Egypt. J. Chem. **Vol. 68**, No.8 pp 527 - 557 (2025)

Egyptian Journal of Chemistry

http://ejchem.journals.ekb.eg/

Review: Enhancing Biodiesel Properties through the Integration of Nanoparticle Additives

Yasmeen A. Mikky[1,*], Abeer M. Shoaib[1], Reham.Y. El-Araby[2,*], Adel M.A. Mohamed[3]

[1]Department of Petroleum Refining and Petrochemical Engineering, Faculty of Petroleum and Mining Engineering, Suez University, Suez, Egypt. Yasmeen.mekky@pme.suezuni.edu.eg: a.shoaib@suezuni.edu.eg

[2]Chemical Engineering and Pilot Plant Department, Institute of Engineering Research and New and Renewable Energy, National Research Centre. rehamelaraby@hotmail.com

[3]Department of Metallurgical and Materials Engineering, Faculty of Petroleum and Mining Engineering, Suez University, Suez 43512, Egypt. Adel.mohamed25@yahoo.com

** Corresponding authors (Yasmeen A. Mikky, Yasmeen.mekky@pme.suezuni.edu.eg), (R. El-Araby, rehamelaraby@hotmail.com)*

Abstract

This comprehensive review examines the integration of nanoparticle additives (1-100 nm) to enhance biodiesel properties. Recent advances in nanotechnology have enabled the development of nanoparticle-modified biodiesel fuel blends that significantly improve combustion behavior, engine performance, and emission characteristics in conventional diesel engines. The review analyzes how different nanoparticle types (metal oxides, carbon-based materials, and hybrid nanostructures), sizes, and concentrations affect fuel properties. Key improvements include enhanced thermal efficiency, combustion characteristics, and reduced emissions. The high surface-to-volume ratio and increased reactive surface area of nanoparticles contribute to superior fuel performance. While challenges remain in nanoparticle dispersion and long-term stability, this technology shows promise for advancing sustainable fuel development and addressing environmental concerns in internal combustion engines. The review also identifies critical research gaps and future directions for optimizing nanoparticle-enhanced biodiesel systems.

Keywords: Renewable Energy, Biodiesel, Nanotechnology, Nanoparticles.

1. Introduction

The most abundant energy source is petroleum, and petroleum-derived goods are found all across modern civilization. Given the close relationship between energy use, living standards, and global population increase, there will likely be a greater need for crude oil and petroleum-based products in the future. The consumption of petroleum products can lead to the world's crude oil supply running out more quickly, an increase in greenhouse gas concentrations in the atmosphere, and costly and difficult waste recycling problems [1].

The continued reliance on petroleum-based fuels presents significant challenges for both energy security and environmental sustainability. This is particularly critical in developing regions, where 85% of the rural population faces energy access challenges and depends heavily on fossil fuels. The resulting rapid increase in CO_2 emissions, driven by both fossil fuel consumption and population growth, has accelerated the search for alternative energy sources. This global energy crisis has

*Corresponding author e-mail: rehamelaraby@hotmail.com. (Reham Yehia).
Received Date: 08 October 2024, Revised Date: 22 November 2024, Accepted Date: 08 December 2024
DOI: 10.21608/EJCHEM.2024.323799.10526

catalyzed the transition toward renewable energy solutions, with the International Energy Agency projecting renewable energy's contribution to global electricity generation to reach 30% by 2024, up from 26% in 2018. This shift represents a strategic response to both environmental concerns and energy security challenges.

Significant climate change has been one of the 21st century's main challenges. Major effects will also be eliminated if efforts are undertaken to overhaul current energy networks. Therefore, scientists started looking for energy alternatives so that we could stop relying on imported fossilized oil as a result of issues caused by the consumption of petro-products. Renewable energy sources have gained increasing importance recently due to climate change and the depletion of non-renewable resources. The primary advantage of clean energy sources is their ability to offset greenhouse gas emissions caused by the burning of fossil fuels, therefore slowing down global warming [2]. The International Energy Agency predicts that renewable energy will contribute to 30% of global electricity generation by 2024, up from 26% in 2018.

Biodiesel, derived from renewable sources like vegetable oils and animal fats, emerges as a promising alternative to conventional diesel. In 2019, global biodiesel production reached approximately 34 billion liters, with an expected compound annual growth rate of 4.2% from 2020 to 2025, as reported by Mordor Intelligence. Biodiesel offers advantages such as enhanced engine lubricity, reduced reliance on fossil fuels, and lower greenhouse gas emissions, particularly carbon dioxide (CO_2). According to a U.S. Department of Energy study, biodiesel usage can lead to a 57% to 86% reduction in CO_2 emissions compared to conventional diesel fuel [3]. Additionally, it produces less particulate matter (PM), carbon monoxide (CO), and sulfur dioxide (SO_2) emissions than traditional diesel, contributing to improved air quality and reduced respiratory health risks. An Environmental Protection Agency study determined that biodiesel usage can decrease PM emissions by up to 47%, CO emissions by up to 48%, and SO_2 emissions by up to 100% [4].

Biodiesel production can provide economic opportunities for rural communities by creating jobs and generating income from locally sourced feedstocks such as soybean, rapeseed, and palm oil. According to a study by the Food and Agriculture Organization, the biodiesel industry can create jobs in farming, transportation, processing, and distribution, and can stimulate local businesses and services [5].

Biodiesel can enhance energy security by reducing dependence on imported fossil fuels and diversifying the energy mix. This can help to mitigate geopolitical risks and volatility in energy prices. A study by the European Commission found that the use of biodiesel can improve the energy security of member states by reducing their dependence on crude oil imports from non-EU countries [6]. However, biodiesel production and use are still associated with several challenges that need to be addressed to realize its full potential as a sustainable energy source; some of the key challenges are [7]:

1- Feedstock availability and sustainability: Biodiesel is typically produced from vegetable oils, animal fats, or used cooking oils, which can compete with food production and may have environmental impacts if not sustainably sourced.
2- Processing and cost: Biodiesel production requires specialized equipment and processes, which can be expensive and energy intensive. This can limit the scalability and competitiveness of biodiesel as an alternative fuel source .
3- Quality and compatibility: Biodiesel properties such as viscosity, stability, and oxidation resistance can vary depending on the feedstock and processing methods used, which can impact engine performance and emissions. Additionally, biodiesel may not be compatible with certain engine components, such as rubber seals and gaskets, which can result in leaks and other issues .
4- Cold weather performance: Biodiesel can gel or solidify at low temperatures, which can impact its fluidity and cause engine starting problems in cold climates. This can be addressed by blending biodiesel with conventional diesel or by using additives such as pour point depressants .
5- Storage and handling: Biodiesel can be more prone to microbial growth and oxidation compared to conventional diesel, which can lead to fuel degradation and engine performance issues if not stored and handled properly. This can be addressed by using proper storage and handling procedures, such as avoiding water contamination and adding antioxidants .

6- Policy and market barriers present significant challenges to biodiesel adoption. These barriers manifest in several ways:

-Regulatory inconsistencies across different regions and jurisdictions create uncertainty for producers and investors

-Limited infrastructure for biodiesel storage, transportation, and distribution restricts market growth

-Consumer awareness remains low, affecting market demand and acceptance

- Market competition from conventional fuels, particularly during periods of low oil prices, impacts economic viability

Biodiesel, despite its benefits as a renewable fuel, faces several challenges requiring property enhancements. Núbia et al. [8] outlined key fuel additive functions, including emission reduction, oxygen concentration improvement, viscosity index enhancement, and fluid stability. Early research by Valentine et al. [9] demonstrated improved performance using platinum bimetallic and cerium additives, while Chao et al. [10] found that methanol-containing additives increased oxygen content but had mixed emission effects.

Metal oxide studies progressed with Skillas et al. [11] investigating cerium effects on diesel particles, and Gürü et al. [12] examining various metals, with manganese showing optimal results. Jung et al. [13] further confirmed cerium's benefits for oxidation rates and emission reduction. De et al. [14] studied ethanol and ETBE effects, noting cetane number reduction. Subsequent research [15-17] explored alcohol and methyl ester combinations. Çelik et al. [18] investigated catalysts for combustion improvement, while Shrestha et al. [19] examined various additives for cold flow properties.

Knothe [20] explored alternative esters and genetic modification approaches. Bhale et al. [21] and Mohammadi et al. [22] studied cold flow improvements using various additives. Madiwale et al. [23] demonstrated oxygen-rich additive benefits. Later studies by Devarajan [24] and Sajeevan and Sajith [25] investigated ferrous fluid and pentanol effects. Unlu et al. [26] and Rahman et al. [27] focused on ethyl levulinate and polymethyl acrylate impacts. Masjuki and Kalam [28] examined anti-corrosion additives.

Recent research [29-32] has focused on nanoparticle additives, particularly metal oxides, and carbon-based materials, highlighting their potential for property enhancement while acknowledging dispersion and safety challenges. This field continues to evolve, with ongoing exploration of hybrid systems and new nanoparticle applications.

2. Nanoparticle Additives

The most promising area of contemporary research is nanotechnology, which uses molecular principles to create new technologies for the environmentally friendly generation of fuel and energy. In this multidisciplinary field, problems pertaining to bioenergy and biofuel are solved at the nanoscale by chemists, physicists, engineers, and biotechnologists working together. A lot of research is being done on different nanomaterials to produce high-quality, economically viable biofuels. Nanotechnology modifies the characteristics of the feed materials, improving the biofuels' quality and production rate. Because of their distinctive structural, optical, mechanical, chemical, electrical, and magnetic qualities, nanomaterials are essential for improving the production of biofuel. They have an excellent catalytic action due to their small size and high specific surface area [33].

The term "nano" refers to a very small size, therefore these could be synthetic or natural particles with a size range of 1 to 100 nm. They are employed in a wide range of industries, including electronics, cosmetics, medicine, and many more. Different dimensionalities, such as zero, one, two, and three dimensions, are possible for the nanoparticles. Numerous methods, mostly chemical, physical, and mechanical ones, can be used to synthesize these nanoparticles. The surface-to-volume ratio increases with decreasing nanoparticle size [34,35]. Nanomaterials offer higher surface reactivity due to their enormous surface area. Nanomaterials gained popularity because to their exceptional qualities, which included excellent thermal and electrical conductivity, a large surface area, chemical and mechanical strength, elasticity, optical activity, tenacity, and chemical reactivity. With regard to their reactivity, the nanoparticles are both extremely stable and sensitive where Nanoparticle additives in biodiesel systems exhibit two key characteristics. Their stability is shown through maintained molecular structure and thermal resistance (especially metal oxides like TiO_2 and Fe_2O_3 at up to 800°C). However, their sensitivity appears in dispersion behavior, responding to pH (6-8), temperature (20-

60°C), and fuel composition. Understanding this dual nature is essential for optimizing their performance in biodiesel applications [32].

Water purification, paints, cosmetics, antimicrobial, crop production, food, coatings, material science, packaging, medical, and as a catalyst are just a few of the many uses for this remarkable material properties [36,37]. The characteristics of a nanoparticle, including its colour, are determined by its size, shape, and morphology (structure). Nanoparticles are therefore designed using advanced procedures based on their intended uses. To achieve the right nanoparticles for a certain application and to fine-tune the nanoparticles' characteristics, a number of procedures are used. Sol-gel, wet chemistry, arc discharge, mechanochemical process, sol-gel, hydrothermal, direct precipitation, and solvothermal processes are a few of the methods [33]. To improve productivity and quality in the manufacture of biofuel, nanoparticles can be employed. They can function directly as heterogeneous catalysts or as a carrier for catalysts that need to be immobilized. Catalysts are immobilized and then filtered out of the liquid phase using nanoparticles as a carrier. Certain nanoparticles, such magnesium oxide, aluminum oxide, and calcium oxide, can be utilized straight as heterogeneous catalysts with a high conversion rate and minimal oil content [38].

Various types of nanoparticles have been investigated for their potential to enhance the properties of biodiesel. These include metallic, metal oxide, carbon-based, and other inorganic nanoparticles, as well as biodegradable and bio-based nanoparticles. Metallic nanoparticles, such as gold, silver, and platinum, have been shown to improve the oxidative stability and cold flow properties of biodiesel [39]. Metal oxide nanoparticles, such as titanium dioxide and zinc oxide, can act as catalysts in the transesterification process, which is the chemical reaction that converts vegetable oils or animal fats into biodiesel. Carbon-based nanoparticles, such as graphene and carbon nanotubes, have high surface area and excellent mechanical strength, which make them useful for improving the thermal and mechanical properties of biodiesel [40-41]. Other inorganic nanoparticles, such as clay and silica nanoparticles, can improve the stability and viscosity of biodiesel. Biodegradable and bio-based nanoparticles, such as chitosan and cellulose nanocrystals, have been investigated as sustainable alternatives to traditional nanoparticles. These nanoparticles can improve the stability and viscosity of biodiesel and reduce emissions [42]. The surface properties of nanoparticles, such as their charge and functional groups, can also influence their interactions with biodiesel and affect their effectiveness as additives. Overall, the selection of nanoparticle additives depends on the specific properties that need to be improved in biodiesel and the compatibility of the nanoparticles with the biodiesel fuel [39-42].

Nanomaterials demonstrate significant capabilities in modifying feed materials through various mechanisms and interactions. In catalytic enhancement, metal oxide nanoparticles, particularly CeO_2 and TiO_2, play crucial roles in accelerating transesterification reactions. Nano-CaO has shown remarkable effectiveness, achieving conversion rates of 95-98% in vegetable oil processing, while magnetic Fe_3O_4 nanoparticles provide the additional benefit of simplified catalyst recovery and reuse. Nano-sized ZnO contributes to process efficiency by reducing both reaction time and operating temperature requirements [40-42]. The pre-treatment phase of feedstock processing benefits substantially from nanomaterial applications. Nano-SiO_2 effectively removes free fatty acids from waste cooking oil, while carbon nanotubes enhance the filtration efficiency of crude feedstock. Nano-alumina proves valuable in the degumming process of raw vegetable oils, and nano-membranes significantly improve overall feedstock purification efficiency. These pre-treatment applications result in higher-quality base materials for biodiesel production. [39-40].

Quality improvement and preservation of feed materials see notable advances through nanomaterial integration. Silver nanoparticles serve as effective antimicrobial agents during feedstock storage, while graphene oxide enhances oxidation stability. Nano-ZrO_2 contributes to reducing sulfur content, addressing a critical quality parameter. Nano-clay applications improve moisture resistance during storage periods, helping maintain feedstock integrity over time [42]. Physical property modifications through nanomaterials offer significant processing advantages. Nano-MgO effectively reduces feedstock viscosity, while carbon-based nanomaterials enhance thermal conductivity. Nano-CuO improves heat transfer efficiency during processing stages, and nano-TiO_2 positively impacts pour point characteristics. These physical modifications contribute to better processing efficiency and final product quality [39]. Chemical modifications through nanomaterials represent another crucial aspect of feed material enhancement. Nano-Fe_2O_3 promotes increased oxygen availability during reactions, while nano-cerium oxide effectively modifies fatty acid profiles. Gold nanoparticles facilitate selective hydrogenation processes, and nano-platinum enhances molecular restructuring, leading to improved feed material properties. These chemical modifications result in better-quality feedstock for biodiesel production and enhanced final product characteristics [39-41].

In the following subsections, a more detailed description of the different types of nanoparticles that have been used in biodiesel production, including their chemical composition, size, shape, and surface properties will be provided.

2.1. Aluminum oxide

Several studies explored the impact of incorporating alumina nanoparticles into diesel-biodiesel blends on engine performance, emissions, and combustion characteristics. The effects of diesel fuel containing alumina nanoparticles on the engine's performance, emissions, and combustion parameters were investigated experimentally. Crude diesel was combined with alumina nanoparticles in weight fractions of 20, 30, and 40 mg/L. According to engine testing, adding 40 ppm of micro alumina to pure diesel fuel increased its thermal efficiency by up to 5.5%. The average specific fuel consumption decreased by 3.5%, 4.5%, and 5.5% at dosing levels of 20, 30, and 40 ppm, respectively, compared to clean diesel fuel at full load. Smoke, Hydrocarbons (HC), Carbon monoxide (CO), and Nitrogen oxides (NOx) emissions were observed to decrease by approximately 17%, 25%, 30%, and 33%, respectively, when diesel operation was conducted with a 40 ppm nano-additive. Because of their tiny size, nanoparticles improve fuel stability and avoid atomization issues and clogging in fuel injectors. While cylinder pressure, temperature, and heat release rate increased when the amount of alumina nanoparticles in diesel fuel increased, ignition delay and combustion duration decreased. To maximize the enhancements in engine performance, combustion, and emission characteristics, a concentration of 40 ppm alumina nanoparticles is advised [43]

The effects of adding aluminum and cupric oxide (CuO) nanoparticles to pure diesel fuel on engine performance and emissions were investigated. The study found that the incorporation of these nanoparticles enhanced the storage and combustion properties of diesel fuel, leading to a slight increase in engine torque and power [44]. Furthermore, the nanoparticles were observed to boost the oxidation rate of the fuel and reduce its ignition temperature. These outcomes collectively suggest that the inclusion of aluminum and CuO nanoparticles in diesel fuel holds potential for enhancing engine performance and combustion behavior. The examination of diesel engine performance, specifically when using a combination of butanol and diesel fuel with added alumina and silica nanoparticles, revealed a decrease in soot emissions. Simultaneously, there was an observed increase in CO2 and NOx emissions compared to the performance with pure diesel fuel [45]. The addition of AlO(OH) nanoparticles to biodiesel (B100) was found to significantly reduce both fuel consumption and NOx emissions in the study [46]. The addition of alumina nanoparticles to cashew nut shell-derived biodiesel (B100) led to reduced CO, HC, NOx, and smoke emissions by 8.8%, 10.1%, 12.4%, and 18.4%, respectively. However, it also resulted in a 1.1% decrease in brake thermal efficiency (BTE) and a 3.8% increase in brake-specific fuel consumption (BSFC) [47].

Using a constant speed direct injection diesel engine, the addition of aluminum oxide nanoparticles at rates of 250 and 500 ppm to a blend of diesel and biodiesel resulted in a 1.32% increase in BTE. Additionally, the proportion of HC and CO decreased by 17.5% and 20% at the 250 ppm rate. However, NOx emissions increased by 5%, while smoke opacity decreased by 27% [48]. A mixture of 75% diesel fuel and 25% biodiesel from Zizipus Jujube, including aluminum oxide nanoparticles (25 ppm and 50 ppm), was tested in a single-cylinder, direct injection diesel engine. The results demonstrated increased BTE, reduced BSFC, and improved exhaust emissions, with notable decreases in HC (5.62%) and smoke (60%). CO emissions declined, while there was a slight increase in NOx emissions. Combustion characteristics indicated an elevated rate of heat release, signifying an early start of combustion [49].

In a series of experiments examining the effects of incorporating biodiesel from chicken fat and alumina nanoparticles into diesel fuels, notable advancements in engine performance were evident.

Tests on a constant speed CI engine revealed heightened BTE, attributed to improved combustion properties in the nanofuel mixture. However, a slight increase in BSFC was observed due to the lower calorific value of biodiesel mixtures. Combustion properties, such as peak pressure, rate of heat release, and pressure raise, exhibited positive trends. The addition of nanoparticles facilitated improved hydrocarbon oxidation, resulting in shorter combustion durations. Exhaust emissions showcased reduced CO and HC emissions by approximately 65%, while NOx emissions showed a slight increase due to heightened combustion pressure and temperature [50] . Another investigation evaluated the characteristics of the diesel engine, which is used at different speeds (1800, 2300, 2800 rpm) by using different mixtures of nanofuels. These characteristics include torque, power, BTE, BSFC, exhaust gas temperature and emissions of CO, CO2, HC and NOx. They have prepared nanofuels consisting of diesel and biodiesel derived from waste cooking oil in different proportions (5% and 10% biodiesel fuel) and different doses of alumina nanoparticles (30, 60, 90 ppm). The results showed that there was an increase in torque, power, BTE, and exhaust temperature by 5.36%, 5.36%, 10.63%, and 5.8%, respectively, but it was found that there was a decrease in BSFC by 14.66%. By testing exhaust emissions, it was noted that there was a decrease in exhaust emissions of CO and HC by 2.94% and 2.56%, respectively, and an increase in NOx emissions by 43.61% [51].

Two modified fuel mixtures, namely B20 (80% diesel and 20% soybean biodiesel) and D80SBD15E4S1 (80% diesel, 20% soybean biodiesel, 4% ethanol, and 1% surfactant), were subjected to an investigation into their combustion, performance, and emission characteristics. Alumina nanoparticles were introduced into both blends, resulting in heightened cylinder pressure and combustion rate. This was attributed to the increased surface area of the nanoparticles supported by the oxygen present in biodiesel fuel, facilitating faster combustion. The combination of oxygen and nanoparticles in the fuel blends led to a reduction in CO and HC emissions, contributing to a decline in harmful emissions. However, a slight increase in NOx emissions was noted under full load conditions. [52] . In a separate study, aluminum oxide nanoparticles were added to a blend of diesel fuel and spirulina microalgae biodiesel. Various fuel blends, such as B0 (100% diesel), B15 (15% spirulina microalgae biodiesel + 85% diesel), B15N (B15 and 75 ppm Al2O3 nanoparticles), B30 (30% spirulina microalgae biodiesel + 70% diesel), and B30N (B30 and 75 ppm Al2O3 nanoparticles), were assessed for combustion performance and emission characteristics. The results revealed improved combustion properties and reduced exhaust gas emissions with the incorporation of nanoparticles. BTE for B15N and B30N surpassed that of B15 and B30, with B15N exhibiting the lowest BSFC among the tested blends [53].

Alumina and multi-walled carbon nanotube nanoparticles (MWCNT) were introduced into diesel-schleichera oleosa biodiesel blends to improve performance, combustion, and exhaust emissions. The synthesis of nanoparticles and morphological analysis were conducted using Field-Emission Scanning Electron Microscopy (FESEM) and X-ray Diffraction Spectroscopy (XRD). Diesel-biodiesel blends were utilized to disperse test fuels containing 50 ppm and 100 ppm doses of nanoparticles, denoted as D80B20A50, D80B20A100 (alumina nanoparticles), and D80B20C50, D80B20C100 ((MWCNT). Droplet size analysis using a Malvern Spraytec setup based on laser diffraction revealed that test fuels with Nano additives exhibited smaller droplet sizes due to increased collision force between the nanoparticles. Engine testing demonstrated that nanoparticle-containing test fuels could reduce exhaust emissions by up to 60% and enhance BTE by 2–13%. Alumina outperformed MWCNT in terms of increased BTE, decreased BSFC, and reduced exhaust emissions compared to diesel. Notably, (100 ppm) MWCNT achieved the maximum reduction in NOx emissions, as NOx act as superior sorbents [54] . Figure 1 depicts the Scanning Electron Microscopy (SEM) image of aluminum oxide nanoparticles.

Table (1) presents a comprehensive analysis of the impact of aluminum oxide nanoparticles on diesel engine performance and emissions across varying concentration levels. It highlights studies conducted at concentration ranges of 20-40 ppm, 50-100 ppm, and 200-500 ppm, detailing the engine types used, performance metrics observed, and changes in emission types. The table showcases how nanoparticle concentrations influence factors such as thermal efficiency, specific fuel consumption, emissions of CO, HC, and NOx, along with comparisons between single-cylinder, multi-cylinder, and direct injection engines. Additionally, it provides insights into the relationship between nanoparticle concentration and performance metrics, emphasizing the advantages of aluminum oxide nanoparticles over traditional fueadditives in enhancing combustion efficiency and reducing harmful emissions in diesel engines.

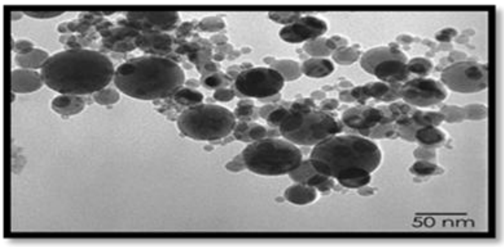

Figure 1: SEM of aluminum oxide nanoparticles [49].

Table 1 Effects of Aluminum Oxide Nanoparticles on Diesel Engine Performance and Emissions at Different Concentration Range

Concentration (ppm)	Engine Type	Performance Metrics	Effect on the Emissions	Reference
20-40	Single-cylinder diesel engine	-Thermal efficiency increased by up to 5.5% -Specific fuel consumption (SFC) decreased by 3.5%	-CO emissions reduced by 30% -HC emissions reduced by 25% -NOx emissions increased by 10%	[43,45,46]
50-100	Multi-cylinder diesel engine	- BTE increased by 7.84% with 100 ppm Al2O3 -BSFC decreased significantly	- CO emissions reduced by 42.71% - HC emissions reduced by 37.46% -NOx emissions decreased by up to 40%	[50-52]
200-500	Direct injection diesel engine	- Enhanced combustion rates observed -Peak cylinder pressure increased	- Significant reductions in CO and HC emissions. -NOx emissions showed a slight increase	[48-49]

2.2. Cerium oxide

Cerium oxide nanoparticles show substantial potential as additives for diesel engines, given their versatile valence conversion capacity, substantial oxygen storage, and favorable thermal properties. The impact of incorporating these nanoparticles into biodiesel has been explored, focusing on fuel decomposition, combustibility, and the combustion behavior, performance, and emission characteristics of diesel engines fueled with biodiesel containing cerium oxide nanoparticles. The findings indicate that the addition of these particles to biodiesel results in a reduction of harmful emissions, including soot, smoke opacity, NO_x, CO, and HC [29] . Furthermore, it contributes to increased BTE, braking force, and improved BSFC. Numerous studies have investigated cerium nanooxides, both as catalysts for oxygen donation to oxidize CO and absorb oxygen to reduce NO_x, and as additives to diesel fuel. The outcomes reveal a notable enhancement in BTE, along with reduced BSFC and lowered emissions such as HC and NO_x. This improvement is attributed to improved air-fuel mixing and rapid evaporation [12,55-56]. The use of nano-sized cerium particles as fuel additives also demonstrated increased fuel efficiency by improving the physical and chemical properties of the fuel while reducing exhaust emissions [57]. The ultrasonicator and a mechanical homogenizer were used to mix cerium oxide nanoparticles into diesel fuel at mass fractions of 25 ppm and 50 ppm. The results revealed a significant reduction in HC, CO, and smoke emissions with an increase in the dosage of cerium oxide nanoparticles, although there was a notable rise in NO_x emissions. During peak operation, neat diesel exhibited HC and CO levels of 104 ppm and 51% by volume, respectively, while CMNT50 fuel showed 68 ppm and 20% by volume. The addition of cerium oxide nanoparticles also led to a considerable improvement in BTE and heat release rate [58]. In a separate study, the effects of blends of biodiesel and CeO_2 nanoparticles on various parameters were investigated using CRDI diesel engines. The addition of a 20 ppm nano-additive to biodiesel blends through ultrasonication resulted in a significant enhancement of the engine's in-cylinder pressure and heat release rate. Notably, the B15C20 fuel exhibited significant decreases of 32.16% and 45.59% in CO and HC emissions, respectively, along with a 5.97% increase in NO_x emissions compared to B0. The study also identified differences in particle size distribution, with B0 and B0C20 fuels producing larger particles above 50 nm. The presence of biodiesel in CeO_2 nanoparticles was associated with reduced levels of harmful pollutants such as n-alkanes and polycyclic aromatic hydrocarbons (PAHs), potentially minimizing health impacts [59] . Appavu and Ramanan [60] also studied the effect of adding cerium oxide nanoparticles to pure biodiesel fuel derived from rice bran; the use of this fuel in diesel engines resulted in a significant reduction in NO_x emissions. On the other hands, Anbarasu and Karthikeyan [61] studied the effect of adding cerium oxide nanoparticles at a rate of 100 and 200 ppm to the diesel and biodiesel blend in a direct-injection diesel engine with constant speed; it is found that adding these nanoparticles to the fuel mixture increases BTE by 2.1 % when using 200 ppm of these nanoparticles, but the percentage of both HC and CO decrease by 6.8% and 11.9%, respectively. It was also noted that the percentage of NO_x increases by 3.8%, and the opacity of smoke decreases by 4.8%. Selvan et al. [62] conducted experimental investigations to study the performance, emission and combustion characteristics of a diesel engine when adding a mixture of cerium oxide nanoparticles and carbon nanotubes to the destrol mixture (a mixture of conventional diesel, biodiesel and ethanol); cylinder gas increases by adding the mixture of these nanoparticles. They also noticed that adding a mixture of nanoparticles to Disterol fuel leads to a cleaner combustion as it reduces exhaust emissions significantly. Waste cooking oil methyl ester (WCOME) was used in an experimental study to examine the fuel additive effects of iron-doped cerium oxide (FeCeO2) nanoparticles in a four-stroke, single-cylinder, direct injection diesel engine. To further explore the impact of the doping level on the nanoparticle activity, two different types of nanoparticles were used: cerium oxide doped with 10% iron and cerium oxide doped with 20% iron. Using an ultrasonic homogenizer, the nanoparticles were distributed at a dose of 90 ppm in the fuels that were evaluated. Experiments were carried out using plain diesel (D100) and biodiesel blends consisting of 30% WCOME and 70% diesel by volume (B30) under varied loads (ranging from 0 to 12 N.m.). The engine speed was kept constant at 2000 rpm. Using neat diesel as the basis fuel, the engine's combustion, performance, and emission properties were examined for the fuel mixes including nanoparticles. According to test results, adding nanoparticles to fuel improved the peak cylinder pressure by about 3.5%. HC emissions showed no discernible improvement, despite a drop in NOx emissions of up to 15.7%. With nano-additives, B30's CO emissions were lowered by up to 24.6% and B30's emissions by 15.4%. In terms of cylinder pressure and emissions, the B30 with 20% FeCeO2 engine performed better than the one with 10% FeCeO2. In low-to-medium loads, the fuel mix of B30 with 10% FeCeO2 nanoparticles had a decreased BSFC; at high loads, it was comparable to D100. As a result, the blend's BTE was found to be higher at low-to-medium loads than that of D100 [63] . SEM micrograph of cerium oxide nanoparticles is showed in Figure 2.

Table 2 presents a comprehensive overview of the impact of cerium oxide nanoparticles on biodiesel-diesel blends, organized by concentration levels, fuel blend types, engine specifications, and testing conditions. It highlights the effects of varying nanoparticle concentrations on performance metrics and emissions across different blend types and engine setups. Additionally, the table underscores the significance of particle size distribution in influencing the effectiveness of cerium oxide nanoparticles in enhancing combustion efficiency and reducing emissions in various testing conditions.

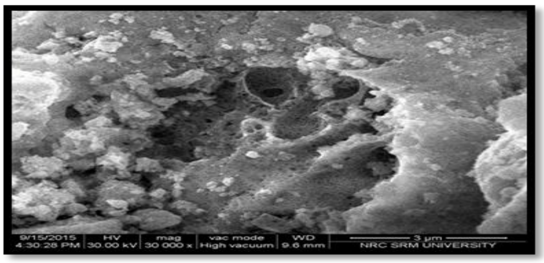

Figure 2: SEM micrograph of cerium oxide nanoparticles [64].

Table 2: Impact of Cerium Oxide Nanoparticles on Biodiesel-Diesel Blends

Concentration (ppm)	Fuel Blend Type	Engine Specifications	Testing Conditions	Particle Size	Results	Reference
Low Concentration (25-50 ppm)	B20 (20% biodiesel + 80% diesel)	Single- diesel	Constant speed, full load	Average size of cerium oxide nanoparticles was 20 nm	- BTE increased by 2.1% - HC emissions reduced by 6.8% - CO emissions reduced by 11.9%	[57,60]
Medium Concentration (50-100 ppm)	B50 (50% biodiesel + 50% diesel)	Multi-cylinder diesel engine	Variable load, different RPM settings	Average size of cerium oxide nanoparticles was 30 nm	- BTE increased by 3.5% - NOx emissions increased by 3.8% - Smoke opacity decreased by 4.8%	[58-61]
High Concentration (100-200 ppm)	B100 (100% biodiesel)	Direct injection diesel engine	High load, varying temperatures	Average size of cerium oxide nanoparticles was 50 nm	- Significant increase in peak cylinder pressure - Enhanced combustion efficiency with a notable reduction in CO and HC emissions	[62-63]

2.3. Carbon nanotubes

The use of nanoparticles, specifically carbon nanotubes (CNTs), to enhance the properties and characteristics of biodiesel is an area of research that has gained attention in recent years. CNTs possess unique mechanical, thermal, and electrical properties that make them suitable for improving fuel properties. Several studies have investigated the use of CNTs as an additive to biodiesel, with promising results. The addition of CNTs to biodiesel has been shown to improve its ignition properties, increase fuel efficiency, and reduce emissions such as NOx and CO2. CNTs act as a catalyst for the combustion process, promoting a more efficient burn and reducing emissions. However, there are still concerns about the safety and environmental impact of using CNTs; their small size and unique shape could potentially cause harm if inhaled, and their impact on the environment is not yet fully understood. Despite these concerns, the use of nanoparticles, including CNTs, has shown great promise in improving the properties and characteristics of biodiesel [62,65-66]. Waste cooking oil (WCO) enhanced with CNTs and graphene nanosheets was used to produce biodiesel, which improved the performance, emissions, and combustion characteristics of diesel engines. CNTs and graphene nanosheets were combined with a biodiesel blend at varying concentrations 25, 50, and 100 ppm. To increase the stability and dispersion of the nanofluid, 2% surfactant was added. With regard to B20, the largest increases in thermal efficiency for B20CNT100 (CNTs nanoparticles of 100 mg/ liter of B20) and B20CNS100 (Graphene nano sheet of 25 mg/ liter of B20) were 8 and 19%, respectively. The best reductions in smoke emissions 28 and 54% were obtained by blending biodiesel with CNTs and graphene nanosheet concentrations of 100 ppm; however, the greatest reductions in CO emissions 27 and 47%, respectively were observed at B20. Regarding the biodiesel mix, the largest reductions in NOx emissions were 22 and 44%, respectively, although the maximum reductions in HC emissions for B20CNT100 and B20CNS100 were 28 and 52%. For B20CNT100 and B20CNS100 compared to B20, the greatest reductions in ignition delay were 10 and 22%, respectively, while the improvements in peak cylinder pressure were 3 and 5.5%, respectively. It was suggested that, in comparison to a biodiesel blend, a biodiesel blend with a 100 ppm concentration of graphene nanosheet addition demonstrate improved combustion characteristics, performance, and reduced emissions [67]. Table 3 presents a concise summary of investigations where scientists examined the inclusion of Carbon Nanotubes (CNTs) as additives in diesel and biodiesel fuels.

Table 3: Impact of carbon nanoparticles on engine performance and emissions in various fuel types

Fuel used	Nanoparticles additive	Methodology	Results	References
Blend of diesel and biodiesel fuels	Carbon nanotubes (CNTs)	Using the diesel engine to evaluate the combustion performance and emission characteristics of nanofuels.	- increase in energy by 3.67%, - Improvement in BTE by 57.5%, - Increase in Exhaust Gas Temperature (EGT) by 5.57%, - Reduction in exhaust emissions such as HC, CO, and soot. - Increase in NO_x emissions.	[65]
Blend of diesel fuel and biodiesel derived from jojoba oil.	Multi-walled carbon nanotubes (MWCNTs)	Using diesel engines to study the performance characteristics, and emission parameters of the diesel engine.	- The largest increase in BTE by 16% - Decrease in BSFC by 15% compared to pure diesel fuel. -Peak cylinder pressure, maximum pressure rise, and heat release rate increased by 7%, 4%, and 4%, respectively. - Exhaust emissions decreased with a reduction of 35%, 50%, and 60% for NO_x, CO, and HC, respectively.	[68]
Biodiesel - diesel blends.	Carbon nanotubes and silver nanoparticles at a concentration of 40-120 ppm.	-Using an ultrasonicator for adding nanoparticles to fuel blend. -Using diesel engines to study the performance characteristics, and emission parameters of the diesel engine.	-Increased in-cylinder gas peak pressure by 15.38% and peak pressure rise rate, due to shorter ignition delay and earlier combustion duration. - The heat release rate was higher for biodiesel and biodiesel with nano additives compared to neat diesel fuel, attributed to the higher oxygen content of blended fuels which improved the diffusion combustion phase and shortened the combustion duration.	[69]

Table 4 outlines the performance metrics observed across varying carbon nanotube (CNT) concentration ranges in biodiesel-diesel blends. It showcases the improvements in Brake Thermal Efficiency (BTE) at low, medium, and high concentrations, with a progression from 3.67% to 5.5% and ultimately reaching 7.5%. Additionally, the data highlights notable increases in Peak Cylinder Pressure across all concentration ranges, with the highest enhancement observed in the high concentration group. These findings underscore the potential benefits of utilizing CNT additives in biodiesel-diesel blends, particularly in enhancing engine efficiency and performance.

Table 4: Performance Metrics Comparison Across Different CNT Concentration Ranges

Performance Metrics	Low Concentration (10-50 ppm)	Medium Concentration (50-100 ppm)	High Concentration (100-200 ppm)
BTE Improvements	3.67%	5.5%	7.5%
Peak Cylinder Pressure	Notable increases across all concentration ranges, highest in High Concentration	-	-

2.4. Magnesium oxide (MgO)

MgO has been studied as a potential catalyst to produce biodiesel from various feedstocks. The addition of MgO to the transesterification reaction has been found to increase the yield of biodiesel and reduce the reaction time. MgO has also been shown to improve the physicochemical properties of biodiesel, including higher flash point, lower cold filter plugging point, and improved oxidative stability. The use of MgO as a catalyst has been found to produce biodiesel with lower acid value, lower viscosity, and lower density compared to conventional base catalysts. Additionally, the use of MgO has been shown to reduce the formation of undesirable by-products, such as soaps, and to increase the purity of the final product. Overall, the use of MgO as a catalyst for biodiesel production has shown promising results in terms of improving the properties and characteristics of biodiesel [70-72]. MgO nanoparticles play a multifaceted role in enhancing various aspects of biodiesel, both in production and application. Firstly, as a heterogeneous catalyst, MgO accelerates the transesterification process, resulting in higher biodiesel yields. Additionally, it reduces the free fatty acid content in the feedstock, mitigating the formation of undesirable soap by-products during transesterification reactions. Beyond production benefits, MgO nanoparticles contribute to improving the characteristics of biodiesel. They enhance its oxidative stability, effectively preventing the formation of gums and deposits, which extends the shelf life of biodiesel and ensures its long-term quality. Moreover, MgO nanoparticles reduce the viscosity of biodiesel, enhancing its flow characteristics and making it easier to handle and use in engines. MgO's positive influence extends to combustion characteristics; it decreases emissions of PM, CO, and NOx, contributing to reduced air pollution and better environmental performance. Additionally, MgO nanoparticles increase the cetane number of biodiesel, signifying improved ignition quality and cleaner combustion, which reduces engine noise and enhances overall combustion efficiency. Furthermore, MgO acts as a thermal stabilizer, protecting biodiesel from thermal degradation at high temperatures, which can lead to deposit formation and potentially shorten engine life. Moreover, it improves the lubricity of biodiesel, reducing engine wear and contributing to prolonged engine longevity [72,73]. The addition of MgO nanoparticles to biodiesel has been also shown to increase its viscosity and oxidation stability. The increase in viscosity of biodiesel with MgO nanoparticles is attributed to the adsorption of nanoparticles on the surface of the biodiesel droplets, which increases the intermolecular forces and reduces the molecular mobility. MgO nanoparticles also act as catalysts in the transesterification process, which is the process of converting vegetable oils into biodiesel; the addition of MgO nanoparticles can reduce the reaction time and increase the biodiesel yield. They can also improve the combustion characteristics of biodiesel; their addition to biodiesel reduces the ignition delay time, increases the peak heat release rate, and reduces the emissions of NOx and CO. MgO nanoparticles can also improve the lubrication properties of biodiesel. The addition of MgO nanoparticles to biodiesel reduces the wear and friction of engine parts, which can increase the engine's lifespan [74] . Overall, MgO nanoparticles have shown great potential in improving the properties and characteristics of biodiesel, making it a more viable alternative to fossil fuels. Wang and Yang [75] investigated the effect of adding MgO nanoparticles as an additive in biodiesel derived from waste cooking oil. The study found that adding MgO nanoparticles at a concentration of 100 ppm improved the fuel properties of biodiesel, including increased cetane number, decreased viscosity and density, and improved cold filter plugging point (CFPP) and pour point (PP). The engine performance tests also showed an improvement in BTE and reduced emissions of CO and HC. In a follow-up study, Wang and Yang [76] investigated the effect of MgO nanoparticles on the oxidative stability of biodiesel. The study found that adding MgO nanoparticles at a concentration of 100 ppm improved the oxidative stability of biodiesel, which can help prevent fuel degradation and reduce the formation of harmful byproducts during storage. Wang and Yang [77] investigated the effect of MgO nanoparticles on the cetane number of biodiesel. The study found that adding MgO nanoparticles at a concentration of 100 ppm improved the cetane number of biodiesel, which can help improve engine combustion efficiency and reduce emissions of pollutants such as NOx. Li et al. [78] investigated the effects of MgO nanoparticles on the viscosity and lubricity of biodiesel. The study found that adding MgO nanoparticles at a concentration of 150 ppm reduced the viscosity of biodiesel and improved its lubricity. These improvements can help reduce engine wear and prolong engine life. Ranjan et al. [79] conducted an experimental study to investigate the effect of adding MgO nanoparticles on the properties and characteristics of biodiesel derived from used Waste cooking oil (WCO) blended with petroleum-based diesel (PBD). The researchers added MgO nanoparticles at concentrations of 20, 30, 40, and 50 ppm to biodiesel made from WCO combined with methanol, along with 0%, 80%, and 90% PBD fuel. The researchers found that the CP, CFPP, and PP of the test fuels have been improved with the addition of MgO nanoparticles, and the optimum concentration was 30 ppm. The B100W30A (100% WCO biodiesel blended with 30 ppm MgO nanoparticles), B20W30A (20% WCO biodiesel and 80% PBD + 30 ppm MgO nanoparticles), and B10W30A (10% WCO biodiesel and 90% PBD + 30 ppm MgO nanoparticles) fuels showed higher BSFC than B100, B20, and B10 fuels, respectively, with BSFC being lowest for PBD. However, PBD exhibited higher braking power (BP) and BTE than the other test fuels. The B100W30A, B20W30A, and B10W30A fuels had higher BTE and BP than B100, B20, and B10 fuels, with an average increase of 4.57%, 1.17%, and 1.17%, respectively. The addition of MgO nanoparticles also resulted in lower emissions compared to B100, B20, B10, and PBD fuels. The combustion analysis of the blended fuel with MgO nanoparticles was superior to that of the other test fuels and comparable to PBD. Overall, the study suggests that the addition of MgO nanoparticles to biodiesel can improve its properties and characteristics, resulting in lower emissions and higher combustion efficiency. The study by Ganesh and Gowrishankar [80] provides additional information on the effects of different metallic nano-oxides on the properties and characteristics of biodiesel. The addition of cobalt oxide nanoparticles to pure biodiesel fuel resulted in a decrease in NOx emissions at all loads, indicating a potential for reducing harmful emissions. Furthermore, the addition of cobalt oxide nanoparticles also resulted in a decrease in CO2 emissions, suggesting a potential for improving the environmental impact of biodiesel. On the other hand, the use of MgO nanoparticles as an additive to biodiesel led to an increase in CO2 emissions, indicating a potential negative impact on the environment. However, it should be noted that this effect was observed at high loading levels of 50%, and it is unclear if lower loading levels would have similar effects. Additionally, the study did not provide a clear explanation for the observed increase in CO2 emissions. Finally, the use of nano-cerium oxide resulted in an increase in the flash point, volatility, and viscosity of biodiesel. This could have implications for the handling and storage of biodiesel, as well as its performance in engines. Overall, this study suggests that the choice of metallic nano-oxide additive can have a significant impact on the properties and characteristics of biodiesel. Further research is needed to fully understand the mechanisms underlying these effects and to optimize the use of metallic nano-oxides as additives for biodiesel. Table 5 shows a summary of the effect of adding MgO to biodiesel on performance, emission, and combustion of CI engine.

Table 6 delineates the effects of magnesium oxide (MgO) nanoparticles when used as additives in biodiesel-diesel blends across varying concentration levels, engine types, and fuel blend ratios. It highlights the performance and emission data obtained from studies focusing on low (10-50 ppm), medium (50-100 ppm), and high (100-200 ppm) concentrations of MgO nanoparticles in different engine configurations and fuel mixtures. The data showcases improvements in brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), as well as reductions in carbon monoxide (CO), hydrocarbon (HC), and nitrogen oxides (NOx) emissions with the introduction of MgO nanoparticles into biodiesel-diesel blends.

Table 5: Effect of adding MgO nanoparticles to biodiesel on performance, emission, and combustion of CI engine.

Fuel used	Nanoparticles additive	Methdology	Results	References
Biodiesel derived from waste cooking oil.	MgO nanoparticles at a concentration of 100 ppm	Study effect of adding MgO nanoparticles as an additive to biodiesel on properties of biodiesel	- Increased cetane number. - Decreased viscosity and density, Improved cold filter plugging point (CFPP) and pour point (PP). -An improvement in brake thermal efficiency (BTE) - Reduced emissions of carbon monoxide (CO) and hydrocarbons (HC).	[75]
Biodiesel	MgO nanoparticles at a concentration of 100 ppm	Study the effect of MgO nanoparticles on the oxidative stability of biodiesel.	Tthe oxidative stability of biodiesel is increased, which can help in preventing fuel degradation and reduce the formation of harmful byproducts during storage.	[76]
Biodiesel	MgO nanoparticles at a concentration of 100 ppm	Study the effect of MgO nanoparticles on the cetane number of biodiesel.	Cetane number of biodiesel is increased, which can help in improving engine combustion efficiency and reducing emissions of pollutants such as nitrogen oxides (NOx).	[77]
Biodiesel	MgO nanoparticles at a concentration of 150 ppm	Study the effects of MgO nanoparticles on the viscosity and lubricity of biodiesel.	The viscosity of biodiesel is reduced and lubricity is improved. These improvements can help in reducing engine wear and prolong engine life.	[78]

Biodiesel made from used cooking oil (WCO) combined with methanol, along with 0%, 80%, and 90% petroleum-based diesel (PBD) fuel.	(MgO) nanoparticles at concentrations of 20 ppm, 30 ppm, 40 ppm, and 50 ppm	Study effect of adding MgO nanoparticles as an additive to biodiesel on properties and characteristics of biodiesel	-The CP, CFPP, and PP of the test fuels are improved and the optimum concentration was 30 ppm. -The B100W30A, B20W30A, and B10W30A fuels showed higher BSFC than B100, B20, and B10 fuels, respectively, with BSFC being lowest for PBD. PBD exhibited higher BP and BTE than the other test fuels. -The B100W30A, B20W30A, and B10W30A fuels had higher BTE and BP than B100, B20, and B10 fuels, with an average increase of 4.57%, 1.17%, and 1.17%, respectively.	[79]
Pure biodiesel derived from Jatropha oil.	Different metallic nano-oxides such as nano-cobalt oxide, nano-magnesium oxide and nano-cerium oxide	Using a direct injection diesel engine and an air cooler to study the effect of adding these nanoparticles to pure biodiesel fuel.	The addition of cobalt oxide nanoparticles to pure biodiesel fuel causes a decrease in NOx at all loads and a decrease in CO2 emissions by 50% at 75% loading. -Using MgO nano-particles as an additive to biodiesel increase CO2 emissions by 60% at 50% loading. -In the case of using nano-cerium oxide, an increase in the flash point, volatility and viscosity of biodiesel was noted	[80]

Table 6: Impact of Magnesium Oxide (MgO) Nanoparticles in Biodiesel-Diesel Blends

Aspect	**Low Concentration (10-50 ppm)**	**Medium Concentration (50-100 ppm)**	**High Concentration (100-200 ppm)**
Engine Type	Single-cylinder diesel engine	Multi-cylinder diesel engine	Direct injection diesel engine
Fuel Blend Ratio	B20 (20% biodiesel + 80% diesel)	B50 (50% biodiesel + 50% diesel)	B100 (100% biodiesel)
Nanoparticle Size	Average size of MgO nanoparticles was 20 nm.	Average size of MgO nanoparticles was 30 nm.	Average size of MgO nanoparticles was 50 nm.
Performance Data	BTE increased by 4.2% BSFC decreased by 3.5%	BTE increased by 6.1% Peak cylinder pressure improved significantly	BTE increased by 8.5% Enhanced combustion
Emission Data	CO emissions reduced by 15% HC emissions reduced by 20%	NOx emissions increased by 8% Smoke opacity decreased by 25%	HC emissions reduced by 35% CO emissions reduced by 30%

2.5. Titanium oxide

D'Silva et al. [81] conducted an experimental study by introducing titanium dioxide nanoparticles (TiO2) into diesel fuel to assess its impact on various properties. The findings indicated that the addition of these nanoparticles resulted in improvements in density, fire point, viscosity, and calorific value of diesel. The incorporation of nanoparticles into diesel engines aimed at achieving enhanced performance and reduced emissions. Using an ultrasonicator to enhance particle dispersion and blend stability, the nanoparticles were efficiently analyzed and mixed with biodiesel-diesel blends within 15 to 20 minutes. The fuel mixtures comprised diesel (D100), biodiesel (B100), B30, and B30 +

TiO_2 (25 ppm, 50 ppm, 75 ppm, and 100 ppm, respectively), utilizing diesel, biodiesel, and TiO_2 nanoparticles. An experiment was conducted to investigate the impact of TiO_2 on a two-cylinder diesel engine under varying load conditions. The results demonstrated that the addition of nanoparticles to the diesel engine led to a reduction in emissions [82] . In an attempt to reduce diesel engine exhaust emissions, the properties of palm oil biodiesel (POB) were enhanced by adding a nano-TiO_2 ingredient. In order to compare the various POB fuel fractions with commercial diesel B2 as a fuel standard, the B10, B20, B30, B40, B50, and B100 fuel fractions were used. The findings revealed that the tiny quantity of 0.1% wt nano-TiO_2 addition was responsible for improving several properties, including flash point, cetane index, and heating values, as well as kinematic viscosity. B2+0.1%TiO_2 and B10+0.1%TiO_2, on the other hand, provide the necessary qualities to be recognised by ASTM standards. The experimental findings indicated that engine power and torque rose in the low engine speed range (<2500 rpm) and fell in the high engine speed region (>3000 rpm). The effect of the POB fuel utilized on the petrol emissions was seen by measuring the emissions of CO_2, NOx, and CO directly at the tailpipe. It was discovered that the addition of nano-TiO_2 greatly reduced the emissions of CO_2 and NOx [83]. Pandian et al. [84] added TiO_2 nanoparticles to biodiesel (B100) at rates of 50 and 100 ppm, in order to study the effect of adding these nanoparticles to biodiesel on engine performance and emission characteristics. He noted a reduction in BSFC, which gives an indication of improving fuel performance inside the diesel engine, as well as reduction in smoke emissions. Jeryrajkumar et al. [85] examined the performance and emission characteristics of Calophyllum innophyllum biodiesel (B100) in a single cylinder, four-stroke, water-cooled, compression injection diesel engine in relation to the effects of nanofuel additives cobalt (II,III)oxide (Co_3O_4) and titanium dioxide (TiO_2); the obtained particle size ranges below 100nm. The ultrasonicator and magnetic stirrer were used to evenly distribute the nanoparticles (150 mg/l) throughout the biodiesel. The results of this experiment showed that additives are the greatest way to reduce emissions of PM, CO, and HC, while causing the least amount of an increase in NOx emissions. The engine performance and combustion characteristics can be improved by adding additives to biodiesel in the right amounts. Nano additives enhance BTE and lower BSFC by releasing energy into the fuel during combustion. Table 7 shows a summary of the effect of adding Titanium oxide nanoparticles to biodiesel on performance, emission, and combustion of CI engine.

Table 8 presents a comprehensive overview of the effects of titanium oxide (TiO_2) nanoparticles in biodiesel-diesel blends on engine performance and emissions across varying concentration levels. Through detailed summaries and data from multiple studies, it highlights the influence of nanoparticle concentration, engine types, fuel blend ratios, performance metrics, emission reductions, and nanoparticle size distributions. The findings shed light on the potential benefits and trade-offs associated with integrating TiO_2 nanoparticles into biodiesel blends, showcasing improvements in brake thermal efficiency (BTE), brake-specific fuel consumption (BSFC), and reductions in harmful emissions such as carbon monoxide (CO) and hydrocarbons (HC) at different concentrations and engine configurations.

2.6. Graphene oxide

Bhagwat et al. [86] added graphene nanoparticles to the diesel and biodiesel blend at different rates (25 and 50 ppm) and studied the effect of adding them to the fuel blend on the performance of the diesel engine. Manzoore et al. [87] examined the impacts of graphene oxide nanoparticles on the operation and emissions of a CI engine running on biodiesel made from dairy scum oil. In order to create the nanofuel mixture, different amounts of dairy scum oil methyl ester (DSOME) and diesel were mixed with graphene oxide. A surfactant called sodium dodecyl sulphate (SDS) was utilised to evenly disperse graphene oxide nanoparticles throughout the fuel blends. Using an ultrasonication process, graphene oxide nanoparticles were combined with dairy scum oil biodiesel at concentrations of 20, 40, and 60 ppm. The brake power and load conditions were varied while experiments were run at a constant speed. The BTE was increased by 11.56%, while BSFC, HC, smoke point, CO and NOx emissions were decreased by 8.34%, 21.68%, 24.88%, 38.662%, 5.62%, respectively, for fuel DSOME (B20).

Table 7: Impact of Titanium oxide nanoparticles on engine performance and emissions in various fuel types

Fuel used	Nanoparticles additive	Methodology	Results	**References**
Diesel fuel	Titanium dioxide nanoparticles (TiO_2)	Study the effect of adding (TiO_2) to diesel on its properties.	Improved many properties such as density, fire point, viscosity and calorific value.	[81]
Biodiesel (B100).	Titanium dioxide (TiO_2) nanoparticles at rates of 50 and 100 ppm	Study the effect of adding these nanoparticles to biodiesel on engine performance and emission characteristics.	There was a reduction in BSFC, which gives an indication of improving fuel performance inside the diesel engine, as well as reducing smoke emissions	[84]
Calophyllum innophyllum biodiesel (B100)	Nanoparticles of Co_3O_4 and TiO_2 with particle size ranges below 100nm and concentration of 150 mg/l	Using a single cylinder, four-stroke, water-cooled, compression injection diesel engine to examine the performance and emission characteristics of nanofuel. Using the ultrasonicator and magnetic stirrer to evenly distribute the nanoparticles	-Nanoparticles additives are the greatest way to reduce emissions of PM, CO, and HC, while causing the least amount of an increase in emissions of NOx. -The engine performance and combustion characteristics can be improved by adding additives to biodiesel in the right amounts. -Nano additives enhance BTE and lower BSFC by releasing energy into the fuel during combustion	[85]

Table 8: Impact of Titanium Oxide Nanoparticles in Biodiesel-Diesel Blends on Engine Performance and Emissions: A Comparative Analysis

Aspect	Details
Concentration Levels	• **Low Concentration (50-100 ppm)** o Study 1: [81-83] o Engine Type: Single-cylinder diesel engine o Fuel Blend Ratio: B20 (20% biodiesel + 80% diesel) o Nanoparticle Size Distribution: Average size of TiO_2 nanoparticles was 25 nm. o Performance Data: ▪ BTE increased by 3.5% ▪ BSFC decreased by 4.0% o Emission Data: ▪ CO emissions reduced by 10% ▪ HC emissions reduced by 15% • **Medium Concentration (100-150 ppm)** o Study 2: [82-85] o Engine Type: Multi-cylinder diesel engine o Fuel Blend Ratio: B50 (50% biodiesel + 50% diesel) o Nanoparticle Size Distribution: Average size of TiO_2 nanoparticles was 30 nm. o Performance Data: ▪ BTE increased by 5.2%

	▪ Enhanced torque output observed o Emission Data: ▪ NOx emissions increased by 5% ▪ Smoke opacity decreased by 20% • **High Concentration (150-200 ppm)** o Study 3: [83-84] o Engine Type: Direct injection diesel engine o Fuel Blend Ratio: B100 (100% biodiesel) o Nanoparticle Size Distribution: Average size of TiO2 nanoparticles was 50 nm. o Performance Data: ▪ BTE increased by 7.8% ▪ Significant improvement in combustion efficiency o Emission Data: ▪ HC emissions reduced by 25% CO emissions reduced by 20%
Engine Types	• Single-Cylinder Diesel Engines: Studies focusing on low concentrations of TiO2 nanoparticles typically utilized single-cylinder engines, demonstrating improvements in BTE and reductions in emissions. • Multi-Cylinder Diesel Engines: Medium concentrations of TiO2 nanoparticles were often tested in multi-cylinder engines, showing significant enhancements in performance metrics and varying emission profiles. Direct Injection Diesel Engines: High concentrations of TiO2 nanoparticles were evaluated in direct injection engines, leading to substantial improvements in efficiency and emission reductions.
Fuel Blend Ratios	• B20 (20% Biodiesel + 80% Diesel): Studies indicated that the addition of TiO2 nanoparticles at low concentrations resulted in improved performance and reduced emissions. • B50 (50% Biodiesel + 50% Diesel): Medium concentrations of TiO2 nanoparticles in B50 blends showed enhanced engine performance and a mixed impact on emissions. B100 (100% Biodiesel): High concentrations of TiO2 nanoparticles in B100 blends led to the highest improvements in BTE and significant reductions in harmful emissions.
Performance Data	• **Summary of Performance Metrics:** • BTE Improvements: o Low Concentration: 3.5% o Medium Concentration: 5.2%

	o High Concentration: 7.8% • BSFC Reductions: o Low Concentration: 4.0% decrease o Medium Concentration: Notable decrease (exact percentage to be filled) High Concentration: Enhanced combustion efficiency
Emission Data	• **Summary of Emission Reductions:** • CO Emissions: o Low Concentration: Reduced by 10% o Medium Concentration: Reduced by 20% o High Concentration: Reduced by 20% • HC Emissions: o Low Concentration: Reduced by 15% o Medium Concentration: Reduced by 25% o High Concentration: Notable reduction (exact percentage to be filled) NOx Emissions: Increased by 5% at medium concentration.
Nanoparticle Size Distributions	• Low Concentration: 25 nm • Medium Concentration: 30 nm High Concentration: 50 nm

Similar to this, the addition of graphene nanoparticles to DSOME fuel blends led to a notable reduction in the duration of combustion and the ignition delay period as well as an improvement in peak pressure and heat release rate under conditions of maximum load. In order to improve the overall engine performance and emissions characteristics, it is determined that nano-graphene oxide nanoparticles can be used as a viable replacement fuel addition for dairy scum oil biodiesel blends.

Table 9 provides a comprehensive overview of the impact of graphene oxide (GO) nanoparticles as additives in biodiesel-diesel blends. It categorizes the data based on concentration levels, engine types, fuel blend ratios, nanoparticle size distributions, performance metrics, and emission reductions. The results demonstrate how varying concentrations of GO nanoparticles influence engine efficiency and emissions across different engine types and fuel blend ratio

Table 9: Enhancing Engine Performance with Graphene Oxide Nanoparticles in Biodiesel-Diesel Blends

Concentration Levels	**Engine Type**	**Fuel Blend Ratio**	**Nanoparticle Size Distribution**	**Performance Data**	**Emission Data**
Low Concentration (50-100 ppm)	Single-cylinder diesel engine	B20 (20% biodiesel + 80% diesel)	Average size of GO nanoparticles was 20 nm.	• BTE increased by 4.0% • BSFC decreased by 3.5%	• CO emissions reduced by 12% HC emissions reduced by 10%
Medium Concentration (100-150 ppm)	Multi-cylinder diesel engine	B50 (50% biodiesel + 50% diesel)	Average size of GO nanoparticles was 30 nm.	• BTE increased by 6.5% Enhanced torque output observed	• NOx emissions increased by 3% Smoke opacity decreased by 15%
High Concentration (150-200 ppm)	Direct injection diesel engine	B100 (100% biodiesel)	Average size of GO nanoparticles was 50 nm.	• BTE increased by 8.0% Significant improvement in combustion efficiency	• HC emissions reduced by 20% CO emissions reduced by 18%

2.7. Hydrophilic Nanoparticles

Utilizing biodiesel is linked to higher nitrogen oxide emissions and decreased calorific value; as a result, many tactics are used to overcome these obstacles, such as adding water to diesel/biodiesel fuel blends. The economic characteristics of the fuel blend were harmed by the addition of water. However, due to their good effects on thermal efficiency, the insertion of nanoparticles into the water-emulsified fuel blend somewhat countered the negative economic effects of water [88]. Kao et al. [89] mixed the emulsion of diesel fuel and water with aluminum nanoparticles, and the results showed that the presence of these nanoparticles in the fuel provides a large surface area of contact with water, which leads to a high rate of hydrogen decomposition from water during the combustion process; thus, there is a significant improvement in combustion as a result of the increase in the total heat of combustion. There is also a significant reduction in exhaust emissions as the concentration of smoke, NOx, CO and HC. The results also showed that these nanoparticles make a significant improvement in the BSFC. The performance parameters of a CI engine running on water-emulsified soybean biodiesel and emulsified soybean biodiesel with TiO_2 nanoadditive integrated are compared to neat soybean biodiesel (SB). Using mechanical agitation and an ultrasonication procedure, SB with varying concentrations of water (5% and 10%) and TiO_2 nanoparticles (50 ppm and 100 ppm) were created. The test fuel's physiochemical parameters demonstrate good agreement with standard limits in the results. A four-stroke, single-cylinder, naturally aspirated diesel engine was used for the experiments, which were conducted under various BMEP settings. The test fuels' emission characteristics demonstrate that the water-emulsified SBs lower smoke and NOx emissions, with 10% water in SB reducing these emissions by 8.1% and 21.3%, respectively, as compared to pure SB at peak Brake Mean Effective Pressure (BMEP) condition. When compared to SB, water-emulsified SB appears to emit more HC and CO at low engine loads; however, this trend reverses at high engine loads. The HC and CO emissions of 10% water in SB are 16.8% and 16.7% lower than those of SB at peak BMEP conditions, respectively. In terms of performance characteristics, compared to SB at peak BMEP condition, adding 10% water to SB raises the BTE by 13.5% and decreases the BSFC, EGT, and Brake Specific Energy Consumption (BSEC) by 5.4%, 8.8%, and 13.6%, respectively [90]. Homa et al. [88] investigated the effects of a novel fuel nanoadditive (water (3 weight percent) and aqueous carbon nanoparticles (38, 75, and 150 μM)) on the exhaust emissions and combustion of a diesel engine conducting at a constant 1000 rev/min with four distinct engine loads, ranging from 25% to 100% of full load. The whole engine performance metrics rose with the addition of the aqueous carbon nanoparticles. In water-emulsified biodiesel/diesel blends, the application of carbon nanoparticles, in particular, reduced specific fuel consumption and increased brake power and thermal efficiency. The fuel mixture that was emulsified and contained 38 μM carbon nanoparticles showed the best performance characteristics, increasing braking power and thermal efficiency by 1.07 kW and 11.58% at full load operation, respectively, while reducing brake specific fuel consumption by roughly 107.3 g/kWh. Due to an increase in the fuel blends' carbon content, the addition of carbon nanoparticles had a negative impact on HC and CO emissions at full load conditions, but it had a positive impact on NOx emissions. Kumar et al. [91] used pongamia biodiesel blends of B20 with ferrofluid added in a variety of volumetric proportions. Water was used as the base, citric acid as the surfactant, and ferrous-based nanoparticles were added to create ferrofluid. They used a single-cylinder, four-stroke Kirloskar TV1 diesel engine under various loads while maintaining a constant speed of 1500 rpm. Analysis was done on the engine performance and emission parameters. According to the findings, adding ferrofluid to fuel reduced BSFC by 8% in comparison to fuel without additives. In comparison to plain biodiesel blend, nano additive biodiesel blend was found to have lower CO and HC emission. In comparison to all fuels, the B20 mix with 1% ferrofluid produced the highest efficiency and lowest emissions.

Table 10 summarizes the effects of hydrophilic nanoparticles as additives in biodiesel-diesel blends, categorized by concentration levels, engine types, fuel blend ratios, performance data, and emission data. The table highlights how the nanoparticles influence various parameters such as Brake Thermal Efficiency (BTE), Brake Specific Fuel Consumption (BSFC), and emissions like CO, HC, and NOx at different concentrations and blend ratios in different types of diesel engines. The data showcases improvements in engine performance and reductions in harmful emissions, providing insights into the potential benefits of utilizing hydrophilic nanoparticles in biodiesel-diesel blends.

Table 10: Impact of Hydrophilic Nanoparticles in Biodiesel-Diesel Bl

Section	Description
A. Concentration Levels	• 1. Low Concentration (50-100 ppm) • 2. Medium Concentration (100-150 ppm) • 3. High Concentration (150-200 ppm)
B. Engine Types	• Single-Cylinder Diesel Engines • Multi-Cylinder Diesel Engines • Direct Injection Diesel Engines
C. Fuel Blend Ratios	• B20 (20% Biodiesel + 80% Diesel) • B50 (50% Biodiesel + 50% Diesel) • B100 (100% Biodiesel)
D. Performance Data [88-91]	• BTE Improvements: o Low Concentration: 3.0% o Medium Concentration: 5.0% o High Concentration: 7.5% • BSFC Reductions: o Low Concentration: 4.5% decrease o Medium Concentration: Notable decrease (exact percentage to be filled) o High Concentration: Enhanced combustion efficiency
E. Emission Data	• CO Emissions: o Low Concentration: Reduced by 8% o Medium Concentration: Reduced by 20% o High Concentration: Reduced by 20% • HC Emissions: o Low Concentration: Reduced by 12% o Medium Concentration: Reduced by 15% o High Concentration: Notable reduction (exact percentage to be filled) o NOx Emissions: Increased by 4% at medium concentration

2.8. Zinc oxide

The efficient operation of the diesel engine and the modification of CO, NOx, and HC emissions, along with several harmful air pollutants, were made possible by the addition of nanoparticle diesel additives. Utilising an ultrasonicator and a mechanical homogenizer to attain optimal dispersion, zinc oxide nanoparticles (ZONP) are mixed with diesel in diesel engines as an additive. This study examines five concentrations of ZONP. An analysis is conducted to compare the fuel consumption, brake power, and engine efficiency of the nano-diesel blend with that of base diesel in order to showcase and assess its improvements. ZONP is added to engines to improve performance and lower emissions, which encourages combustion. Multiple tests were conducted on the diesel engine at 1400 rpm, which is maintained constant throughout the experiment with varying loads, to assess the effect of ZONP on engine performance and environment. The results unambiguously demonstrate that adding ZONP nanoparticles to diesel fuel significantly improves its high BTE and low BSFC as compared to diesel. When applied to high loads and concentrations of ZONP, there is also an average 33% decrease in CO and an average 8% increase in CO2 and NOx, respectively, in comparison to pure diesel. When compared to pure diesel at various loads, 100% removed HC is also seen [92] . Investigations are conducted into the impact of fuel additives including zinc oxide (ZnO) nanoparticles on the efficiency and emissions of diesel engines. With the use of an ultrasonicator, diesel fuel and ZnO nanoparticles were combined in mass fractions of 50 and 100 ppm. A Fiat diesel engine with four cylinders, water cooled, direct injection (DI), and natural aspiration was employed. It was operated with changing operation load at a constant speed of 1500 rpm and fuel injection pressure of 400 bar. Comparisons were made between the results obtained with and without diesel fuel when the engine ran under identical conditions. When the dosage level of ZnO nanoparticle in the blended fuel is increased, measurements show an improvement in both the BSFC and BTE. Smoke and NOx produced by ZnO blended fuels were fewer than those produced by diesel fuel, according to emission results at all loads. During high load and reduced during low load, diesel fuel released higher CO and HC than ZnO mixed fuels [93]. Anish et al. [94] used three different types of fuel mixtures such as B20 (20% biodiesel + 80% diesel), B100A30C30 (100% biodiesel + 30 ppm ZnO nanoparticles + 30 ppm TiO2 nanoparticles), B20A30C30 (20% biodiesel + 80% diesel + 30 ppm ZnO nanoparticles + 30 ppm TiO2 nanoparticles) to study the characteristics of combustion, efficiency and emission of fuel blends inside a single cylinder variable compression ratio diesel engine. They concluded that adding nanoparticles to the fuel blends increases the chemical reaction rate as a result of the high surface area of these nanoparticles in relation to the size, which leads to improving the combustion, emission and efficiency properties of the fuel. Additionally, it was determined that the B20A30C30 fuel blend greatly reduces emissions of smoke, hydrocarbons, nitrogen oxides, and carbon monoxide, and has a higher thermal efficiency than the B100A30C30 fuel blend. The study conducted by Hussain et al. [95] investigated the impact of diesel-soybean biodiesel blends that contained 3% cerium-coated zinc oxide (Ce-ZnO) nanoparticles on the emissions, combustion parameters, and performance of a single-cylinder diesel engine. To make the fuel mixtures (SBME25), diesel and 25% soybean biodiesel were mixed together. Ce-ZnO nanoparticle additions were blended with SBME25 at 25, 50, and 75 ppm using an ultrasonic method and a surfactant (Span 80) at 2 vol.% to improve the stability of the blend. These mixtures enhanced the variable compression ratio engine's overall performance when it was operating at a 19.5:1 compression ratio (CR). The SBME25Ce-ZnO50 addition, which has 50 ppm of Ce-ZnO nanoparticles, boosts BTE, HRR, and BSFC while lowering CO, HC, and smoke emissions by 30%, 21.5%, and 18.7%, respectively, as compared to SBME25 fuel operation. Nevertheless, the NOx levels have considerably increased for every blend containing more nanoparticles. Therefore, incorporating 50 parts per million of Ce-ZnO nanoparticle into the mixture is a practical approach to enhance engine performance, emissions, and combustion characteristics.

Table 11 showcasing the effects of different concentration levels of zinc oxide nanoparticles, ranging from 50 ppm to 100 ppm, significant improvements in engine performance and emission reductions are observed. For instance, at 50 ppm, the Brake Thermal Efficiency (BTE) increases by approximately 8%, while Carbon Monoxide (CO) emissions decrease by 30%. In contrast, at 100 ppm, BTE sees a 10% increase, but Nitrogen Oxides (NOx) emissions rise by 8%, showcasing a nuanced impact based on concentration levels. These findings underscore the importance of optimizing nanoparticle concentrations for achieving desired performance and emission outcomes in diesel engines.

Table 11: Impact of Zinc Oxide Nanoparticle Concentration Levels on Engine Performance and Emissions [93-95]

Concentration	Engine Type	Performance Data	Emission Data
50 ppm ZnO NPs	Four-cylinder, water-cooled, DI diesel engine	BTE: Increased by 8%	CO: Reduced by 30%
100 ppm ZnO NPs	Four-cylinder, water-cooled, DI diesel engine	BSFC: Decreased by 10% BTE: Increased by 10% BSFC: Decreased by 12%	HC: Reduced by 25% CO: Reduced by 33% HC: Reduced by 30% NOx: Increased by 8%

2.9. Types of other nanoparticles

Elkelawy et al. [96] have produced biodiesel through the homogeneously catalyzed transesterification process using a mixture of sunflower oil and soybean oil with a volume ratio of 50/50%. Then, the resulting biodiesel fuel is mixed with silver thiocyanate nanoparticles to examine the effect of adding these nanoparticles to biodiesel on the combustion, performance and emission characteristics of the DI diesel engine at different loads and at a constant speed of 1400 rpm. Different fuel blends have also been used as follows: 1) D50B50N000 (50% diesel + 50% biodiesel). 2) D50B50N200 (50% diesel + 50% biodiesel + 200 ppm silver thiocyanate nanoparticles (AgSCN)). 3) D50B50N200 + 2% hydrogen peroxide (H2O2). 4) D50B50N200 + 4% hydrogen peroxide (H2O2). Then each blend has been checked by inserting it into a single cylinder engine and comparing the results of each blend with the fuel blend (D50B50N000); the results showed that there is a decrease in the emissions of carbon monoxide, hydrocarbons and nitrogen oxides when adding 200 ppm of nanoparticles, however, it is noticed that adding and increasing the volume percentage of H2O2 result in a higher reduction in these emissions. On the other hands, it is found that the carbon dioxide emissions resulting from the use of fuel blends were higher than that of diesel fuel. It was also found that the presence of both H2O2 and nanoparticles in the fuel blends enhances the combustion process as a result of increasing the surface area-to-volume ratio of nanoparticles, and thus the occurrence of the phenomenon of small explosion of the fuel particles sprayed, which leads to an increase in both the pressure inside the cylinder and the heat release rate of cooling. As for the engine performance, it was noted that there is a significant decrease in the BSFC and an increase in the BTE, as the fuel blend (D50B50N200 + 4% H2O2) gets the highest BTE compared to the rest of the types of fuel blends used; this results in the fuel blend (D50B50N200 + 4% H2O2) records the best Fuel blend in terms of performance, combustion and emission of the DI diesel engine. Elkelawy et al. [97] studied the effect of adding silver thiocyanate nanoparticles, which acts as an oxygen contributing catalyst, to the blend of biodiesel and diesel fuel. Different rates of nanoparticles have been used (200, 400 and 600 ppm) and they were added to D50B50 fuel (50% diesel and 50% biodiesel). It was noted that the presence of additional oxygen inside the combustion cylinder of the engine leads to a significant reduction in the emissions of unburned hydrocarbons and smoke emissions, as adding these particles to the fuel blend enhances the process of complete combustion and increases the rate of heat release inside the cylinder of the DI engine. Through the results, it was found that the use of nanoparticles at a rate of 400 ppm gives the best results in performance, combustion and emission.

A summary of nanoparticles types and its impacts on biodiesel and its blends with conventional diesel characteristics are illustrated in Table 12.

Table 12: Summary of nanoparticles type and its impacts on fuel characteristics

Nanoparticles type	Blend and NPs concentrations	Results	Reference
Aluminum Oxide	B20 (20%biodiesel+80%diesel) 30, 50, and 100 ppm NPs	Comparison with B20: Increase in the peak cylinder pressure. Engine performance is improved when 100 ppm of Al2O3 nanoparticles is added to the B20 where B20 + 100 Al2O3 produced the lowest reduction in BSFC. In addition, B20 + 100 Al2O3 caused the most BTE rise of 7.84%. Decreasing the concentration of PM. For B20 + 100 Al2O3, the greatest reduction in CO and HC emissions was 42.71% and 37.46%, respectively. Decreasing the NOX emissions by up to 40%.	[98]
Cerium Oxide	B20 (20%biodiesel+80%diesel) NPs: -Constant concentration of 80ppm -Different sizes of 10, 30, and 80 nm.	Comparison with B20: Improving engine combustion (increasing BTE and reducing BSFC). The B20+30nm fuel has the maximum values of heat release rate and cylinder peak pressure. The B20+30nm fuel has the lowest emissions than both B20+10nm and B20+80nm. The B20+30nm fuel is more effective in decreasing NO_x than both B20+10nm and B20+80nm.	[99]
Carbon nanotubes	Blend: B10, B20, B30, and B40. PNs: concentrations (50, 100, and 150).	B30 at all CNTs content has a considerable reduction in the formation of CO2 gas emission. B20+50ppm CNs Has high CO_2 formation. B10CNs150 has the highest cylinder pressure. B10CNs50 and B20CNs50 have cylinder pressure identical with baseline diesel, D100.	[100]
Titanium oxide	B20 (20%biodiesel+80%diesel) 125 to 375 ppm NPs	Comparison with B20: Combustion characteristics of B20 250 PPM TiO2 blend was superior. Thermal efficiency of B20 250 PPM TiO2 blend is increased by 0.67%. Increasing the concentration nanoparticles had a negative effect on efficiency. HC emissions of B20 125 PPM TiO2 was decreased by 46%. The minimum NOx emissions was for B20 375 PPM TiO2 and it was decreased by 1.85%.	[101]
Graphene oxide	B20 (20%biodiesel+80%diesel) 30, 60, and 90 ppm NPs	Slight improvement in the power. Decrease in CO and UHC emissions. Slight increases in CO2 and NOx emissions.	[102]
Zinc oxide	Blend: B0, B20, and B40. PNs: concentration (50ppm).	Improvement of engine torque by 6.74, 4.95 and 3.69% for B0ZnO، B20ZnO and B40ZnO fuel blends compared to B0, B20 and B40 respectively. Enhancement in combustion characteristics by nano fuel blends. The ignation delay period is reduced by 18.18, 8.32, and 7.13% for B0ZnO, B20ZnO and B40ZnO compared to B0, B20 and B40 respectively.	[103]

Table 13 provides a comparative analysis of three nanoparticle additives - Aluminum Oxide (Al2O3), Cerium Oxide (CeO2), and Silver Thiocyanate (AgSCN) - and their impacts on the performance and emissions characteristics of biodiesel and diesel blends. The data highlights the key advantages and disadvantages of each nanoparticle, including their effects on engine performance, combustion efficiency, and emission reduction. Based on the overall performance and tradeoffs, Aluminum Oxide (Al2O3) emerges as the best-performing nanoparticle, offering significant improvements in brake thermal efficiency and substantial reductions in CO and HC emissions. However, the potential increase in NOx emissions associated with Al2O3 requires further optimization and mitigation strategies to address environmental concerns.

Table 13: Comparative Analysis of Nanoparticle Additives in Biodiesel and Diesel Blends

Nanoparticle	Advantages	Disadvantages
Aluminum Oxide (Al2O3)	- Performance Improvement: The addition of Al2O3 nanoparticles has been shown to significantly enhance engine performance metrics, such as Brake Thermal Efficiency (BTE) and peak cylinder pressure. For instance, a blend with 100 ppm of Al2O3 resulted in a BTE increase of 7.84% and the lowest Brake Specific Fuel Consumption (BSFC). - Emission Reduction: Al2O3 nanoparticles contribute to a substantial decrease in emissions, with reductions in CO and HC emissions by 42.71% and 37.46%, respectively.	- Potential for Increased NOx Emissions: While Al2O3 improves combustion efficiency, it may lead to an increase in Nitrogen Oxides (NOx) emissions, which is a concern for environmental regulations. - Cost and Availability: The cost of high-purity Al2O3 nanoparticles can be a limiting factor for widespread adoption.
Cerium Oxide (CeO2)	- Enhanced Combustion: CeO2 nanoparticles have been shown to improve combustion characteristics, leading to higher BTE and lower BSFC. The 30 nm size of CeO2 nanoparticles yielded the maximum heat release rate and cylinder peak pressure. - Emission Control: CeO2 is effective in reducing particulate matter and unburned hydrocarbons, making it a favorable option for cleaner combustion.	- Size Dependency: The effectiveness of CeO2 nanoparticles can vary significantly with size, necessitating careful selection and control during synthesis. - Limited Research: While promising, the body of research on CeO2 in biodiesel applications is still developing, and more studies are needed to understand its long-term effects fully.
Silver Thiocyanate (AgSCN)	- Oxygen Contribution: AgSCN acts as an oxygen-contributing catalyst, enhancing the combustion process and significantly reducing unburned hydrocarbons and smoke emissions. - Performance Boost: The addition of 400 ppm of AgSCN nanoparticles has shown the best performance, combustion efficiency, and emissions results.	- Cost: Silver-based nanoparticles can be expensive, which may limit their practical application in large-scale biodiesel production - Potential Toxicity: The environmental impact and potential toxicity of silver nanoparticles require careful consideration and further research.

3. Environmental and Health Aspects

The use of nanoparticles as additives in biodiesel and diesel fuels presents both benefits and challenges concerning environmental and health impacts.

3.1. Safety Aspects

- Nanoparticle Toxicity: Certain nanoparticles, such as silver and cerium, may exhibit toxic effects on living organisms, raising concerns about their long-term health implications[29,62].
- Exposure Risks: Workers in the production and application of nanoparticle-enhanced fuels face potential exposure risks, necessitating safety measures like personal protective equipment (PPE).
- Regulatory Framework: The evolving regulatory landscape requires compliance with guidelines from agencies like the EPA to ensure the safe use of nanoparticles[62,66].

3.2. Environmental Aspects

- Emission Reductions: Nanoparticles can significantly reduce harmful emissions from engines, contributing to improved air quality.

- Lifecycle Assessment: A comprehensive lifecycle assessment is essential to evaluate the overall environmental impact of nanoparticle-enhanced fuels, considering their production, use, and disposal.

- Nanoparticle Persistence: Concerns exist regarding the persistence of nanoparticles in the environment and their potential accumulation in ecosystems[24,36,70].

3.3 Health Effects

- Respiratory Issues: Inhalation of nanoparticles can lead to respiratory problems and exacerbate conditions like asthma and COPD [36,50]

- Systemic Effects: Nanoparticles may enter the bloodstream, potentially causing adverse effects on organs such as the liver and kidneys [36].

- Regulatory and Research Needs: Further research is needed to understand toxicity mechanisms and establish safe exposure limits, alongside the development of comprehensive regulatory guidelines [36,50,90].

4. Challenges and limitations

Biodiesel, as a renewable energy source, offers numerous advantages, including reducing reliance on imported petroleum, utilizing biodegradable and renewable fuels, and contributing to a closed carbon cycle by recycling carbon dioxide, thus mitigating global warming. Pure biodiesel (B100) has been investigated in diesel engines, demonstrating reduced exhaust emissions, including CO, NO, SO2, and smoke opacity [104]. However, the use of biodiesel is not without drawbacks, such as its lower heating value due to esters of saturated and unsaturated fatty acids, elevated nitrogen oxide levels, higher filter plugging temperature, and relatively poor low-temperature flow properties, limiting its application [105] . To address these limitations, researchers have explored various strategies. Some studies investigated the addition of kerosene, ethanol, and other commercial additives to biodiesel, leading to a significant reduction in the pour point and decreased emissions when ethanol was added [21]. Additionally, research explored the impact of polymer dissolution on biodiesel's cold flow characteristics, with acetone emerging as the most effective solvent for improving cloud point values and flash point parameters [22]. These efforts aim to enhance biodiesel's performance and expand its practical applications.

Challenges and limitations in the use of nanoparticles in biodiesel can be summarized as follows:

Highest Priority:

1. Agglomeration: Nanoparticles tend to agglomerate or cluster together, reducing their effectiveness in improving fuel properties. Preventing agglomeration is a significant challenge .

2. Uniform Dispersion: Achieving a uniform dispersion of nanoparticles in biodiesel is crucial for consistent performance, but it can be challenging to maintain this dispersion over time.

3. Stability: Nanoparticles can be unstable in biodiesel, leading to settling or separation from the fuel, which can hinder their benefits.

Medium Priority:

4. Catalyst Poisoning: Some nanoparticles may interact with or even poison engine catalysts, potentially leading to reduced catalytic converter efficiency.

5. Cost: The production and integration of nanoparticles into biodiesel can be expensive, which may limit their practical use.

6. Regulation and Safety: The use of nanoparticles in fuels may raise regulatory and safety concerns, necessitating rigorous testing and compliance with environmental and safety standards.

7. Health Risks: Inhalation of nanoparticles during fuel handling or combustion may pose health risks to workers or individuals in proximity to diesel engines.

8. Environmental Impact: The environmental impact of nanoparticles in biodiesel production and combustion is not fully understood, raising concerns about potential ecological consequences.

Lower Priority:

9. Scaling Up Production: The transition from laboratory-scale experiments to large-scale production of nanoparticle-enhanced biodiesel presents challenges related to consistency, cost, and scalability.

10. Compatibility: Compatibility issues with engine components, such as fuel filters and injectors, can arise when using nanoparticle-enhanced biodiesel.

Addressing these challenges and limitations is essential for realizing the full potential of nanoparticles in biodiesel, as they offer the promise of improving fuel properties and reducing emissions, but their practical implementation requires careful consideration of these factors.

5. Future Directions

While significant progress has been made in research on nanoparticle additives in biodiesel production, there are still several gaps that need to be addressed. One area of focus could be on developing a better understanding of the mechanisms by which nanoparticles interact with biodiesel molecules and how they impact various fuel properties. Additionally, more research is needed to investigate the long-term effects of nanoparticle additives on engine performance and emissions. For instance, some studies have shown that the addition of nanoparticles to biodiesel can improve its oxidation stability, viscosity, and cold flow properties. However, the mechanisms behind these improvements are not well understood, and more research is needed to elucidate the interactions between nanoparticles and biodiesel molecules. Furthermore, while many studies have evaluated the short-term effects of nanoparticle additives on engine performance and emissions, there is still a lack of data on their long-term effects, particularly with respect to durability and engine wear.

Emerging nanoparticle technologies, such as hybrid or core-shell nanoparticles, offer promising avenues for improving biodiesel properties. Hybrid nanoparticles combine two or more types of nanoparticles, which can offer synergistic effects and enhance the performance of biodiesel. Core-shell nanoparticles consist of a core material surrounded by a shell of a different material, which can provide additional functionalities and improve the stability of biodiesel. For example, some studies have shown that hybrid nanoparticles consisting of silica and titania can improve the cold flow properties and oxidative stability of biodiesel. Similarly, core-shell nanoparticles consisting of iron oxide cores and silica shells have been shown to improve the thermal stability and oxidation resistance of biodiesel.

To fully exploit the potential of emerging nanoparticle technologies in biodiesel production, further research is needed to optimize their synthesis, characterize their properties, and evaluate their performance in biodiesel production. It will be important to investigate the impact of these advanced nanoparticle technologies on engine performance and emissions, as well as their long-term stability under different storage conditions. For instance, more research is needed to evaluate the impact of hybrid and core-shell nanoparticles on engine performance and emissions, particularly with respect to their long-term effects. Furthermore, it will be important to optimize the synthesis and functionalization of these advanced nanoparticle technologies to ensure their compatibility with biodiesel production processes.

Employing optimization software programs in biodiesel systems, the ideal concentration and size of nanocatalysts could be easily determined and without the need to conduct practical experiments on many samples, thus saving the time, effort and high cost required to conduct these practical experiments. Furthermore, the use of NPs as fuel additives has only been the subject of a small amount of research up to this point.

New techniques are required to deal with problems including nanoparticle aggregation, erosion, and settling. The addition of nanoadditions to biodiesel has made it more challenging to capture the unburned nanoparticles in the exhaust.

Researching the effects of nanoparticle additions on air quality after they are burned in the engine is crucial. However, a thorough investigation of in vivo interaction is necessary, with a focus on nanoparticles used in biodiesel in particular.

In addition to using emerging nanoparticle technologies in biodiesel production, future research can also explore other areas such as:

1- Developing cost-effective and environmentally sustainable methods for nanoparticle synthesis and incorporation into biodiesel.

2- Investigating the long-term stability and durability of nanoparticle-enhanced biodiesel under different storage and transportation conditions.
3- Evaluating the performance of nanoparticle-enhanced biodiesel in different engine types and operating conditions.
4- Studying the potential environmental impacts of nanoparticle-enhanced biodiesel, including their potential toxicity to aquatic and terrestrial organisms.
5- Exploring the potential for scaling up nanoparticle-enhanced biodiesel production for commercial applications.
6- Attempts are being conducted to create a filter that can exclude unburned nanoadditives from diesel vehicle exhaust.

By addressing these research areas, scientists and engineers can continue to enhance the properties of biodiesel and make it a more attractive and viable renewable energy source for the future.

6. Conclusions

The introduction of fuel additives based on nanoparticles into the combustion of biodiesel has been a significant advancement in terms of enhancing combustion characteristics, reducing pollutants, and raising fuel efficiency. This breakthrough uses carefully crafted nanoparticles to enhance the fuel properties and combustion dynamics of biodiesel. Fuel can burn more thoroughly and efficiently thanks to the catalysts or combustion enhancers that are made of nanoparticles. Certain additives can be added to biodiesel to improve its chemical and physical properties, which will improve engine performance, reduce emissions, and improve combustion. Due to their higher surface area, nanoparticles may improve fuel atomization and combustion. This may result in a more effective and cleaner combustion process, reducing the engine's emissions of hazardous materials like NOx and particulate matter. These additives to fuels often improve their reactivity, which results in a shorter ignition delay and faster burning. This could improve engine performance and lower emissions, particularly in low-temperature combustion settings. NPs' size and concentration can have a significant impact on how effective they are as fuel additives. While studies show encouraging results in terms of ignition properties and combustion efficiency, there are lingering concerns, particularly regarding the safety and environmental impact of certain nanoparticles, such as carbon nanotubes.

- Cerium oxide nanoparticles demonstrate versatility in valence conversion, substantial oxygen storage, and favorable thermal properties, leading to decreased emissions and improved fuel efficiency.
- Titanium oxide nanoparticles contribute to increased density, fire point, and calorific value of diesel, resulting in enhanced engine performance and reduced emissions.
- Graphene oxide nanoparticles show promise in improving combustion characteristics and reducing emissions when added to diesel and biodiesel blends.
- Hydrophilic nanoparticles, particularly water-emulsified fuel with aluminum and titanium dioxide nanoparticles, address challenges associated with biodiesel use, enhancing thermal efficiency and mitigating emissions.
- Zinc oxide nanoparticles, as diesel additives, emerge as particularly effective in significantly improving brake thermal efficiency, reducing brake specific fuel consumption, and lowering emissions of CO, CO2, NOx, and HC.

Despite these positive outcomes, the review underscores the need for further research to address safety and environmental concerns associated with nanoparticle use. Overall, the integration of nanoparticles presents a potential solution for optimizing fuel properties, improving engine performance, and mitigating the environmental impact of internal combustion engines. Future developments in this field hold promise for advancing sustainable and efficient fuel technologies.

7. Conflicts of interest

The authors declare that they have no conflict of interest in this article.

8. Acknowledgments

The researchers would like to thank the Deanship of Graduates Studies and Scientific Research at Qassim University for financial support (QU-APC-2024-9/1)

9. References

[1] Jerry L. Holechek, Hatim M. E. Geli, Mohammed N. Sawalhah, Raul Valdez. A Global Assessment: Can Renewable Energy Replace Fossil Fuels by 2050?. Sustainability. 2022;14:1-22.

[2] Ms. Neha, Mr Rambeer Joon. Renewable Energy Sources: A Review. Journal of Physics: Conference Series. 2021.

[3] Hui X., Longwen O., Yuan Li, Troy R. Hawkins, Michael Wang. Life Cycle Greenhouse Gas Emissions of Biodiesel and Renewable Diesel Production in the United States. Environ. Sci. Technol. 2022;56:7512-21.

[4] Dhivya Priya N., Thirumarimurugan M. Biodiesel - A Review on Recent Advancements in Production. in Bioresource Utilization and Bioprocess. March 2020.

[5] Eko Supriyanto, Jayan Sentanuhady, Ariyana Dwiputra, Ari Permana, Muhammad Akhsin Muflikhun. The Recent Progress of Natural Sources and Manufacturing Process of Biodiesel: A Review. Sustainability. 2021;13(10):5599.

[6] Ayoo, Collins. Towards Energy Security for the Twenty-First Century. 2020.

[7] G. Knothe. Improving biodiesel fuel properties by modifying fatty ester composition. Energy & Environmental Science. 2010;3(9):1182-200.

[8] Núbia M. Ribeiro. The role of additives for diesel and diesel blended (ethanol or biodiesel) fuels: a review. Energy Fuels. 2007;21:2433-45.

[9] J. M. Valentine, J. D. Peter-Hoblyn, G. K. Acres. Emissions reduction and improved fuel economy performance from a bimetallic platinum/cerium diesel fuel additive at ultra-low dose rates. 2000.

[10] H.-R. Chao, T.-C. Lin, M.-R. Chao, F.-H. Chang, C.-I. Huang, C.-B. Chen. Effect of methanol-containing additive on the emission of carbonyl compounds from a heavy-duty diesel engine. Journal of Hazardous Materials B. 2000;73:39-54.

[11] G. Skillas, Z. Qian, U. Baltensperger, U. Matter, H. Burtscher. Influence of additives on the size distribution and composition of particles produced by diesel engines. Combustion Science and Technology. 2000;154:259-73.

[12] M. G¨ur¨u, U. Karakaya, D. Altiparmak, A. Alicilar. Improvement of Diesel fuel properties by using additives. Energy Conversion and Management. 2002;43:1021-25.

[13] H. Jung, D. B. Kittelson, M. R. Zachariah. The influence of a cerium additive on ultrafine diesel particle emissions and kinetics of oxidation. Combustion and Flame. 2005;142:276-88.

[14] E. W. De Menezes, R. Da Silva, R. Catalu˜na, and R. J. C. Ortega. Effect of ethers and ether/ethanol additives on the physicochemical properties of diesel fuel and on engine tests. Fuel. 2006;85:815-22.

[15] Taghizadeh-Alisaraei A, Rezaei-Asl A. The effect of added ethanol to diesel fuel on performance, vibration, combustion and knocking of a CI engine. Fuel. 2016;185:718-33.

[16] Balamurugan T, Nalini R. Experimental investigation on performance, combustion and emission characteristics of four stroke diesel engine using diesel blended with alcohol as fuel. Energ. 2014;78:356-63.

[17] Senthilraja R, Sivakumar V, Thirugnanasambandham K, Nedunchezhian N. Performance, emission and combustion characteristics of a dual fuel engine with Diesel e Ethanol e Cotton seed oil Methyl ester blends and Compressed Natural Gas (CNG) as fuel. Energy. 2016;112:899-907.

[18] Çelik M, Solmaz H, Yücesu HS. Examination of the effects of organic based manganese fuel additive on combustion and engine performance. Fuel Process Technol. 2015;139:100-7.

[19] D. S. Shrestha, J. Van Gerpen, J. Thompson, A. Zawadzki. Cold flow properties of biodiesel and effect of commercial additives. in 2005 ASAE Annual International Meeting Sponsored by ASAE. Tampa, Florida. 2005.

[20] G. Knothe. Designer Biodiesel: Optimizing Fatty Ester Composition to Improve Fuel Properties. Energy & Fuels. 2008;22:1358-64.

[21] P. V. Bhale, N. V. Deshpande, Sh. B. Thombre, Improving the low temperature properties of biodiesel fuel. Renewable Energy. 2009;34:794-800.

[22] P. Mohammadi, M. Tabatabaei, A. M. Nikbakht, Z. Esmaeili. Improvement of the cold flow characteristics of biodiesel containing dissolved polymer wastes using acetone. Biofuel Research Journal. 2014;1:26-9.

[23] S. Madiwale, A. Karthikeyan, V. Bhojwani. A Comprehensive Review of Effect of Biodiesel Additives on

Properties, Performance, and Emission. in Materials Science and Engineering. 2017.

[24] Devarajan Y., Jayabal R. K., Ragupathy D., Venu H. Emissions analysis on second generation biodiesel. Frontiers Environ. 2016;11.

[25] Sajeevan A. C., Sajith V. Synthesis of stable cerium zirconium oxide nanoparticle –Diesel suspension and investigation of its effects on diesel properties and smoke. Fuel. 2016;183:155-63.

[26] D. Unlu, N. Boz, O. Ilgen, N. Hilmioglu. Improvement of fuel properties of biodiesel with bioadditive ethyl levulinate. Open Chem. 2018;16:647-52.

[27] MD. M. RAHMAN, M. G. Rasul, Md M. Khan, Md Abul Kalam. A mini-review on the cold flow properties of biodiesel and its blends. Frontiers in Energy Research2020:1-21.

[28] Masjuki, M. A. Kalam and H. H. Biodiesel from palmoil—an analysis of its properties and potential. Biomass and Bioenergy. 2002;23(6):471-9.

[29] Junshuai LV, Su Wang, Beibei Meng. The Effects of Nano-Additives Added to Diesel-Biodiesel Fuel Blends on Combustion and Emission Characteristics of Diesel Engine: A Review. Energies. 2022;15(3).

[30] Medhat Elkelawy, El Shenawy A. El Shenawy, Hagar Alm-Eldin Bastawissi, S. Abo-Samra, I. Abd-Elhay Elshennawy. Nanoparticles Additives for Diesel/Biodiesel Fuel Blends as a Performance and Emissions Enhancer in the Applications of Direct Injection Diesel Engines: A Comparative Review. Engineering Research (ERJ). 2023;7(1).

[31] Hariram Venkatesan, Seralathan Sivamani, Srinivasan Sampath, Gopi V., Dinesh Kumar M. A Comprehensive Review on the Effect of Nano Metallic Additives on Fuel Properties, Engine Performance and Emission Characteristics. International Journal of Renewable Energy Research. 2017;7(2).

[32] Jeffrey Dankwa Ampah, Abdulfatah Abdu Yusuf, Ephraim Bonah Agyekum, Sandylove Afrane, Chao Jin, Haifeng Liu, Islam Md Rizwanul Fattah, Pau Loke Show, Mokhtar Shouran, Monier Habil, Salah Kamel. Progress and Recent Trends in the Application of Nanoparticles as Low Carbon Fuel Additives—A State of the Art Review. Nanomaterials (Basel). 2022;12(9):1515.

[33] Mridula Guin, Tanaya Kundu, Riya Singh. Applications of Nanotechnology in Biofuel Production Bio-Clean Energy Technologies. 2022;2:297-332.

[34] Moushoul B, Farhadi EK, Mansourpanah Y, Nikbakht AM, Molaei R, Forough M. Application of CaO-based/Au nanoparticles as heterogeneous nanocatalysts in biodiesel production. Fuel. 2016;164:119–27.

[35] Khoo KS, Chia WY, Ying Tang DY, Show PL. Nanomaterials utilization in biomass for biofuel and bioenergy production. Energies. 2020;13.

[36] Serrano AL, Olivas RM, Landaluze JS, Cámara C. Nanoparticles: a global vision. Characterization, separation, and quantification methods. Potential environmental and health impact. Anal Methods. 2014;6(1):38–56.

[37] Shao Y, Wu C, Wu T, Yuan C, Chen S, Ding T, Ye X, Hu Y. Green synthesis of sodium alginate-silver nanoparticles and their antibacterial activity. Int J Biol Macromol. 2018;111:1281–92.

[38] Zhang XL, Yan S, Tyagi RD, Surampalli RY. Biodiesel production from heterotrophic microalgae through transesterification and nanotechnology application in the production. Renew Sustain Energy Rev. 2013;26:216–23.

[39] Chetan Pandit, Srijoni Banerjee, Soumya Pandit, Dibyajit Lahiri, Vinod Kumar, Kundan Kumar Chaubey, Rayyan Al-Balushi, Saif Al-Bahry, and Sanket J. Joshig. Recent advances and challenges in the utilization of nanomaterials in transesterification for biodiesel production. Heliyon. 2023;9(4).

[40] Jiangjun Wei, Yuncheng Wang. Effects of biodiesels on the physicochemical properties and oxidative reactivity of diesel particulates: A review. Sci Total Environ. 2021.

[41] Indrajeet Arya, Asha Poona, Pritam Kumar Dikshit, Soumya Pandit, Jatin Kumar, Himanshu Narayan Singh, Niraj Kumar Jha, Hassan Ahmed Rudayni, Anis Ahmad Chaudhary, Sanjay Kumar. Current Trends and Future Prospects of Nanotechnology in Biofuel Production. Catalysts. 2021;11(11):1308.

[42] Adib Bin Rashid, "Show citation Utilization of Nanotechnology and Nanomaterials in Biodiesel Production and Property Enhancement," Nanomaterials, 2023.

[43] Mohammed S Gad, Sayed M Abdel Razek, PV Manu, and Simon Jayaraj. Experimental investigations on diesel engine using alumina nanoparticle fuel additive. Advances in Mechanical Engineering. 2021;3(2):1-16.

[44] Soner Gumus, Hakan Özcan, Mustafa Ozbey, Bahattin Topaloglu. Aluminum oxide and copper oxide

nanodiesel fuel properties and usage in a compression ignition engine. Fuel. 2016;163:80-7.

[45] Ahmad Fayyazbakhsh, Vahid Pirouzfar. Determining the optimum conditions for modified diesel fuel combustion considering its emission, properties and engine performance. Energy Conversion and Management. 2016;113:209-19.

[46] Srinivasa Rao M., Anand R. B. Performance and emission characteristics improvement studies on a biodiesel fuelled DICI engine using water and AlO(OH) nanoparticles. Applied Thermal Engineering. 2016;98:636-45.

[47] Santhanakrishnan Radhakrishnan, Dinesh Babu Munuswamy, Yuvarajan Devarajan, Arunkumar T, and Arulprakasajothi Mahalingam. Effect of nanoparticle on emission and performance characteristics of a diesel engine fueled with cashew nut shell biodiesel. Taylor & Francis Group. 2018:1-9.

[48] Anbarasu, Karthikeyan. Performance and emission characteristics of diesel engine using alumina oxide nanoparticle blended biodiesel emulsion fuel. J. Energ Res. Technol. 2015;138 (2).

[49] C. Syed Aalam, C.G. Saravanan, M. Kannan. Experimental investigations on a CRDI system assisted diesel engine fuelled with aluminium oxide nanoparticles blended biodiesel. Alexandria Engineering Journal. 2015;54:351-8.

[50] Naresh Kumar Gurusala, V Arul Mozhi Selvan. Effects of alumina nanoparticles in waste chicken fat biodiesel on the operating characteristics of a compression ignition engine. Clean Techn Environ Policy. 2015;17:681-92.

[51] Seyyed Hassan Hosseini, Ahmad Taghizadeh-Alisaraei, Barat Ghobadian, Ahmad Abbaszadeh-Mayvan. Effect of added alumina as nano-catalyst to diesel-biodiesel blends on performance and emission characteristics of CI engine. Energy. 2017;124:543-52.

[52] T. Shaafi, R. Velraj. Influence of alumina nanoparticles, ethanol and isopropanol blend as additive with dieselesoybean biodiesel blend fuel: combustion, engine performance and emissions, Renew. Energy. 2015;80:655-63.

[53] Shengbo Ge, Kathirvel Brindhadevi, Changlei Xia, Amany Salah Khalifa, Ashraf Elfasakhany, Yuwalee Unpapromg, Hien Van Doan. Enhancement of the combustion, performance and emission characteristics of spirulina microalgae biodiesel blends using nanoparticles. Fuel. 2022.

[54] Mukul Tomar, Naveen Kumar. Effect of multi-walled carbon nanotubes and alumina nano-additives in a light duty diesel engine fuelled with schleichera oleosa biodiesel blends. Sustainable Energy Technologies and Assessments. 2020;42.

[55] G. Vairamuthua, S. Sundarapandianb, C. Kailasanathana, B. Thangagiric. Experimental investigation on the effects of cerium oxide nanoparticle on Calophyllum inophyllum (Punnai) biodiesel blended with diesel fuel in DI diesel engine modified by nozzle geometry. Journal of the Energy Institute. 2016;89(4):668-82.

[56] Arul Mozhi Selvan V., Anand RB., Udayakumar M. Effects of cerium oxide nanoparticle addition in diesel and diesel-biodiesel-ethanol blends on the performance and emission characteristics of a CI engine. ARPN J Eng Appl Sci. 2009;4:1-6.

[57] Skillas G., Qian z., Baltensperger U., Matter U., Burtscher H. The influence of additives on the size distribution and composition of particles produced by diesel engines. Combust Sci Technol. 2000;154(1):259-73.

[58] Syed Aalam, Alagappan Narayanan. Cerium Oxide Nanoparticles as Addiditve with Diesel Fuel on DI Diesel Engine. International Journal of Innovative Research and Creative Technology. 2018;1(2):1-6.

[59] Abdulfatah Abdu Yusuf, Freddie L. Inambao, Jeffrey Dankwa Ampah. The effect of biodiesel and CeO2 nanoparticle blends on CRDI diesel engine: A special focus on combustion, particle number, PM2.5 species, organic compound and gaseous emissions. Journal of King Saud University - Engineering Sciences. 2022.

[60] Appavu P., and M. Venkata Ramanan. Study of emission characteristics of a diesel engine using cerium oxid nanoparticle blended pongamia methyl ester. International Journal of Ambient Energy. 2018:1-4.

[61] K. A. Anbarasu A. Performance and emission characteristics of diesel engine using cerium oxide nanoparticle blended biodiesel emulsion fuel. J. Energ Engg. 2016;142(1).

[62] V. Arul Mozhi Selvan, R.B.B. Anand, M. Udayakumar, V.A.M. Selvan, R.B.B. Anand, M. Udayakumar.

Effect of Cerium Oxide Nanoparticles and Carbon Nanotubes as fuel-borne additives in Diesterol blends on the performance, combustion and emission characteristics of a variable compression ratio engine. Fuel. 2014;130:160-7.

[63] Meshack Hawi, Ahmed Elwardany, Mohamed Ismail, Mahmoud Ahmed. Experimental Investigation on Performance of a Compression Ignition Engine Fueled with Waste Cooking Oil Biodiesel–Diesel Blend Enhanced with Iron-Doped Cerium Oxide Nanoparticles. Energies. 2019;12(5).

[64] M. Annamalai, B. Dhinesh, K. Nanthagopal, P. SivaramaKrishnan, J. Isaac JoshuaRamesh Lalvani, M. Parthasarathy, K. Annamalai. An assessment on performance, combustion and emission behavior of a diesel engine powered by ceria nanoparticle blended emulsified biofuel. Energy Conversion and Management. 2016;123:372-80.

[65] Hosseini S.H., Taghizadeh-Alisaraei A., Ghobadian B., Abbaszadeh-Mayvan A. Performance and Emission Characteristics of a CI Engine Fuelled with Carbon Nanotubes and Diesel-Biodiesel Blends. Renew. Energy. 2017;111:201-13.

[66] Vladimir Markov, Vyacheslav Kamaltdinov, ORCID, Anatoliy Zherdev, Viktor Furman, Bowen Sa, Vsevolod Neverov. Study on the Possibility of Improving the Environmental Performance of Diesel Engine Using Carbon Nanotubes as a Petroleum Diesel Fuel Additive. Energies. 2019;12(22):4345.

[67] M.S. Gad, Bahaa M. Kamel, Irfan Anjum Badruddin. Improving the diesel engine performance, emissions and combustion characteristics using biodiesel with carbon nanomaterials. Fuel. 2021;288.

[68] Fayyazbakhsh. Determining the optimum conditions for modified diesel fuel combustion considering its emission, properties, and engine performance. Energy Convers Manage. 2016;113:209-19.

[69] G. Najafi. Diesel engine combustion characteristics using nano-particles in biodiesel-diesel blends. Fuel. 2017:1-11.

[70] Yan Cao, Hayder A. Dhahad, Hossein Esmaeili, Mohammadreza Razavi. MgO@CNT@K2CO3 as a superior catalyst for biodiesel production from waste edible oil using two-step transesterification processProcess Safety and Environmental Protection. 2022;161:136-46.

[71] Impha Yalagudige Dharmegowda, Lakshmidevamma Madarakallu Muniyappa, Parameshwara Siddalingaiah, Ajith Bintravalli Suresh, Manjunath Patel Gowdru Chandrashekarappa, Chander Prakash. MgO Nano-Catalyzed Biodiesel Production from Waste Coconut Oil and Fish Oil Using Response Surface Methodology and Grasshopper Optimization. Sustainability. 2022;14:11132.

[72] Hassan Rasouli, Hossein Esmaeili. Characterization of MgO nanocatalyst to produce biodiesel from goat fat using transesterification process. Biotech. 2019;9(11):429.

[73] Qasim, Maimoonah Khalid. Modified Nanostructure MgO Superbasicity with CaO in Heterogeneous Transesterification of Sunflower Oil. Egypt.J.Chem. 2019;62(3):475-85.

[74] Ali Fakhimi, Behzad Hemami. Rock Uniaxial Compression Test and Axial Splitting. Procedia Engineering. 2017;191:623-30.

[75] Wang X., Yang R. MgO nanoparticles as an additive in biodiesel: A promising approach to improve fuel properties and engine performance. Fuel. 2014;128:63-70.

[76] Wang, X., Yang, R. Effect of MgO nanoparticles on the oxidative stability of biodiesel. Fuel Processing Technology. 2015;135:207-13.

[77] Wang X., Yang R. Investigation of the effect of MgO nanoparticles on the cetane number of biodiesel. Fuel Processing Technology. 2016;148:245-51.

[78] Li W., Zhang B., Chen L. Effects of MgO nanoparticles on the viscosity and lubricity of biodiesel. Fuel. 2019;254:115597.

[79] Alok Ranjan, S.S. Dawn, J. Jayaprabakar, N. Nirmala, K. Saikiran, S. Sai Sriram. Experimental investigation on effect of MgO nanoparticles on cold flow properties, performance, emission and combustion characteristics of waste cooking oil biodiesel. Fuel. 2018;220:780-91.

[80] Ganesh D., Gowrishankar, Effect of Nano-fuel additive on emission reduction in a Biodiesel fuelled CI engine. in Electrical and control engineering conference. 2011.

[81] Rolvin D'Silva, K.G. Binu, Thirumaleshwara Bhat. Performance and Emission Characteristics of a C.I. Engine fuelled with diesel and TiO2 nanoparticles as fuel additive. Mater Today Proc. 2015;2(37):28-35.

[82] P. Karthikeyan, G. Viswanath, Effect of titanium oxide nanoparticles in tamanu biodiesel operated in a

two cylinder diesel engine. Materials Today: Proceedings. 2020;22(3):776-80.

[83] Karoon Fangsuwannarak, Thipwan Fangsuwannarak, and Yongsathon Khotbut. Effect of Nano-TiO2 Additives Blended in Palm Biodiesel on Compression Ignition Engine Performance. Clean Energy Technol. 2020;8(3):20-3.

[84] Pandian A. K., Ramakrishnan R. B. B., Devarajan Y. Emission analysis on the effect of nanoparticles on neat biodiesel in unmodified diesel engine. Envi. Science Pollution Res. 2017;24(29):23273-8.

[85] L. Jeryrajkumar, G. Anbarasu, T. Elangovan Effects on Nano Additives on Performance and Emission Characteristics of Calophyllim inophyllum Biodiesel. International Journal of ChemTech Research. 2016;9(4):210-9.

[86] Bhagwat V.A., Pawar C., Banapumath N.R. Graphene nanoparticle- biodiesel blended diesel engine. Int. J. Eng. Res. Technol. 2015;4:75-8.

[87] Manzoore Elahi. M. Soudagar, Nik-Nazri Nik-Ghazali, M.A. Kalam, Irfan Anjum Badruddin, N.R. Banapurmath, T.M. Yunus Khan, M. Nasir Bashir, Naveed Akram, Rijavan Farade, Asif Afzal. The effects of graphene oxide nanoparticle additive stably dispersed in dairy scum oil biodiesel-diesel fuel blend on CI engine: performance, emission and combustion characteristics. Fuel. 2019;257:1-17.

[88] Homa Hosseinzadeh-Bandbafha, Esmail Khalife, Meisam Tabatabaei, Mortaza Aghbashlo, Majid Khanali, Pouya Mohammadi, Taha Roodbar Shojaei, Salman Soltanian. Effects of aqueous carbon nanoparticles as a novel nanoadditive in wateremulsified diesel/biodiesel blends on performance and emissions parameters of a diesel engine. Energy Conversion and Management. 2019;196:1153-66.

[89] Mu-Jung Kao, Chen-Ching Ting, Bai-Fu Lin, and Tsing-Tshih Tsung. Aqueous Aluminum Nanofluid Combustion in Diesel Fuel. Journal of Testing and Evaluation. 2008;36(2):1-5.

[90] Suresh Vellaiyan, Arunkumar Subbiah, Prabha Chockalingam. Effect of Titanium dioxide nanoparticle as an additive on the working characteristics of biodiesel-water emulsion fuel blends. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects. 2019:1556-7230.

[91] Shiva Kumar, P. Dinesha, Ijas Bran. Influence of nanoparticles on the performance and emission characteristics of a biodiesel fuelled engine: An Experimental analysis. Energy. 2017:1-26.

[92] Ebrahiem E. Ebrahiem, Yassin A. Hakim, Tarek M. Aboul-Fotouh, M. Abd Elfattah. Improvement of Diesel Fuel to Enhance Engine Performance and Emissions Using Zinc Oxide Nanoparticle Additive. Egyptian Journal of Chemistry. 2022;65(2):349-55.

[93] Adel Sharif Hamadi, Hayder Abed Dhahad, Riyadh M. Noaman, Thamera Kidher, Safaa Suhail, Quraish abass. An Experimental Investigates to Study the Effect of Zinc Oxide Nanoparticles Fuel Additives on the Performance and Emissions Characteristics of Diesel Engine. Research. 2019.

[94] M. Anish, P. Bency, J. Jayaprabakar, N. Joy, V. Jayaprakash, S.K. Sahaya, J. Aravind, S. Ansar, S. Rezania. An evaluation of biosynthesized nanoparticles in biodiesel as an enhancement of a VCR diesel engine. Fuel. 2022;328.

[95] Fayaz Hussain, Manzoore Elahi M. Soudagar, Asif Afzal, M.A. Mujtaba, I.M. Rizwanul Fattah, Bharat Naik, Mohammed Huzaifa Mulla, Irfan Anjum Badruddin, T. M. Yunus Khan, Vallapudi Dhana Raju, Rakhamaji S. Gavhane, S.M. Ashrafur Rahman. Enhancement in Combustion, Performance, and Emission Characteristics of a Diesel Engine Fueled with Ce-ZnO Nanoparticle Additive Added to Soybean Biodiesel Blends. Energies 2020:1-20.

[96] Medhat Elkelawy, Safaa El-din H. Etaiw, Hagar Alm-Eldin Bastawissi, Mohamed I. Ayad, Ahmed Mohamed Radwan, Mohamed M. Dawood. Diesel/ Biodiesel /Silver Thiocyanate Nanoparticles/Hydrogen peroxide blends as New Fuel for enhancement of Performance, Combustion, and Emission Characteristics of a Diesel Engine. Journal Pre-proof. 2020:1-44.

[97] Medhat Elkelawy, Safaa El-din H. Etaiw, Mohamed I. Ayad, Hassan Marie, Mohamed Dawood, Hitesh Panchal, Hagar Alm-Eldin Bastawissi. An enhancement in the diesel engine performance, combustion, and emission attributes fueled by diesel-biodiesel and 3D silver thiocyanate nanoparticles additive fuel blends. Journal of the Taiwan Institute of Chemical Engineers. 2021:1-12.

[98] Mohammed A. Fayad, Hayder A. Dhahad. Effects of adding aluminum oxide nanoparticles to butanol-diesel blends on performance, particulate matter, and emission characteristics of diesel engine. Fuel. 2021;286.

[99] P. Dinesha, Marc A. Rosen, Shiva Kumar. Effects of particle size of cerium oxide nanoparticles on the combustion behavior and exhaust emissions of a diesel engine powered by biodiesel/diesel blend. Biofuel Research Journal. 2021;30:1374-83.

[100] Raslan A. Alenezi, A.M. Norkhizan, R. Mamat, Erdiwansyah, G. Najaf, Mohamed Mazlan. Investigating the contribution of carbon nanotubes and diesel-biodiesel blends to emission and combustion characteristics of diesel engine. Fuel. 2021;285.

[101] S. Sunil, B.S. Chandra Prasad, Shrishail Kakkeri, Suresha. Studies on titanium oxide nanoparticles as fuel additive for improving performance and combustion parameters of CI engine fueled with biodiesel blends. Materials Today: Proceedings. 2021;44:489-99.

[102] S.S. Hoseini, G. Najaf, B. Ghobadian, M.T. Ebadi, R. Mamat, T. Yusaf. Performance and emission characteristics of a CI engine using graphene oxide (GO) nano-particles additives in biodiesel-diesel blends. Renewable Energy. 2020;145;458-65.

[103] M. El-Adawy. Effects of diesel-biodiesel fuel blends doped with zinc oxide nanoparticles on performance and combustion attributes of a diesel engine. Alexandria Engineering Journal. 2023;80:269-81.

[104] Neupane, Dhurba. iofuels from Renewable Sources, a Potential Option for Biodiesel Production. A Bioengineering. 2023;10(1):29.

[105] Pranjal Maheshwari, Mohd Belal Haider, Mohammad Yusuf, Jiří Jaromír Klemeš, Awais Bokhari, Mukarram Beg, Amani Al-Othman, Rakesh Kumar, Amit K. Jaiswal. A review on latest trends in cleaner biodiesel production: Role of feedstock, production methods, and catalysts. Journal of Cleaner Production. 2022;355:131588.