

REVIEW

A comparative study of the impact on combustion and emission characteristics of nanoparticle-based fuel additives in the internal combustion engine

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Abstract

The search for an effective solution to improve performance and emission characteristics of internal combustion (IC) engines used in the commercial sector is regarded as one of the most important and essential issues in recent years due to increasing levels of pollution. Nanoparticles with their additive ability to increase fuel reactivity and atomization, due to their large surface area and high heat transfer coefficient, can improve the performance and emission characteristics of a fuel. This review highlights the use of nanoparticles as fuel additives to enhance the emission and performance characteristics of IC engines. Detailed comparisons of performance, emission, and combustion characteristics of IC engines using fuels blended with nanoparticles have been done. Nanoparticles were observed to be an oxygen buffer for fuel combustion and boost fuel atomization, thus enhancing engine performance. While alumina exhibited a decrease in levels of HC and CO but a considerable increase in NO_x, graphene nanoparticles and ceria were found to be particularly effective in enhancing engine performance. Detailed study has been done on other nanoparticles, including metal-oxide, nonmetal-oxide as well as carbon nanoparticles. Overall, the use of nanoparticles can enhance the thermophysical characteristics of fuels, improving the emission and performance characteristics of engines. The review suggests that selecting the right

Abbreviations: ADV IT, advanced injection timing; AgSCN, 3D silver thiocyanate nanoparticles; Al₂O₃, aluminum oxide or alumina; AOT, aerosol-OT; BSFC, brake-specific fuel consumption; bTDC, before top dead center; BTE, brake thermal efficiency; C, graphite; CeO₂, cerium oxide or ceria; CI, compression ignition; CNT, carbon nanotube; CO, carbon monoxide; CuO, copper oxide; CVD, chemical graphite deposition; DI, direct injection; ENOB, emulsion of *Nerium oleander* biofuel; FFO, ferrous ferric oxide; GNP, graphene nanoparticle; GO, graphene oxide; GR, graphene; HC, hydrocarbons; HVO, hydrotreated vegetable oil; LBG, liquefied biogas; LNG, liquified natural gas; NMs, nanomaterials; NO_x, nitrous oxide; ODSs, ozone depleting substances; PAHs, polycyclic aromatic hydrocarbons; RET IT, retarded injection timing; SEM, scanning electron microscopy; Sr@ZnO, strontium-zinc oxide; TEM, transmission electron microscopy; TiO₂, titanium oxide; VOCs, volatile organic compounds; XRD, X-ray diffraction analysis; ZEV, zero emission vehicle.

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dosage and variety of nanoparticles is crucial for optimizing engine performance, and thus directly helps in tackling the ongoing pollution problem.

KEYWORDS

combustion characteristic, emission characteristic, internal combustion engine, nanoparticles

1 | INTRODUCTION

Conventional fossil fuels are diminishing over time, and it is predicted they will become extinct in the next few years. Figure 1 shows a rise in the average world temperature as well as rise in global emissions, and the rise in temperature can be associated with an increase in conventional fuel emissions. Therefore, finding new nonrenewable fossil fuel substitutes is becoming more crucial with time.¹

Along with the temperature, the level of greenhouse gas (GHG) emissions also incrementally increased throughout the year, which is the major reason why there is a hike in global temperature. As GHGs are the main contributing factor to global warming, decreasing the GHGs will definitely help tackle the ongoing problem of global warming. Figure 2 shows the GHG emissions throughout the years in various areas of the world.^{2,3}

Biofuels are considered as a good alternative fuel to replace nonrenewable conventional fuels from an economic and environmental standpoint. All alternative biofuels must be easy to renew, have higher availability, and be environmentally friendly to be effective. The main

challenge faced by the alternative fuel industry is the emissions; it has been suggested that the best method to reduce these car emissions is to use vehicles fueled through alternative fuels, like electricity, biofuels, and hydrogen. A thorough analysis of the elements affecting the use of these alternative fuels for automotive use is required due to common concerns about the sustainability of their use, potential hazards, and what will happen to them when their supplies are over. Although fuel cell and battery-powered vehicles are “locally” emission-free, but their market penetration and customer acceptance are limited due to resource scarcity, infrastructure restrictions, and their high cost.⁴ The greenhouse effect significantly contributes to maintaining the world warm. Average global temperature of the planet would be significantly lower without a greenhouse effect, making it impossible for life to exist on Earth as it is today. Emissions caused by vehicles are a major threat to the ozone layer, causing it to deplete with time.⁵ Other than that, vehicle smoke, soot, unburnt hydrocarbons, carbon monoxides, carbon dioxides, aldehydes, polycyclic aromatic hydrocarbons, volatile organic compounds (VOCs), and particulate matters also contribute to the overall pollution, which are the outcomes of the broad and indiscriminate use of conventional fossil fuels in transportation. These cause a very detrimental impact on the atmosphere, including the development of smog and ozone depletion, which give a push to the global warming too.^{*} Although the stratospheric ozone is beginning to recover from previous loss, but uncertainties surrounding unexpected emissions of ozone depleting substances (ODSs), increases in short-lived anthropogenic ODSs that are uncontrolled and natural ODSs brought on by climate change could put off the restoration of stratospheric ozone levels by several decades, making it crucial to continue implementing the Montreal Protocol effectively, expand atmospheric observations of ODSs and improve knowledge of how ozone recovery and climate change interact.⁶

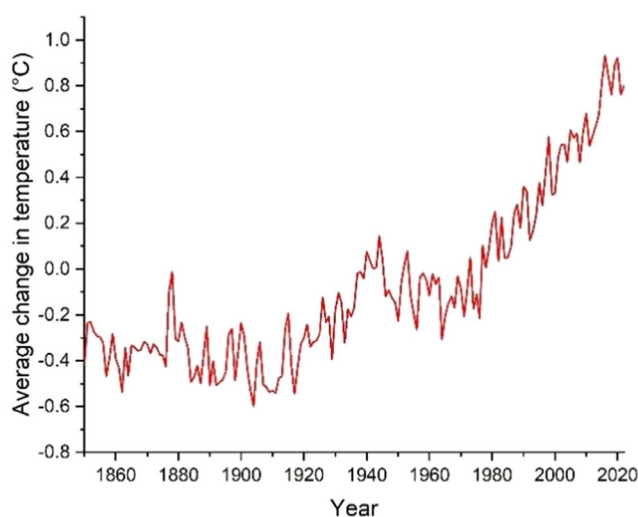


FIGURE 1 Anomaly in the average temperature as compared with the average throughout the years 1961–1990.¹

*Cradle to grave lifecycle analysis of US light-duty vehicle.

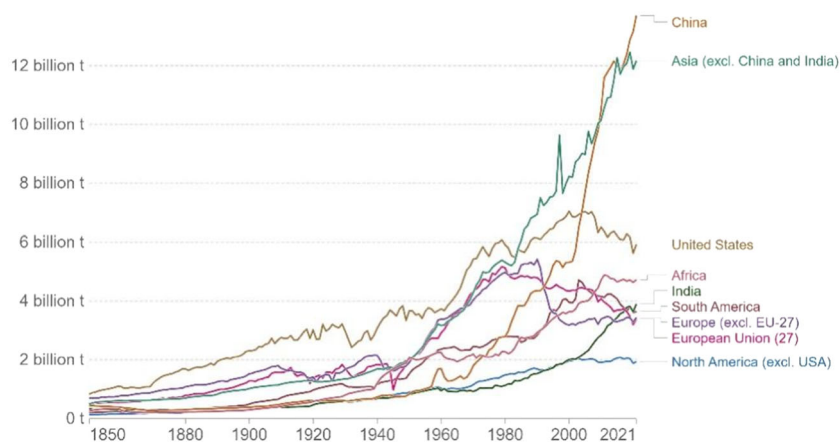


FIGURE 2 Regional greenhouse gas emissions through years 1750–2022.²

International Maritime Organization due to the ongoing scenario of greenhouse emissions and stricter controls have been placed on various aspects of international sea transport operations to preserve the environment due to an increase in pollution levels. Researchers have explored potential paths and technologies for decarbonizing global maritime transport operations, specifically through the use of alternative energy sources like biofuels, which can reduce emissions by 25%–100%, but challenges like supply constraints and technical limitations must be addressed before they can be fully utilized.⁷ In another study, the issue of environmental pollution in the resource-recycling automobile gearbox production sector was investigated. The report's analysis of the factory depicts that there are 54 different kinds of VOCs that led to the estimation of emission factors. The study also identified the primary sources of contaminants and modeled the spread of VOCs at various heights. According to the study, most of these VOCs are generated during cleaning and sand-blasting processes, and the concentration of VOCs was higher at 3.0 m than at 1.5 m. The most prevalent and dominant of all emissions were volatile halogenated hydrocarbons and aromatic organic molecules. Primary sources of dichloromethane and toluene were processing additives and lubricating oil. According to the study, gearbox remanufacturing released about 25.59 g of VOCs into the atmosphere. To reduce VOC emissions from the remanufacturing process, the researchers recommended employing more ecofriendly production techniques and environmental protection measures.⁸ Apart from that, everyone in the globe faces obstacles, but China's industry for remanufacturing used cars offers greater advantages than recycling. Uncertain recycling laws apply to Chinese trashed cars, and there are various categories and types of recycling models. Research is being done to come up with a method to promote recycling. However, certain approaches encounter

difficulties, like informational barriers. But active work is done to help build a structure for empirical research on automobile recycling for remanufacturing.⁹ To tackle this problem, active research is being done to boost the introduction of substitute marine fuels, including hydro-treated vegetable oil, liquified natural gas, liquefied biogas, ammonia, hydrogen, ethanol, methanol, nuclear power, and electricity, for maritime decarbonization, and evaluates the current system of international law governing the regulation of these fuels and addressing risks they pose, while exploring viable solutions to address future specific marine environmental threats.¹⁰ Reducing noxious emissions from vehicles through alternative fuels like electricity, hydrogen, and biofuels is ideal, but their sustainable resource availability, risks, and end-of-life fate need to be assessed. While battery and fuel cell-powered vehicles emit zero emissions, they are relatively expensive and face resource scarcity and infrastructure limitations, hindering their market acceptance. Biofuels, on the other hand, face challenges in feedstock procurement and reducing problems of fuel versus food. Addressing these challenges is critical for sustainable use of alternative fuels as the main source of vehicle fuel, requiring a comparative analysis of their categorized challenges. This research serves as a reference for informed decisions towards achieving the Paris Agreement goals of reducing global temperature.⁴ Engine performance can be increased by mixing nanoparticles with traditional or alternative fuels. Its long-term use is however constrained by problems like clogging, stability, increasing NO_x emissions, and high rates of consumption. Using several nanoparticles as fuel additives to boost performance and emission characteristics is the main topic of this review. By serving as a catalyst and boosting the qualities of heat and mass transport, nanoparticles' large surface area enhances the combustion process and engine performance. The review depicts that adding nanoadditives significantly affects engine

parameters, which can lower the pollution levels caused by conventional fossil fuels.¹¹

According to widely acknowledged observations,¹² traditional diesel engines have faced many ongoing difficulties, such as the development of localized rich zones inside the combustion chamber, lack of adequate mixing, and problems with autoignition. Numerous low-temperature combustion strategies^{13–17} have been developed in response to these difficulties, utilizing modern combustion technologies, like, Homogeneous Charge Compression Ignition (HCCI), Partially Premixed Compression Ignition, Reactivity Controlled Compression Ignition (RCCI), and Intelligent Charge Control Compression Ignition engines. Significant reductions in NO_x emissions, very few exhaust soot production, increased thermal efficiency, improved fuel adaptability, and precise control over the rate of heat release are just a few of the advantages these novel approaches have shown. These engines have found wide applications in automotive transportation, small engine equipment, industrial machinery, and marine transportation.^{13,16,18}

For instance, RCCI is a type of combustion process in internal combustion (IC) engines that combines the principles of both gasoline spark ignition engines and diesel compression ignition engines.

There are several advantages to using RCCI over Premixed Charge Compression Ignition (PCCI) and HCCI engines:

- **Improved efficiency:** RCCI engines can achieve high levels of efficiency because they can operate at a higher compression ratio than conventional engines without experiencing knocking. RCCI engines also have a higher thermal efficiency than PCCI and HCCI engines, because they have a longer combustion duration and a more complete combustion process.
- **Lower emissions:** RCCI engines can significantly reduce emissions of nitrogen oxides (NO_x) and particulate matter (PM) compared with conventional engines. RCCI engines can also achieve lower emissions than PCCI and HCCI engines because they have better control over the combustion process.

- **Greater fuel flexibility:** RCCI engines can operate on a wide range of fuels, including gasoline, diesel, and biofuels. This makes RCCI engines more flexible than PCCI and HCCI engines, which are typically limited to a narrow range of fuels.
- **Wider load range flexibility:**

In RCCI engines, the combustion process is controlled by adjusting the reactivity of the fuel mixture, which is achieved by blending two different types of fuels with different combustion characteristics. Usually, a highly reactive fuel, such as gasoline or ethanol, is mixed with a less reactive fuel, such as diesel or biodiesel. The mixture is then injected into the engine's combustion chamber in two separate streams, one of which is injected early and the other injected late in the engine's compression cycle. Table 1 summarizes the investigated studies depicting the effect of fuel ratio on engine performance.

After investigating the advancements and applications, authors have identified the need to present a comprehensive analysis of the application of nanoparticles in these engine environments.

2 | NANOPARTICLE TYPES

Various nanoparticles are used for the unique properties they hold due to their compact size and large surface area-to-volume ratio. Nanoparticles are added to fuel as it enhances combustion efficiency, decreases emissions, and improves fuel properties. There are several types of preparation and blending techniques for nanoparticles used in fuels, some of them are as follows:

2.1 | Metal nanoparticles

Metal-based nanoparticles are created by larger metals down to nanometric sizes, either destructively or constructively. Nearly any metal can be synthesized into its nanoparticle form. The most often used metals for

TABLE 1 Summary of the investigated studies demonstrated finding effect of fuel ratio on engine performance and emissions in diesel engines operated under RCCI mode.

Fuel low/high	Load (bars)	LRF ratios (%)	Performance	CA50	NO _x	Soot	UHC	CO	Reference
Gasoline/diesel	9	82, 86, and 89	↑	Retarded	↓	↑	↑	↑	[13]
NG/diesel	9	50–85	↑	Advance	↓	↓	↑	↑	[18]
Methanol/diesel		0–80	↑	–	↓	↔	↑	↑	[19]
<i>n</i> -Butanol/biodiesel		80, 85, and 90	↓	Advance	↓	↓	↑	↑	[20]

Abbreviations: LRF, likelihood reduction factor; NG, natural gas; RCCI, Reactivity Controlled Compression Ignition; UHC, unburnt hydrocarbons.

creating nanoparticles are iron (Fe), gold (Au), copper (Cu), lead (Pb), cobalt (Co), zinc (Zn), silver (Ag), and cadmium (Cd). They may be in the sizes between 10 and 100 nm, the other distinguishing characteristics of these types of nanoparticles may be pore size, surface charge density, large surface area-to-volume ratio, spherical and cylindrical shapes, amorphous and crystalline structures, color, reactivity and sensitivity to environmental factors like air, heat, moisture, and sunlight are just a few of the distinguishing characteristics of the nanoparticles.²¹

2.2 | Metal-oxide nanoparticles

Synthesis of metal-oxide-based nanoparticles alters the characteristics of corresponding metal-based nanoparticles. In contrast to iron nanoparticles, iron oxide (Fe_2O_3) readily oxidizes to iron nanoparticles (Fe) at ambient temperature, enhancing their reactivity. The primary reasons for synthesizing metal-oxide nanoparticles are their improved reactivity and effectiveness. They include titanium oxide (TiO_2), silicon dioxide (SiO_2), iron oxide (Fe_2O_3), aluminum oxide (Al_2O_3), zinc oxide (ZnO), and cerium oxide (CeO_2). Comparing these nanoparticles to their metal counterparts reveals they have extraordinary qualities.²²

2.3 | Carbon-based nanoparticles

These nanomaterials (NMs), which might be shaped like spheres, ellipses, or hollow tubes, frequently include carbon. Carbon nanotubes (CNTs), fullerenes (C_{60}), carbon onions, carbon nanofibers, graphene (Gr), and carbon black are among the carbon-based NMs in this group. Important industrial processes like arc discharge, laser ablation, and chemical vapor deposition are used to create these carbon-based molecules.²³

2.4 | Composite-based nanoparticles

These materials have a single nanoscale phase and are composed of multiphase nanoparticles that can be coupled with other nanoparticles, with bulkier or larger

materials (like, hybrid nanofibers), or with more intricate structures, like metalorganic frameworks. The composites may be created from any mixture of metal, carbon, or organically based nanometals and bulk components made of metal, ceramic, or polymer. On the basis of the specifications for the intended usage, different properties of these composite-based nanoparticles are created.²⁴

3 | WAYS OF PREPARATION AND BLENDING OF NANOADDITIVES

3.1 | Sol-gel method

This technique uses a procedure to create nanoparticles through a chemical reaction that involves the development of a sol at first, which is a liquid solution of the nanoparticles. This is followed by gelation, in which the sol turns into a solid gel. Centrifugation, filtering, or sedimentation can be used to collect the nanoadditives. This technique is frequently used to create nanoparticles for use in electronics, sensors, and catalysis (Figure 3).²⁵

To combat environmental pollution and meet strict emission standards, in an experimental investigation, a compression ignition (CI) direct-injection (DI) diesel engine was run using cerium oxide nanoparticles mixed with an emulsion of *Nerium oleander* biofuel. For the investigation, a single-cylinder, direct-injection, four-stroke (CI) engine was used. An original *N. oleander* biofuel was extracted, esterified, and then transformed into an *N. oleander* biofuel emulsion. The outcomes demonstrated that the emulsion caused diluted nitrogen oxide emissions and decreased smoke opacity emission. In contrast to plain *N. oleander* biofuel, it slightly increased CO and HC emissions. The findings conc that the emulsion caused reduced nitrogen oxide emissions and decreased smoke opacity emissions. In contrast to plain *N. oleander* biofuel, it slightly increased CO and HC emissions. Additionally, when compared with neat *N. oleander* biofuel, conventional fossil diesel, and an emulsion of *N. oleander* biofuel at different power outputs, the nanoparticle blended emulsion of *N. oleander* biofuel demonstrated a significant reduction in emissions. It was determined that DI and CI engines may utilize the nanoemulsion of *N. oleander* biofuel without

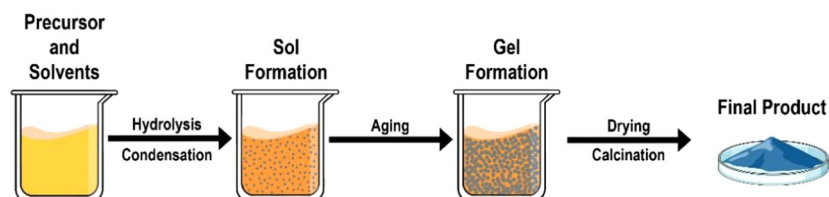


FIGURE 3 Nanoparticle synthesis by sol-gel method.

requiring hardware modifications.²⁶ Another study demonstrates the impact on engine performance and emissions of adding 25 ppm of alumina nanoparticles to a blend of biodiesel, diesel, and ethanol. The nanoparticles were created and studied using scanning electron microscopy (SEM) and X-ray diffraction (XRD) measurements, and three alternative injection times were examined. The findings demonstrated that while introducing nanoparticles at advanced injection timing increased pressure and emissions, doing so at retarded injection timing (RET IT) enhanced engine performance and decreased emissions. The most efficient method for increasing engine performance and lowering emissions was the addition of 25 ppm Al_2O_3 in RET IT at 19° before top dead center (bTDC).²⁷

3.2 | Microemulsion method

Microemulsion is a commonly used technique for creating nanoparticles, where two immiscible liquids, usually oil and water, are mixed to form a stable and transparent mixture. A surfactant and cosurfactant are added to the mixture to create a template for the formation of nanoparticles. Sizes and properties of these nanoparticles can be regulated by adjusting the composition of the microemulsion. To create nanoparticles using microemulsion, a precursor solution is added dropwise to the microemulsion, while continuously stirring the mixture. The nanoparticles start to form during this process, and their size and properties can be adjusted by varying the concentration of the precursor solution and the composition of the microemulsion. Once the nanoparticle synthesis is complete, the nanoparticles are separated from the microemulsion using techniques, such as centrifugation (Figure 4).²⁸

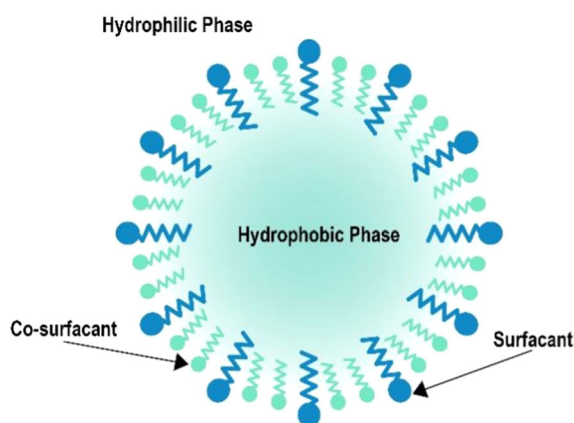


FIGURE 4 Microemulsion formation.

A water-in-oil microemulsion was used as the reaction media in a study to synthesize iron (III) oxide nanoparticles. A particular composition of *n*-heptane as water, oil phase, and AOT as the surfactant was used to create the microemulsion. Ammonium hydroxide served as a precipitating agent, and iron (III) chloride served as the starting material. Fe_2O_3 nanoparticles were created in the microemulsion's aqueous core. The mixture's water content may be changed to control the particle size; a higher water concentration produces larger particles. The produced nanoparticles were of the hematite phase and had a hexagonal shape, having an average size of under 100 nm.²⁹

3.3 | Hydrothermal method

A common method for synthesizing nanoadditives is the hydrothermal method, which involves heating a precursor solution containing the desired metal or metal-oxide to high temperatures and pressures in a container sealed off using a hydrothermal reactor. The narrow size distribution and great purity of the nanoparticles produced by this technique allows for precise control of particle size and shape. Addition of dopants or other metals into the nanoparticles is also possible using this technique, which can influence their characteristics of the nanoparticle and in turn affecting the properties of the blend. The resulting nanoparticles have been reported in a study that highlights how vital it is for engines to mix air and fuel properly with respect to the fuel injector's orientation. Researchers can design the fuel injection system more effectively to enhance this process. Another catalyst, cerium oxide nanoparticle (CeO_2), was utilized to enhance combustion efficiency. Diesel engine with various injector and nozzle hole shapes was evaluated. Ultralow sulfur diesel, *Calophyllum inophyllum* methyl ester, and CeO_2 were combined to create the fuel. The amount of CeO_2 was then further tuned to reduce hydrocarbon and NO_x emissions even further, increase brake thermal performance, and use less fuel.³⁰ Another paper examined copper oxide thin films made using the sol-gel-like dip method and a cupric chloride solution in methanol. The baking temperature was adjusted to create films in many phases, with 360°C producing the CuO phase and $400\text{--}500^\circ\text{C}$ producing the Cu_2O phase. XRD analysis confirmed the films' phase. Using optical absorption measurements, optical band gap energies for CuO and Cu_2O films were found to be 2.10 and 1.90 eV, respectively. These values were comparable with earlier studies. The study depicts the creation and characteristics of copper oxide thin films, which may find use in many different fields.³¹

3.4 | Homogeneous addition method

The homogeneous addition method is a technique for uniformly dispersing nanoadditives in a host material. This involves dispersing the nanoadditives in a solvent, and then mixing them with the host material to ensure even distribution. The mixture is then subjected to a process, such as evaporation or precipitation, to remove the solvent and produce a homogeneously dispersed nanoadditive material. This method offers better control over the distribution of nanoadditives in the material, resulting in improved properties, such as increased strength, conductivity, or catalytic activity. This method was employed in a study based on the testing of nanoparticles for their ability to combat harmful microorganisms. To create zinc acetate, diethylene glycol, and triethylene glycol were refluxed for 2–3 h with and without sodium acetate. Ultraviolet visible spectroscopy, XRD, Fourier transform infrared spectroscopy, thermogravimetric analysis, field emission SEM, energy dispersive, and X-ray spectroscopy transmission electron microscopy (TEM) were among the characterization methods used to examine the nanoparticles. The antibacterial and antibiofilm activities of the nanoparticles against two different species of bacteria varied in strength. The size of the nanoparticles was inversely correlated with their efficacy, with the smallest particles (15 nm) exhibiting the most potential for biological applications.³² Another research paper based on automobile engineering examines the effects of adding nickel oxide nanoparticles to a blend of conventional diesel fuel (NBE25) and *Azadirachta indica* biodiesel on the performance of a CI engine at various fuel injection timings. Four dosing levels of nickel oxide nanoparticles (25, 50, 75, and 100 ppm) were tested, and fuel injection timing was varied at 23° bTDC, 19° bTDC, and 27° bTDC. Addition of nanoparticles resulted in enhanced engine performance, with higher brake thermal efficiency (BTE) and lower brake-specific fuel consumption

(BSFC) observed at the timing of 27° bTDC compared with 23° bTDC. The study also found that the presence of nanoparticles improved secondary atomization and enhanced the complete combustion of fuel, leading to reduced NO_x emissions. Structural and physical characteristics of the nickel oxide nanoparticles were confirmed using many characterization techniques.³³

3.5 | Sonication method

A common technique for preparing various materials, including suspensions, emulsions, and nanoparticles, is sonication. It is frequently used to disperse and mix particles or materials in a liquid media without the addition of any outside agents. High-frequency sound waves are applied to the sample in this method to produce small bubbles, which form quickly and burst. As a result, cavitation and shear forces effectively disperse clumps and increase the homogeneity of the dispersion. To improve the quality and stability of products, sonication is a flexible technique used in the pharmaceutical, cosmetic, and food processing sectors (Figure 5).³⁴

A study that demonstrates the sonication-produced zinc oxide nanoparticles' antibacterial activity was investigated. Nanoparticle size and antibacterial properties were examined in relation to how the calcination conditions were modified. They employed many methods, such as XRD, TEM, and thermogravimetric analysis, to characterize the particles. The results depicted that the smallest particle size achieved was 8 nm. Researchers tested the nanoparticles on *Lactobacillus plantarum* and found that all the bacteria were killed after 24 h of exposure to 1000 ppm. They also observed that the lethal effect of nanoparticles increased with longer calcination times, with significant killing effects observed after 6 h of exposure at 100 or 1000 ppm.³⁵ As concerns regarding the sustainability of petroleum fuels continue to rise, there is increasing interest in studying alternative fuels. Biodiesel

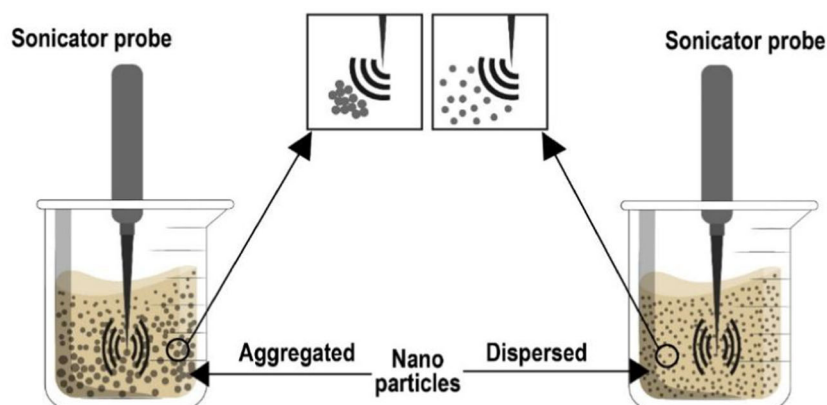


FIGURE 5 Sonication method.

is a promising option, as it is renewable, biodegradable, and produces fewer emissions. Various fuel blends with additives have been studied by researchers with the goal of increasing efficiency. Pongamia biodiesel was used with ferrofluid as an additive. This was done by mixing ferrous-based nanoparticles utilizing water as a base and citric acid as a surfactant. Engine performance and emission parameters were analyzed at varied loads on a Kirloskar TV1 diesel engine, while keeping the speed constant at 1500 rpm. According to the findings, adding ferrofluid improved fuel efficiency, a decrease of 8% in BSFC was observed compared with base fuel. Also, compared with the neat biodiesel mix, CO and HC emissions were reduced for the nanoadditive biodiesel blend. Compared with all other fuel mixes, the B20 with 1% ferrofluid combination had the highest efficiency and lowest emissions.³⁶

4 | EFFECT OF NANOADDITIVES ON PERFORMANCE AND EMISSION CHARACTERISTICS

Various nanoparticles like alumina, ceria, titanium oxide, zinc oxide, and many more are studied for their emission and performance characteristics when blended with some sort of fuel. It was seen that some of them enhanced the combustion characteristics, whereas some improved the emission characteristics, when compared with the base fuel. Table 2 depicts all the results documented in a tabular form, which encapsulates all the performance and emission results portrayed by the various proportions of nanoparticles blended with fuel.

4.1 | Performance characteristics of nanoadditives

4.1.1 | Brake thermal efficiency

BTE was determined by the input of various papers using different nanoadditives. The paper used in the procurement of the data for BTE was kept constant for all the other parameters that were considered. It was observed from Figure 6 that the BTE% of GNP was the highest, following that was CeO₂, CuO, ZnO, TiO₂, Al₂O₃, CNT, and the lowest BTE among all was observed to be produced by FFO.

The researcher using GNP stated that better BTE was achieved by GNP because of the higher carbon-oxidation rate, which led to a more effective combustion process and lower fuel consumption. In addition, it was found

that GNP reduced burnout time and reduced the amount of late combustion during exhaust stroke, which reduced incomplete combustion.^{70–73}

4.1.2 | Brake-specific fuel consumption

Upon analysis, it was seen that the BSFC of GNP and CeO₂ was the lowest among all the nanoadditives used as visible in Figure 7. This was in sync with the BTE results that were discussed earlier. Figure 8 depicts the trend of BSFC and BTE that allows us to correlate both the parameters easily. The researchers using CeO₂ and GNP attributed the lower BSFC to the fact that using the nanoadditives increased the surface area, therefore making the surface area-to-volume ratio higher, which made the rate of combustion go up and thus decreasing the BSFC.^{72,74–76}

4.2 | Emission characteristics of nanoadditives

4.2.1 | Nitrous oxides (NO_x)

It was observed that when CNT was used, the maximum reduction in NO_x emission was attained, and the researcher backed it up with the logic that because the water-emulsified CNT was able to absorb heat quickly during the combustion phase, thus resulting in rapid decrease of in-chamber temperature resulting in the lower levels of emission of NO_x.⁷⁷ In contrast, the Al₂O₃ nanoadditive increased the NO_x levels significantly (Figure 9), this might be because of the presence of Al₂O₃ nanoadditive, due to which the in-cylinder pressure as well as the temperature increased because of the rapid burning of the fuel, this increase in-chamber temperature resulted in the increase of NO_x formation, as stated by the reaction mechanism by Zeldovich.^{78–80}

4.2.2 | Hydrocarbon emission (HC)

The levels of HC emission as seen in Figure 10 depict that the least or most reduction in the levels of HC was observed from GNP. Decrease in this HC level was contributed to the higher catalytic activity that was facilitated by GNP, which can be due to an increase in the ratio of their surface area and volume that resulted in increased mixing of the air and fuel mixture, leading to improved combustion.^{76,81,82} In

TABLE 2 Performance, combustion, and emission characteristics of nanoblended fuels.

Name of the paper	Engine used	Fuel used	Additive used		Performance			Emission			
			Name	Quantity	BTE	BSFC	EGT	NO _x	CO	CO ₂	HC
Venu and Appavu ³⁷	Single-cylinder diesel engine	Polanga biodiesel	Al ₂ O ₃	25 ppm	↑	↓	–	↓	↓	–	↓
				50 ppm	↑	↓	–	↓	↓	–	↓
Venu and Madhavan ²⁷	Four-stroke, air-cooled, single-cylinder direct-injection (DI) diesel engine	Diesel (70%) + biodiesel (20%) + ethanol (10%)	Al ₂ O ₃	25 ppm	–	↓	↑	↓	↓	↑	↑
Al-Kheraif et al. ³⁸	Air-cooled, single-cylinder, four-stroke compression ignition engine	Candle nut and soap nut biodiesel (20%) + diesel (80%)	Al ₂ O ₃	25 ppm	↑	↑	↑	↓	↓	–	↓
Fayad and Dhahad ³⁹	DI diesel engine, water-cooled, and four-cylinders	Butanol (20%) diesel (80%) blend.	Al ₂ O ₃	30 mg/L	↑	↓	–	↓	↓	↑	↓
				50 mg/L	↑	↓	–	↓	↓	↑	↓
				100 mg/L	↑	↓	–	↓	↓	↑	↓
Venu et al. ⁴⁰	Single-cylinder DI diesel engine	Jatropha biodiesel (20%) + ethanol (10%) + diesel (70%)	Al ₂ O ₃	10 ppm	↓	↑	–	↑	↓	–	↓
				20 ppm	↓	↑	–	↑	↓	–	↓
				30 ppm	↓	↑	–	↑	↓	–	↓
Kalaimurgan et al. ⁴¹	4-Stroke single-cylinder DI diesel engine	Algae biodiesel (20%) + diesel (80%)	CeO ₂	25 ppm	↑	↓	↑	–	–	–	–
				50 ppm	↑	↓	↑	–	–	–	–
				75 ppm	↑	↓	↑	–	–	–	–
				100 ppm	↑	↓	↑	–	–	–	–
Mohan and Dinesha ⁴²	4-Stroke, single-cylinder, water-cooled, DI diesel engine	Waste cooking oil biodiesel (20%) + hydrogen peroxide (1.5%) + diesel (78.5%)	CeO ₂	40 ppm	↑	↓	↑	↓	↓	↑	↓
				80 ppm	↑	↓	↑	↓	↓	↑	↓
Alex et al. ⁴³	4-Stroke, single-cylinder, air-cooled, DI diesel engine	Diesel (100%)	CeO ₂	15 ppm	↑	↑	↓	↓	↓	–	–
				25 ppm	↑	↓	↓	↔	↓	–	–
		Orange peel biodiesel (100%)	CeO ₂	15 ppm	↑	↑	↓	↓	↓	–	–
				25 ppm	↑	↑	↓	↑	↓	–	–
Gad et al. ⁴⁴	Single-cylinder, air-cooled, 4-stroke diesel engine	Jatropha biodiesel (20%) + diesel (80%)	CNT	25 ppm	↔	↑	↓	↓	↓	–	↔
				50 ppm	↑	↑	↓	↓	↓	–	↑
				100 ppm	↑	↔	↓	↓	↓	–	↑
			TiO ₂	25 ppm	↑	↓	↓	↑	↓	–	↓
				50 ppm	↑	↑	↓	↓	↓	–	↓
				100 ppm	↓	↑	↓	↑	↓	–	↔
		Al ₂ O ₃	Al ₂ O ₃	25 ppm	↑	↓	↓	↑	↓	–	↓
				50 ppm	↑	↓	↓	↓	↓	–	↔
				100 ppm	↑	↓	↔	↑	↓	–	↑

TABLE 2 (Continued)

Name of the paper	Engine used	Fuel used	Additive used		Performance			Emission			
			Name	Quantity	BTE	BSFC	EGT	NO _x	CO	CO ₂	HC
Manigandan et al. ⁴⁵	Single-cylinder, 4-stroke, CI engine with dual combustion mode	Hydrogen (0.2 kg) + diesel (0.78 kg)	TiO ₂	0.02 kg	↑	↓	↑	↓	↓	↓	↓
			CNT	0.02 kg	↓	↓	↑	↓	↓	↓	↓
			Al ₂ O ₃	0.02 kg	↓	↓	↑	↑	↓	↓	↓
			CuO	0.02 kg	↓	↓	↑	↑	↓	↓	↓
			CeO ₂	0.02 kg	↓	↓	↑	↓	↓	↓	↓
Gad et al. ⁴⁶	Single-cylinder, air-cooled, 4-stroke diesel engine	Waste cooking oil biodiesel (20%) + diesel (80%)	TiO ₂	25 mg/L	↓	↑	↑	↑	↓	–	↓
				50 mg/L	↓	↑	↑	↑	↓	–	↓
				100 mg/L	↓	↑	↑	↑	↓	–	↓
			Al ₂ O ₃	25 mg/L	↓	↑	↑	↑	↓	–	↓
				50 mg/L	↓	↑	↑	↑	↓	–	↓
				100 mg/L	↓	↑	↑	↑	↓	–	↓
			CNT	25 mg/L	↓	↑	↑	↑	↓	–	↓
				50 mg/L	↓	↑	↑	↑	↓	–	↓
				100 mg/L	↓	↑	↑	↑	↓	–	↓
Zhang et al. ⁴⁷	Heavy-duty, four-stroke, CRDI diesel engine	Diesel (100%)	CeO ₂	40 ppm	–	↑	–	↓	↑	–	↓
			CNT	40 ppm	–	↔	–	↓	↓	–	↓
Bitire and Jen ⁴⁸	Single-cylinder, 4-stroke, DI, air-cooled, diesel engine	Parsely biodiesel (20%) + diesel (80%)	CuO	50 ppm	↓	↓	–	↓	↓	↑	↓
				100 ppm	↓	↓	–	↓	↓	↑	↓
Chatur et al. ⁴⁹	VCR, DI, diesel engine	Waste cooking oil biodiesel (20%) + diesel (80%)	CuO	20 ppm	↑	↑	↑	↓	↓	↑	↓
				30 ppm	↑	↑	↑	↓	↓	↑	↓
				40 ppm	↑	↑	↑	↓	↓	↑	↓
Ağbulut et al. ⁵⁰	Naturally aspirated, air-cooled, DI diesel engine	Diesel (100%)	CuO	1000 ppm	↑	↓	↓	↓	↓	–	↓
				2000 ppm	↑	↓	↓	↓	↓	–	↓
Sathish et al. ⁵¹	Single-cylinder, 4-stroke diesel engine	Waste cooking oil biodiesel (20%) + diesel (80%)	CNT	100 ppm	↑	↑	–	↓	↓	–	↑
			Al ₂ O ₃	100 ppm	↑	↑	–	↓	↓	–	↓
			CNT (50%) + Al ₂ O ₃ (50%)	100 ppm	↑	↑	–	↓	↓	–	↓
Lenin et al. ⁵²	1-Cylinder vertical water-cooled 4-stroke diesel engine	Tomato seed oil biodiesel (20%) + diesel (80%)	CuO	40 ppm	↑	↑	–	↓	↑		↑
				80 ppm	↑	↑	–	↑	↑		↓
				120 ppm	↑	↑	–	↑	↓		↓
Chacko and Jeyaseelan ⁵³	Twin-cylinder, four-stroke turbocharged diesel engine	Waste cooking oil biodiesel (20%) + diesel (80%)	GO	20 ppm	↓	↑	–	↑	↓	–	↓
				40 ppm	↓	↑	–	↑	↓	–	↓
				60 ppm	↓	↑	–	↑	↓	–	↓
			GNP	20 ppm	↓	↑	–	↓	↓	–	↓
				40 ppm	↓	↑	–	↓	↓	–	↓
				60 ppm	↓	↑	–	↓	↓	–	↓

(Continues)

TABLE 2 (Continued)

Name of the paper	Engine used	Fuel used	Additive used		Performance			Emission			
			Name	Quantity	BTE	BSFC	EGT	NO _x	CO	CO ₂	HC
Yugandharsai et al. ⁵⁴	Single-cylinder, four-stroke diesel engine	Sapota seed oil biodiesel (20%) + diesel (80%)	GO	50 ppm	↓	↑	–	↓	↑	↑	↓
Razzaq et al. ⁵⁵	Four-stroke, single-cylinder, water-cooled, DI diesel engine	Palm oil biodiesel (30%) + dimethyl carbonate (10%) + diesel (60%)	GNP	40 ppm	↑	↑	–	↓	↓	–	↑
				80 ppm	↑	↑	–	↓	↓	–	↑
				120 ppm	↓	↑	–	↑	↓	–	↓
Sharma et al. ⁵⁶	Water-cooled, 3-cylinder, indirect-injection diesel engine	Waste cooking oil biodiesel (40%) + butanol (20%) + diesel (40%)	GNP	100 ppm	↑	↓	–	↓	↑	↑	–
			C	100 ppm	↑	↓	–	↓	↔	↑	–
Ağbulut et al. ⁵⁷	4-Stroke, single-cylinder diesel engine	Waste cooking oil biodiesel (15%) + diesel (85%)	GO	100 ppm	↑	↓	↓	↓	↓	–	↓
				500 ppm	↑	↓	↓	↓	↓	–	↓
				1000 ppm	↑	↓	↓	↓	↓	–	↓
Soudagar et al. ⁵⁸	4-Stroke, single-cylinder, water-cooled diesel engine	Dairy scum oil biodiesel (20%) and diesel (80%)	GNP	20 ppm	↓	↑	–	↑	↑	–	↑
				40 ppm	↓	↑	–	↑	↑	–	↑
				60 ppm	↓	↑	–	↑	↑	–	↑
Suhel et al. ⁵⁹	Vertical, 4-stroke diesel engine	Chicken fat biodiesel (20%) + diesel (80%)	FFO	50 ppm	↓	↑	↑	↑	↓	–	↓
				100 ppm	↓	↑	↓	↑	↓	–	↓
				150 ppm	↓	↑	↑	↑	↓	–	↓
Elkelawy et al. ⁶⁰	4-Stroke, single-cylinder, water-cooled DI diesel engine	Waste cooking oil biodiesel (50%) + diesel (50%)	AgSCN	200 ppm	↑	↔	↓	↓	↓	↓	↓
				400 ppm	↑	↓	↓	↓	↓	↓	↓
				600 ppm	↑	↑	↓	↓	↓	↓	↓
Karthikeyan and Viswanath ⁶¹	4-stroke, two-cylinder, DI diesel engine	Tamanu biodiesel (30%) + diesel (70%)	TiO ₂	25 ppm	–	–	–	↓	↑	↓	↑
				50 ppm	–	–	–	↓	↓	↓	↓
				75 ppm	–	–	–	↓	↓	↓	↑
				100 ppm	–	–	–	↓	↓	↓	↑
Jayaraman et al. ⁶²	Single-cylinder, four-stroke, water-cooled diesel engine	Manilkarazapota seed oil biodiesel (20%) + diesel (80%)	TiO ₂	50 ppm	↓	↑	–	↓	↑	↑	↑
				75 ppm	↓	↑	–	↓	↑	↑	↑
				100 ppm	↓	↑	–	↓	↑	↑	↑
Vigneswarn et al. ⁶³	Single-cylinder, four-stroke, DI diesel engine	Water (10%) + surfactant (0.2%) + diesel (89.8)	TiO ₂	30 ppm	↑	↑	–	↓	↓	–	↑
				60 ppm	↑	↑	–	↔	↓	–	↑
				90 ppm	↑	↑	–	↑	↓	–	↔
Soudagar et al. ⁶⁴	4-Stroke, single-cylinder, BS-IV, water-cooled diesel engine	Castor bean oil biodiesel (20%) + diesel (80%)	Sr@ZnO	30 ppm	↓	↑	–	↑	↑	↑	↑
				60 ppm	↓	↑	–	↑	↓	↓	↓
				90 ppm	↓	↔	–	↑	↑	↑	↑

TABLE 2 (Continued)

Name of the paper	Engine used	Fuel used	Additive used		Performance			Emission			
			Name	Quantity	BTE	BSFC	EGT	NO _x	CO	CO ₂	HC
Dhahad and Chaichan ⁶⁵	4-Stroke, four-cylinder, DI, water-cooled diesel engine	Diesel (100%)	Al ₂ O ₃	50 ppm	↑	↓	–	↑	↓	–	↓
				100 ppm	↑	↓	–	↑	↓	–	↓
			ZnO	50 ppm	↑	↓	–	↑	↓	–	↓
				100 ppm	↑	↓	–	↑	↓	–	↓

Abbreviations: AgSCN, silver thiocyanate nanoparticles; BSFC, brake specific fuel consumption; BTE, brake thermal efficiency; CNT, carbon nanotube; CRDI, common rail direct injection; EGT, exhaust gas temperature; FFO, ferrous ferric oxide; GNP, graphene nanoparticle; GO, graphene oxide; VCR, variable compression ratio.

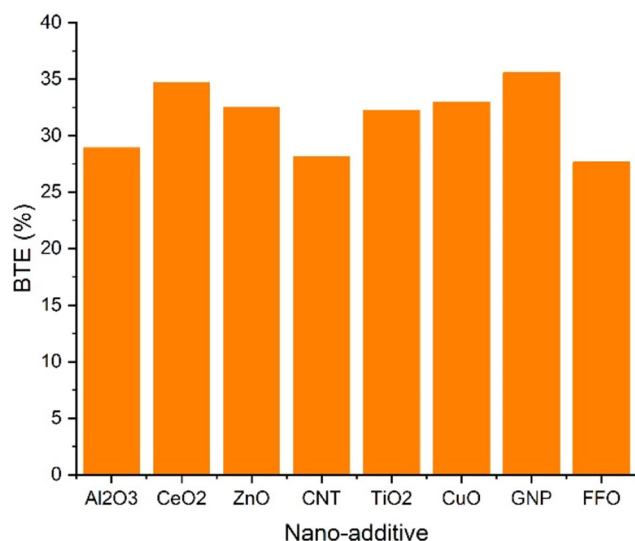


FIGURE 6 Brake thermal efficiency (BTE%) versus nanoadditive. BTE, brake thermal efficiency; CNT, carbon nanotube; FFO, ferrous ferric oxide; GNP, graphene nanoparticle.^{48,59,62,65–69}

the case of HC levels of TiO₂, it produced higher levels of HC than that of its base fuel, the reason stated for this was the incomplete combustion of the air–fuel mixture, resulting in the higher levels of HC.^{83,84}

4.2.3 | Carbon monoxide (CO)

Maximum reduction in the levels of CO was seen in the nanoadditive Al₂O₃, this was attributed to the extra oxygen available in the Al₂O₃ that helps in making the burning reaction quick and improves the air–fuel mixture combustion. This leads to increased burning efficiency and thus produces considerably less CO compared with that of base fuel used.⁶⁸ Minimum reduction of CO levels was observed by the TiO₂, which was attributed to the fact that there was partial

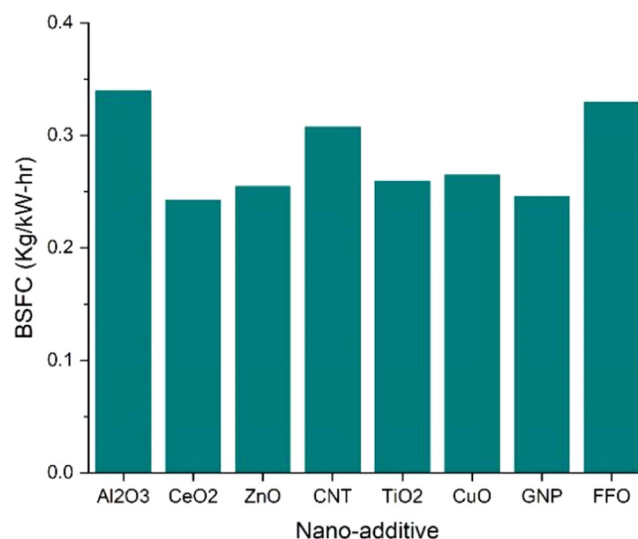


FIGURE 7 BSFC versus nanoadditive. BSFC, brake-specific fuel consumption; CNT, carbon nanotube; FFO, ferrous ferric oxide; GNP, graphene nanoparticle.^{48,59,62,65–69}

air–fuel mix combustion, which caused higher CO levels (Figure 11).^{83,84}

5 | EFFECT OF NANOADDITIVES ON COMBUSTION CHARACTERISTICS

Emission and performance characteristics and impacts were discussed in the above sections, now considering the combustion characteristics, two major parameters are taken into consideration for the evaluation of the impact of the addition of nanoadditives to a reference fuel. The two parameters taken into consideration are In. Cylinder Pressure and Heat Release Rate (HRR). Various reports were studied on the test runs of biodiesel blends with various nanoadditives under various conditions. The gist of was seen in Table 3,

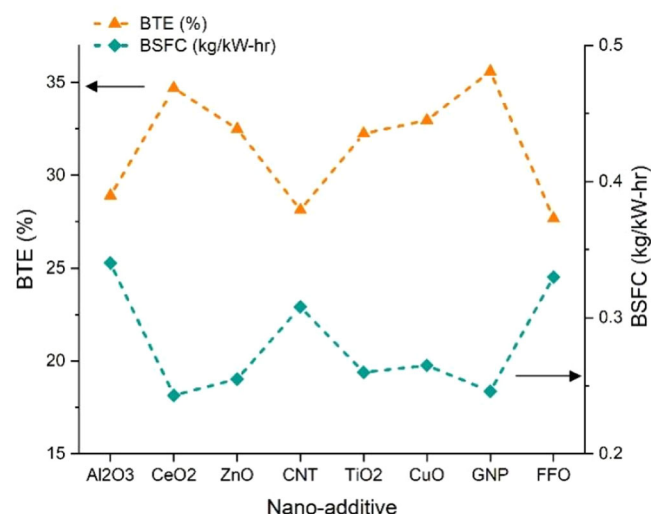


FIGURE 8 BTE (%) versus nanoadditive versus BSFC (kg/kW-h). BSFC, brake-specific fuel consumption; BTE, brake thermal efficiency; CNT, carbon nanotube; FFO, ferrous ferric oxide; GNP, graphene nanoparticle.^{48,59,62,65–69}

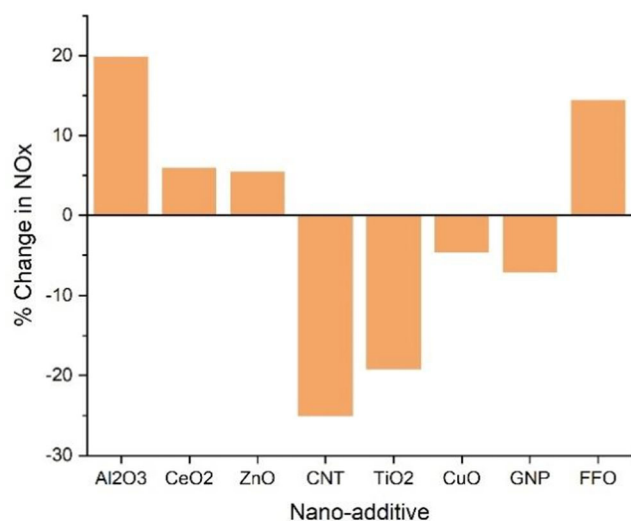


FIGURE 9 Percentage change in NO_x versus nanoadditive. CNT, carbon nanotube; FFO, ferrous ferric oxide; GNP, graphene nanoparticle.^{48,59,62,65–69}

which summarized the two major parameters of combustion characteristics as discussed.

5.1 | In. Cylinder Pressure

With the consideration of various metallic and carbon-based nanoparticles that could be used for the evaluation of combustion parameters, it was seen that the nanoparticles CeO₂, CuO, ferrocene (F), Al₂O₃, CNT, TiO₂, GNP, and ZnO performed the best when it came to the

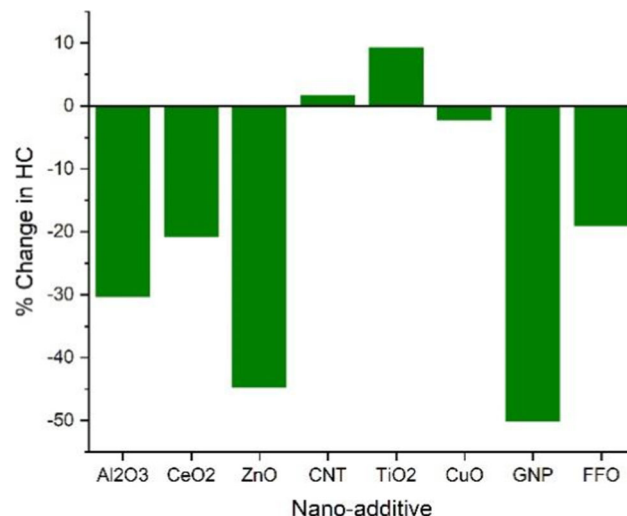


FIGURE 10 Percentage change in NO_x versus nanoadditive. CNT, carbon nanotube; FFO, ferrous ferric oxide; GNP, graphene nanoparticle; HC, hydrocarbons.^{48,59,62,65–69}

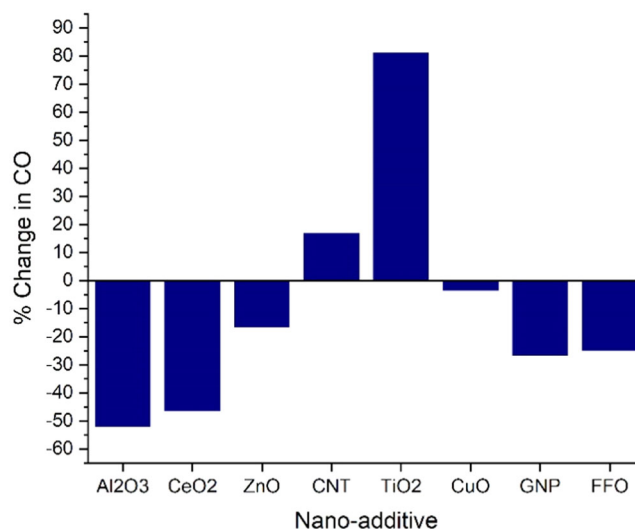


FIGURE 11 Percentage change in CO versus nanoadditive. CNT, carbon nanotube; FFO, ferrous ferric oxide; GNP, graphene nanoparticle.^{48,59,62,65–69}

analysis of combustion parameters. The cylinder pressure of reference fuel was taken into account, and the change in the cylinder pressure after adding the nanoparticle was observed. Further percentage change before and after the addition of the nanoparticle was considered and represented in a graphical format in Figure 12. It is quite visible from the given analysis that the maximum difference in the pressure was made by the nanocatalyst GNP, otherwise known as graphene nanoparticles. Following that, CNT made quite a significant change in the cylinder pressure when compared with the biofuel

TABLE 3 Combustion characteristics of nanoblended fuels.

Name of paper	Engine used	Fuel used	Additive used		Combustion	
			Name	Quantity	In. Cylinder Pressure	Heat Release Rate
Simhadri et al. ⁸⁵	Single-cylinder water-cooled diesel engine	Diesel (80%) + mahua oil biodiesel (20%)	CeO ₂	25 ppm	↓	↓
				50 ppm	↓	↓
				75 ppm	↓	↓
				100 ppm	↓	↓
Jit Sarma et al. ⁸⁶	Single-cylinder, computerized multifuel diesel engine	Diesel (80%) + mahua oil biodiesel (20%)	TiO ₂	200 mg/L	↑	↑
Manimaran et al. ⁸⁷	Single-cylinder, water-cooled, diesel engine	Diesel + <i>Trichosanthes cucumerina</i> oil biodiesel + water emulsion	CeO ₂	10 ppm	↑	↑
				20 ppm	↑	↑
				30 ppm	↑	↑
Perumal and Ilangkumaran ⁸⁸	Water-cooled, single-cylinder, four-stroke cycle, diesel engine	Pongamia biodiesel (20%) + diesel (80%)	CuO	50 ppm	↓	↓
				100 ppm	↑	↑
Karthikeyan et al. ⁸⁹	Water-cooled, single-cylinder, four-stroke, direct-injection, normally aspirated diesel engine	<i>Caulerpa racemosa</i> biodiesel (20%) + diesel (80%)	Bi ₂ O ₃	50 ppm	↓	↓
				100 ppm	↓	↓
Tamilvanan et al. ⁹⁰	Single-cylinder, water-cooled, four-stroke, direct-injection diesel engine	<i>Calophyllum inophyllum</i> biodiesel (20%) + diesel (80%)	CuO	30 mg/L	↑	↑
Gad et al. ⁴⁶	Single-cylinder, air-cooled, diesel engine	Waste cooking oil biodiesel (20%) + diesel (80%)	Al ₂ O ₃	100 ppm	↑	↑
			CNT	100 ppm	↑	↑
			TiO ₂	100 ppm	↑	↑
Bayindirli et al. ⁹¹	Single-cylinder, direct-injection, diesel engine	Cotton seed oil biodiesel (100%)	C	50 ppm	↑	↑
				75 ppm	↑	↑
			GO	50 ppm	↑	↑
				75 ppm	↑	↑
Soudagar et al. ⁵⁸	4-Stroke, single-cylinder, water-cooled diesel engine	Dairy scum oil biodiesel (20%) and diesel (80%)	GNP	20 ppm	↑	↑
				40 ppm	↑	↑
				60 ppm	↑	↑
Elwardany et al. ⁹²	Single-cylinder, air-cooled, four-stroke diesel engine	Waste frying oil biodiesel (30%) + diesel (70%)	F	300 mg/L	↑	↑
El-Adawy ⁹³	Single-cylinder, four-stroke, naturally aspirated diesel engine	Waste cooking vegetable oil biodiesel (20%) + diesel (80%)	ZnO	50 ppm	↑	↑

Abbreviations: CNT, carbon nanotube; F, ferrocene; GNP, graphene nanoparticle; GO, graphene oxide.

blend used without the additive. This can be explained by the higher surface area and also that there was a common trend seen in the use of carbon-based nanoparticles, which has various properties that led to the

increment of the cylinder pressure, and therefore improving the parameter in review for this particular test. The increment of the cylinder pressure can be attributed to the increased surface area-to-volume ratio,

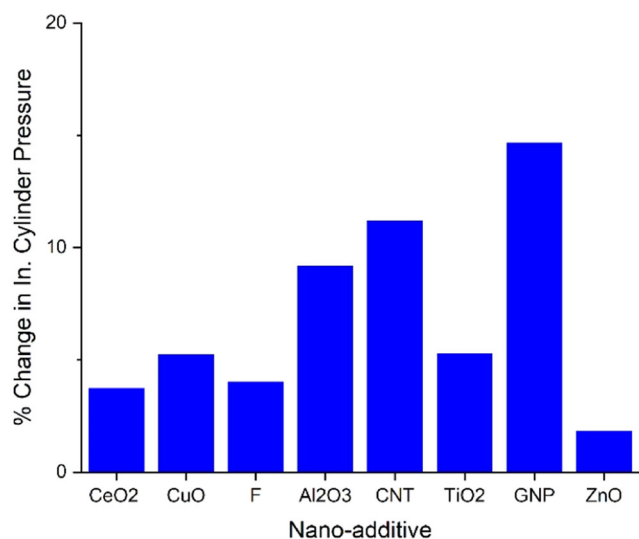


FIGURE 12 Percentage change in In. Cylinder Pressure versus nanoadditives. CNT, carbon nanotube; F, ferrocene; GNP, graphene nanoparticle.^{46,58,85,90,92,93}

which results in better atomization of the fuel, which means better mixing of the air–fuel blend. Also, with this inclusion of carbon-based nanoparticles, it is observed to have a positive impact on the evaporation rate too, which could also be related to the higher surface area-to-volume ratio of carbon-based nanoparticles. Other than this, the inclusion of carbon-based nanoadditives also depicted an increase in thermal conductivity and catalytic activity too. It could be observed from the previous sections that carbon-based nanoparticles performed relatively well compared with other metallic and nonmetallic nanoparticles intended to increase the quality of combustion, thus enhancing the performance and emission characteristics as well.^{67,94–96}

5.2 | Heat Release Rate

The best-obtained result for the percentage increase in the HRR from various studies using different nanoadditives was summarized in a graph in Figure 13. It was observed that the HRR for the GNP was increased drastically, which is in sync with the results obtained in cylinder pressure from Figure 12 as well. This can again be attributed to the fact that carbon-based nanoparticles indeed increase the quality of combustion when mixed in correct proportions with the bio-diesel blend. This can again be contributed to the fact that carbon-based nanoparticles due to their higher surface area-to-volume ratio increase the quality of the mixing of air and fuel, thus subsequently increasing the rate of evaporation as well.^{97,98}

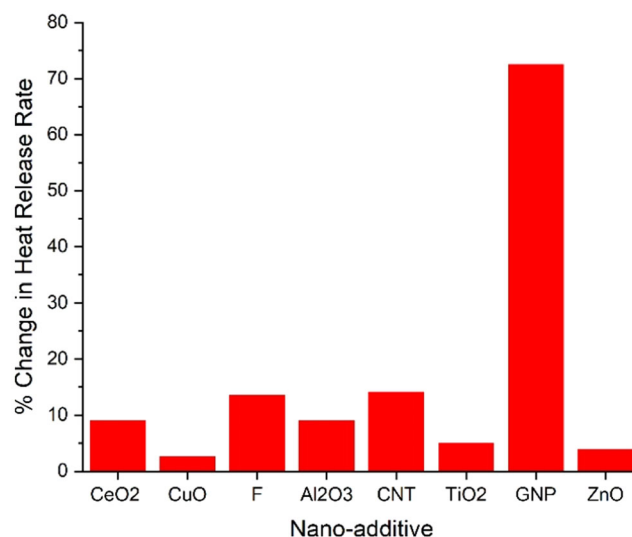


FIGURE 13 Percentage change in HRR versus nanoadditives. CNT, carbon nanotube; F, ferrocene; GNP, graphene nanoparticle; HRR, Heat Release Rate.^{46,58,85,90,92,93}

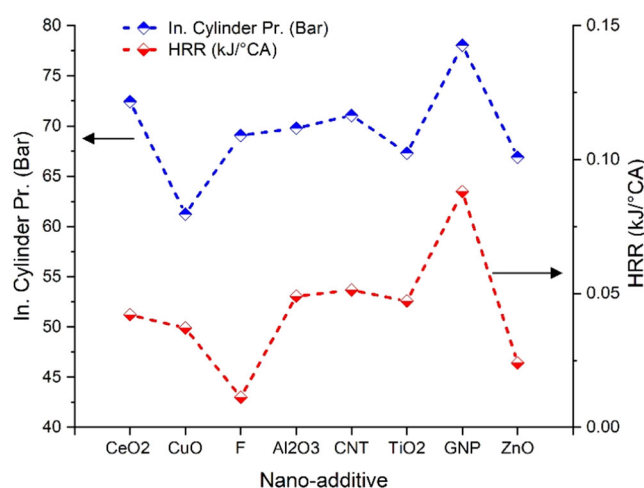


FIGURE 14 In. Cylinder Pressure (bar) versus nanoadditive versus HRR (kJ/°CA). CNT, carbon nanotube; F, ferrocene; GNP, graphene nanoparticle; HRR, Heat Release Rate.^{46,58,85,90,92,93}

Further from Figure 14, it could be seen the actual cylinder pressure and HRR for each nanoadditive taken into consideration. It could be observed that both the HRR as well as the cylinder pressure are higher in terms of the carbon-based nanoparticles used as additives for the increment of the combustion quality of the blended biodiesel fuel at various proportions. This gives us an idea about the correlation as well as the trend of the usage of various nanoadditives used in the biodiesel to enhance the quality of the biodiesel and overcome its shortcomings like longer ignition delay, lower peak cylinder pressure, as well as the HRR, which would subsequently affect the combustion efficiency as well.

From the graph presented in Figure 14 it makes a clear and bold statement of how carbon-based nanoparticles like GNP and CNT can be a potential nanoadditive for the enhancement of the quality of the biodiesel.⁹⁹

6 | CONCLUSION

The study depicts how nanoadditions impact fuel blends and how they affect different engines. Findings revealed that some nanoparticles enhance thermal efficiency and overall engine performance by acting as a source of buffer oxygen, resulting in better combustion of fuel. Additionally, nanoadditives increased engine performance, with an increase in BTE and a reduction in BSFC. GNP and CeO₂ depicted promising enhancements in performance characteristics, as nanoadditives depicted an improvement in fuel atomization, resulting in fine droplets and increased mixing capability in the combustion chamber. However, it was seen that some nanoparticles also increased HC emissions and NO_x formation, but had a positive impact on CO emissions. The addition of CNT and TiO₂ was seen to have a noticeable reduction in the NO_x levels, but the CO and HC levels were seen to have increased with the addition of these nanoadditives. In contrast, Al₂O₃ depicted the maximum increase in NO_x emissions but a significant reduction in CO was observed by additive. Although almost all nanoparticles had a positive impact on the HC levels, but GNP resulted in the maximum reduction of HC levels compared with the other nanoadditives. GNP and CNT were also seen to be very effective for the enhancement of performance characteristics as well. This was attributed to the larger surface area-to-volume ratio which resulted in better atomization, and the thermal conductivity was also improved with the addition of the carbon-based nanoadditives. Overall, the results could be summarized in the following points:

- The use of nanoparticles generally acted as an oxygen buffer, which improved the thermal efficiency and overall engine performance, which were judged by the cylinder pressure and HRR.
- Carbon-based nanoparticles were seen to have a drastic positive impact on the combustion characteristics, which was attributed to their thermal conductivity as well as the surface area-to-volume ratio.
- The addition of nanoadditives resulted in increased engine performance, which was characterized by the increase in the BTE and reduced BSFC.
- While most of the nanoadditives seem to decrease the emission levels, but increase the NO_x emission levels, it was seen that CNT and TiO₂ had a positive impact on the NO_x levels too.

Therefore, the review suggests that selecting the correct proportion and variety of nanoparticles is essential in optimizing engine performance. More emphasis is required on the carbon-based nanoparticles which can be the solution to ongoing problems associated with the application of biodiesel. The use of nanoparticles can enhance the overall thermophysical characteristics of a fuel, thus resulting in the improvement of the fuel's combustion, performance as well as emission characteristics.

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