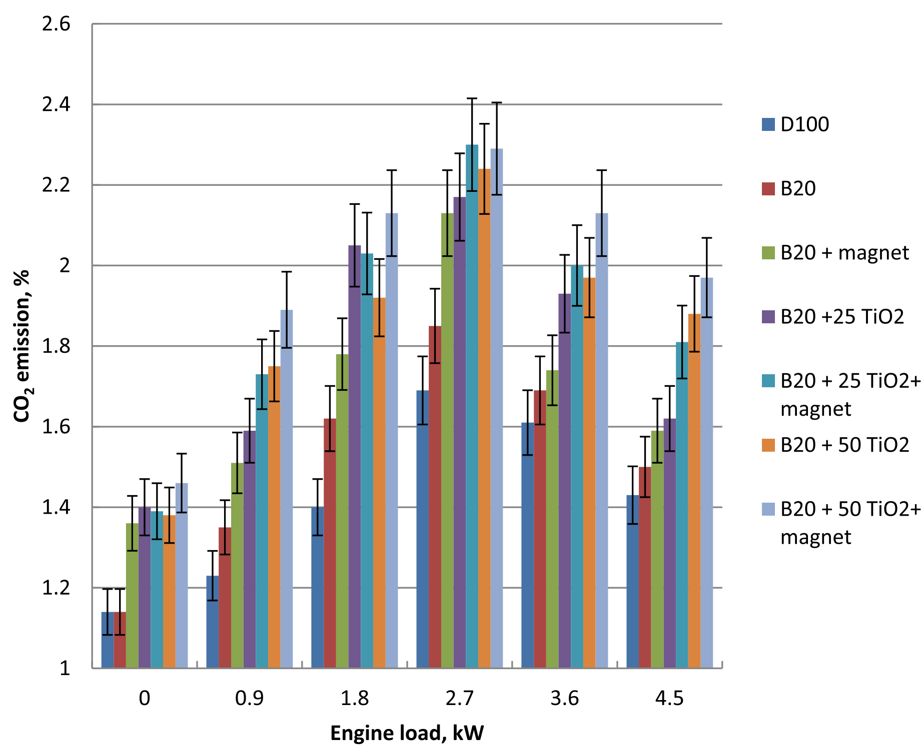


Fig. 11 Effect of nanoadditive and magnetism on CO_2 emission

Due to the fuel being ionized by the magnetic field and producing a homogenous mixture that provides the superior combustion efficiency, carbon monoxide emissions are rising while employing magnetic field. This enhanced fuel atomization, improved fuel–air mixing, and CO concentration reduction were brought about by the magnetic field. The average increases in CO_2 emissions for B20 + magnet, B20 + 25 TiO_2, B20 + 25 TiO_2 + magnet, B20 + 50 TiO_2, and B20 + 50 TiO_2 + magnet were 7, 19, 20, 25, and 29%, respectively, at load range.

4 Engine Performance and Emissions Comparative Analysis

Table 6 shows a comparison of CI engine emissions and performance utilizing biodiesel blends with magnet and nanoadditives as B20 + magnet, B20 + 25 TiO2, B20 + 25 TiO2 + magnet, B20 + 50 TiO2, and B20 + 50 TiO2 + magnet. The variations of parameters about B20 were shown.

5 Conclusions

WCO was utilized to make biodiesel, which was mixed with pure diesel at 20% volume proportion. The methyl ester mixture was exposed to various nanoconcentrations of nanoTiO_2 as 25 and 50 mg/litre. Blends of methyl ester mixture with nanoparticles have been studied and found to meet ASTM standards. A magnetic coil placed before the fuel injector was used to apply a magnetic field to a biodiesel blend including nanoadditions. This is a summary of the key conclusions:

- The average decreases in specific fuel consumption for B20 + magnet, B20 + 25 TiO_2, B20 + 25 TiO_2 + magnet, B20 + 50 TiO_2, and B20 + 50 TiO_2 + magnet were 1.2, 2, 4, 5 and 6%, respectively, at engine load range.
- The average increases in BTE for B20 + magnet, B20 + 25 TiO_2, B20 + 25 TiO_2 + magnet, B20 + 50 TiO_2 and B20 + 50 TiO_2 + magnet were 1, 1.5, 3.5, 5.5, and 6.5%, respectively, at load range.
- Average declines in exhaust gas temperature for B20 + magnet, B20 + 25 TiO_2, B20 + 25 TiO_2 + magnet, B20 + 50 TiO_2, and B20 + 50 TiO_2 + magnet were 3, 4.5, 5, 5.5, and 6%, respectively, at load range.
- Tested fuels as B20 + magnet, B20 + 25 TiO_2, B20 + 25 TiO_2 + magnet, B20 + 50 TiO_2, and B20 + 50 TiO_2 + magnet had the average drops in CO emissions as 5, 7, 10, 12, and 15%, respectively, at brake power range.
- Average reductions in NO_x emissions for biodiesel blend with magnet, 25 ppm, 25 ppm + magnet, 50 ppm, and 50 ppm + magnet were 7.5, 9, 17, 20, and 26%, respectively, at load range.
- B20 + magnet, B20 + 25 TiO_2, B20 + 25 TiO_2 + magnet, B20 + 50 TiO_2, and B20 + 50 TiO_2 + magnet had the average declines in HC emissions as 8, 12, 17, 21, and 32%, respectively, at engine output power range.
- The average increases in CO_2 emissions for B20 + magnet, B20 + 25 TiO_2, B20 + 25 TiO_2 + magnet, B20 + 50 TiO_2, and B20 + 50 TiO_2 + magnet were 7, 19, 20, 25, and 29%, respectively, at load range.
- Adding of nano-TiO_2 to WCO biodiesel produces the best improvements to engine performance and emissions reductions. This result supports the significant contribution that nanoparticle addition makes the improvement in catalytic reactivity, thermal conductivity, heat transfer rate, and rate of evaporation for blending of 20% biodiesel. To operate in a variety of diesel engine applications, biodiesel mixture mixing with 50 ppm dose of nanomaterial under magnetic field effect is strongly advised to achieve the emissions reductions and engine performance enhancement. WCO biodiesel with nano-TiO_2 concentration of 50 ppm under magnetic field is recommended as substitute fuel in diesel engines.

5.1 Impact of Nanoadditives Mixing on Fuel System

To improve lubricating performance, nanoparticles can be added to fuel. Because of the protective barrier that forms between the contact surfaces, low concentrations of all types of nanoparticle additions work better. Nanoparticle addition reduces friction in fuel system components as filter, fuel pump, and injector. When compared to base fuel, nanofuel had the best anti-wear performance in fuel system. Smooth surface in fuel injection system may be achieved effectively by adding nanoparticles [46]. The increase in the concentration level increases the surface roughness. These results could be explained that the increased interaction among the nanoparticles at higher concentration levels exacerbated the agglomeration of these particles. Therefore, the presence of nanoparticle aggregates with over-high concentrations produced a higher amount of wear debris which negatively affects the above surfaces. Compared to the base fuel, wider spray angles and reduced breakup lengths are detected from the modified fuel that contains metal nanoparticles [47]. This result is driven mainly by the secondary atomization resulting in lower surface tension, fuel viscosity, and smaller average diameters observed among the fuel droplets. Low nanoparticle size improves dispersion and enhances the lubrication of fuel system components. The diameter of the diesel engine fuel filter mesh is around 30 μm. TiO_2 has an average particle size of 24.8 nm. As a result, the fuel filter's mesh size is 1000 times greater than that of the nanoparticles. Using an ultrasonicator and agitation to ensure that the additives were not filtered, the homogenous distribution of nanoadditives in the

Table 6 Comparison of performance and emissions compared to a biodiesel blend at full load is shown ((+) for an increase and (−) for a drop)

Relative change, %	B20 + magnet (%)	B20 + 25 TiO_2 (%)	B20 + 25 TiO_2 + magnet (%)	B20 + 50 TiO_2 (%)	B20 + 50 TiO_2 + magnet (%)
BSFC	− 1.2	− 2	− 4	− 5	− 6
BTE	+ 1	+ 1.5	+ 3.5	+ 5.5	+ 6.5
Exhaust gas temperature	− 3	− 4.5	− 5	− 5.5	− 6
CO emission	− 5	− 7	− 10	− 12	− 15
NO_x	− 7.5	− 9	− 17	− 20	− 26
HC emission	− 8	− 12	− 17	− 21	− 32
CO_2 emission	+ 7	+ 19	+ 20	+ 25	+ 29

fuel was continually monitored. Moreover, the use of surfactants improved the stability. All these techniques guarantee that the fuel filter will not capture the nanoparticles. The uniform dispersion of nanotitanium oxide and the inclusion of surfactants minimize the likelihood of forming clusters and decrease lamination [48].

As the fuel injection system's pressure rose, so did the need for improved lubrication. At high-pressure pumping system (common rail or unit injector), the wear and friction problems increase. At long run operation, the issues in wear and friction of fuel system components increase [47]. The lubrication of fuel system components is enhanced by the low nanoparticle size and increased concentration in long run. Improved dispersion of nanoadditives enhances the high-pressure pumping system lubrication. Improved dispersion of nanoadditives reduces the wear impact in injector orifice or pintles. The size of nanoadditives is less than the diameter of injector pintle [48].

The engine has a mechanical fuel pump operated by the cam shaft. The fuel injector nozzle in this tested engine has a single hole. The hole orifice diameter of the injector is about 0.25 mm. The length of orifice is near to 0.3 mm. The nanoadditive particle diameter is less than the hole orifice diameter and its length. The nanoadditives cannot be accumulated. Using ultrasonication and agitation, the nanoadditives were evenly distributed throughout the biodiesel mixture. Utilizing the surfactants Span80 and Tween80 improved the stability. The uniform dispersion of nanoadditives in the fuel was regularly checked using an ultrasonicator and agitation to make sure the additives that were not accumulated in the fuel system components. These methods all ensure that the nanoparticles would not be captured by the fuel injector. Nanoadditives are uniformly dispersed to reduce the lamination, sedimentation, and chance of cluster formation.

5.2 Exhaust Treatment of Nanoparticles

Biodiesel blend contained the dissolved nanoparticles. To boost the surface area and surface activation, nanotitanium oxide is employed as a catalyst. Very tiny amounts of nanoadditives are introduced, so it cannot be seen in the exhaust analysis. Using an ultrasonicator and agitation, the uniform dispersion of nanoadditives in the fuel was periodically monitored to ensure the additives that were not building up in the fuel system and exhaust components. All of these techniques guarantee that the nanoparticles cannot accumulate in the exhaust system [45]. Addition of nanoadditives leads to the reductions of CO, NO_x, and HC emissions due to the catalytic reactivity, oxygen content, and improved thermal properties about base fuel [46]. The reductions of CO emissions reduce the global hazard, climate changes, and global warming. Very small amounts of nanoadditives were introduced, so it cannot affect on the exhaust system. Using an ultrasonicator and agitation, the uniform dispersion of nanoadditives in the fuel was monitored to ensure the additives that were not building up in the fuel system and exhaust components. All of these techniques guarantee that the nanoparticles cannot accumulate in the exhaust system [47]. The nanoparticles should be fine with small diameter size and dose to be dispersed easily in the fuel. This is the preventive method to reduce the nanoparticles in exhaust system.

5.3 Future Work and Recommendation

Future studies can look at how varied nano-TiO_2 particle sizes affect the characteristics of fuel, engine performance, and emissions. Moreover, various nanoadditives, such as CNT and Al_2O_3, can be employed and contrasted with TiO_2 to demonstrate how they affect engine emissions and performance. Hybrid nanoadditives as Al_2O_3, TiO_2, and CNT can be applied to improve the fuel properties, engine performance, and reduce exhaust emissions. Magnetic field can be applied using intensity variation. The ideal dose for every kind of additive including nanoparticles should be investigated. This is crucial because, at larger concentrations, the efficiency of nanoparticles can reduce both engine performance and cost-effectiveness.

5.4 Practical Implications of this Work

Addition of nano titanium oxide enhanced engine performance; however, the resulting rise in fuel cost must be carefully considered. To guarantee the economic sustainability of these biodiesel blends, future research should concentrate on striking a balance between cost and efficiency advantages. Examine the long-term impact of nanoTiO_2 on engine durability. For this additive to be used practically in the industrial sector, it will be crucial to comprehend how they affect engine wear and friction over lengthy periods of time. By improving thermal efficiency and lowering brake specific fuel consumption, TiO_2 nanoparticles were added to biodiesel blends, increasing their cost- and energy-effectiveness. There were notable decreases in CO, NO_x, and HC emissions, which helped diesel engines to run cleaner and more in line with strict environmental laws.

Funding Open access funding provided by The Science, Technology & Innovation Funding Authority (STDF) in cooperation with The Egyptian Knowledge Bank (EKB).

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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ARTICLES FOR FACULTY MEMBERS

COMPARATIVE ANALYSIS OF WASTE COOKING OIL BIODIESEL MIXED WITH NANOPARTICLE ADDITIVES ON PHYSICOCHEMICAL PROPERTIES AND DIESEL ENGINE PERFORMANCE

Nano-additive blends examination of performance and emission profile of CI engines fuelled with waste cooking oil based-biodiesel / Fasogbon, S. K., & Oyedepo, S. O.

Journal of Thermal Engineering
Volume 11 Issue 1 (2025) Pages 1–15
https://doi.org/10.14744/thermal.0000899
(Database: Yıldız Technical University Press, İstanbul, Turkey)

Journal of Thermal Engineering
Web page info: https://jten.yildiz.edu.tr
DOI: 10.14744/thermal.0000899

Research Article

Nano-additive blends examination of performance and emission profile of CI engines fuelled with waste cooking oil based-biodiesel

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ARTICLE INFO

Article history
Received: 25 May 2022
Revised: 22 October 2023
Accepted: 25 November 2023

Keywords:
Aluminum Oxide Nano-additive; Compression Ignition Engines; Emission; Performance; Waste Cooking Oil

ABSTRACT

Waste Cooking Oil (WCO) could become the alternative raw material for biodiesel production to sustain energy globally. Fossil diesel causes emissions of dangerous gases in compression ignition engines, and this had led to the use of biodiesel in the engines to reduce hazardous emissions. Researchers have also used nano additives with biodiesels to further improve CI engine performance and emission characteristics; behaviors are however Fuels-Nano additives combinations specific. This work therefore studied CI engines on the combination effects of blends of diesel, waste cooking oil-based biodiesel: B0 to B100 at 10 % incremental step, and aluminum oxide ($Al_2 O_3$) nanoparticles additive with dosages of 5 g/l and 10g/l on each fuel blends. The biodiesel was produced through the transesterification process in the presence of potassium methoxide as a catalyst. All mixtures containing nano additives were ultrasonicated at a frequency of 25 Hz to prevent agglomeration. The experiment was carried out in a four-stroke, single-cylinder, air-cooled compression ignition engine at engine speeds of 500, 1000, 1500, and 2000 rpm. The result showed a decrease in the CO emissions, brake-specific fuel consumption, and an increase in NOx emissions, brake power, and brake thermal efficiency when the percentage of biodiesel increased for pure biodiesel-diesel blend at higher engine speeds. Blends containing 5 g/l and 10 g/l aluminum oxide ($Al_2 O_3$) Nano-additive showed a significant increase in brake power, brake thermal efficiency and a significant decrease in brake-specific fuel consumption, CO and NOx emissions. For all blends tested, (B20+10 g/l) showed the best result for performance and emissions at all investigated speeds and torques; as it gave Highest BP of 8.5 % for low speed of 500 RPM and 9.7 % for high speed of 2000 RPM, Highest BTE of 19.4 % at high-speed of 2000 RPM and Highest NOx reduction of 42.9 % at low engine torque of 25 Nm and 32 % NOx reduction at high engine torque of 100 Nm; Highest CO reduction of 28.6 % at low engine torque of 25 Nm and 20.6 % NOx reduction at high engine torque of 100 Nm. In conclusion, for better performance and emission characteristics, waste cooking oil-based biodiesel blend with aluminum oxide; B20 +10 g/l can be used to fuel the compression ignition engine.

Cite this article as: Fasogbon SK, Oyedepo SO. Nano-additive blends examination of performance and emission profile of CI engines fuelled with waste cooking oil based-biodiesel. J Ther Eng 2025;11(1):1–15.

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This paper was recommended for publication in revised form by Editor-in-Chief Ahmet Selim Dalkılıç

Published by Yıldız Technical University Press, İstanbul, Turkey

INTRODUCTION

Fossil fuels are largely used in compression ignition engine; it happens to be a naturally existing substance. The need for replacement of fossil fuels has been an issue to look into due to the dangerous emission in compression ignition engines. In addition, the demand for fossil fuels is continuously increasing globally there by resulting in a rapid depletion of fossil fuels deposits [1 An internal combustion engine (ICE) is a type of heat engine that uses an oxidizer (usually air) and a combustion chamber that is a part of the working fluid flow circuit to burn fuel. The internal combustion engine's rotor, nozzle, turbine blades, and pistons are frequently subjected to direct force from the expansion of the high-temperature, high-pressure gases created during the combustion process. This force transfers chemical energy into mechanical energy that can be used to move the component across a distance [2].

Ahmad et al., and Carraretto et al., recalled that Diesel engines are compression ignition engines which are usually used to power various types of vehicles such as: Automobiles, Trains, Ships and Airplanes. They are also used to power Irrigation pumps and in an extension used to produce electric power. Combustions of fossil diesel in theses engines produce emissions that have serious negative effect on the ecosystem and the human health. To overcome these problems, global effort exists to develop clean substitute fuels that are easily available and technically feasible [3,4].

According to Demirbas, renewable energy sources have demonstrated a high potential for availability, and biodiesel has become the most widely used alternative fuel to fossil diesel [5]. On the other hand, Palash et al., Mofijur et al., and Mofijur et al. observed that the use of biodiesel in CI engines is met with certain limitations, such as a slight decrease in brake-specific fuel consumption, slightly poor fuel atomization, marginally higher density, lower cloud and pour points, piston ring sticking, issues with cold starting, and higher NOX emission [6–8]. On the other hand, Kadarohman et al. found that the limitations of biodiesel can be addressed by using certain fuel modification techniques, such as the addition of fuel additives like nanoparticles or the use of hybrid fuel [9]. Shaafi and Velraj et al., revealed that among the recent fuel modification methods, nanoparticles additions have emerged to be novel and promising; thus, many researchers have investigated the impacts of nano additives addition on the performance and emission characteristics of Internal combustion engines [10–18].

Produced from vegetable oil and other organic materials, biodiesel is an alternative fuel that bears a lot of similarities to fossil diesel. It operates in the current diesel engines using a fuel based on vegetable oil (soy or canola oil), with no changes in hardware. Transesterification is one way to produce biodiesel. The increasing demand for fossil fuels has led to a greater awareness of how quickly they are depleting. This means that using an effective and less polluting diesel fuel substitute will be necessary to address its effects. Because of its benefits to the environment and economy, biodiesel has been the fuel of choice for diesel engines during the past 20 years. Still a lot of work has to be done for further enhancement of biodiesel as a fuel.

Raghuveer et al. and Chen et al. produced biodiesels from palm kernel, the biodiesel produced by them was made through base-catalyzed transesterification of the palm kernel oil with alcohol [19, 47]. Fatty acids are gotten from the transesterification process, which is then converted to alkyl esters through acid catalysis. Non-edible Jatropha oil was also employed by Anand and Sadhik to produce biodiesel through standard transesterification process [20]. They made use of viscometer to determine the kinematic viscosity of the fuel blends at c, and also carried out a density check through the use of digital density meter. Avagyan et al. also analyzed the benefits of algae for biodiesel production and sustainable development; and submitted that Microalgae biomass production has accounted for 65–85% of the overall cost of biofuel [21]. They also analyzed microalgae and macro algae cultivation and harvesting, with a description of the complexities involved in algal biofuel production. Keskin et al. investigated fuel additives impact on Biodiesel; and reported that metallic fuel additives improved the pour point and viscosity values properties of biodiesel [22]. The Datura biodiesel is a perfect replacement to diesel because this is derived from indigenous sources and is renewable. Nevertheless, due to its high viscosity and lower calorific value, it cannot be used directly in the diesel engine [23].

Many researchers have also conducted studies regarding the impact of fuel additives and on engine combustion, performance, and emission characteristics, according to Taghizadeh-Alisaraei, Rezaei-Asl, and Devarajan et al. [24, 48]. Shaafi and Velraj, for example, investigated the combustion, performance, and emission characteristics of an engine running on two modified fuel blends: D80SBD15E4S1 (diesel-soybean oil-based biodiesel-ethanol blends) and B20 (diesel-soybean oil-based biodiesel), with alumina (Al_2O_3) acting as a nano-additive. It was noticed that the cylinder pressure arising from combustion and the heat release rate were higher than those of diesel fuel. The presence of oxygen in the soybean oil-based biodiesel and the better mixing capabilities of the nano particles must have been responsible for the reduction of CO and UHC; and slight increase of NOx at full load condition [25]. Gumus et al. looked into the effects of adding nanoparticles of cupric oxide (CuO) and alumina to fossil-diesel fuels. Additionally, the impacts of the additives on engine emissions and performance were examined. By including the nanoparticles, the characteristics of storage and combustion were enhanced. By adding alumina and cupric oxide to pure diesel, engine torque and brake power output were also marginally boosted [26]. Another study by Guru et al. empirically investigated the impact of adding copper, magnesium, manganese, and calcium to diesel fuel on quality of fuel ignition, efficiency, and pollution. Along with the amounts of pollutants including SO_2, CO_2, and CO, they also looked at the number of fuels in two scenarios: pure diesel and diesel with additives [27].

Researchers have specifically studied a number of performance parameters. Debbarma and Misra, for example, fueled compression ignition engines (CIE) using a blend of neat diesel (ND) and iron nanoparticles (INP) [28]. The results showed that the brake specific fuel consumption (BSFC) decreased by 1.55% for ND+INP and 2.71% for PB20+INP, while the brake thermal efficiency (BTE) increased by 2.06% for PB20+INP and roughly 0.36% for ND+INP. Experimental research on cerium oxide-mahua oil was conducted by Ramarao and Bharathkumar on a single-cylinder, air-cooled, four-stroke direct injection diesel engine [29]. Brake specific energy consumption (BSEC), exhaust gas temperature (EGT), and brake thermal efficiency (BTE) were among the metrics used to assess the performance characteristics. When the load was increased, the mahua biodiesel-Ce02 blend's BTE was found to be at its maximum, and at lesser loads, it tended to decrease. Praveen et al. [30] conducted an experimental study to assess the efficiency and emission characteristics of compression ignition engines using exhaust gas recirculation (EGR) and mixes of Calophyllum and Inophyllum biodiesel with TiO2 nanoadditives. A volumetric technique was used to combine 20% of Calophyllum Inophyllum biodiesel with 80% diesel (B20) to create the Calophyllum Inophyllum biodiesel-diesel blend. The outcome revealed a notable decrease in exhaust gas circulation as well as an increase in brake thermal efficiency.

Fasogbon and Asere studied the effects of soybean methyl ester on the performance characteristics of compression ignition engine, they ran the CI engine on various biodiesel-petrol diesel blends (0/100, 10/90, 20/80, 30/70 and 40/60), they found out the performance of CI engine was the best at B20 (blend 20/80) [2]. Praveen et al studied the effect of biodiesel-diesel fuel blend on compression ignition engine [30]. The study showed that the biodiesel-diesel fuel blend decreased engine performance and increased its emission characteristics. Gurusala and Selvan experimented the emissions characteristics of a compression ignition (CI) engine fueled with waste chicken fat biodiesel with alumina nanoparticles as an additive [31]. They observed a significant reduction in hydrocarbons and carbon monoxide emissions after the experiment. Fasogbon studied environmental friendliness of melon oil methyl ester in internal combustion engines; with the findings that the fuel is a near perfect environmentally friendly one [32]. Pradipta et al; 2022 assessed combustion characteristics of a 4-stroke compression ignition dual-fuel engine using a blend of diesel-Karanja biodiesel with variations of engine loadings. With the result that, the dual-fuel fired engine, indicates apex point of net heat release rate and marginal cylinder pressure curve from top dead centre. And the highest peak cylinder pressure recorded for Diesel-5DEE-PG (6.68 MPa) at 15° after TDC, as compared to Diesel only (6.11 MPa) at 9° after TDC [33].

El-seesy et al studied the Influence of Multi-Walled Carbon Nanotubes Additives into non-edible biodiesel-diesel fuel blends on Diesel engine performance and emissions, they found out that multi walled nanotube helps to improve engine performance parameters [34]. Pandian et al. investigated the effect of TiO2 nanoparticles on mahua biodiesel (BD100) at 100ppm (BD100T100) and 200 ppm (BD100T200); it was observed that (BD100T200) gave a reduction of 9.3% for CO, 5.8% for HC, 6.6% for NO and 2.7% for a smoke when compared to neat mahua biodiesel [35]. Anand et al. demonstrated that engine performance and emissions were significantly improved when 25 to 50 ppm of alumina nanoparticles, with a size of 51 nm, were added to Jatropha biodiesel fuel [36]. Arock-iasamy et al. tested the impact of a nanoparticle additive at a dosage level of 30 ppm in Jatropha biodiesel using a single cylinder diesel engine. Using neat diesel as the basis fuel, performance and emission parameters were examined. The findings showed a 9% decrease in NOx emissions, a 17% decrease in smoke opacity, a 33% decrease in HC emissions, and a 20% decrease in CO emissions. Additionally, the research revealed a 5% increase in brake thermal efficiency [12]. Sadhik and Anand combined carbon nanotube at 25, 50, and 100 ppm with a Jatropha methyl ester water emulsion. With a single cylinder diesel engine, they were able to reduce NOx emissions by 29% and smoke emissions by 28% [37]. An experimental examination was conducted by Sadhik et al. and Amit on alumina nanoparticles blended at 25 and 50 ppm in a water diesel emulsion. Along with a little drop in HC and CO emissions, there was a notable 40% reduction in smoke opacity and a 27% reduction in NOx [38, 39 The performance and emissions characteristics of a diesel engine running on a diesel-soybean oil -based biodiesel mix B20 with alumina (Al_2O_3) as the nano additive were investigated by Ojeda et al. and Shaafi et al. The discovery was made that the biodiesel derived from soybean oil had higher cylinder pressure and heat release rate than diesel fuel. This led to the hypothesis that the reductions in CO and HC emissions were caused by the oxygen present in the biodiesel and the enhanced mixing abilities of the nanoparticles [40, 41].

Hoseini et al., studied, the effects of graphene oxide (GO) nano-particles on power, exhaust gas temperature (EGT), carbon monoxide (CO), carbon dioxide (CO2), unburned hydrocarbons (UHCs), and nitrogen oxides (NOx), of a diesel engine fueled with Oenothera lamarckiana biodiesel. With the results that GO inclusion increases power and EGT significantly. It also significantly reduces CO (~5%–22%) and UHCs (~17%–26%); but slightly increases CO2 (~7%–11%) and NOx (~4%–9%) emissions [42]. Junshuai LvORCID et al., reviewed and summarized the recent research progress of nanoparticles as additives for diesel-biodiesel fuel blends. They described in detail the excellent properties of nanoparticles, and summarized

/ discussed the preparation methods. Additionally, they examined the effects of a number of widely used nanoparticles on the performance of combustion and emissions of harmful substances, including CO, NOx, UHC, and emissions from brake-specific fuel consumption, as well as the effects of diesel-biodiesel fuel blends. They also talked about the effects of nano-additives on internal combustion engines, the environment, and human health. This paper's work can make a significant contribution to the fuel industry's use of nanomaterials. The authors of the study arrived at the conclusion that their research could facilitate the effective selection of appropriate nano-additives for internal combustion engines, hence promoting low-emission features and efficient combustion [43]. Devaraj et al., discussed the effect of nano particles on engines performance and emission parameters and engine life in their paper. The paper also discussed the effect of different size and dosage of nano particles on diesel engine behaviour; and the preparation of nanofluid, several characterization methods and enhancement of biodiesel stability via various techniques [44].

Burning fossil fuels in the presence of an oxidizer, such as air, releases damaging greenhouse gas (GHG) emissions in addition to converting the chemical energy in molecular bonds into mechanical energy that can be used. Vehicles powered by lithium-ion batteries and hydrogen are two of the several green transportation options that are soon to be available. Researchers have however investigated the potential of nanoparticles fuel additives as a possible solution the harmful greenhouse gas emission. Previous studies in this direction however show that extensive fundamental and applied studies have been done on impacts of addition of cerium oxide, iron-strontium, graphene and copper to biodiesel and its blends on performance, combustion, and the reactivity of the resulting emission by internal combustion engines. Literature is sparse on the inclusion of alumina nanoparticles in biodiesel and its blends with diesel. To this end, this paper contributorily studied the effect of alumina (Al_2O_3) nanoparticles as an additive to diesel-biodiesel blends on the performance and emissions characteristics of a compression ignition engine. Future study can however investigate the toxicity of nanoparticles. The Cost analyses of nanoparticles inclusions should also be investigated vis a vis one hundred percent CO_2 taxed fossil fuels and other alternative 'renewable' fuels.

MATERIALS AND METHODS

Experimental Setup

The test engine is a four-stroke single cylinder, direct injection, air cooled Compression Ignition engine; and the detail of the engine specification employed is as shown in Table 1. The engine was run under ambient temperature of 22 ^{O}C and atmospheric pressure of 878 Mbar. In order to determine and measure the engine load and torque, the Diesel engine employed was directly coupled to an eddy current dynamometer as shown in the Figure 1. A mobile AVL flue gas analyzer was used to determine the emission characteristics of the combustion products (Table 1).

Table 1. Test engine specifications (Kama; air cooled diesel engine)

Engine Variables	The values
Combustion System	Direct Injection
No of Cylinder	Single Cylinder
Max Output	2.8 kW - 3.1kW
Con Output	2.5 kW - 2.8kW
Engine Speed	500 rpm - 2000 rpm
Bore X Stroke	70 mm x 55 mm
Fuel Used	Light Diesel Oil
Displacement	0.211
Fuel Tank Capacity	2.5 L
Starting System	Recoil or Electric Starter

Emission Analyzer AVL DITEST GAS 1000, Mobile petrol/gas emission tester, Emission diagnostics of HC, CO, CO2, O2, NOx, and lambda.

Figure 1. A pictorial view of the experiment setup.

1- Compression ignition engine
2- Eddy current dynamometer
3- Exhaust gas analyzer
4- Galvanometer

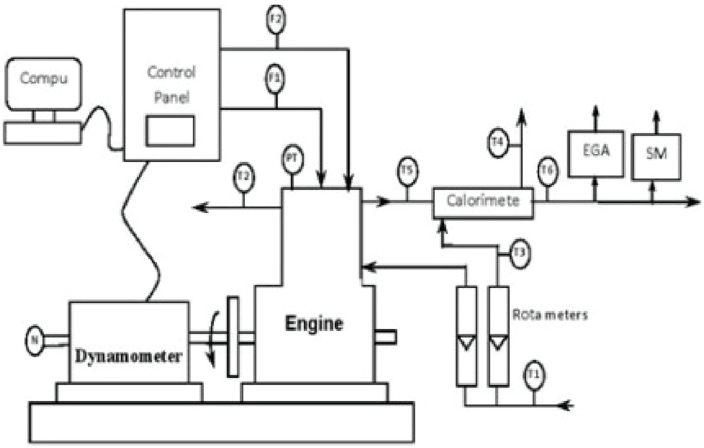
Fuel Preparation

In this experiment, a 250 mL conical flask was filled with 10.5 mL of used cooking oil, which was measured and heated to 50 °C. Potassium hydroxide pellet (0.25 g; catalyst concentration of 0.5 percent) and methanol (63 mL; mole ratio of oil to methanol of 1: 6) were combined to create a potassium methoxide solution inside the 250 mL conical flask. After vigorous stirring, the potassium hydroxide pellet completely dissolved in the fluid. After heating the potassium methoxide solution to 60 degrees Celsius, it was added to warm leftover frying oil and vigorously stirred with a stirrer for 50 minutes. The mixture was left to settle for 24 hours in a separating funnel. After that, warm water was used to wash the biodiesel in order to remove any last bits of soap and glycerol from the funnel. This was carried out up until the biodiesel was covered by the clear water in the separating funnel. The aluminum oxide and biodiesel-diesel fuel mixes were combined in an ultrasonicator to create the nano additive fuel blend. By dispersing the nano additive throughout the base fuel using the ultrasonicator technique, the nano additive was able to return to the nanoscale range. As illustrated in Figure 2, the nano additive particles were weighed to a predefined mass fraction of 5 g/l and then distributed throughout the biodiesel-diesel for 15 to 30 minutes using an ultrasonicator set to a frequency of 25 kHz. The same process was repeated for the mass fraction of 10 g/l to prepare the aluminum oxide-biodiesel fuel blends fraction of 10 g/l to prepare the aluminum oxide-biodiesel fuel blends. The density, Flash point, Cetane Index and Calorific value of each fuel blends were determined immediately after the fuel preparations according to ASTM standard. Table 2 and 3 presents the all-fuel blends properties measured according to ASTM standard guidelines. Stability of each fuel-blends was 3 h after preparation.

Figure 2. Pictorial view of blends in the ultrasonicator.

Experimental Procedure

The engine was run for 10 minutes for each blend to ensure the removal of remnants in the fuel line. After the initial analysis and error detection, some of the tests were repeated. The amount of flywheel power (P) available in the engine flywheel (brake power) is equal to P ¼ 2pTN/60000 (kW), where T (Nm) is torque available in the flywheel and N (rpm) is the engine speed. The experiments in this work were conducted on four engine speeds of 500 rpm, 1000 rpm, 1500 rpm, and 2000 rpm under full load with three replicates. The torque, power, fuel consumption, ambient temperature, ambient pressure, and environmental humidity were recorded during each test. Following the automatic recording of torque and engine speed by the dynamometer with a connected control panel, the engine power is calculated. The output torque and engine rotation speed have a significant impact on the engine power. The amount of gasoline (measured in grams) needed to generate one kW-hour of real work in the engine is known as specific



PT Pressure Transducer
N Rotary encoder
Wt Weight
F1 Fuel flow
F2 Air flow
F3 Jacket water flow
F4 Calorimeter water flow
T1 Jacket water inlet temperature
T2 Jacket water outlet temperature
T3 Calorimeter water inlet temperature = T1
T4 Calorimeter water outlet temperature
T5 Exhaust gas to calorimeter tempera
T6 Exhaust gas from calorimeter temperature

Figure 3. Experimental test engine rig.

Table 4. The accuracies of the measurements and the uncertainties in the calculated results

Variables	Measurement Boundary	Precision	Uncertainties
Density	0.60 – 3.5 g/cm^3	±0.0001 g/cm^3	±0.004
Temperature	0 – 1000 ^{O}C	±1 ^{O}C	±0.1
Cetane index	120 min	-	±0.01
Calorific value	0 – 100000 kJ/kg	±1 kJ/kg	±0.1
BTE	0 – 100 %	-	±0.02
CO	0-15.0 vol %	±0.01 vol %	±0.07
NO_X	5000 ppm vol.	±1 ppm vol.	±0.1
Speed	0 – 2000 rpm	±5 rpm	±0.05
Torque	0 – 100 Nm	±0.05 Nm	±0.05
Power	0 – 85 kW	±0.02 kW	±0.07
Flow Rate	0.1 – 35 l/hr	±0.02 l/hr	±0.07

fuel consumption (SFC, g/kWh). The dynamometer and exhaust gas analyzer readings were obtained three times to cut down on error. Figure 3 depicts the engine test rig.

Uncertainty Analysis

It is inevitable that each measurement you take, regardless of how accurate your instrument is, will have some degree of uncertainty. A measurement's uncertainty is constrained by the measuring device's accuracy and precision as well as any additional variables that can influence the experimenter's capacity to perform the measurement.

$$\text{Measurement} = (\text{measured value} \pm \text{standard uncertainty}) \text{ unit of measurement.} \quad (1)$$

where the ± standard uncertainty indicates approximately a 68% confidence interval

$$\text{Relative Uncertainty} = \frac{uncertainty}{measured\ quantity} \quad (2)$$

$$\text{Relative Error} = \frac{measured\ value - expected\ value}{expected\ value} \quad (3)$$

When we report the average value of *N* measurements, the uncertainty we should associate with this average value is the standard deviation of the mean, often called the standard error (SE).

$$\sigma = \frac{s}{\sqrt{N}} \quad (4)$$

The precisions and uncertainties in the variables measured are as shown in Table 4.

RESULTS AND DISCUSSION

Fuel Blends Characterizations

The determined physicochemical properties of the produced WFO based biodiesel and its blends are as stated in Table 2, while that of of WFO based biodiesel blends and Al_2O_3 Nano additives are as stated in Table 3. It could be seen in Table 2 that as the percentage composition of the biodiesel increases in the earlier part 0 - 40 % increase, the density increases, cetane index increases, while the flash point decreases. For the percentage composition of the biodiesel higher than 40 %, the density decreases, cetane index increases and flash point increases. For all the blends B0,

Table 2. Physicochemical properties of biodiesel and its blends

Properties	Method	B0	B10	B20	B30	B40	B50	B60	B70	B80	B90	B100 (Tested)	B100 (Standard)
Density at 15.56 °C kg/m^3	ASTM D-4052	830.2	856.5	855.7	856.6	893.1	848.9	845.1	841.2	837.4	833.5	829.7	-
Flash point °C	ASTM D-92	72	69	60	62	78	95	111	225	143	160	176	130
Cetane index	ASTM D-976	60.21	60.54	60.72	62.12	62.34	62.55	62.77	62.99	63.21	63.42	63.64	47 min
Calorific value kJ/kg	ASTM D-224	47107	47022	43954	43325	43255	43185	43115	43045	42975	42905	42835	48500

Table 3. Physicochemical properties of biodiesel blends and Al_2O_3 nano additives

Properties	Method	B0 (Diesel)	B0+5g/l	B0+10g/l	B10	B10+5g/l	B10+10g/l	B20	B20+5g/l	B20+10g/l	B0 (Standard)
Density at 15.56 °C kg/m^3	ASTM D-4052	830.2	830.0	829.9	856.5	856.2	856.1	855.7	855.5	855.2	860-900
Flash point °C	ASTM D-92	72	72.1	72.3	69	69.2	69.3	60	60.3	60.4	248
Cetane index	ASTM D-976	60.21	60.22	60.24	59.54	59.56	59.58	60.72	60.74	60.76	55
Calorific value kJ/kg	ASTM D-224	47107	47108	47109	47022	47023	47023	43954	43956	43956	45500

B10 and B20 tested in Table 3, as the percentage composition of Al_2O_3 Nano additives increases from 0 g/l, 5 g/l and 10 g/l, both the Density and Cetane index decrease, while Flash point the calorific value increase. These observations in the blend's properties are in tandem with the works of Rao and Dash, 2016 [46] and Hosseini et al., 2017 [49].

Engine Performance Parameters

Plot of BSFC against speed for pure biodiesel-diesel blends

Figure 4 shows the graph of brake specific fuel consumption against engine speed for biodiesel-diesel blends. Increase in blend ratio leads to an increase in brake specific fuel consumption, this could be as a result of the high density, high viscosity and low calorific value of the biodiesel. The lower calorific value of the biodiesel, could have led to more fuel being injected into the combustion chamber during combustion; thereby leading to a rise in the amount of fuel consumed. The high density and viscosity make the atomization of the fuel slower, thus leading to an increase in the amount of fuel injected into the combustion chamber simultaneously. At each engine speed, it was observed that pure biodiesel has maximum specific fuel consumption while diesel fuel has the lowest specific fuel consumption. These results corroborate the works of Aalam and Saravanan; 2015 [11], Bet-Moushoul et al., 2016 [16] and El-Seesy et al., 2018 [18].

Plot of BSFC against speed when 5g/l of aluminum-oxide was introduced blends

The brake specific fuel consumption decreased when aluminum oxide nano-additive Al_2O_3 was introduced in the blend as shown in Figure 4. It is suspected that abundance oxygen in the lattice structure of the additive could have aided the BSFC decrease during combustion. The introduction of 5g of Al_2O_3 to the blends B0, B10, B20, B30, B40, B50, B60, B70, B80, B90 and B100, led to a BSFC decrease of 20%, 19.4%, 14.7% ,11,04%, 12.6% 16.4% 14.7% 13.7% 13.6% 4.9% 5.1% at low engine speed (500 RPM) and a decrease of 31.7% 30.4% 32.2% 30.2% 28.1% 33.8% 31.7% 30.4% 23.0% 15.1% 14.1% at high engine speed (2000 RPM). These results follow the works of Arockiasamy and Anand, 2015 [12], Debbarma and Misra, 2018 [17] and Anand and Sadhik, 2013 [19].

The concentration of aluminum oxide nano additive in the blend affects the brake specific fuel consumption, the higher the concentration of the nano additive the less the BSFC. Figure 5 shows that the dose of 10g/l of Al_2O_3 led to a further reduction of the brake specific fuel consumption compared to the case of 5g/l dose. This observation is likely to have been due to the availability of more oxygen

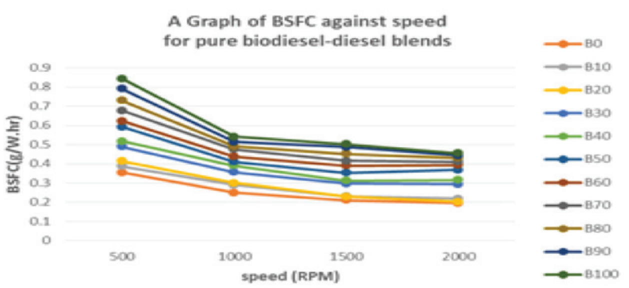


Figure 4. A graph of BSFC against speed for pure biodiesel-diesel blends.

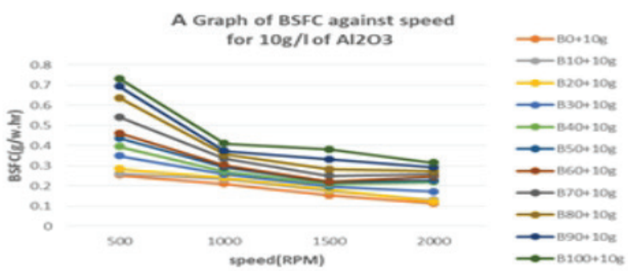


Figure 5. A graph of BSFC against speed when 10g/l of aluminum oxide was introduced blends.

for combustion. At low engine speed (500 RPM), there was a decrease of 29%, 32.6%, 31.8%, 28.8%, 23.6%, 26.6%, 26.1%, 20.1%, 13.0%, 12.5% and 13.4% for blends B0, B10, B20, B30, B40, B50, B60, B70, B80, B90 and B100 when 10g of Al2O3 was added and at high engine speed (2000 RPM), 42.5%, 37.3%, 39.6%, 41.8%, 30.9%, 38.5%, 37.6%, 36.7% ,34.5% and 31.0% reduction was seen for blends. These results agree with the works of Shaafi and Velraj, 2015 [25], Gumus et al., 2015 [26] and Debbarma and Misra, 2018 [28].

Plot of Brake power against speed for pure biodiesel-diesel blends

The behaviour of brake power is shown in Figure 6. The waste cooking oil-based biodiesel and its blends exhibit similar characteristics as the diesel fuel. The brake power decreases with an increasing amount of biodiesel in the fuel mixture, this could have been due to high density, viscosity and low calorific value of the biodiesel. The high density and viscosity of the biodiesel reduce the efficiency of the combustion process there by leading to a decrease in the brake power. The behaviours follow the works of Rao, 2016 [29], Gurusala and Selvan, 2015 [31], Sadhik and Anand, 2010 [35] and EL-Seesy, et al., 2018 [53].

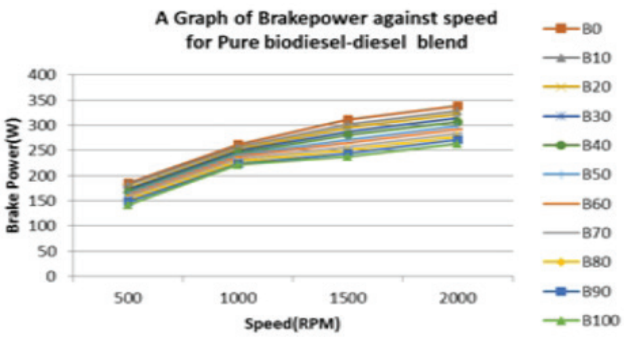


Figure 6. A graph of Brake power against speed for pure biodiesel-diesel blends.

Plot of Brake power against speed when 5g/l of aluminum oxide was introduced blends

The brake power of the engine showed a significant rise when Al_2O_3 was added is shown in Figure 7, this could be as a result of the availability of oxygen in the lattice of Al_2O_3 which enhanced the efficiency of combustion in the chamber. As performance of the engine got better, torque and speed of the engine improved, this led to an increase in the brake power of the blends B0, B10, B20, B30, B40, B50, B60, B70. The blends B0, B10, B20, B30, B40, B50, B60, B70, B80, B90 and B100 showed an increase of 0.88%, 0.47%, 4.2%, 0.76%, 0.54%, 0.63%, 0.87%, 0.57%, 0.39%, 0.51%, 1.6% at low engine speed (500 RPM) and 0.95, 0.74%, 6.6%, 0.98%, 0.78%, 0.86%, 0.75%, 0.68%, 0.93%, 0.63%, 1.0% at high engine speed (2000 RPM). Praveen, 2018 [30], The works of Pandian, 2017 [34], Sadhik and Anand, 2012 [37] and Ghanbari, et al., 2017 (54) corroborates this work.

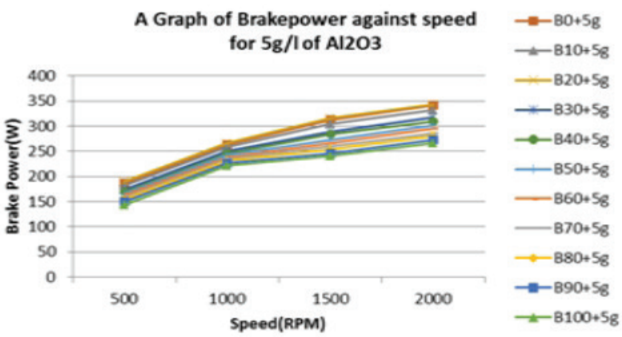


Figure 7. A graph of Brake power against speed when 5g/l of aluminum oxide was introduced blends.

A graph of Brake power against speed when 10g/l of aluminum oxide was introduced blends

Figure 8 explains the 10g/l nano-additive effect of aluminum oxide on brake power. The concentration of 10g/l of Al_2O_3 showed a further improvement in the brake power of the blends compared to 5g/l concentration. The catalytic nature of the nano additive helps the combustion to take place at lower activation energy. As a result of this, the engine was able to operate at a higher speed and torque. The blends B0, B10, B20, B30, B40, B50, B60, B70, B80, B90 and B100, showed an increase of 2.1%, 1.7%, 8.5%, 1.5%, 1.7%, 1.6%, 1.4%, 1.71%, 1.57%, 2.5% and 2.6% at low engine speed (500 RPM) and 2.0%, 1.8%, 9.7%, 2.0%, 1.6%, 2.3%, 1.7%, 1.8%, 1.7%, 1.9% and 2.9% at high speed (2000 RPM). The observation is inline with the works of Amit, 2015 [38], Shaafi and Velraj, 2015 [41], Rao and Dash, 2016 [46] and Gumus, et al., 2016 [55].

A graph of BTE against speed for pure biodiesel-diesel blends

As shown in Figure 9, the brake thermal efficiency of the blends increases with increase in the blend ratio, this

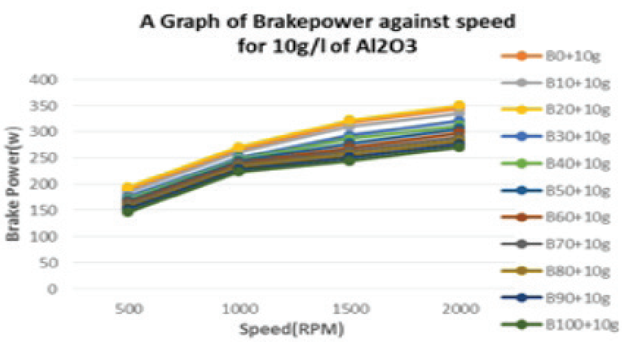


Figure 8. A graph of Brake power against speed when 10g/l of aluminum oxide was introduced blends.

is as a result of increase in brake power developed as speed increased. Brake thermal efficiency and shows a direct relationship with brake power and an inverse relationship with BSFC and calorific value. As a result of this the brake thermal efficiency is higher for low brake specific fuel consumption. The blends (B0, B10, B20, B30, B40, B50, B60, B70, B80, B90, B100) had efficiencies 6.7%, 6.25%, 5.94%, 5.13%, 4.94%, 4.38%, 4.24%, 3.98%, 3.76%, 3.54% and 3.34%, at low engine speed (500 RPM) and 12.02%, 11.01%, 11.9%, 8.61%, 7.57%, 7.04%, 6.71%, 6.56% and 6.37% at high engine speed (2000 RPM). The findings follow favourably with the works of Ojeda et al., 2015 [40], Abdel-Razek et al., 2017 [45], Sadhik and Anand, 2010 [47] and Hoseini, et al., 2018 [56].

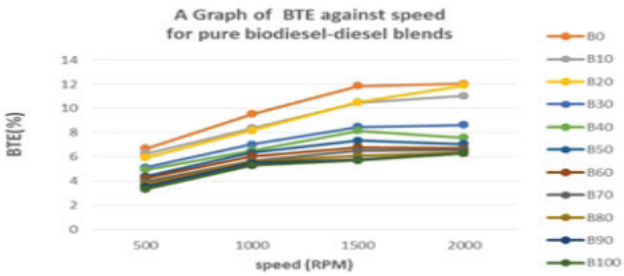


Figure 9. A graph of BTE against speed for pure biodiesel-diesel blends.

Plot of BTE against speed when 5g/l of aluminum oxide was introduced blends

Figure 10 shows plot of BTE against speed when 5g/l of aluminum oxide was introduced in the blends. There was an increase in the brake thermal efficiency when 5g/l of aluminum oxide was introduced. This can be due to reduction in the brake specific fuel consumption of engine which was as a result of the abundance of oxygen in the lattice aluminum oxide. Also, the catalytic nature of aluminum oxide could have caused improved secondary atomization in the combustion chamber. Blends (B0+5g/l, B10+5g/l, B20+5g/l, B30+5g/l, B40+5g/l, B50+5g/l, B60+5g/l, B70+5g/l, B80+5g/l, B90+5g/l, B100+5g/l) had efficiencies 8.2%, 7.5%, 6.75%, 5.6%, 5.5%, 5.1%, 4.9%, 4.5%, 4.3% and 3.7% at low engine speed (500 RPM) and 3.55% and 17.3%, 15.3%, 17.5%, 11.9%, 10.9%, 10.4%, 9.7%, 9.3%, 8.17%, 7.4% and 7.27% at high engine speed (2000 RPM). These results are in line with the works of Shaafi and Velraj, 2015 [41], Sadhik and Anand, 2014 [48], Hosseini et al., 2017 [49] and Khalife, et al., 2017 [57].

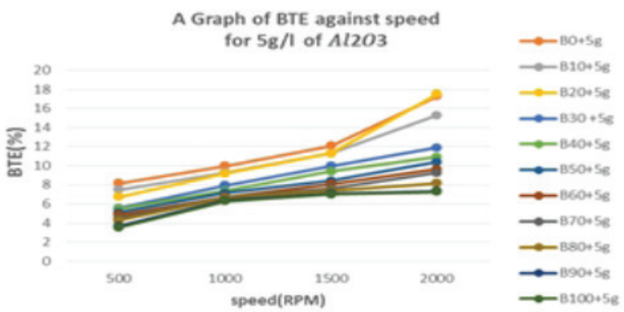


Figure 10. A graph of BTE against speed when 5g/l of aluminum oxide was introduced blends.

Plot of BTE against speed when 10g/l of aluminum oxide was introduced blend

Figure 11 shows plot of BTE against speed when 10g/l of aluminum oxide was introduced in the blends. The introduction of 10g/l of aluminium oxide led to the further increment in the brake thermal efficiency compared to the pure blends, this could be as a result of the secondary atomization offered by aluminium oxide. The secondary atomization leads to an increase in surface area to volume ratio of the fuel, and also the catalytic effect of the nano additive is improved as result of increase in concentration. This eventually led to an increase in the brake thermal efficiency. The blends (B0+10g/l, B10+10g/l, B20+10g/l, B30+10g/l, B40+10g/l, B50+10g/l, B60+10g/l, B70+10g/l, B80+10g/l, B90+10g/l, B100+10g/l) had efficiencies 9.1%, 8.9%, 8.4%, 6.9%, 6.3% 5.8%, 5.6%, 4.9%, 4.2%, 4.0%, 3.9% at low engine speed (500 RPM) and 19.1%, 16.9%, 19.4%, 14.2%, 12.07%, 11.13%, 10.6%, 10.3%, 9.9% at high engine speed (2000 RPM). The findings follow the works of Debbarma and Misra, 2018 [17], Gumus et al., 2015 [26], Gurusala and Selvan, 2015 [31], Arul, et al., 2014 [58] and Attia, et al., 2014 [59].

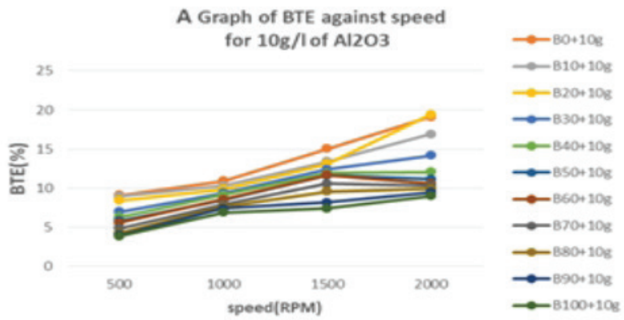


Figure 11. A graph of BTE against speed when 10g/l of aluminum oxide was introduced blend.

Emissions Parameters

Plot of CO against Torque for pure biodiesel-diesel blend

Figure 12 shows the graph of CO emission against torque. Carbon monoxide is an intermediate combustion product and is formed due to insufficient of oxygen and incomplete combustion. The pure diesel fuel has the highest emission of CO, as the volume of the biodiesel in the blends increase the amount of CO emission reduced, this is because the oxygen content of biodiesel is higher than that of diesel. The presence of more oxygen tends to improve the air to fuel ratio in the combustion chamber, this makes the CO emission reduce as the biodiesel content increase in the blends. At low engine torque (25 NM), the emission of the CO is minimal but at higher engine torque (100 NM), the emission of CO is higher this is as a result of reduction in the air to fuel ratio in the combustion chamber. The results corroborate the works of Pandian, 2017 [34], Sadhik and Anand, 2012 [37], Abdel-Razek et al., 2017 [45], Sadhik and Anand, 2014 [48] and Prabu, et al., 2015 [60].

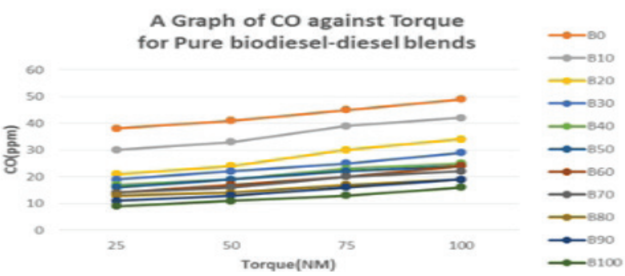


Figure 12. A graph of CO against Torque for pure biodiesel-diesel blend.

CO against Torque when 5g/l of nano additive was introduced into the blends

The graph of CO against torque is shown in the Figure 13. The introduction of aluminum oxide into the blends helps to reduce the emission of CO, this is because the Al_2O_3 introduces more oxygen into the combustion chamber which helps to reduce the incomplete combustion of carbon. At low engine torque (25 NM), the CO emissions of B0, B10, B20, B30, B40, B50, B60, B70, B80, B90, B100 reduced by 5.3% ,6.67%, 14%, 10.5%, 5.9%, 6.25%, 7.1%, 14.3% ,7.7%, 9.1% and 11%. Also, at high engine torque (100 NM), the amount of emissions reduced by 2.04%, 4.8%, 11.76%, 7%, 8%, 4.2%, 8.3%, 9.1%, 5.26%, 10.5% and 6.25%. The results agree favourably with Debbarma and Misra, 2018 [17] and Anand and Sadhik, 2013 [19] and Gumus et al., 2015 [26], Abdel-Razek et al., 2017 [45].

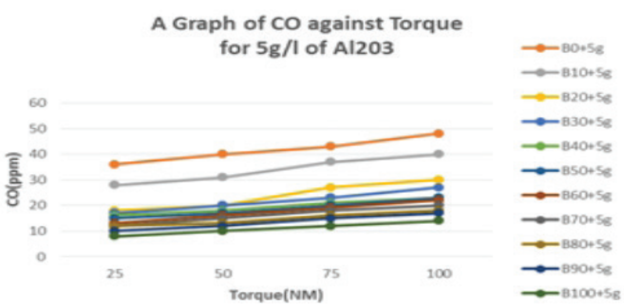


Figure 13. A graph of CO against Torque when 5g/l of nano-additive was introduced into the blends.

Plot of CO against Torque when 10g/l of nano additive was introduced into the blends

The presence of 10g/l of Aluminium oxide as shown in Figure 14, brought about a further reduction in the CO emissions compared to Figure 2-4 because more oxygen was present in the combustion chamber due to increase in the concentration of aluminium oxide. Also the ignition delay was shortened .and there was a further improvement in the air to fuel ratio in the combustion chamber. At low engine torque (25 NM), when 10g/l of aluminium oxide was introduced into the blends B0, B10, B20, B30, B40, B50, B60, B70, B80, B90 and B100 the amount of CO emissions reduced by 10.5%, 13.3%, 28.6%, 21.1% ,11.7%, 12.5%, 14.3%, 21.4% ,15.4%, 18.2% and 22.2%. At high engine torque (100 NM), the amount of CO emissions reduced by 6.1%, 7.14%, 20.6%, 13.8%, 16.0%, 8.33%, 16.7%, 13.6%, 15.8%, 1.9 % and 18.8%. The results are in tandem with that of Sadhik and Anand, 2012 [38], Amit, 2015 [39], Shaafi and Velraj, 2015 [41] and Sadhik and Anand, 2010 [47].

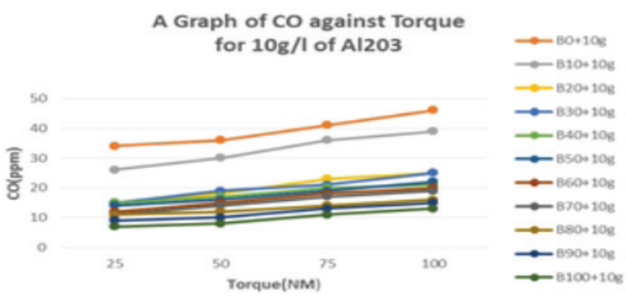


Figure 14. A graph of CO against Torque when 10g/l of nano additive was introduced into the blends.

Plot of NOx against Torque for pure biodiesel-diesel blend

Figure 15 shows graph of NOx against torque. NOx is formed as a result of high temperature in the combustion chamber. The increase in blend ratio leads to an increase in the NOx emissions. This can be as a result of high cetane number of the biodiesel. Also, the increase in NOx emission could be as a result of double bond molecules present in the biodiesel which leads to a higher adiabatic temperature. The high temperature in the chamber could also have been caused as a result of increased engine speed, which enables the nitrogen in the air to form NOx in the combustion chamber. The high cetane number causes an increase in the bonding of the biodiesel, also the double bond molecules in the biodiesel causes a rise in the combustion temperature, this is as a result of the difficulty in the breaking of the double bond. The works of Abdel-Razek et al., 2017

[45], Sadhik and Anand, 2010 [47 and Hosseini et al., 2017 [49] agreed favourably to these results.

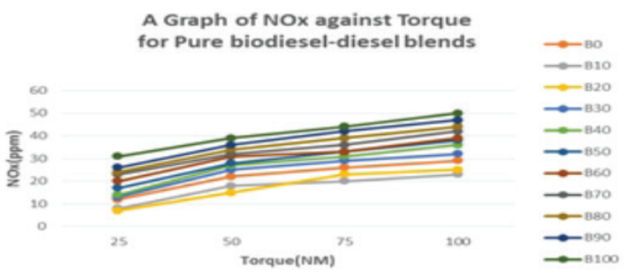


Figure 15. A graph of NOx against Torque for pure biodiesel-diesel blend.

Plot of NOx against Torque when 5g/l of Nano additive was introduced into the blends

Figure 16 shows the graph of NOx against torque. The introduction of Aluminum oxide Nano-additive reduced the NOx emissions in the compression ignition engine. This reduction can be due to the catalytic activity of the Nano-additive, the catalytic activity enables the reaction in the combustion chamber to take place faster, as the reaction in the chamber speeds up, the double bond in the biodiesel takes less time to break. The fuel spent less time in the chamber, this therefore gives room for an unnecessary increase in the combustion temperature in the combustion chamber simply because the rate of reaction is faster. At low engine torque (25 NM), the NOx emissions of B0, B10, B20, B30, B40, B50, B60, B70, B80, B90 and B100 reduced by 16% ,25% ,28.6%, 7.7%, 5.9%, 5.0%, 4.3%, 4.2%, 3.8% and 3.2% and at high engine torque (100 NM), the NOx emission reduced by 3.45%, 8.7%, 16%, 3.1%, 2.78%, 2.6%, 2.5%, 4.76%, 2.3%, 4.3% and 4.0%. The works of Sadhik and Anand, 2010 [36], Sadhik and Anand, 2012 [38], Sadhik and Anand, 2014 [48] and Hosseini et al., 2017 [49] agreed favourably to the results.

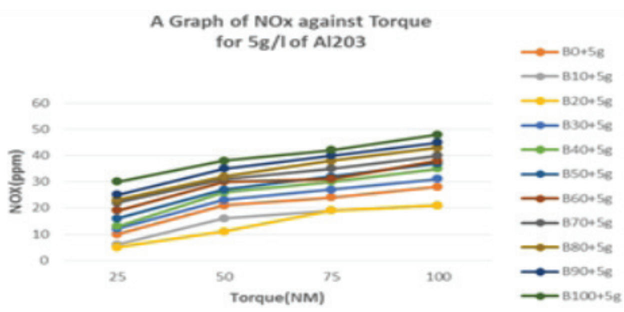


Figure 16. A graph of NOx against Torque when 5g/l of Nano additive was introduced into the blends.

Plot of NOx against Torque when 10g/l of Nano additive was introduced into the blends

Figure 17 shows the graph of NOx against torque. It exhibits a similar characteristic with the 5g/l. The extra 5g/l of aluminum oxide gives room for a further decrease in the amount of NOx produced. At low engine torque (25 NM), the amount of NOx reduced by 25%, 25.1%, 42.9%, 15.4%, 14.3%, 11.7%, 10%, 8.6%, 8.3%, 7.6% and 6.5% for blends of B0, B10, B20, B30, B40, B50, B60, B70, B80, B90 and B100. At high engine torque (100 NM) the amount of NOx reduced by 10.3%, 13%, 32%, 9.4%, 5.6%, 5.3%, 5.13%, 9.52%, 6.82%, 6.4% and 8.0%. These findings agreed favourably with the works of Bet-Moushoul et al.,[16], Debbarma and Misra, [28], Pandian, [35], Sadhik and Anand, [36], Arul Mozhi Selavn, et al., [61], Basne et al [62], Asalekar et al, [63] and Gowda et al,[64].

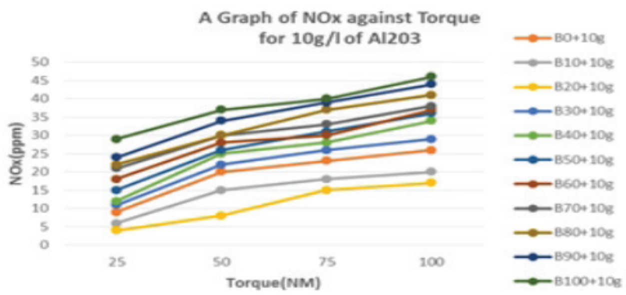


Figure 17. A graph of NOx against Torque when 10g/l of Nano additive was introduced into the blend.

CONCLUSION

This work studied the combinational effects of blends of diesel, waste cooking oil-based biodiesel: B0 to B100 on CI engines; at 10 % incremental step, and aluminum oxide (Al_2O_3) nanoparticles additive with dosages of 5g/l and 10g/l on each fuel blends. From our findings, the following inferences are drawn:

(i) The presence of nano additive in blends of diesel and waste cooking oil-based biodiesel, improves the performance and emission characteristics of compression ignition engine

(ii) The percentage increase of biodiesel in the pure biodiesel-diesel blend at higher engine speeds, gives a decrease in the CO emissions, brake-specific fuel consumption, and an increase in NOx emissions, brake power and brake thermal efficiency

(iii) Blend B20+10g/l gave the best result for performance and emissions characteristics at all investigated speeds and torques, as it increased brake power and BTE by 9.7% and 5% respectively, compared to the pure diesel; and reduced the BSFC by 38%, and CO and NOx emissions by 20.6% and 16% respectively compared to pure diesel.

Thus, in general, it is safe to conclude that, for top performance and emission characteristics of CI engines; pure diesel-waste cooking oil-based biodiesel blend with aluminum oxide nano additive in the proportion of B20 +10 g/l, could be used to fuel compression ignition engines.

Recommendation

It is recommended that the stability of nanofluid based additives through ultrasonic vibration, addition of surfactants and pH control, be investigated. It is further recommended that effect of peak cylinder pressure and heat release rate in CI Engines due to effect of ignition delay and nanofluid based diesel-biodiesel blends calorific values be studied.

NOMENCLATURE

B0	One hundred percent fossil diesel
B0 + 5 g/l	One hundred percent fossil diesel plus 5 g/l of aluminum oxide Nano-additive
B0 + 10 g/l	One hundred percent fossil diesel plus 10 g/l of aluminum oxide Nano-additive
B10	Ten percent biodiesel in diesel-biodiesel blend
B10 + 5 g/l	Ten percent biodiesel in diesel-biodiesel blend plus 5 g/l of aluminum oxide Nano-additive
B10 + 10 g/l	Ten percent biodiesel in diesel-biodiesel blend plus 10 g/l of aluminum oxide Nano-additive
B20	Twenty percent biodiesel in diesel-biodiesel blend
B20 + 5 g/l	Twenty percent biodiesel in diesel-biodiesel blend plus 5 g/l of aluminum oxide Nano-additive
B20 + 10 g/l	Twenty percent biodiesel in diesel-biodiesel blend plus 10 g/l of aluminum oxide Nano-additive
B30	Thirty percent biodiesel in diesel-biodiesel blend
B30 + 5 g/l	Thirty percent biodiesel in diesel-biodiesel blend plus 5 g/l of aluminum oxide Nano-additive
B30 + 10 g/l	Thirty percent biodiesel in diesel-biodiesel blend plus 10 g/l of aluminum oxide Nano-additive
B40	Forty percent biodiesel in diesel-biodiesel blend
B40 + 5 g/l	Forty percent biodiesel in diesel-biodiesel blend plus 5 g/l of aluminum oxide Nano-additive
B40 + 10 g/l	Forty percent biodiesel in diesel-biodiesel blend plus 10 g/l of aluminum oxide Nano-additive
B50	Fifty percent biodiesel in diesel-biodiesel blend
B50 + 5 g/l	Fifty percent biodiesel in diesel-biodiesel blend plus 5 g/l of aluminum oxide Nano-additive
B50 + 10 g/l	Fifty percent biodiesel in diesel-biodiesel blend plus 10 g/l of aluminum oxide Nano-additive
B60	Sixty percent biodiesel in diesel-biodiesel blend
B60 + 5 g/l	Sixty percent biodiesel in diesel-biodiesel blend plus 5 g/l of aluminum oxide Nano-additive
B60 + 10 g/l	Sixty percent biodiesel in diesel-biodiesel blend plus 10 g/l of aluminum oxide Nano-additive
B70	Seventy percent biodiesel in diesel-biodiesel blend
B70 + 5 g/l	Seventy percent biodiesel in diesel-biodiesel blend plus 5 g/l of aluminum oxide Nano-additive
B70 + 10 g/l	Seventy percent biodiesel in diesel-biodiesel blend plus 10 g/l of aluminum oxide Nano-additive
B80	Eighty percent biodiesel in diesel-biodiesel blend
B80 + 5 g/l	Eighty percent biodiesel in diesel-biodiesel blend plus 5 g/l of aluminum oxide Nano-additive
B80 + 10 g/l	Eighty percent biodiesel in diesel-biodiesel blend plus 10 g/l of aluminum oxide Nano-additive
B90	Ninety percent biodiesel in diesel-biodiesel blend
B90 + 5 g/l	Ninety percent biodiesel in diesel-biodiesel blend plus 5 g/l of aluminum oxide Nano-additive
B90 + 10 g/l	Ninety percent biodiesel in diesel-biodiesel blend plus 10 g/l of aluminum oxide Nano-additive
B100	One hundred percent biodiesel
B100 + 5 g/l	One hundred percent biodiesel plus 5 g/l of aluminum oxide Nano-additive
B100 + 10 g/l	One hundred percent biodiesel plus 10 g/l of aluminum oxide Nano-additive
CI	Compression Ignition Engines
CO	Carbon monoxide
NO_X	Nitrogen Oxide
EGT	Exhaust Gas Temperature

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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ARTICLES FOR FACULTY MEMBERS

COMPARATIVE ANALYSIS OF WASTE COOKING OIL BIODIESEL MIXED WITH NANOPARTICLE ADDITIVES ON PHYSICOCHEMICAL PROPERTIES AND DIESEL ENGINE PERFORMANCE

Performance, emission analysis and optimization of biodiesel blend with CuO nano particle additive in di diesel engine / Manimaran, M., Sakthi Balan, G., Ravichandran, M., Mohanavel, V., & Dhinakaran, V.

AIP Conference Proceedings
Volume 2283 (2020) 020131 Pages 1-11
https://doi.org/10.1063/5.0024978
(Database: AIP Publishing)

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Cite as: AIP Conference Proceedings **2283**, 020131 (2020); https://doi.org/10.1063/5.0024978
Published Online: 29 October 2020

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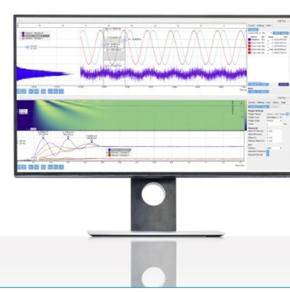

Performance, Emission Analysis and Optimization of Biodiesel blend with CuO Nano particle additive in DI Diesel Engine

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Abstract. Disposal of waste cooking oil (WCO) is a difficult process, so it is chosen for the production of biodiesel. The impact of CuO, nanoparticle additive on biodiesel blend obtained from waste cooking oil was tested in DI diesel engine. The obtained waste cooking oil is subjected to filtering process and it is trans-esterified to form biodiesel. This biodiesel is mixed with diesel to produce different blends D90+B10 (90% Diesel +10% Biodiesel), D80+B20 (80% Diesel +20% Biodiesel), D80+B20+50mg (80% Diesel +20% Biodiesel+50mg additive). These blends are subjected to emission test and performance test and the values are obtained. Based on the test report it is found that this (D80+B20-80% Diesel+20% Biodiesel) blend has higher emission properties. To control the emission the copper oxide additive is added to that blend and it is subjected to emission and performance test and it is found that brake thermal efficiency is decreased by 17.9%, specific fuel consumption is decreased by 14.11%, CO emission is decreased by 70.8%, HC emission is decreased by 17.45%, and NOx emission is increased by 15.65% this value is obtained by comparing with the blend D80+B20.

INTRODUCTION

The major crisis which the growing countries like India face is the uninterrupted rise in the cost of petroleum products. The researchers and scientists were struggling for many years to find any alternative sources for the fuel. Biodiesel is one which founds to be a suitable alternative for petroleum products, which can be extracted from either animal fat or edible oils. The properties such as flash point, fire point, calorific value and water contents in fuels play a vital role in the combustion property of biofuels.The biodiesel can be obtained from various sources, which involves investment in the purchase of raw materials, so we have chosen the waste cooking oil which can be obtained from the restaurants and other oil-based industries. The first process is done in this biodiesel extraction by the trans-esterification reaction. List of materials required for carrying this process is methanol and NaOH. This trans-esterification process is not done manually in this recent days, it is done by the use of biopro190 recently introduced for carrying the biodiesel conversion process. Thus, the given waste cooling oil is filtered and subjected to the biopro190, where the conversion is done. The obtained Biodiesel is then subjected to performance and emission test and the analysis is done. Titanium oxide is added as an additive in biodiesel blend. It is found that there where the emission of additional gas along with CO, HC, NOX. The additional gas which is emitted is found to be toxic. So, titanium oxide is not selected as additive [1]. The anti-oxidant additives are found to be more efficient to increase properties such as thermo-oxidative stability, low-temperature properties, lubricity, and rheological properties. The thermal and oxidative stability of the fuel was enhanced by the addition of natural anti-oxidant additives [2]. Making of biodiesel blend using petrodiesel has the properties of lower CO2, HC, emissions but it suffers from its drawbacks including higher viscosity, lower volatility, lower heating value, and higher NOx

Proceedings of International Conference on Recent Trends in Mechanical and Materials Engineering
AIP Conf. Proc. 2283, 020131-1–020131-10; https://doi.org/10.1063/5.0024978
Published by AIP Publishing. 978-0-7354-4013-5/$30.00

emissions [3]. Acetylferrocene and palladium-based additives were blended with the biodiesel and its performance and emission characteristics were compared, among them acetylferrocene shows the increased brake thermal efficiency as well as decreased CO emission [4]. The carbon-coated aluminum is used as an additive along with ethanol. Here the emission of NOx is reduced but there is an emission of HC gas due to ethanol [5]. Their view the paper on nanoparticle addition on the biodiesel blend gives different results about the penetration and dispersal properties of nanoparticles in the liquid fuels. Then it is also found that nanoparticles emission may emit some toxic gases which are harmful to health and those were studied [6].

MATERIALS AND METHODS

Waste cooking oil

Normally cooking oil is obtained from plant or animal fat which contains more cholesterol. Cooking oil is commonly used for frying purposes. Nowadays most of the restaurants and hotels after using the oil for the cooking purpose they are being disposed in ground or drainage, which causes and pollution as well as water pollution due to this microorganism may get destroyed. So, in this work chosen the waste cooking oil as the raw material due to low cost and contribute something good to this environment by disposing the waste cooking oil.

FIGURE 1. Process Flow for Biodiesel Production

Copper oxide (CuO)

Copper oxide chosen as additive in this work, it is just blended with the biodiesel and used for combustion processes. The main reason for choosing this as an additive is to reduce the unwanted emission of gases while burning of the biodiesel. The unburnt fuel is the main reason for the pollution, this unburnt fuel when reacts with the copper oxide the CO emission percentage is decreased while the fuel is burnt maximum percentage.

$$2CuO + C = 2Cu + CO_2 \quad (1)$$

$$CuO + CO = Cu + CO_2 \quad (2)$$

BIO PRO190

Bio pro 190 is an automated machine which is used to prepare biodiesel .Generally its operation is like a washing machine .This bio pro 190 has separate chambers to pour WCO, KOH, Methanol and Sulphuric acid .This machine is used to heat the oil and to mix KOH, Methanol with the oil to make bio diesel.

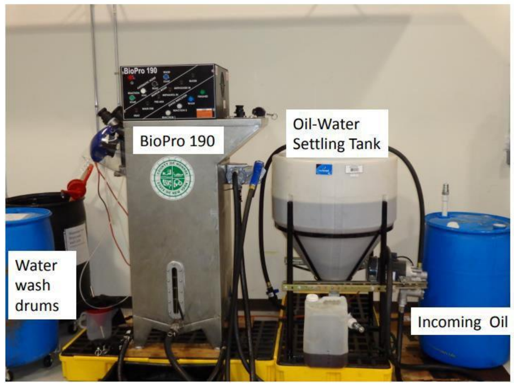

FIGURE 2. Photographic view of Transesterification process

Filtering

Filtering is the first step to make bio diesel. This is because WCO contains more wastes in it and to remove these wastes filtration process is used. To filter the oil use filters or mesh. If we use oil without filtering it then the properties of bio diesel will be poor .So it is very important to filter the oil. A three-step filtering process is carried out to ensure the absence of any foreign particles in the waste cooking oil.

Transesterification

Trans-esterification is the process of remove fatty acids from the oil with adding alcohol like methanol to get product of bio diesel with glycerin. It is done by heating the oil for about 120^{o}Celsius. This process takes place in bio pro 190 automated machine. Here the oil is heated and mixed for about 24 hours. Thenthe methanol, KOH are mixed to it to produce biodiesel and glycerin. The process will run for about 48 hours. Then the oil is made to cool and glycerin and biodiesel are separated.

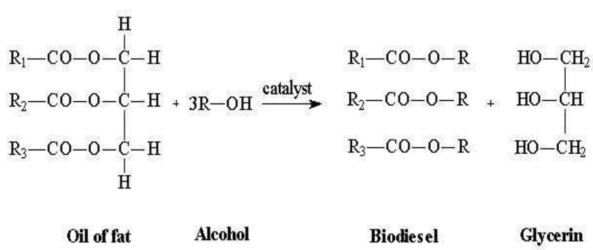

FIGURE 3. Transesterification process

TABLE 1. Properties ofFuels

Properties	Diesel	Raw WCO	WCO Biodiesel
Density (kg/m^3)	823	918.4	887
Viscosity (cst)	3.6	12.6	5.87
Flash point ^{o}C	58	205	115
Fire point ^{o}C	61	217	122
Cetane number	48	52.1	53
Calorific value MJ/Kg	45.2	30	40.67

EXPERIMENTAL ANALYSIS

To determine the performance and emission characteristics of Waste cooking methyl ester oil with CuO additives was tested in 4-stroke 1-cylinder DI diesel engine. The engine was connected with an eddy current dynamometer to taken the reading for different load. Initially the engine was running to warm up by pure diesel fuel for first 20 minutes. The emission characteristics were noted for the different blends by using AVL-444 digasanalyser.

TABLE 2. Engine specifications

Engine manufacturer	Kirloskar oil engines ltd
Bore & stroke (mm)	87.5 &110
Number of cylinders	1
Compression ratio	17.5:1
Speed	1500rpm
Method of cooling	Water cooled
Fuel timing	27^o by spill (BTDC)
Rated power	3.5 kW@1500rpm
No of Strokes	4

After the biodiesel is collected it is mixed with diesel as 3 blends by using the magnetic stirrer.

D90+B10 - 90% Diesel +10%Biodiesel

D90+B10+50mg - 90% Diesel +10% Biodiesel+50 mg additive

D80+B20 - 80% Diesel +20%Biodiesel

D80+B20+50mg - 80% Diesel +20% Biodiesel+50mg additive

After the blend is prepared it is tested in a diesel engine and the observation values are noted.

FIGURE 4. Image of waste cooking oil and obtained biodiesel

RESULTS AND DISCUSSION

Performance characteristics

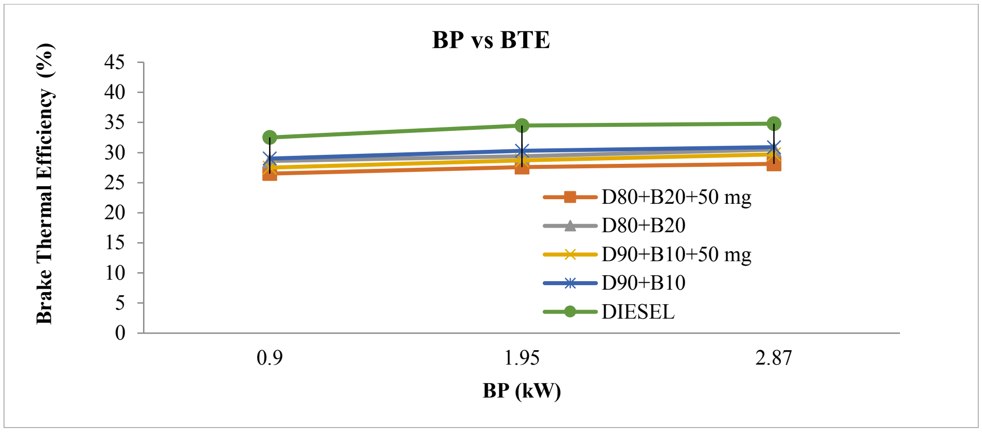

FIGURE 5. Brake Power vs BTE

It can be seen from the graph between BP and BTE that the Brake thermal efficiency of the fuel decreases by addingthe Biodiesel proportion, the low Brake thermal efficiency is due to the lower air-fuel mixing, higher viscosity and lower calorific values of the blending proportions. The brake thermal efficiency is calculated using the formula given below.

Brake thermal efficiency = Brake power / Mass of fuel supplied× Calorific value
(3)

Specific fuel consumption

The Specific Fuel Consumption is calculated using the formula given below.

Specific Fuel Consumption = Mass of fuel consumption / Engine brake power
(4)

The below graph shows the relation between the Brake power and Specific fuel consumption of the three different blends prepared in the previous steps. It can be seen that the specific fuel consumption of the fuel decreases with increase in load, but the SFC increases by adding the biodiesel to the diesel. Since specific fuel consumption is increased for biodiesel blends due to higher mass and lower calorific value compare with diesel fuels.

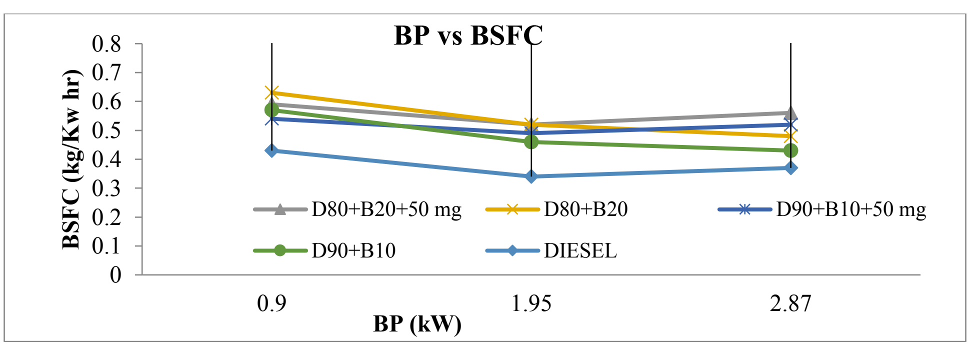

FIGURE 6. Brake Power vs BSFC

EMISSION CHARACTERISTICS

CO emission

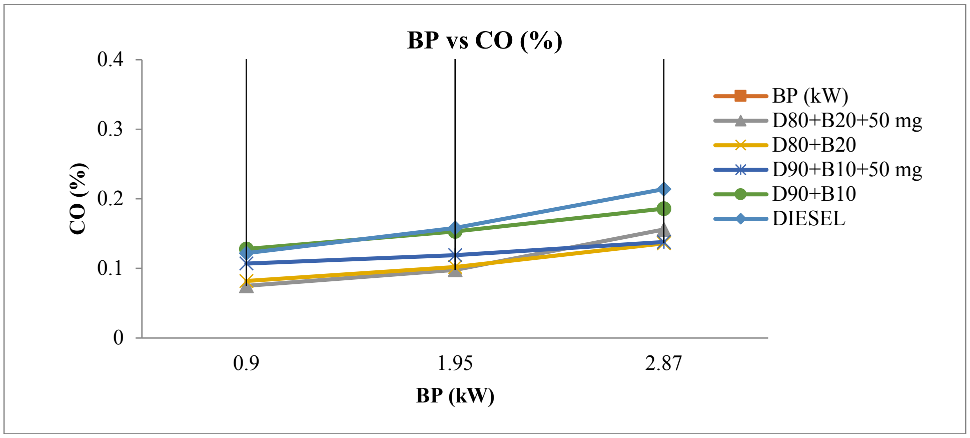

FIGURE 7. Brake Power vs CO Emission

It can be seen from the graph that the level of CO emission decreases by the increase of biodiesel blends. Normally, the CO emission was formed insufficient of oxygen content in the fuels and low flame temperature. if the percentage of biodiesel increases CO emission is decreases while in case of addition of additive CuO added with biodiesel blends the oxygen content was increased in the blends due to that the CO emission was reduced in blends.

Hydro carbon emission

It can be seen from the graph that the level of HC emission decreases by the increase of biodiesel content i.e, if the percentage of biodiesel increases HC emission is decreased while in case of addition of additive the HC emission is lowered since the complete fuel combustion is possible in case of adding CuO additive with biodiesel blends. HCemission is one of the harmful gases which causes global warming.

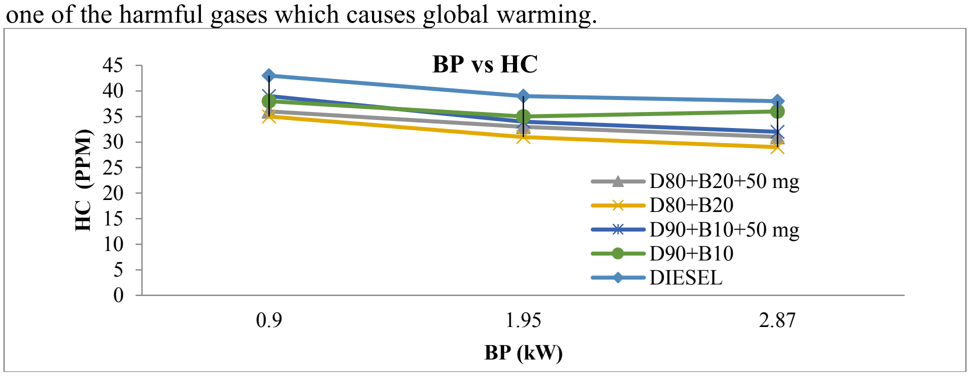

FIGURE 8. Brake Power vs HC Emission

Oxides of nitrogen emission

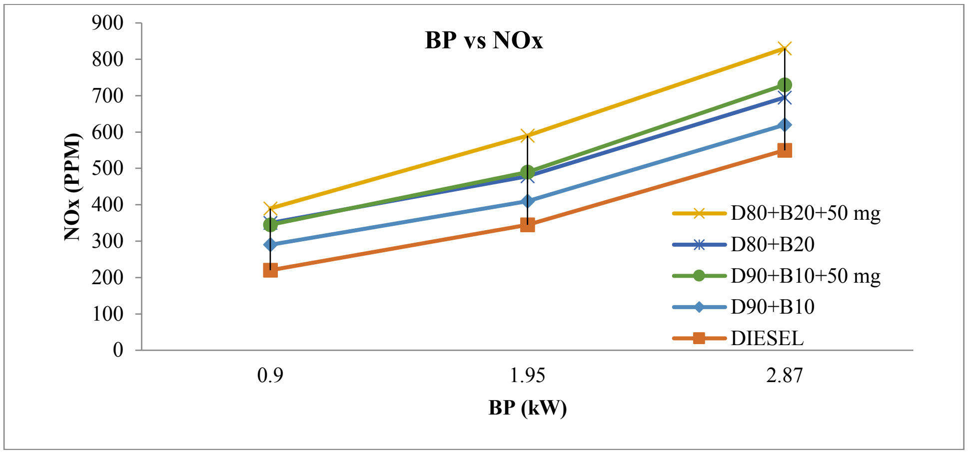

FIGURE 9. Brake Power vs NOx Emission

The above graph value discuss between the brake power and NOx emission for different biodiesel and diesel fuels. It can be seen from the graph that the level of NO_X emission increases by the increase of biodiesel content. NO_X is considered to be one of the most toxic gases which is being exhausted by the various fuels during the combustion process.

Optimization of emission results

Optimization and design of experiments (DOE) process is done to analyze the obtained results from the experiments and to find out the most influencing factor that affects the results. It is also done to find the optimum input values which can produce the optimum results. Many techniques and design methods are followed to do optimization in which the simplest method is Taguchi optimization. In Taguchi L4 orthogonal array is chosen, through which four different blends are obtained and the design was suggested by the Taguchi design in MINITAB 17 software. The L4 orthogonal array design and the results obtained are tabulated in the table 3 and 4. Regression analysis was done and the ANOVA table was obtained through which the most influencing factor can be found from the F-value. The R-Squared value, the design can be checked for its significance and the regression equation can also be obtained for each responses. In this design two factors with two levels and four responses were analyzed and the contour plots are obtained, which clearly indicates the optimum input values for the required responses. In this design the values are optimized for smaller is better concept, as the emission levels are to be maintained at lower levels.

TABLE 3.ANOVA for CO

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	2	2.0609	1.0305	8.41	0.237
WCO	1	0.4225	0.4225	3.45	0.314
CuO	1	1.6384	1.6384	13.37	0.17
Error	1	0.1225	0.1225		
Total	3	2.1834			

TABLE 4. Model summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.35	94.39%	83.17%	10.23%

Regression equation

$$CO = 1.445 - 0.0650\ WCO + 0.02560\ CuO \quad (5)$$

TABLE 5. ANOVA for HC

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	2	23.2813	11.6406	82.78	0.077
WCO	1	8.2656	8.2656	58.78	0.083
CuO	1	15.0156	15.0156	106.78	0.061
Error	1	0.1406	0.1406		
Total	3	23.4219			

TABLE 6. Model summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.375	99.40%	98.20%	90.39%

Regression equation

$$HC = 17.188 - 0.2875\ WCO + 0.07750\ CuO \quad (6)$$

TABLE 7. ANOVA for NOx

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	2	0.55445	0.27722	20.96	0.153
WCO	1	0.44222	0.44222	33.44	0.109
CuO	1	0.11222	0.11222	8.49	0.211
Error	1	0.01323	0.01323		
Total	3	0.56767			

TABLE 8. Model summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.115	97.67%	93.01%	62.73%

Regression equation

$$NOX = 2.607 - 0.0665\ WCO - 0.00670\ CuO \quad (7)$$

TABLE 9. ANOVA for CO_2

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	2	5.91545	2.95772	86.42	0.076
WCO	1	1.65122	1.65122	48.25	0.091
CuO	1	4.26422	4.26422	124.59	0.057
Error	1	0.03422	0.03422		
Total	3	5.94968			

TABLE 10. Model summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.185	99.42%	98.27%	90.80%

Regression equation

$$CO2 = 7.442 - 0.1285\ WCO - 0.04130\ CuO \quad (8)$$

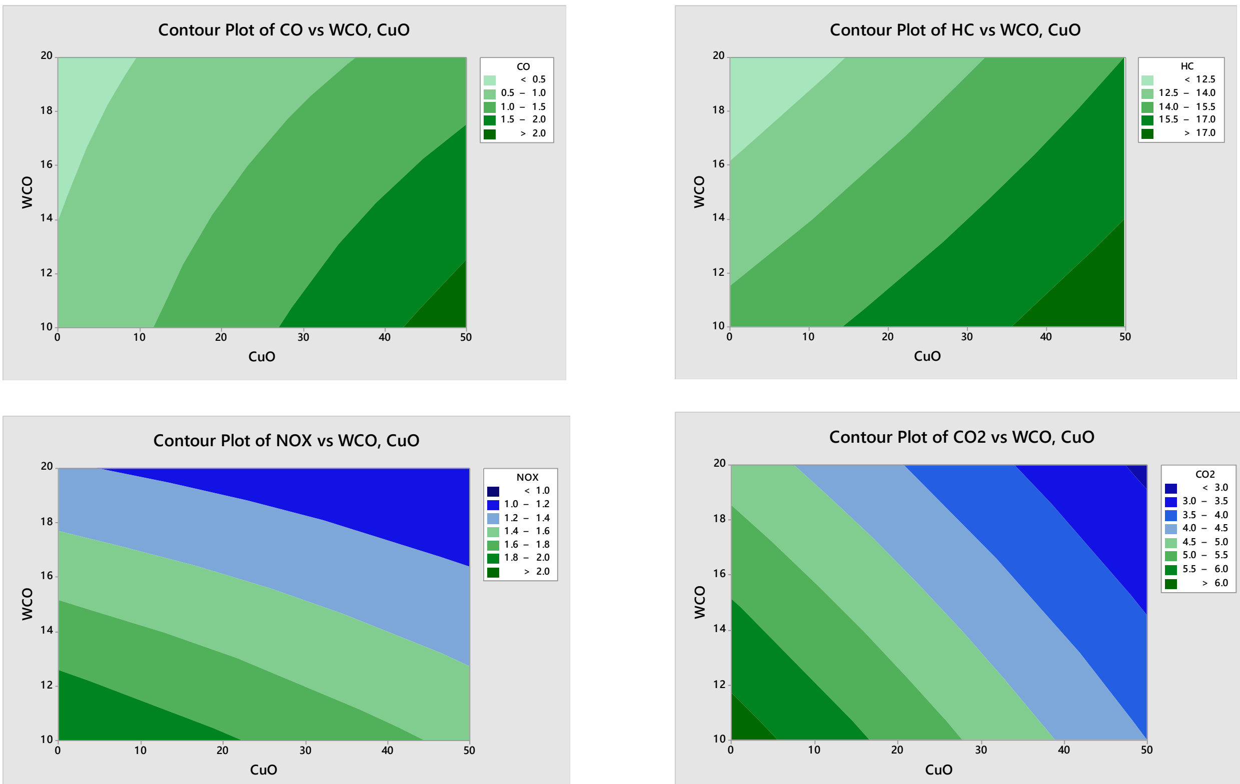

FIGURE 10. Contour plots for different emissions vs Input factors

CONCLUSION

The experimental investigation of CuO Nano-particle additive on biodiesel blend obtained from waste cooking oil was tested in DI diesel engine. Among the various blend prepared from the Biodiesel such as D90+B10 (90% Diesel +10% Biodiesel), D80+B20 (80% Diesel +20% Biodiesel) and pure diesel, it was found that the blend D80+B20 (80% Diesel +20% Biodiesel) exhibit the higher emission value. The ultimate aim of the project is to reduce the emission by adding CuO Nano-particle additive. Since the blend D80+B20 (80% Diesel +20% Biodiesel) shows higher emission value Nano- particle is added to this blend.

The new blend prepared after the addition of Nano-particle is D80+B20+50mg (80% Diesel + 20% Biodiesel + 50mg additive). After this it is concluded that the new blend shows some positive result in case of specific fuel consumption, CO emission and HC emission. It is found that CO and HC emission is reduced while comparing with the non-additive blend, it is also proved that SFC of additive added blend is efficient. But the BTE is decreased after the addition of biodiesel blend and theCO2 and NOX emission is increased.

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Thank you.

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