Journal of Thermal Engineering
https://jten.yildiz.edu.tr/
https://doi.org/10.47481/jten.0032

RESEARCH ARTICLE

# Influence of nanoparticle additives on performance and emissions of biodiesel blends: a critical review

K. Sunil Kumar[1,*], Raviteja Surakasi[2], Vidhya S.[3], Kannan A.[4], Grynal D'Mello[5]

[1]Department of Mechanical Engineering, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences, Chennai, 602105, Tamil Nadu, India
[2]Department of Mechanical Engineering, Vignan's Institute of Information Technology, Duvvada, Visakhapatnam, 530049, Andhra Pradesh, India
[3]Department of Mathematics, Panimalar Engineering college, Chennai, 600123, India
[4]Department of Mathematics, Vel Tech Multi Tech Dr. Rangarajan Dr. Sakunthala Engineering College, Avadi, 600062, India
[5]Nitte (Deemed to be University), NMAM Institute of Technology, Department of Mechanical Engineering, Nitte, 574110, India

## Abstract

The present paper addresses the critical quest for a viable substitute fuel for compression-ignition engines. With rising crude oil prices and the increasing urgency to reduce emissions, our study indicates the substantial potential of nano-additives. Through a succession of extensive experiments, we have discovered their high degree of effectiveness. In our tests, nano-additives were introduced into the fuel, and their effects were closely monitored using sophisticated methods such as gas chromatography. We have identified significant gaps in current research, particularly regarding the timing of nano-additive application and the streamlining of the testing methodology. The findings are quite promising: the addition of novel nano additives not only enhances engine performance but also drastically reduces harmful emissions. The study is particularly noteworthy because it thoroughly examines the use of various nano-additives combined with biodiesel, demonstrating their versatility and suitability across diverse applications. These coatings reduce the amount of heat loss, increase combustion temperatures, and result in significant emission cuts: carbon monoxide emissions were reduced by 20%, hydrocarbons by 24.5%, and nitrogen by a staggering 27.8% over conventional diesel fuel. This study not only moves alternative fuel research in a whole new direction but also sets the stage for more efficient and cleaner diesel engines. With these new solutions, we can make significant strides toward a promising, sustainable energy future.

**Keywords:** Nano additives, emission, performance, combustion, diesel engine

**Cite this article as:** Kumar, K. S., Surakasi, R., Vidhya, S., Kannan, A., & D'Mello, G. (2026). Influence of Nanoparticle Additives on Performance and Emissions of Biodiesel Blends: A Critical Review. Journal of Thermal Engineering, 12(4), 1324–1336. https://doi.org/10.47481/jten.0032

## 1. Introduction

Internal combustion engines are more acceptable to engineers because of their low emissions, and diesel engines are especially known for economical fuel consumption. Diesel engines are designed to maximize fuel efficiency. Recent testing has demonstrated cleaner combustion. Biodiesel also leads to better air quality and safety, since it has a higher cetane number, which allows engines to start faster. Additionally, biodiesel enhances fuel lubricity, thereby reducing premature wear of engine parts by 3–5%. In the United States, biodiesel is used less for vehicle transportation. This paper is dedicated to changing the fuel used in diesel engines. Blending biodiesel and diesel fuel so that they can be used interchangeably is possible and large amounts of biodiesel are being generated [1]. Exhaust contributed to sustaining and engine performance leading to the reduction of pollutants emitted and the overall efficiency [2]. Engine biodiesel performance, structure and biodiesel blends have been discussed in many review papers since the launch of the biodiesel blend [3]. These studies have also found positive results regarding injection timing and its effects. The study conducted in [4] is simple and has shown that there are considerable gains. The effects of using different levels of biodiesel in diesel engines were investigated using four types of biodiesels, specifically on indicated power and NOx emissions. Most literature reviews highlight energy production,

*Corresponding Author
E-mail Adress: sunilkumarkresearcher@gmail.com

**Submitted:** 15 May 2025 ; **Accepted:** 1 November 2025

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

Published by Yıldız Technical University, İstanbul, Türkiye

which focuses on emissions control and the products of combustion to optimize the energy that can be extracted from exhaust gases. The purpose of this work is to introduce the biodiesel blends, their injection properties, and nano-additives. The results of past studies that tested nano additives on combustion performance have been reported to be excellent, although the intended purpose of the added nano additives is modest.

The objective of the research is to systematically evaluate, synthesize, and critically appraise the existing scientific and modeling literature on nanotechnology additives in biodiesel blends, with the aim of identifying consistent emission patterns, theoretical limitations, and priority areas for further research and commercialization. The Particular aims of this study is v Gather rigorous scientific and modeling research that examines microscopic contents, in renewable fuels or diesel-biodiesel mixtures, in the last 20 years and obtain universal records such as tiny particle category, size, percentage, extraction, combustibility, transmission properties, and results tracked. Compare and contrast the effects of different types of tiny particles metal compounds, carbon-based, and multipurpose on key indicator values brake energy use, some fuel use, utilization measures and pollutants (nitrogen oxides, carbon monoxide, hydrogen cyanide, PM, CO2 with a focus on consistent patterns and exceptions. Determine the degree of methodological and reporting rigor: including consistency of collection, dissemination, assurances, monitoring methodology, statistical evaluation: identify common sources of bias and lack of consistency. Summarize physiological explanation thermal, enzyme-surface, and even vaporization within the scientific community, and assess the degree to which field research supports these theories. Develop a detailed list of practical suggestions for the best approaches to testing, evaluation criteria, and key research questions relevant to empirical research on growth. Point out social, behavioral, and biological variables that have been poorly addressed or omitted in the available literature on nanoscale presence, hazards, recycling, and economic evaluations. The objectives of this study relate to pressing issues in mechanical engineering, such as compatibility with the latest CI engine technology, the affordability of additives, and the optimization of combustion followed by advanced continuous integration engine technology compatibility. Modern CI engine designs also require fuels and compounds that do not compromise engine functionalities, such as the high-performance conventional-rail injectors, turbochargers, recirculation of exhaust gases (EGR), and recuperation devices. Many conventional fuels and changes cause injector plugging, impeded filtration, or increased attrition. Evaluating the additions of nanotechnology ($TiO_2$, $Al_2O_3$, CNTs) in biodiesel blends is indirectly related to fuel- engine performance, ensuring effective vaporization, reduction in accumulation, and uniform behavior of the complex CI technology.

There are many fuel additives that have proven effective in small-scale experiments, but have failed in industrial use because of the high costs of generation, processing, or dosing. Carmakers also need technologies that are cost-effective, scalable, and that enhance biofuels without raising production costs. Introduction: The study will help to maximise profitability through a comprehensive analysis of the efficacy of nanotechnology prescriptions, the dependability of distribution, and the merging techniques to determine nanomaterials or hybrid combinations that provide the greatest benefit at the lowest cost. Compression combustion machines face a trade-off between performance and emissions: ethanol has been shown to improve respiration, but increase NOx emissions, and nanocrystals can potentially affect combustion retardation, heat evacuation rate, or flaming velocity. Achieving a balance among braking effectiveness, piston pressure specifications, and pollution remains a fundamental challenge. The study's focus on nanotechnology additions facilitates combustion, aiming to improve vaporization, increase the amount of heat released, reduce ignition retardation, and decrease gaseous emissions (CO, HC, nitrogen oxides) and smoke.

This paper follows a systematic approach to categorize data based on the key engine operating variables: brake heating efficiency (BTE), brake-specific mileage, cylinder inflation, and pollutants (nitrogen oxides, carbon monoxide, hydrocarbons, carbon dioxide, smoke). This study explains special trends and outcomes by considering the combination of these variables in vast amounts of nanoparticles and mixes, which have been previously under-researched. Much of the scientific literature is based on single-cylinder, compression-ignition test engines, which are useful for study under controlled conditions but may not reflect real-world conditions. This discussion brings together the results of various engine designs and biofuel feedstocks, identifying connections between small-scale tests and the potential to scale up to larger automobiles, agricultural vehicles, and permanent vehicles. It also distinguishes better performances that are conditional on the combustion process from those that are not related to feedstock and are therefore more general. Critical Analysis of Nanoparticle Incorporation: The summary provides a critical evaluation of nanoparticle concentration, dispersion strength, and integrated tenacity, rather than merely reporting positive results. It places greater emphasis on the trade-offs between sustainability and affordability, as well as on the concrete obstacles to business development, and links scientific findings to business application.

## 2. Nano additives

The addition of nano additives in biodiesel blends has been performed, and it has been observed that it does not produce adverse effects. The addition of nano compounds and of the engine during testing. Water renders the fuel colourless and tasteless, thereby producing uniform improvements. These nano-additives have a high surface area; hence, their effects are concentrated in the engine. Some of the nano-sized materials include in the food industry e.g. nano salt which is added in small amounts. Also, nano polyline oxidation occurs, in which tooth oil is the source of particulates, owing to the introduction of nano-gradients. These substances are in high demand across different countries. The stomach receives a boost of nano minerals and one food item is of minimal size at 100 nm, leading to an increase in levels of performance. Bioactive proteins help to enhance nutritional value. Increasing the concentrations of nano-based beneficial probiotic bacterial species, lycopene, vitamins, and nanoparticles in the gastrointestinal tract is of increasing interest. Products with nano additives are gaining popularity food dairy products. In a study [5] involving Calophyllum Inophyllum methyl ester biodiesel, engine trials revealed that its use resulted in 100 percent engine improvement with addition of the additives. Nano-sized functional herbs stabilize polysaccharides, (such as pectin and inulin, ), carrots, and cryo powder of red sheets. These formulations also include butter. Further research [6] nanoparticles found that they enhance, with three different nanoparticles utilized in experiments. Such varied properties draw our attention on the importance of nano additives as an important step in the biodiesel preparation that can be made out of the residual cooking oil by using alkaline transesterification [7]. The biodiesel mixture in different weight proportions was sprayed with aluminium oxide and small-sized cerium oxide particles using an ultrasonic cleaning bath. In this paper, the evaluation fuels were prepared using different concentrations of nanomaterials (260 milligrams to 780 mg/millilitre, in steps of 260 mg/l). Inquiries showed that a highly aggressive surface promoted chemical reaction, which better ignited. One per cent and eight per cent improvements were observed in the brake thermal efficiency and specific combustibility of the biodiesel mixture, respectively, when nanoparticles were dispersed. Moreover, the partial combustion byproducts such as carbon dioxide, unburnt hydrocarbons and smoky volume decreased by five per cent, 9 per cent and sixteen per cent, respectively. On the other hand, the result of the full combustion(nitrogen oxides)was reduced by up to eight percentage points [8]. Recent research has demonstrated the integration of minute fragments that are conductive, non-conductive, fresh, amorphous, or combinations thereof in diesel-biodiesel fuel emulsions. The findings indicated a modification. The effect of the dispersion of the pellets to the enhancement of efficiency parameters leading to a subsequent reduction of the emissions in a CI engine using diesel-biodiesel blends is investigated. The next goal is the establishment of a low cost and viable particulate additive to biodiesel and fuels [9]. To evaluate performance and emissions, a test rig was mounted on a single-cylinder diesel engine. The combination of biodiesel and nano $Al_2O_3$, termed as J20Al100, was shown to increase the average heat transfer by 6.5 percent in comparison to all the other fuels used. The Jatropha, or biodiesel blend with CNTs, referred to as J20CNT5030D,differed by approximately thirty-six per cent and half-twenty, respectively, relative to all other fuels. The Jatropha bio-diesel blend with titanium dioxide reduces hydrocarbons and fumes by about 22 per cent and 50 per cent, respectively, relative to other fuel types. Jatropha biodiesel mixed with the nanomaterials named J20 exhibited improvements in acceleration and a reduction in pollutants when compared to the rest of the biofuels tested [10]. Adding 50 ppm cerium oxide to diesel-ethanol reduced the penetration length by two per cent and increased the spray funnel inclination by 4.3 per cent, compared with 25 ppm. Mahua biofuel was treated with 40, 80, and 120 ppm of iron oxide nanoparticles, which increased its BTE by 1.58%, 1.62%, and 2.34%, respectively. Compared to pure diesel, carbon emission reduced by 10 percent in case of TiO2 combinations, 22 percent in case of Al2O3 combinations, 18 percent in case of CuO combinations and 7.2 percent in case of cerium oxide. Nonetheless, there are other outstanding issues, which are among the key issues that need to be addressed to make nanotechnology hydrocarbons economically viable for producing energy [11]. A combination of biodiesel made from Jatropha with different ingredients has been reported to be under investigation. Tiny particles studied experimentally include aluminium, copper, zinc oxide, carbon, graphite oxide, graphene in the form of tiny plates, and multiwalled graphite nanotubes. Except for jatropha biodiesel and blends, nanoparticle additions reduced ignition delay. The burning process was initiated early, which led to a decrease in fuel consumption by the brakes and an increase in the brakes' thermal effectiveness. Much research has shown that biofuels have certain drawbacks, such as high density, low fluctuation, low calorific value, and high nitrogen oxide emissions, although. Certain scientists know that these drawbacks can be alleviated with the help of using compounds and the increased use of biofuels [12]. Nano-additives used in biofuel blends have been shown to enhance fuel efficiency and reduce emissions. Nevertheless, a number of gaps in research remain. The first significant issue is whether these small additives, when combined with biodiesel, remain stable over the long term. The interactions of these additives with the components of biodiesel and the degradation or agglomeration that can occur over time should be understood. Although nano-additives can increase combustibility, their impacts on the environment, such as potential toxicity and disposal, need to be considered. Whether the commercial, large-scale use of nano-additives in biodiesel production is economically viable is not yet well established, and . Standardized protocols for the production and use of nano-additives in biodiesel formulations do not exist, making it difficult to compare findings across studies. Moreover, the impact of nano-additives on engine operation and their compatibility with the existing powertrain systems require additional research. Lastly, the risks linked to the manipulation of nano-additives during production, use, and burning are not well understood at present. The gaps identified reinforce the need to undertake interdisciplinary studies to integrate nano-additives into biodiesel mixtures safely and effectively.

**Table 1.** Examples of some nano additives in added to biodiesel blends

| Engine | Nano additives | Engine speed | Bio diesel blend | References |
|---|---|---|---|---|
| Four stroke cylinder | Cerium oxide | 1500 rpm | Momordica | [13] |
| Four stroke | Alumina oxide | 1500 rpm | Schleichera oleosa | [14] |
| Four stroke | Zinc oxide | 1500 rpm | Jatropha methyl ester | [15] |
| Four stroke | Titanium dioxide | 2000 rpm | CVOME | [16] |
| Four stroke | Copper oxide | 1500 rpm | Pongamia methyl ester | [17] |

Studies on the use of nano-additives are now being directed more towards their potential to improve the performance and environmental qualities of bio-diesel blends. Some of the most significant would be listed below. They use Metal oxide nanoparticles such as titanium dioxide and cerium oxide. The substances improve fuel efficiency and reduce greenhouse gas emissions, including unburned pollutants and nitrogen oxides. Carbon-Based Nanomaterials: Graphite oxide and carbon nanotubes are characterized by high thermal conductivity, which enhances the performance of biodiesel blends. Table 1 lists examples of nanoadditives, and Table 2 presents observations and the amounts present in nano additives.

**Table 2.** Nano additives and observations.

| Nano additives | Observation and result | References |
|---|---|---|
| $CeO_2$ | Completely eliminate NOx emissions | [18] |
| $AlO_2$ | Reduced emissions found | [19] |
| $TiO_2$ | $TiO_2$ nanoparticles results in lower emissions. | [20] |
| ZnO | CO, HC and smoke are seen less | [21] |
| CUO | Gain in BTE while significantly BSFC lower. | [22] |

## 2.1. Cerium oxide

$CeO_2$ nano additive containing 25ppm of NOx has been added to blends of fuel. The brakes performed better in this period, in particular with regard to thermal efficiency [23]. $CeO_2$ nano additives led to lower emissions, which were tested on the BCM20 and BCM40 blends. The studies emphasized in [24] are aimed at reducing the pollutants with the help of cerium oxide nanoparticles. Research has shown that the incorporation of $CeO_2$ into the nanoparticle fuels improves the physicochemical properties of the fuel demonstrated to enhance engine enhancement upon the use of $CeO_2$ [25].

## 2.2. Alumna oxide

Based on the research [26] explored the application of B20 biodiesel blended with different amounts of aluminium oxide ($Al_2O_3$) that is, 0.05 and 0.01. The aim of this study was to get a result comparing these $Al_2O_3$ and B20 blends. Also, the paper evaluated such key performance indicators like brake specific fuel consumption (BSFC), brake torque efficiency (BTE), and nitrogen oxide (NOx), hydrocarbons (HC) and carbon monoxide (CO) emissions. Study [27,28] investigated with aluminium oxide, such as B10 with 20 ppm $Al_2O_3$, B20 with 20ppm $Al_2O_3$ and B30 with 20ppm $Al_2O_3$. As mentioned in [29], the primary aim of using nanotubes. Also, the study conducted in [30] proved that the combination of PBD and 50 ppm $Al_2O_3$ had the best mean fuel burnout (MFB).This mixture also exhibited the shortening of ignition delay time. The particle size distribution(PSD) analysis showed that the PBD mixed with 25 ppm $Al_2O_3$ resulted in the smallest particles in different engine load conditions. Lastly, the paper in [31] examined the use of plastic oil combined with $Al_2O_3$ as a nano additive, and was able to analyse the emissions of CO, $CO_2$, and NOx. The results of the addition of aluminium oxide were agreeable with the available data in [32].

## 2.3. Titanium dioxide

Metal nanoparticles, titanium oxide, and various fuel blend ratios are tested in this research on diesel engines [33]. This is because the emissions are lowered as they perform better and combust more [34]. The findings of biodiesel percentage 60% with 10% bioethanol had the optimal blend due to its low BTE and a more extensive BSEC range. Such emission due to the attaching TiO2 nanoparticles has been reduced [35]. Based on [36], the effort to different engine factors was explored. The experiments gave predominant results. The value of carbon emission is reduced because of more TiO2 nano additive in the research [37,38]. The modified fuel blend has TiO2 nanoparticles which can be used as fuel without altering the functioning or design characteristics [39].

## 2.4. Zinc oxide

The experiment showed changes in fuel composition when several additives, such as zinc oxide nanoparticles [40], were added. It was found that, under full-load conditions, this modified fuel had higher brake thermal efficiency and lower brake-specific fuel consumption than a biodiesel-ethanol blend [41]. The study of Ag-ZnO nanoparticles and biodiesel mixtures with zinc oxide also demonstrated considerable changes.

## 2.5. Bismuth oxide

The microalgae oil behaviour and their mixtures with $Bi_2O_3$ nano additives have been examined. The study demonstrates that the addition of $Bi_2O_3$ lowers the viscosity and raises the volatility and leads to increased atomization, vaporization and mixing. Also, these blends are supplemented with metal nanomaterials, like silver (Ag) and other metal nanostructures, to enhance the quality of sparks and minimize the emission of particles. Moreover, hybrid nano-additives that involve the combination of aluminium oxide with carbon-based materials, such as silica and iron oxide are being used to improve the ignition and dispersion properties.

## 2.6. Copper oxide

The experiment was on the application of copper oxide (CuO) nano-additives in Braunii algae oil, which analyzed the engine operation parameters. The CuO nano-additives were experimented at 25, 50, 75 and 100 parts per million(ppm). They were applied to B20 biodiesel mixtures and run at different loads to test engine performance. The results indicated a reduction in emissions. Particularly, the blends to be tested were B20 + 100 of the CuO nano additive. Furthermore, the study will seek to know the effects of CuO nanoparticles on the combustion properties and emissions of diesel fuel. The results indicate that the addition of nanoparticles to biodiesel leads to reduce $NO_X$ emissions. Table 3 is a representation of $CeO_2$, $TiO_2$ and $Al_2O_3$ Nanoparticles combustion-emission dynamics.

**Table 3.** $CeO_2$, $TiO_2$, and $Al_2O_3$ Nanoparticles combustion-emission dynamics

| SNO | Nano Additive | Mechanism | Physicochemical Effects |
|---|---|---|---|
| 1 | $TiO_2$ | Dispersed management. | Improves the dispersal of combustion |
| 2 | $Al_2O_3$ | Rise in Pollution. | Enhanced fuel-air interaction |
| 3 | $CeO_2$ | oxygen buffering | Enhances the supply with oxygen |

Micro-additions improve brake thermal efficiency through several complementary mechanisms. Enhancement of Heterogeneous Emission Nanostructures of metal oxides, $CeO_2$ and $Al_2O_3$ promotes the complete energy reduction and reduces the number of remaining hydrocarbons during combustion. A high presence of Breathable CeO2 enhances a more complete burn of the fuel by liberating oxygen during combustion through Ce4+•Ce3+ oxidation recycling. Enhancements in Nanostructures improve the transmission of heat to the chamber, enhancing combustion heat transfer, accelerating and distributing the flame. Enhanced Atomised and Spray Properties. Nanotechnology stabilisers enhance fuel-air contact and aerosol dispersion by reducing friction and rigidity. A faster ignition speed will improve the BTE, thereby enhancing the combustion cycle's efficiency and raising maximum tensions.Very good Heat degree of conductivity. Mineral oxides like $Al_2O_3$ and $CeO_2$ are better than base combustibility, and carbon nanotubes can have conductivity of over 3500 W/mk. The outcome enhances flame spread and minimises isolated scalding by hastening heat evacuation from the furnace bowl. Carbon nanotubes have been discovered at up to 22.5 per cent, implying that burning occurs faster and more efficiently. Brake Thermal Effectiveness improves, and optimal chamber levels increase as a result. Enhanced Dispersion of In-Cylinder Warmth. By reducing temperature gradients and facilitating continuous burning, nanocrystals serve as thermal intermediaries, spreading heat more equally throughout the burning region. The small particles improve combustion by deteriorating, which consequently leads to more complete combustion and greater energy release. Enhanced fragmentation reduces the combustibility of waste by enhancing the fuel-air blend. Increased calorific significance: The energetic content of the composite is enhanced by certain components, such as CNTs and $CeO_2$. Make Engine Load Profiling Universal. Reliable load cycles are to be repeated during trials with programmed dynamometers. The result is a reduction in emission bursts and a shift in the timing of burning. Regulate the Timing of Injections: Inject at specific timing in 20 -30 and 27 -30 BTDC with an electronically controlled infusion system at 20 -30 BTDC, enriched with $TiO_2$, shows superior BTE and reduced NOx, as per research. Controllable conditions: Control the temperature and humidity of the immediate surroundings by putting the test equipment in a controlled climate chamber. These considerations affect the lag between ignition, along with the behaviour of nanoparticles [42].

## 3. Experimental set up

**Figure 1.** Actual Experimental set up [43]

Figure 1 shows a schematic of the actual trial rig that is to be used in conducting experiments on various blending trial combustibility, the effectiveness of the motor, in terms of braking thermal efficacy, specific fuel and pollutant characteristics, ranging under different loads of 0 per cent, 25 per cent, 50 per cent, 75 per cent, and full load conditions through a breathing oxygen analysis. To give different loads to the engine, the eddy current dynamo is connected to the engine flywheel. The calorie gauge is used to sustain thermal equilibrium between the amount of exhaust gas and the flow of water using a pipe-in-pipe system. The fluid pump is used to pump the liquid from the storage tank to the generator, the thermometer, and the device for cooling. An ignition detector in the engine's combustion chamber measures ignition characteristics, such as the internal pressure and exhaust temperature. Engine specifications are specified in Table 4.

**Table 4.** Engine specifications

| Type | Four strokes, Direct Injection diesel engine |
|---|---|
| Piston geometry | Hemispherical |
| Swept volume | 663 cc |
| Injection timing | 23 deg before Top Dead Center (static) |
| Number of nozzles and spray hole diameter | 6 and 0.4 mm |
| Bore | 90 mm |
| Rated power and speed | 5.2 kW at 1500 rpm |
| Stroke | 120 mm |
| Compression ratio | 18:1 |

## 4. Nano additives added to biodiesel blends effects

Numerous studies agree that adding nano additives to fuel enrichment is an excellent option. Nano additives are used to improve fuel quality, enhance performance characteristics, and achieve reasonable emission control without modifying the compression-ignition engine. Table 5 illustrates the nano additives added to biodiesel blends.

**Table 5.** Nano additives added to biodiesel blends effect

| Diesel Mixing | Percentage of blends | Nano additive | PPM | Main effect | References |
|---|---|---|---|---|---|
| Jatropha | 25 | Alumina | 25 | Accelerated combustion | [44] |
| Polanga | 25 | Alumina | 25 | Reduced emissions | [45] |
| Cooking Oil | 20 | Titanium | 50 | Reduced emissions | [46] |
| Algae | 100 | Zinc | 100 | Reduced emissions | [47] |

## 5. Nano additive on engine performance and emissions

Nano-additives in performance fuel have created a host of new opportunities for engineers to reduce fuel consumption and overcome some of the performance trade-offs that accompany the use of internal combustion engines and biofuels [48]. Table 6 presents the emission performance outcomes for different nano additives. Table 7 is Measures of the Performance of Traditional Nanoparticle Additives.

**Table 6.** Nano additives added Emission performance and emission result

| Blended oil | Nano additives | BTE | SFC | HC | CO | $NO_x$ | Smoke | Reference |
|---|---|---|---|---|---|---|---|---|
| Calophyllum | $CeO_2$ | ↓ | ↑ | ↓ | ↓ | ↓ | ↓ | [49] |
| Palm Oil | $CeO_2$ | ↓ | ↑ | ↓ | ↓ | ↓ | ↓ | [50] |
| Polanga | $Al_2O_3$ | ↓ | ↑ | ↓ | ↓ | ↓ | ↓ | [51] |
| pinnata | CuO | ↑ | ↑ | ↓ | ↓ | ↓ | ↓ | [52] |
| Karanja | $TiO_2$ | ↓ | ↑ | ↓ | ↓ | ↓ | ↓ | [53] |

**Table 7.** Measures for the Performance of Conventional Nanoparticle Additives

| S.No | Catalyst | Dispersion Durability | Lifetime cost analysis | Combustion Stability |
|---|---|---|---|---|
| 1 | $CeO_2$ | Better dispersion | Higher cost | Excellent oxygen |
| 2 | ZnO | Thermally stable | Low-to-moderate | Improves atomization |
| 3 | MgO | Moderate dispersion | Moderate cost | Catalytic effect |
| 4 | $Al_2O_3$ | sedimentation | Relatively cheap | Enhances oxidation |
| 5 | $TiO_2$ | Tends to agglomerate | Abundant | oxygen delay |

## 6. Nano additives added to biodiesel blends that different research work

The research method used by the researchers in testing engines is to look for decreases and improvements in thermal efficiency and fuel consumption. Significant fuel savings, higher thermal efficiency and elimination of all available emissions. Due to operating conditions, the time emission was also reduced. Adjustment blends performed very well, and further tests have demonstrated that biodiesel is working in combustion and that emissions are again reduced [54]. Based on [55], who experimented with algal biodiesel and noted reduced emissions, resulting in improved performance, and re-studied the timing of injection. This was due to smoke testing and BTE testing. There are many experimental studies that have reduced NOx and smoke and decreased other BTE reactions. Developing [56] work on alumina nanoparticles, testing alternative injection conditions and blending times. The three alternate injection methods are called 23 deg bTDC, advanced timing 27 deg bTDC advanced timing and 19 deg bTDC retarded timing . The consequences of the experiment were based on [57], who researched emission quality and neochloro-rich methyl ester. The successful recipes were zinc oxide nanoparticles, and the final nano additive (ZnO) turned out to be satisfactory, though not accepted, as the nano blend was not quite.

## 7. Worked for optimization

The purpose of the experiment is to reduce smoke, capacity, NOx emissions, efficiency, and brake-specific fuel consumption [58]. Regression models were created, achieving an accuracy of 4%. It was observed that a 10% diesel injection is optimum for operation and that a 21° CA before top dead centre (bTDC) cyclohexanol/diesel mixture reduced NOx emissions by 43.1 per cent, smoke capacity by 32.4 per cent, and increased BSFC by 4 per cent. The cylinder temperature is lowered by the later injection timing, which slightly reduces NOx emissions [59]. The optimisation focus is on partial combustion. The obtained results were more precise compared to the simulated results. Further, the biodiesel emission methodology included the effects of 10- and 20-nanometer cerium oxide nanoparticles of different sizes. Other fuels have been studied, and the needed emission-reducing techniques have been developed. The study suggests that the effects of graphene nanoparticle composites on mixed oils should be investigated; this will be explored in the present investigation. The MINITAB statistical software and the Taguchi method were used to optimise, resulting in the identification of the best operating conditions for improving biodiesel performance [60].

## 8. Measurement of engine performance

### 8.1. Brake thermal efficiency

Brake thermal efficiency is improving, and the addition of nanoparticles enhances combustion by increasing the surface-to-volume ratio. Although brake thermal efficiency has increased, it still remains lower than that of pure diesel [61]. This is because alumina nanoparticles improve thermal efficiency but do not reduce fuel consumption. Operating the engine at a fixed speed of 1000 rpm results in a higher surface-to-volume ratio of the nanoparticles. Experimental studies indicate that the brake thermal efficiency value for B20 fuel blends is very low compared to that of pure diesel. However, incorporating nanoparticles, which facilitates greater fuel evaporation, increases BTE. When alumina nanoparticles are added to the blend, the brake thermal efficiency improves in comparison to pure diesel [62].

### 8.2. Brake specific fuel consumption

BSFC is calculated by dividing the required amount of fuel by the available brake power. The same diesel fuel and mixes were used. Specific fuel consumption is very low; get the diesel, loads peaking, and changes in blends, more loads [63]. According to [64], this research helps to identify the properties of blends and to increase the density of combined fuels. In a fuel-burning condition, BSFC decreases with load. The fuel sample CB5 has the lowest BSFC, SB10CB10 has the highest, and CB20 has the second-highest in the current study. From [65], fuels are well kept in brake-specific fuel consumption.

The addition of nanoparticles to the injection timing increased the combustion rate and decreased ignition delay. Because of the time of the injection when adding nanoparticles, there is a high heat release rate and low cylinder pressure. Reducing the ignition delay and early fuel injection ensures complete BDE combustion, increasing combustion duration and lowering BSFC. The results show that studies on BSFC for diesel values are very few [66,67].

## 9. Effect of emission properties

### 9.1. Hydrocarbon

A method of staying under the HC on a precompute carbureted car. This will make the idle slow down, and the burn will take longer and be hotter. The engine is being tested to determine whether it can reduce hydrocarbon emissions and lower the flammability limit. Molecular forms are hard to comprehend, and fossil fuels are used to generate energy. Emissions of ethylene, isoprene, and monoterpene HC compounds can be minimised, as demonstrated by numerous experiments. This is among the properties of diffusion combustion. There is also a shrinking and closing down of hydrocarbon distances. When HC levels are high, it enhances the burning of lubricating oil. Nano additions are compared with an HC that has a very low value, and diesel is compared with the emission, which is also very low. Oxygen buffer is supplied by nanoparticles and oxygen. It also produces a stoichiometric mixture, and nanoparticles are highly efficient at reducing hydrocarbon emissions [68].

### 9.2. Carbon monoxide

Nanoparticles enhance combustion performance by increasing temperature and increasing the availability of molecular oxygen, leading to lower carbon monoxide (CO) emissions. The presence of metal oxide nanoparticles in blends increases the oxygen content, as CO levels are very low. The molecular oxygen content increases while the cylinder temperature rises, promoting oxidation and reducing viscosity. These factors collectively contribute to lower CO emissions in diesel-algal fuel blends, with incomplete combustion as the only significant finding reported [69]. Compared with other nano-additive blends and regular diesel, CO emissions from the diesel-algal mix are lower. The CO emissions from diesel engines at various loads are reported as 0.21 g/kWh for blends [70,71]. Adding nanoparticles to the fuel increases combustion efficiency, reducing CO emissions. In particular, the CO emissions of the blends are reduced by 9.3, 16.27, 34.88, and 51.16, respectively, compared with plain diesel fuel. Also, a combination of B20 and $TiO_2$ gave good results.

### 9.3. Nitrogen oxide

Oxidation of nitrogen and oxygen occurs during chemical reactions to form NOx. In most experiments, very high temperatures were found to be the major cause of NOx emissions. The reaction temperatures are important factors that affect the concentrations of oxygen and NOx. The high temperatures not only reduce the ignition delay but also aid in reducing NOx emissions. Also, a low quantity of water is formed due to the presence of NOx. The NOx emissions have a very short duration, and this short period affects the performance of different oxidation processes [72].

### 9.4. Smoke

Two of the emissions-reduction techniques are using cleaner, less damaging materials and installing carbon-sequestering systems on factory smokestacks to eliminate pollutants. There are various fuel mixtures in smoke [73]. Combustion efficiency is normally higher when the fuel is burned at full load, which increases combustion and decreases smoke production. Smoke Opacity is a ratio used to compare the emissions of various fuels; it is produced by rich fuel and carbon-rich areas.

## 10. Safety aspects

Examples of nanoparticles that can lead to allergic reactions, toxicity, or the production of reactive oxygen species include titanium dioxide, aluminium oxide, magnesium oxide, cerium oxide, and Zinc. Dry particles are very dangerous; their safe storage requires implementation of safeguards, secure mixing processes and proper waste management procedures. In energy preparation, ultrasonication and the integration of surfactants may pose additional risks, such as residual contaminants and unpredictable mixtures. Nanocrystals formed during agglomeration can block filtration units and injection apparatus, leading to service issues. Sediments caused by storage impede operations and can increase employee vulnerability during redemption. Nanoparticles in exhaust and lubricant oils could pose ecological risks to communities due to the remnants. Nanomaterials (unlike $CO_2$ or NOx) are persistent and can be bio accumulative. Nanoscale exposure regulations are still in development and therefore pose uncertainty for the business.

## 11. Conclusions

The experiments above have explored the effects of mixing biodiesel with nanoparticles as additives. The issue of alternative fuels and different biodiesel-nanoadditives mixtures has been studied extensively. The blending of biodiesel with diesel engines also helps reduce air pollution, and biodiesel mixed with water has optimal emulsifying capabilities. The majority of these experiments were confined to single-cylinder engines, focusing on the efficiency and performance of the products. Heat transfer may even limit the engine's performance, as insulation is required at high temperatures. The combustion and performance outcomes indicate that engine development considers the duration of testing and optimisation of the combustion process in diesel engines. The delay at injection is closely related to injection timing, as the air-fuel mixture takes longer to undergo combustion. To test various injection methods using biodiesel blends, experiments were carried out to measure injection timings, delays, and developments, and these became standard. Most investigations have sought to measure the effects of nanoparticles in fuel blends in engines. Adding nanoparticles has been shown to enhance the combustion characteristics while decreasing ignition time. This will also lead to a decrease in cylinder pressure and brake-specific fuel consumption due to changes in injection timing. Moreover, the use of microparticles helps reduce emissions and enhances overall performance. The use of nanoadditives in biodiesel has several interesting benefits.

- Oxides that catalyse the conversion of carbon monoxide and hydrocarbons into carbon monoxide gas and hydrogen peroxide, respectively, enhance the level of effectiveness of ignition.
- The buffering processes. When burned, $CeO_2$ and copper oxide produce air to circulate, which helps the fuel oxidise completely, and CeO2 completely reduces NOx by 22.3%.
- Improved Thermal Properties, like TiO2 and Al2O3, reduce the tendency for cold spots and enhance the homogeneity of facades in flaming by improving heat transfer.
- Improved spray breakup, minuscule droplets, and enhanced air-fuel blending are all results of fragmentation of backing components like $TiO_2$ and $Al_2O_3$, which reduce NOx by 12.2% for $TiO_2$ and 15.6% for $Al_2O_3$, respectively.
- Multi-Institutional Partnerships Collaborate on the development of small additives specifications, assessment methods and information sources through collaborating academic institutions, businesses, and government agencies.
- Integrating virtual twins reduces the cost of actual testing and speeds up licensing by validating nano-additive performance across platforms, combustibility, and regions through simulation-based virtual twins.
- Nano-additives have the potential to enhance fuel properties and maximise combustion, and show significant potential in the study and application of biodiesel.
- Their incorporation into biofuel compositions may improve energy efficiency, reduce pollutants, and enhance thermodynamic stability, all essential for the broader acceptance of blended biodiesel.
- The focus will be on the mathematical consequences of micro-additives and their significance in a society with diverse backgrounds.
- In discussing developments such as enhanced oxidising resilience and reduced pollutants like NOx, it is imperative to emphasise their contribution to sustainability, tackling global issues such as minimising environmental impacts and promoting healthier energy alternatives.

## Copyright and permission statement

Figure 1. Actual experimental setup [43] is reproduced with permission from Results in Engineering. All other figures used in this study belong to the authors.

## Appendices

| | |
|---|---|
| $AlO_2$ | Aluminum oxide |
| ASTM | American Society for Testing and Materials |
| B20 | 20% biodiesel +80% diesel |
| NOx | Nitrogen Oxide |
| BTE | Brake thermal efficiency |
| BSFC | Brake Specific fuel consumption |
| BSEC | Brake Specific Energy Consumption |
| CNT | Carbon Nano tubes |
| bTDC | Before top dead Centre |
| CIME | Calophyllum Inophyllum Methyl Ester |
| CO | Carbon monoxide |
| CI | Compression Ignition |
| $CO_2$ | Carbon dioxide |
| CeO2 | Cerium Oxide |
| EGR | Exhaust gas recirculation |
| J20 | 20% Jatropha oil + 80% diesel |
| J20CNT5030D | 20% Jatropha oil +50% Carbon Nanotubes +30% diesel |
| MWCNTs | Multiwalled graphite nanotubes |
| 100Al | 100% Alumium oxide |
| $SiO_2$ | Silica Oxide |
| $Fe_2O_3$ | Iron oxide |
| HC | Hydrocarbons |
| HRR | Heat Release Rate |
| PPM | Parts per million |
| ZnO | Zinc Oxide |
| $TiO_2$ | Titanium Oxide |
| PSD | Particle size distribution |

## References


[1] Sakthimurugan, V. and Yuvarajan, D., 2025. A comprehensive assessment on recent advancements in spent fuel reprocessing and waste management: pioneering technologies for a sustainable nuclear future. Kerntechnik, 90(2), pp.125-138.. https://doi.org/10.1515/kern-2024-0120

[2] Amsal, M., Tran, M.V., Lee, C.C., Nurmukan, D., Hung, Y.M., Scribano, G. and Chong, C.T., 2023. Numerical simulation of nitrogen oxides and carbon monoxide emissions of biodiesel diffusion flame. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 45(5),p.253.https://doi.org/10.1007/s40430-023-04177-y

[3] Veeraraghavan, S.M., Kaliyaperumal, G., Dillikannan, D. and De Poures, M.V., 2024. Influence of Hydrogen induction on performance and emission characteristics of an agricultural diesel engine fuelled with cultured Scenedesmus obliquus from industrial waste. Process Safety and Environmental Protection, 187, pp.1576-1585.https://doi.org/10.1016/j.psep.2024.05.042

[4] Ashok, B., Nanthagopal, K., Mohan, A., Johny, A. and Tamilarasu, A., 2017. Comparative analysis on the effect of zinc oxide and ethanox as additives with biodiesel in CI engine. Energy, 140, pp.352-364.https://doi.org/10.1016/j.energy.2017.09.021

[5] Bednarski, M., Orliński, P., Wojs, M.K. and Sikora, M., 2019. Evaluation of methods for determining the combustion ignition delay in a diesel engine powered by liquid biofuel. Journal of the Energy Institute, 92(4),pp.1107-1114.https://doi.org/10.1016/j.joei.2018.06.007

[6] Bishnoi, D., 2023. Pressure exertion and heat dissipation analysis on uncoated and ceramic(Al2O3, TiO2 and ZrO2)coated braking pads. Materials Today: Proceedings, 74, pp.774-787.10.1016/j.matpr.2022.11.170

[7] Bui, K.Q., Perera, L.P. and Emblemsvåg, J., 2022. Life-cycle cost analysis of an innovative marine dual-fuel engine under uncertainties. Journal of Cleaner Production, 380, p.134847. DOI:10.1016/j.jclepro.2022.134847

[8] Chen, A.F., Adzmi, M.A., Adam, A., Othman, M.F., Kamaruzzaman, M.K. and Mrwan, A.G., 2018. Combustion characteristics, engine performances and emissions of a diesel engine using nanoparticle-diesel fuel blends with aluminium oxide, carbon nanotubes and silicon oxide. Energy conversion and management, 171, pp.461-477.https://doi.org/10.1016/j.enconman.2018.06.004

[9] Chen, G., Wei, F., Zhang, K., Xiao, R., Wang, Z. and Yang, S., 2023. Investigation on combustion characteristics and gas emissions of a high-pressure direct-injection natural gas engine at different combustion modes. Energy Conversion and Management, 277, p.116617.https://doi.org/10.1016/j.enconman.2022.116617

[10] Yuvarajan, D., Babu, M.D., BeemKumar, N. and Kishore, P.A., 2018. Experimental investigation on the influence of titanium dioxide nanofluid on emission pattern of biodiesel in a diesel engine. Atmospheric Pollution Research, 9(1), pp.47-52. https://doi.org/10.1016/j.apr.2017.06.003

[11] Dinesha, P., Kumar, S. and Rosen, M.A., 2021. 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, 8(2), pp.1374-1383.DOI:10.18331/BRJ2021.8.2.3

[12] Elkelawy, M., Bastawissi, H.A.E., Esmaeil, K.K., Radwan, A.M., Panchal, H., Sadasivuni, K.K., Ponnamma, D. and Walvekar, R., 2019. Experimental studies on the biodiesel production parameters optimization of sunflower and soybean oil mixture and DI engine combustion, performance, and emission analysis fueled with diesel/biodiesel blends. Fuel, 255, p.115791.https://doi.org/10.1016/j.fuel.2019.115791

[13] Sakthimurugan, V., Yuvarajan, D., Ganesan, S., Upadhye, V.J., Gill, A. and Kailiappan, N., 2025. Investigation on Influence of Acetylene Enrichment in Diesel Engines Operating With Microalgae-Waste Plastic Oil-Heptane Fuel Mixture. Energy Science & Engineering, 13(6), pp.3107-3122.https://doi.org/10.1002/ese3.70089

[14] Devarajan, Y., Nagappan, B. and Subbiah, G., 2019. A comprehensive study on emission and performance characteristics of a diesel engine fueled with nanoparticle-blended biodiesel. Environmental Science and Pollution Research, 26(11), pp.10662-10672.https://doi.org/10.1007/s11356-019-04446-1

[15] Gopal, K., Sathiyagnanam, A.P., Rajesh Kumar, B., Damodharan, D., De Poures, M.V., Saravanan, S., Rana, D. and Sethuramasamyraja, B., 2020. Prediction and optimization of engine characteristics of a DI diesel engine fueled with cyclohexanol/diesel blends. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 42(16), pp.2006-2017.https://doi.org/10.1080/15567036.2019.1607923

[16] Harsha, C.S., Suganthan, T. and Srihari, S., 2020. Performance and emission characteristics of diesel engine using biodiesel-diesel-nanoparticle blends-an experimental study. Materials Today: Proceedings, 24, pp.1355-1364.10.1016/j.matpr.2020.04.453

[17] Jamuna Rani, G., Rao, Y.H. and Balakrishna, B., 2022. Fuel injection timing impact on diesel engine performance, combustion and emission characteristics of nano additive biodiesel blends. International Journal of Ambient Energy, 43(1),pp.2078-2085.https://doi.org/10.1080/01430750.2020.1725119

[18] Janakiraman, S., Lakshmanan, T. and Raghu, P., 2021. Experimental investigative analysis of ternary (diesel+ biodiesel+ bio-ethanol) fuel blended with metal-doped titanium oxide nanoadditives tested on a diesel engine. Energy, 235, p.121148. https://doi.org/10.1016/j.energy.2021.121148

[19] Javed, S., Murthy, Y.S., Satyanarayana, M.R.S., Reddy, R.R. and Rajagopal, K., 2016. Effect of a zinc oxide nanoparticle fuel additive on the emission reduction of a hydrogen dual-fuelled engine with jatropha methyl ester biodiesel blends. Journal of Cleaner Production, 137, pp.490-506. DOI: 10.1016/j.jclepro.2016.07.125

[20] Devarajan, Y., Munuswamy, D.B. and Mahalingam, A., 2018. Influence of nano-additive on performance and emission characteristics of a diesel engine running on neat neem oil biodiesel. Environmental Science and Pollution Research, 25(26), pp.26167-26172.https://doi.org/10.1007/s11356-018-2618-6

[21] Jayaraman, J., Dey, K., Arunkumar, T., Appavu, P. and Joy, N., 2021. Investigation on titanium oxide nano particles as additives for operating biodiesel fuelled engine. Materials Today: Proceedings, 44, pp.3525-3529.DOI:10.1016/j.matpr.2020.09.291

[22] Kalaimurugan, K., Karthikeyan, S., Periyasamy, M. and Mahendran, G., 2020. Experimental investigations on the performance characteristics of CI engine fuelled with cerium oxide nanoparticle added biodiesel-diesel blends. Materials Today: Proceedings, 33, pp.2882-2885.DOI:10.1016/j.matpr.2020.02.778

[23] Karthikeyan, S., Prathima, A., Periyasamy, M. and Mahendran, G., 2020. Empirical studies upon the performance of the CI working with Stoechospermum marginatum, brown marine algae with nano fluid. Materials Today: Proceedings, 33, pp.3993-3999.DOI:10.1016/j.matpr.2020.06.340

[24] Yaramati, S. and Sakthimurugan, V., 2019, July. Effect of Tio2 nanoparticles in spirulina biodiesel-diesel blends at various injection strategies: Performance, combustion and emission characteristics. In IOP Conference Series: Materials Science and Engineering (Vol. 574, No. 1, p. 012016). IOP Publishing. DOI: 10.1088/1757-899X/574/1/012016

[25] Logesh, K., Tiwari, R., Harish, R. and Ajay, S., 2019. Experimental Studies On Convective Heat Transfer Coefficient of Al203/Ethylene Glycol-Carbon Nano Tube Nanofluids. Materials Today: Proceedings, 18, pp.4738-4744. DOI: 10.1016/j.matpr.2019.07.461

[26] Sakthimurugan, V., Ganesh, B., Arulraj, P., Logesh, K., Anbuchezhiyan, G. and Zenebe, G., 2024, May. Investigation of Ignition Delay and In-Cylinder Pressure Characteristics of Waste Plastic/Octanal/Diesel in a Diesel Engine. In International Conference on Mechanical Engineering: Researches and Evolutionary Challenges (pp. 225-238). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-96-7576-0_20

[27] Manoj, P.S., Kalyan, B.S., Jayaraman, J., Appavu, P., Joy, N. and Mariadhas, A., 2021. Experimental assessment of alumina nano additives on the performance of CI engine fuelled with a high-performance fuel blend. Materials Today: Proceedings, 44, pp.3544-3549.DOI: 10.1016/j.matpr.2020.09.373

[28] Menzel, G., Och, S.H., Mariani, V.C., Moura, L.M. and Domingues, E., 2020. Multi-objective optimization of the volumetric and thermal efficiencies applied to a multi-cylinder internal combustion engine. Energy Conversion and Management, 216, p.112930.https://doi.org/10.1016/j.enconman.2020.112930

[29] Muruganantham, P. and Pandiyan, P., 2021. Analysis on performance and emission characteristics of corn oil methyl ester blended with diesel and cerium oxide nanoparticle. Case Studies in Thermal Engineering, 26, p.101077.https://doi.org/10.1016/j.csite.2021.101077

[30] Nanthagopal, K., Ashok, B., Tamilarasu, A., Johny, A. and Mohan, A., 2017. Influence on the effect of zinc oxide and titanium dioxide nanoparticles as an additive with Calophyllum inophyllum methyl ester in a CI engine. Energy Conversion and Management, 146, pp.8-19.https://doi.org/10.1016/j.enconman.2017.05.021

[31] Oni, B.A., Sanni, S.E. and Olabode, O.S., 2021. Production of fuel-blends from waste tyre and plastic by catalytic and integrated pyrolysis for use in compression ignition(CI) engines. Fuel, 297, p.120801.https://doi.org/10.1016/j.fuel.2021.120801

[32] Örs, I., Sarıkoç, S., Atabani, A.E., Ünalan, S.E.B.A. and Akansu, S.O., 2018. The effects on performance, combustion and emission characteristics of DICI engine fuelled with TiO2 nanoparticles addition in diesel/biodiesel/n-butanol blends. Fuel, 234, pp.177-188.https://doi.org/10.1016/j.fuel.2018.07.024

[33] Parida, M.K., Mohapatra, P., Patro, S.S. and Dash, S., 2024. Effect of TiO2 nano-additive on performance and emission characteristics of direct injection compression ignition engine fueled with Karanja biodiesel blend. Energy sources, part A: recovery, utilization, and environmental effects, 46(1), pp.7521-7530. https://doi.org/10.1080/15567036.2020.1756991

[34] Perumal, V. and Ilangkumaran, M., 2018. The influence of copper oxide nano particle added pongamia methyl ester biodiesel on the performance, combustion and emission of a diesel engine. Fuel, 232, pp.791-802.https://doi.org/10.1016/j.fuel.2018.04.129

[35] Praveena, V., Martin, M.L.J. and Geo, V.E., 2020. Experimental characterization of CI engine performance, combustion and emission parameters using various metal oxide nanoemulsion of grapeseed oil methyl ester. Journal of Thermal Analysis and Calorimetry, 139(6), pp.3441-3456.https://doi.org/10.1007/s10973-019-08722-7

[36] Pullagura, G., Bikkavolu, J.R., Vadapalli, S., Siva, P.V.V., Chebattina, K.R.R., Barik, D., Nayyar, A., Sharma, P. and Bora, B.J., 2024. Amplifying performance attributes of biodiesel–diesel blends through hydrogen infusion and graphene oxide nanoparticles in a diesel engine. Clean Technologies and Environmental Policy, 26(7),pp.2235-2257.https://doi.org/10.1007/s10098-023-02714-w

[37] Qi, D., Li, K., Zhang, C. and Wang, T., 2022. Effect of split injection strategies on diverse characteristics of a common rail direct injection diesel engine operating with diesel-palm oil-ethanol micro-emulsions. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 236(6),pp.1210-1226.https://doi.org/10.1177/09576509221077545

[38] Rajendran, S., Ganesan, P. and Anandkumar, G., 2023. A comparative assessment on performance, combustion and emission characteristics of diesel engine fuelled by juliflora biodiesel-diesel blends. Australian Journal of Mechanical Engineering, 21(1), pp.257-269.https://doi.org/10.1080/14484846.2020.1842294

[39] Thandavamoorthy, R., Devarajan, Y. and Mehar, K., 2026. Synthesis of ZnO Nanoparticles From Pergularia daemia Fibre: Potential for Caries Prevention and Infection Control. International Dental Journal, 76(2),p.109396.DOI : 10.1016/j.identj.2025.109396

[40] Ramalingam, K., Kandasamy, A., Subramani, L., Balasubramanian, D. and Thadhani, J.P.J., 2018. An assessment of combustion, performance characteristics and emission

control strategy by adding anti-oxidant additive in emulsified fuel. Atmospheric Pollution Research, 9(5),pp.959-967. https://doi.org/10.1016/j.apr.2018.02.007

[41] Rangabashiam, D., Rathinam, S., Subbiah, G. and jb, S., 2020. Emission behaviour studies on the cause of ZnO nanoparticle inclusion in neat biodiesel. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 42(16),pp.1989-1996. https://doi.org/10.1080/15567036.2019.1604909

[42] Rao, T.S., Rao, H.S.B., Jilani, S.A.K. and Mutluri, A., 2021, April. Effect of cerium oxide nanoparticles additive blended in palm oil biodiesel as alternative fuel used in diesel engine. In IOP Conference Series: Materials Science and Engineering (Vol. 1112, No. 1, p. 012012).IOP Publishing. DOI 10.1088/1757-899X/1112/1/012012

[43] Raja, T. and Devarajan, Y., 2025. Development of hemp fiber-reinforced epoxy composite with cobalt oxide nanoparticles for fuel cell and energy storage applications. Results in Engineering, 25, p.103839.https://doi.org/10.1016/j.rineng.2024.103839

[44] Venu, H. and Madhavan, V., 2017. Effect of diethyl ether and Al2O3 nano additives in diesel-biodiesel-ethanol blends: Performance, combustion and emission characteristics. Journal of Mechanical Science and Technology, 31(1),pp.409-420. https://doi.org/10.1007/s12206-016-1243-x

[45] Venu, H., Subramani, L. and Raju, V.D., 2019. Emission reduction in a DI diesel engine using exhaust gas recirculation(EGR)of palm biodiesel blended with TiO2 nano additives. Renewable energy, 140, pp.245-263.https://doi.org/10.1016/j.renene.2019.03.078

[46] Sanjeevannavar, M.B., Banapurmath, N.R., Soudagar, M.E.M., Atgur, V., Hossain, N., Mujtaba, M.A., Khan, T.Y., Rao, B.N., Ismail, K.A. and Elfasakhany, A., 2022. Performance indicators for the optimal BTE of biodiesels with additives through engine testing by the Taguchi approach. Chemosphere, 288, p.132450.https://doi.org/10.1016/j.chemosphere.2021.132450

[47] Saravanan, P., Mala, D., Jayaseelan, V. and Kumar, N.M., 2023. Experimental performance investigation of Partially Stabilized Zirconia coated low heat rejection diesel engine with waste plastic oil as a fuel. Energy sources, part A: recovery, utilization, and environmental effects, 45(4),pp.11046-11059. https://doi.org/10.1080/15567036.2019.1683647

[48] Sarıdemir, S. and Ağbulut, Ü., 2022. Combustion, performance, vibration and noise characteristics of cottonseed methyl ester–diesel blends fuelled engine. Biofuels, 13(2),pp.201-210. https://doi.org/10.1080/17597269.2019.1667658

[49] Sathyamurthy, R., Salman, M.S., Vijayabalan, P., Sundar, S.P. and Dharmaraj, V., 2022. Analysis of DI CI engine fueled with neat plastic oil and titanium oxide nanomaterial as an additive. Materials Today: Proceedings, 50, pp.560-564.DOI: 10.1016/j.matpr.2020.11.204

[50] Tamil, S.P. and Goteti, G.S., 2020. Experimental analysis of VCR engine operated with Prosopis juliflora biodiesel blends. International Journal of Renewable Energy Research, 10(2), pp.978-987.

[51] Shaisundaram, V.S., Chandrasekaran, M., Shanmugam, M., Padmanabhan, S., Muraliraja, R. and Karikalan, L., 2021. Investigation of Momordica charantia seed biodiesel with cerium oxide nanoparticle on CI engine. International Journal of Ambient Energy, 42(14), pp.1615-1619.https://doi.org/10.1080/01430750.2019.1611657

[52] Sharma, A. and Murugan, S., 2015. Combustion, performance and emission characteristics of a DI diesel engine fuelled with non-petroleum fuel: a study on the role of fuel injection timing. Journal of the Energy Institute, 88(4),pp.364-375. https://doi.org/10.1016/j.joei.2014.11.006

[53] Shatrov, M.G., Sinyavski, V.V., Dunin, A.Y., Shishlov, I.G. and Vakulenko, A.V., 2017. Method of conversion of high-and middle-speed diesel engines into gas diesel engines. Facta Universitatis, Series: Mechanical Engineering, 15(3), pp.383-395. DOI: 10.22190/FUME171004023S

[54] Sodeifian, G., Saadati Ardestani, N. and Sajadian, S.A., 2019. Extraction of seed oil from Diospyros lotus optimized using response surface methodology. Journal of forestry research, 30, pp.709-719.https://doi.org/10.1007/s11676-018-0631-8

[55] Srimanickam, B. and Kumar, S., 2021. Drying investigation of coriander seeds in a photovoltaic thermal collector with solar dryer. Int. J. Mech. Eng. Technol, 14, pp.659-668.DOI: 10.18186/thermal.1297575

[56] Sun, J., Zhao, B. and Su, Y., 2019. Advanced control of NO emission from algal biomass combustion using loaded iron-based additives. Energy, 185, pp.229-238.https://doi.org/10.1016/j.energy.2019.07.042

[57] Sunaryo, S., Sesotyo, P.A., Saputra, E. and Sasmito, A.P., 2021. Performance and fuel consumption of diesel engine fueled by diesel fuel and waste plastic oil blends: An experimental investigation. Automotive Experiences, 4(1), pp.20-26.https://doi.org/10.31603/ae.3692

[58] Thomas, T.J., Thangapandian, N., Sakthivel, D., Mohideen, S.M.S.F., Basha, S., Brindhadevi, K. and Ramya, G., 2022. Experimental analysis of CI engine using pyrolyzed plastic oil blended with alumina nano additive. Fuel, 312, p.122929. https://doi.org/10.1016/j.fuel.2021.122929

[59] Tian, Z., Wang, Y., Zhen, X. and Liu, D., 2022. Numerical comparative analysis on performance and emission characteristics of methanol/hydrogen, ethanol/hydrogen and butanol/hydrogen blends fuels under lean burn conditions in SI engine. Fuel, 313, p.123012.https://doi.org/10.1016/j.fuel.2021.123012

[60] Tomar, M. and Kumar, N., 2020. 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, 42, p.100833. DOI: 10.1016/j.seta.2020.100833

[61] Kumar, K.S. and Muniamuthu, S., 2024. Design and fabrication of nickel-chromium reinforced 2-stage energy efficient pyrolysis reactor for waste plastics applications. International Journal of Ambient Energy, 45(1),p.2288148. https://doi.org/10.1080/01430750.2023.2288148

[62] Raja, T. and Devarajan, Y., 2025. Development of hemp fiber-reinforced epoxy composite with cobalt oxide nanoparticles for fuel cell and energy storage applications. Results in Engineering, 25, p.103839.https://doi.org/10.1016/j.rineng.2024.103839

[63] Kumar, K.S., Alqarni, S., Islam, S. and Shah, M.A., 2024. Royal poinciana biodiesel blends with 1-butanol as a potential alternative fuel for unmodified research engines. ACS omega, 9(12),pp.13960-13974.https://doi.org/10.1021/acsomega.3c09014

[64] Vignesh, R. and Rahim, A.A., 2025. Optimization and potential utilization of agro-industrial by-products as binders in quaternary blended pastes–A sustainable approach. Case Studies in Construction Materials, 22, p.e04588.https://doi.org/10.1016/j.cscm.2025.e04588

[65] Selvam, D.C., Devarajan, Y. and Raja, T., 2026. Biodiesel and alcohol-biodiesel blends in marine diesel engines: Fuel properties, engine behavior, environmental impacts, and operational challenges. Marine Pollution Bulletin, 224, p.119169.10.1016/j.marpolbul.2025.119169

[66] Kumar, K.S. and Muniamuthu, S., 2024. Assessment of performance, combustion, and emission characteristics of single cylinder diesel engine fuelled by pyrolysis oil+ CeO2 nanoparticles and 1-butanol blends. International Journal of Ambient Energy, 45(1),p.2344568.https://doi.org/10.1080/01430750.2024.2344568

[67] Yang, W.M., An, H., Chou, S.K., Chua, K.J., Mohan, B., Sivasankaralingam, V., Raman, V., Maghbouli, A. and Li, J., 2013. Impact of emulsion fuel with nano-organic additives on the performance of diesel engine. Applied energy, 112, pp.1206-1212.https://doi.org/10.1016/j.apenergy.2013.02.027

[68] You, J., Liu, Z., Wang, Z., Wang, D., Xu, Y., Du, G. and Fu, X., 2020. The exhausted gas recirculation improved brake thermal efficiency and combustion characteristics under different intake throttling conditions of a diesel/natural gas dual fuel engine at low loads. Fuel, 266, p.117035.https://doi.org/10.1016/j.fuel.2020.117035

[69] Vignesh, R. and Rahim, A.A., 2024. Emerging eco-friendly fiber-reinforced concrete with shaped synthetic aggregates using Taguchi grey relational analysis and utility concept. Construction and Building Materials, 447, p.138039.https://doi.org/10.1016/j.conbuildmat.2024.138039

[70] Yusuf, A.A., Inambao, F.L. and Ampah, J.D., 2022. Evaluation of biodiesel on speciated PM2. 5, organic compound, ultrafine particle and gaseous emissions from a low-speed EPA Tier II marine diesel engine coupled with DPF, DEP and SCR filter at various loads. Energy, 239, p.121837.https://doi.org/10.1016/j.energy.2021.121837

[71] Muniamuthu, S., Kumar, K.S., Raja, K. and Rupesh, P.L., 2022. Dynamic characterization of hybrid composite based on flax-/E-glass epoxy composite plates. Materials Today: Proceedings, 59, pp.1786-1791.10.1016/j.matpr.2022.04.379

[72] Zhang, Z., Lv, J., Li, W., Long, J., Wang, S., Tan, D. and Yin, Z., 2022. Performance and emission evaluation of a marine diesel engine fueled with natural gas ignited by biodiesel-diesel blended fuel. Energy, 256, p.124662.https://doi.org/10.1016/j.energy.2022.124662

[73] Aswathanrayan, M.S., Santhosh, N., Venkataramana, S.H., Kumar, K.S., Kamangar, S., Arabi, A.I.A., Algburi, S., Al-Sareji, O.J. and Bhowmik, A., 2025. Prediction of performance and emission features of diesel engine using alumina nanoparticles with neem oil biodiesel based on advanced ML algorithms. Scientific Reports, 15(1),p.12683.https://doi.org/10.1038/s41598-025-97092-2