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Review Article

Nanotechnology-based biodiesel: A comprehensive review on production, and utilization in diesel engine as a substitute of diesel fuel

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Abstract. As a sustainable replacement for fossil fuels, biodiesel is a game-changer in the energy sector. There is no strategy to minimize biodiesel's significance as a sustainable, clean fuel source in light of the increasing climate change and environmental sustainability concerns. Nevertheless, conventional biodiesel production methods often run into problems like inadequate conversion efficiency and inappropriate fuel properties, which impede their broad adoption. The revolutionary potential of nanotechnology to circumvent these limitations and revolutionize biodiesel consumption and production is explored in this review paper. There are new possibilities for improving biodiesel output and engine efficiency, thanks to nanotechnology, which can alter matter at the atomic and molecular levels. Using nano-catalysts, nano-emulsification processes, and nano-encapsulation procedures, researchers have made significant advances in improving biodiesel qualities such as stability, combustion efficiency, and viscosity. Through a comprehensive analysis of current literature and research data, this article elucidates the crucial role of nanotechnology in advancing biodiesel technology. By shedding light on the most current advancements, challenges, and potential future outcomes in nano-based biodiesel manufacturing and consumption, this review hopes to add to the growing corpus of knowledge in the field and inspire additional innovation. In conclusion, there is great hope for a sustainable energy future, increased economic growth, and reduced environmental impacts through the application of nanotechnology.

Keywords: Biodiesel; Alternative fuels; Sustainability; Circular economy; Nanotechnology; Engine performance; Emission characteristic

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1. Introduction

In addition to urbanization, choking emissions, population growth, and industrial development are all expanding rapidly (Minh Loy *et al.*, 2020; Sitompul and Sinaga, 2020). This is resulting in an urgent need for energy, which is another aspect of the continual expansion and development that is taking place (Aisman *et al.*, 2020; Ilham *et al.*, 2022; Villegas *et al.*, 2020). Coal, petroleum, and natural gas are examples of traditional energy sources that continue to meet the bulk of the world's energy needs (Bello and Solarin, 2022; Bortnowska, 2009). On the other hand, the influence that its utilization has on the environment cannot be ignored since the use of fossil fuel could release a large amount of CO_2 and greenhouse gas into the environment (Bakır *et al.*, 2022; Nguyen *et al.*, 2021). Hence, alternative sources of fuel and renewable energy are promoted (V. G. Nguyen *et al.*, 2023; Oladeji *et al.*, 2021; Soulayman and Ola, 2019). Due to this reason, the use of bioenergy is needed to achieve decarbonization and net zero emissions in the future at a more rapid pace (Desniorita *et al.*, 2019; Hasibuan *et al.*, 2020; Rahman *et al.*, 2023). This is to achieve sustainable development as well as other crucial worldwide recommendations for restoring environmental health (Chen *et al.*, 2022; Usman *et al.*, 2022).

Natural resources are utilized extensively in a variety of fields, including human life, science, and technology, all around the world. As a consequence of the increasing rate of industrialization and urbanization, it is anticipated that the total global energy consumption will increase by a substantive proportion in the upcoming decade (Elumalai *et al.*, 2021; Fernández *et al.*, 2020a; Jeyakumar *et al.*, 2020). Moreover, the accessibility of petroleum-derived fuel supplies is limited to select locations worldwide. Diesel fuel, gasoline, liquefied petroleum gas, and natural gas are among the fuels utilized in

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various types of transportation (Lamas *et al.*, 2015; Serbin *et al.*, 2022; Yang *et al.*, 2019; Zhao *et al.*, 2020). However, there has been a significant surge in the quantity of transportation means in recent years, increasing the demand for petroleum products (Lu *et al.*, 2021; Marković *et al.*, 2023). In addition, diesel engines dominate as the primary power source for commercial vehicles owing to their cost-effective operational expenses, superior fuel efficiency, extended lifespan, and dependable performance (Das *et al.*, 2020; Minchev *et al.*, 2023; Tran *et al.*, 2023). Diesel engines emit lower levels of unburned hydrocarbons as well as carbon monoxide compared to gasoline engines (Hoang, 2019; Lilik and Boehman, 2011). Diesel engines, even though they generate power under accepted standards, are responsible for releasing a significant amount of particulate matter into the atmosphere (Semin *et al.*, 2020; Stelmasiak *et al.*, 2017; Wambui *et al.*, 2023). Diesel automobiles are more economically feasible and have fewer adverse effects on the environment, but particulate matter has a significantly greater number of adverse effects, particularly adverse effects on human health (Hassan *et al.*, 2021; Olszewski *et al.*, 2023). Fossil fuels are considered non-renewable because we cannot replace them at the same pace as we consume them (Manimaran *et al.*, 2022; Venugopal *et al.*, 2021). Furthermore, fluctuations in the price of oil, increased energy use, global warming brought on by emissions of greenhouse gases, pollution of the environment, and the rapid depletion of fossil fuel supplies, amongst others are also urgent issues (Kowalski and Tarelko, 2009a; Singh and Singh, 2012; Yoro and Daramola, 2020). All of these factors contribute to the essential requirement for clean and environmentally friendly fuels aiming to achieve the net-zero goals (Dong and Sharma, 2023; Nguyen and Le, 2023; V. N. Nguyen *et al.*, 2023b; Zeńczak and Gromadzińska, 2020). Indeed, scientists are looking at many types of biofuels such as biodiesel (V. N. Nguyen *et al.*, 2023a; Radhakrishnan Lawrence *et al.*, 2022; Sharma *et al.*, 2022), bio-alcohol (such as ethanol, methanol, propanol) (Labeckas *et al.*, 2018; Truong *et al.*, 2021; Veza *et al.*, 2022), furan-based fuels (such as DMF, MF) (Hoang *et al.*, 2022a; Hoang and Pham, 2021; Vuong *et al.*, 2022), ether (including dimethyl ether and ethyl ether) (Changxiong *et al.*, 2023; Doan *et al.*, 2022; Wang and Yao, 2020), bio-oil (fuels originated from thermochemical conversion of biomass, scrap tire, plastic waste, municipal solid waste) (Kumaravel *et al.*, 2016; Yaqoob *et al.*, 2021), hydrogen (Fernández *et al.*, 2020b; Hoang *et al.*, 2023a), biogas (Bora *et al.*, 2022; V. G. Bui *et al.*, 2022; Chellapandi and Saranya, 2023), and syngas (Fiore *et al.*, 2020; Huang *et al.*, 2019) because they are considered as the great potential replacement for traditional fuels due to the current fuel scarcity.

Taking into consideration the current circumstances, experts are concentrating their efforts on potential alternatives to fossil fuels. Their primary objective is to create technology that is both capable of self-regeneration and has no negative impact on the environment. Extensive research has demonstrated that biodiesel, bioethanol, and biogas are superior to fossil fuels in terms of energy production (Cherwoo *et al.*, 2023; Nguyen *et al.*, 2024; Priya *et al.*, 2022). Biodiesel, which is also known as fatty acid methyl ester, has been utilized as a viable alternative to fossil fuels for a considerable amount of time (Jeyakumar *et al.*, 2023; Raheman and Padhee, 2014; Yuvenda *et al.*, 2022). Many benefits are associated with the use of biodiesel in comparison to diesel and gasoline, in which its biodegradability, high flash point, non-toxicity, and high cetane number are just a few of the features that it possesses regarding its properties (Karthickeyan *et al.*, 2020; Tuan Hoang *et al.*, 2021). When compared to diesel and gasoline, biofuel can generate a lower number of emissions that contribute to the emission of greenhouse gases (Hanaki and Portugal-Pereira, 2018; Le *et al.*, 2024). Not only does it decrease the amount of time that the ignition delay takes, but it also improves the efficiency of the combustion process, which in turn extends the life of the engine. However, biodiesel is found to cause deposit formation and corrosion to the mechanical part of engines (Hoang and Le, 2019; Nguyen and Vu, 2019), as well as poor atomization due to high kinematic viscosity (Hoang, 2021a; Hoang *et al.*, 2022b). Biodiesel is often produced by utilizing a variety of feedstocks, including microalgae, animal fats, edible and inedible oils, and other substances (Arumugam and Ponnusami, 2019; Hoang *et al.*, 2023b, 2021; Sharma and Sharma, 2021a, 2020; Ungwiwatkul and Chantarasiri, 2022). According to the recent findings the feedstock alone was responsible for 75% of the total cost of producing biodiesel. Different feedstocks used for biodiesel synthesis are depicted in Figure 1.

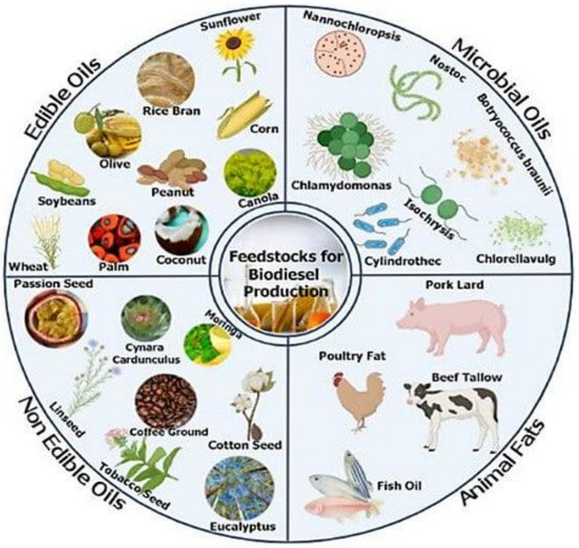


Fig 1. Biodiesel from different feedstock (Sales *et al.*, 2022)

From Figure 1, it could be realized that selecting the appropriate feedstock before the beginning of production is critically important to cut down on the overall cost of producing biodiesel (Maheshwari *et al.*, 2022). Consuming oil has the potential to serve as a feedstock for the production of biodiesel. The most significant concern, on the other hand, is that the price of food products can go up to an unsustainable level as a result of the rising cost of these feedstocks. This tragedy will have a disproportionately negative impact on countries whose economies are still in the formative stages of development. There were also several disadvantages, including the high cost of biodiesel, the negative impact on the environment, and the restricted land area for the cultivation of edible feedstock. As a result of this problem, tropical countries that are completely dependent on palm oil have seen deforestation. The generation of biodiesel using this technology is highly likely to contribute to climate change and to have adverse consequences on the plant and animal life that live in tropical regions. To address these concerns, researchers have developed advanced biofuels, which comprise biofuels of the second, third, and fourth generations. These more recent biofuels could be able to assist in alleviating some of the problems that are associated with the older ones (L. R. Kumar *et al.*, 2021; Kumar and Aggarwal, 2024). Alternately, feedstocks that are obtained from crops that are not edible are said to be of the second generation. Different

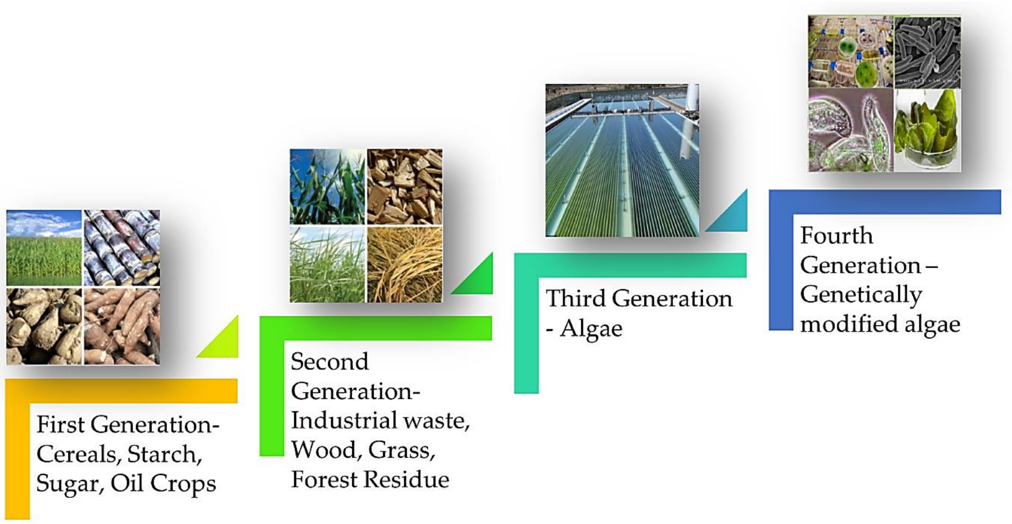


Fig 2. Different generation of biodiesel based on feedstock types (Khan *et al.*, 2021)

generations of biodiesel are depicted in Figure 2.

The first-generation feedstocks are those that are produced from plants that can be consumed. To attain carbon neutrality, third-generation feedstocks are utilized. These feedstocks obtain their biomass through the collection and utilization of solar energy and carbon dioxide (CO_2) and then proceed to transform it into fuel (Nanda *et al.*, 2018; Rather and Bano, 2019). In contrast, the foundation of feedstocks for the fourth generation is comprised of solar energy and the capture and usage of carbon dioxide (Mustafa *et al.*, 2020). When feedstocks with diverse chemical compositions are employed, it is much simpler to achieve the necessary yield after the reaction. The properties of biodiesel are determined by a considerable number of factors, such as the quantities, the chemical composition, and the sources of FFA feedstock (Vani *et al.*, 2023; Yadav *et al.*, 2021). To produce the vast majority of biodiesel and fatty acid methyl esters, transesterification of oils and fats with short-chain alcohols is the process used. The stoichiometric ratio of the reaction between triglycerides and alcohol is one to three. This ratio is observed during the process of transesterification. Following the completion of the procedure, one mole of glycerol and three moles of mono-alkyl ester (biodiesel) are produced as byproducts. Although it is sluggish and does not produce much, it is necessary to use a catalyst to make it more efficient (Mathew *et al.*, 2021). This is achieved by reducing the activation energy while improving the response rate to attain equilibrium. Conventional catalysts, whether they are homogeneous or heterogeneous, as well as biocatalysts, are utilized in the manufacturing process of biodiesel for industrial purposes (Babatunde *et al.*, 2022; Semwal *et al.*, 2023). It is important to note that these catalysts have significant negative effects on the environment, the economy, and technology (Huang *et al.*, 2018). In addition, the extraction of oil through transesterification often includes the consumption of a significant amount of solvent, which gives rise to a variety of concerns regarding the economy and the environment simultaneously. The production of biodiesel and oil have both been the subject of a significant amount of research, to find ways to make both processes more ecologically friendly and efficient (Di Serio *et al.*, 2008; Thangaraj *et al.*, 2019). The utilization of nanomaterials, which are small enough to be fewer than 100 nanometres in size, is one technique that might be taken to improve the oil processing efficiency during the synthesis of biodiesel (Esmaeili *et al.*, 2021). Additionally, nanoparticles have the potential to assist in alleviating the environmental and economic issues that are generated by the solvents that are used to extract the oil (Bin Rashid, 2023; Pandit *et al.*, 2023). Nanoparticles are exceptional catalysts that can boost the output and production rate of biodiesel during the transesterification process (Ahmed *et al.*, 2023). Through the utilization of nanotechnology in the manufacture of biodiesel, Sustainable Development Goals (SDGs) 7 (clean and inexpensive energy), and Sustainable Development Goals 13 (climate action) are all connected with this particular application of nanotechnology (Bhattacharya and Seth, 2023; Guin *et al.*, 2022). However, because this technology raises issues regarding its ramifications on the technological, economic, and ecological fronts, it is necessary to do further research and study on the subject.

Even though nanotechnology has been used in several biodiesel processes, there has not yet been a complete study that examines the benefits and drawbacks of nanomaterials in the essential oil extraction and transesterification steps (Hosseini, 2022). Moreover, numerous conversations have taken place on the behavior of nanoparticles when they are burned in biodiesel, there is still a dearth of detailed information regarding the behavior of these particles throughout the process of transesterification. The concerns regarding the potential adverse effects that nanoparticles could have on technology, the economy, and the environment have not been effectively addressed by the research that has been conducted in the past. During the process of fuel extraction, the exploitation of nanoparticles in biodiesel synthesis has also been under-discussed in past review studies. A typical arrangement of its implementation is depicted in Figure 3.

The primary objective of this comprehensive review is to fill current knowledge gaps in the domain of nanoparticles blended biodiesel-powered engines. A comprehensive examination of various biodiesel production techniques was reviewed with special emphasis on the role of nanotechnology in biodiesel synthesis. The effects of adding the nanoparticles in different kinds of fuel blends concerning engine performance as well as emission characteristics were reviewed. The authors hope to get a complete grasp of the function of nanoparticles in improving engine performance and emission reduction. Furthermore, this research critically evaluates the obstacles and restrictions

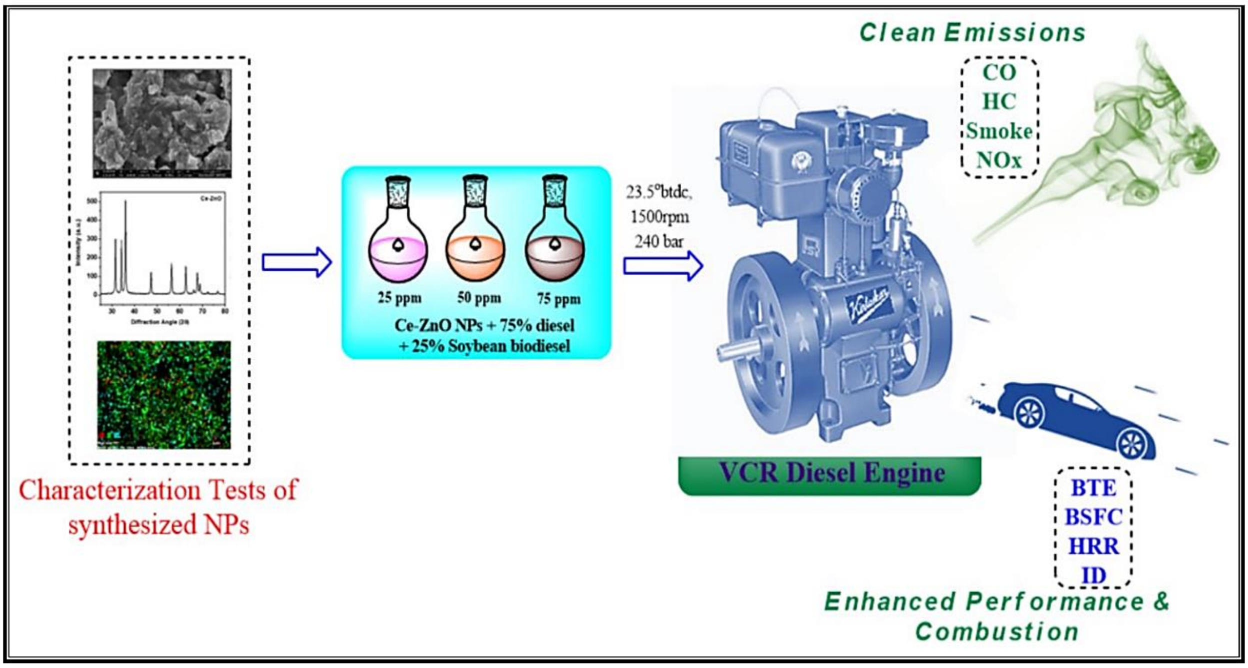


Fig 3. Application of nanoparticles blended fuel-powered engine (Hussain *et al.*, 2020)

associated with using different nanoparticles across biodiesel manufacturing and their application for powering engines. Through this work, we hope to highlight both the benefits and limits of using nanotechnology for biodiesel synthesis, from feedstock processing to engine use.

2. Biodiesel production techniques

The production of biodiesel, which serves as a substitute for fossil fuels for engines and is produced from renewable feedstocks, involves the utilization of a wide variety of methods (Kolakoti *et al.*, 2022; Siregar, 2015). As a potential solution to the issues of environmental degradation and rising emissions of greenhouse gases, biodiesel has recently come to the forefront of the discussion (Kalyani *et al.*, 2023). Transesterification is a chemical reaction that involves the exchange of ester groups between an ester compound and an alcohol (Elma *et al.*, 2017). This reaction is widely employed in a range of industrial processes, especially in the manufacturing of biodiesel and in organic synthesis. Transesterification is employed in biodiesel production to transform triglycerides, commonly found in vegetable oils or animal fats, into fatty acid methyl esters, which serve as the primary constituents of biodiesel (Hadiyanto *et al.*,2020). The process usually entails combining triglycerides with an alcohol (typically methanol or ethanol) in the presence of a catalyst (like sodium or potassium hydroxide) to generate biodiesel and glycerol as byproducts (Long *et al.*, 2021; Salaheldeen *et al.*, 2021). Transesterification is one of the time-honored processes that has been utilized in the manufacturing of biodiesel for a considerable amount of time (Silviana *et al.*, 2022). The steps involved in this process involve mixing lipids derived from animals or vegetables with alcohol in the presence of a catalyst (Sharma and Sharma, 2022, 2021b). However, these technologies also come with a few drawbacks that should be considered. The advancements that have been made in the fields of biotechnology, chemistry, and engineering have made it possible to create new methods of producing biodiesel. These methods are designed to be more inexpensive, ecologically friendly, and efficient. Several novel approaches, including enzymatic processes, microbial fermentation, nanotechnology, and others, are currently being investigated by scientists to find a solution to the challenges that are associated with the standard techniques of producing biodiesel (Lotti *et al.*, 2018; Rai *et al.*, 2016; Wang *et al.*, 2021). In addition, there is optimism that the incorporation of nanotechnology will be able to enhance the quality of biodiesel, reduce the amount of energy inputs, and improve the efficiency of conversion.

In this section, the various approaches being used for biodiesel synthesis including its fundamental principles, prospective uses, advantages, and downsides are presented. To shed light on the most recent advancements and inspire more innovation in the vital subject of renewable energy, the following are the main types of biodiesel synthesis methods:

Transesterification

- When making biodiesel, transesterification is the process of choice, as shown in Figure 4.
- This process requires a catalyst, like sodium hydroxide or potassium hydroxide, and an alcohol, usually methanol or ethanol, to react with triglycerides, which can be either animal-based or vegetable-based fats (MEHER *et al.*, 2006; Yang *et al.*, 2018).
- Fatty acid methyl esters (FAME), often known as biodiesel, and glycerol are the end products that break down the triglycerides (Akubude *et al.*, 2019).
- Through the process of the reaction, the triglycerides are broken down into fatty acid methyl esters (FAME), which are biodiesel, and glycerol is produced as a byproduct (Khoobbakht *et al.*, 2020).

Acid-catalyzed transesterification

- This process is similar to base-catalyzed transesterification but utilizes acid catalysts (such as

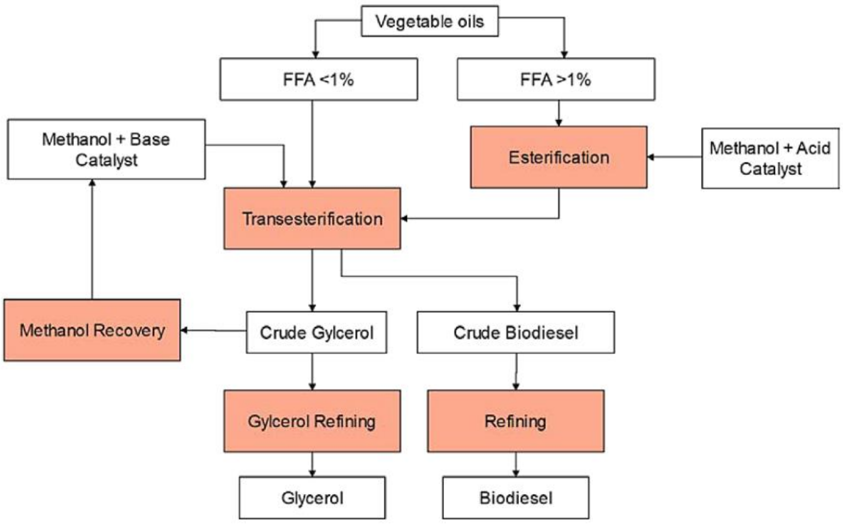


Fig 4. Transesterification process flow chart (Trirahayu *et al.*, 2022)

hydrochloric acid or sulfuric acid) instead of base catalysts (Ataya *et al.*, 2007).

- The temperatures and pressures at which it functions are often lower than those at which base-catalyzed techniques operate (Tran-Nguyen *et al.*, 2020).
- Particularly well-suited for feedstocks of low quality that contain a high percentage of free fatty acids.

Transesterification via enzymatic processes

- This process utilizes lipase enzymes as a catalyst for the transesterification reaction to get the desired results (Moazeni *et al.*, 2019).
- When compared to chemical catalysts, it operates under settings that are less severe, including lower temperatures and pressures (Kalita *et al.*, 2022).
- It has the potential to offer advantages in terms of selectivity, decreased energy usage, and less impact on the environment (Brask *et al.*, 2011).
- Nevertheless, because enzymes are so expensive, they often have a greater production cost than other products.

Fluid transesterification at supercritical temperatures:

- Utilizes supercritical fluids (such as supercritical methanol or supercritical ethanol) as both the solvent and the reactant in conjunction with the reaction (Reddy *et al.*, 2018).
- Performs operations at high temperatures and pressures, often at a level that is higher than the fluid's critical threshold (Anitescu and Bruno, 2012).
- When compared to traditional methods, it provides higher conversion rates and faster reaction rates (Gumba *et al.*, 2016).
- Entails the utilization of specialist apparatus and the meticulous management of the operational circumstances.

Transesterification with the assistance of microwaves

- This method involves the application of microwave irradiation to speed up the transesterification reaction (Hassan and Smith, 2020).
- In comparison to more traditional heating processes, it provides the advantage of faster reaction times and higher yields (Nayak *et al.*, 2019).
- This allows for improved control over the parameters of the reaction, such as the temperature and the mixing (Mohamad Aziz *et al.*, 2021). Nevertheless, it might be necessary to optimize the parameters of the reaction and take into account the implications of scaling up.

Transesterification is a commonly employed and highly effective method for generating biodiesel from sustainable feedstocks. It provides numerous benefits, such as the use of sustainable resources, the decrease in greenhouse gas emissions, and the possibility of achieving energy self-sufficiency. It is crucial to fine-tune reaction conditions, carefully choose catalysts, and implement effective purification steps to achieve optimal yield and quality in biodiesel production. These techniques differ from one another in terms of their fundamentals, operating circumstances, advantages, and barriers to entry. The choice of process is determined by several distinct elements, including the properties of the feedstock, the desired product quality, the volume of production, and economic considerations.

3. Nanomaterials for biodiesel synthesis

Nanomaterials play a vital role in improving a variety of aspects of biodiesel production (Mandotra *et al.*, 2018). These improvements range from strengthening the fuel characteristics of biodiesel to further enhancing the productivity of the transesterification process (Balasubramanian *et al.*, 2020; Rai *et al.*, 2016). The nanoparticles employed as catalysts in biodiesel synthesis are termed nanocatalysts and help in improving the biodiesel yield. Nanocatalysts have a wide reaction area and strong catalytic activity, making them useful in overcoming mass transfer resistance, quick deactivation, and inefficiency. Overall, nanomaterials are important not only in the synthesis of alternative biodiesel, but also in the manufacturing of cellulosic fuels, renewable application of chemical products, and other bio-based goods via the adaptable bio-refinery platform (Ingle *et al.*, 2020).

Several approaches have been employed in this domain successfully for improvement including nanotechnology-based transesterification, gasification, anaerobic digestion, pyrolysis, and hydrogenation to create fatty esters, biogas, and renewable HC. These approaches have been improved by integrating with nanotechnology, demonstrating cost-effectiveness and efficiency. Nanotechnology especially has evoked widespread interest in the research community to employ nanomaterial-based catalysts to improve biodiesel production. It has been demonstrated that the creation of more efficient, cost-effective, long-lasting, and stable nano-catalysts results in enhanced quality of final product quality and yields (Nizami and Rehan, 2018). Recent research has demonstrated that immobilized lipase is also an ecologically friendly, cost-effective, and efficient biocatalyst for biodiesel generation. Nanomaterials are suited for biodiesel generation due to their catalytic activity, low mass transfer constraints, and ease of dispersion. For biodiesel synthesis, researchers have looked at nanostructured materials such as carbon nanotubes, nanofibers, and metal-organic frameworks, as well as typical nanomaterials such as nano-silicon, magnetic nanoparticles, and nano-metal particles. Because of their distinct features, nanomaterials have a wide range of uses and have become a part of our daily lives. Several parameters, including synthesis techniques, temperature, dispersion agent, surfactant, and so on, have a considerable influence on the quality and quantity of generated nanoparticles, as well as their attributes (Khan and Arasu, 2019; Yaqoob *et al.*, 2020). The following is an in-depth summary of the nanomaterials that are typically utilized in the manufacturing of biodiesel:

Metal-based nanoparticles

- Metal nanoparticles, especially those containing noble metals such as palladium, gold, and silver, have demonstrated promising catalytic activity in biodiesel generation.
- These nanoparticles work as highly efficient catalysts in the transesterification step, converting triglycerides into biodiesel and glycerol (Joshi *et al.*, 2023).
- Palladium nanoparticles, for example, have shown outstanding catalytic activity and stability, resulting in increased conversion rates and biodiesel output (Chen *et al.*, 2020).
- Gold and silver nanoparticles have also been studied for their catalytic characteristics, which show promise for improving reaction kinetics and selectivity in biodiesel production (Al-Zaban and Abd El-Aziz, 2024; Al-Zaban *et al.*, 2022).

Metal oxide-based nanoparticles

- The multifunctional features of metal oxide nanoparticles, such as titanium dioxide (TiO_2) and zinc oxide (ZnO), have attracted a lot of attention in the field of biodiesel generation (Dasta *et al.*, 2022; Qamar *et al.*, 2023).
- These nanoparticles have the potential to function as catalysts or catalyst supports, which will result in the transesterification reaction being facilitated and the synthesis of biodiesel being promoted (Vasić *et al.*, 2020).
- TiO_2 nanoparticles, in particular, have demonstrated remarkable catalytic activity in transesterification processes, which has led to improvements in conversion rates and the amount of biodiesel produced (Jan *et al.*, 2022).
- There has also been research conducted on ZnO nanoparticles to investigate their catalytic capabilities and the possibility that they could improve the efficiency of biodiesel production efficiencies.

Carbon-based nanoparticles

- Carbon-based nanomaterials, such as carbon nanotubes (CNTs) and graphene, have unique features that can be used to increase biodiesel production and fuel quality (Bhagat *et al.*, 2021).
- CNTs, with their large surface area and great mechanical strength, have been investigated as catalyst supports and additives in the production of biodiesel (Konwar *et al.*, 2014). Functionalized CNTs have demonstrated good results in terms of reaction kinetics, catalyst stability, and biodiesel yield.
- Graphene, due to its two-dimensional structure and superior electrical and mechanical capabilities, has the potential to improve the reliability and efficiency of biodiesel fuel (Jume *et al.*, 2020).
- Graphene-based nanocomposites have been studied as additives for improving the thermal stability, lubricity, as well as combustion properties of biodiesel.

In general, nanomaterials offer fascinating opportunities for improving biodiesel manufacturing procedures while simultaneously enhancing the quality and performance of biodiesel fuel. Research & development efforts that are now being conducted in this area have the potential to result in the creation of a biodiesel technology that is more efficient, environmentally friendly, and economically viable.

4. Effects of nanoparticles-blended biodiesel on engine performance

According to the findings of the research, nanoparticles greatly improve both the performance of engines and the temperatures of exhaust gases. It has been demonstrated that nanoparticles dispersed in diesel-biodiesel have the potential to atomize and eliminate obstructions, which can be used to optimize the air-fuel combination (EL-Seesy *et al.*, 2020; Kegl *et al.*, 2021). Indeed, each of these nanoparticles increases the surface area/volume, which results in improved combustion and a reduction in the amount of fuel that is consumed (Fayaz *et al.*, 2021; Kumar *et al.*, 2017a). Additionally, nanoparticles (NPs) have an impact on the temperature of the exhaust gas and the performance of the engine. Obviously, the addition of graphene oxide (GO) nanoparticles to diesel-biodiesel resulted in a significant increase in the braking power of the engine, as discovered by Hoseini *et al.* (Hoseini *et al.*, 2020). This was attributed to the fact that GO NPs have a greater ratio of surface area vs volume, which led to the enhanced coefficient of heat transfer. This, in turn, results in higher in-cylinder pressures together with a faster rate of heat delivery. The Jatropha-nanoparticle blends led to lower EGT by as much as 27 %. One possible explanation for this is that the nanoparticles have enhanced capabilities for in-cylinder combustion and fuel-air mixing, both of which contribute to greater engine performance (Murugesan *et al.*, 2022). In a study by Das *et al.* (Das *et al.*, 2024) used a multi-cylinder engine powered by biodiesel-diesel-nanoparticles to investigate its emission and performance. The synthesis of biodiesel from Nahar oil was carried out using two steps of transesterification. In this scenario, 30% Nahar bioidiesel-70% diesel was employed to power the test engine.

The various proportional of carbon nano tubes CNTs were introduced in the biodiesel-diesel blends. The results of the testing show that Nahar oil biodiesel and its mixtures with carbon nanotubes can replace diesel as fuel in diesel engines effectively. Recently, the research community has been concentrating on the dependability aspects of biofuels, as well as the strengthening of engine performance components and burning qualities, to reduce exhaust emissions from conventional diesel engines through the utilization of diesel-biodiesel fuel mixtures that are loaded with NPs (Basha *et al.*, 2022; Nachippan *et al.*, 2022; Pullagura *et al.*, 2024). Recent research studies on the utilization of nano-sized metals, nonmetals, natural, and mixed elements in the fundamental fuel for diesel engines have been published in the academic literature (Jin and Wei, 2023; Yusof *et al.*, 2020). Fuel modification is one of the most important techniques for enhancing performance and lowering exhaust emissions, according to a review that was conducted by Shaafi *et al.* (Shaafi *et al.*, 2015). This is specifically in comparison to engine modification and post-discharge gas management, which are also essential approaches. This is accomplished by boosting surface area to volume fraction, thermal conductivity, and mass diffusivity when the nanoparticles are disseminated in a liquid medium. The usage of nanoparticles as additives in diesel fuel results in an improvement in thermophysical parameters (Bidir *et al.*, 2021; Hatami *et al.*, 2020; Murugesan *et al.*, 2023). In the case of a specific CI engine, the combustion process usually involves a combination of premixed as well as diffusion burning (Hoang *et al.*, 2022c; Sathish *et al.*, 2023a). Various variables can influence the mechanics of these intricate phenomena, such as the selection of fuel, the time of injection, the pressure of intake, the temperature, the load on the engine, and the compression ratio (Abdullah *et al.*, 2014; Calam *et al.*, 2019; Nayak *et al.*, 2022). The efficiency of the combustion process is the primary factor that determines the engine's overall performance and the pollutants produced by the exhaust (Balasubramanian *et al.*, 2019). Ignition delay (ID) is a crucial measure of the time it takes for combustion to start. It serves as a key indicator of engine performance in terms of fuel economy and emissions. ID refers to the period that begins with the injection of fuel and concludes with the burning of fuel within the combustion chamber (Basha and Raja Gopal, 2012; Senthilraja *et al.*, 2010). Both physical and chemical factors have the potential to impact ID. Prior studies indicate that shorter ID can result in improved combustion efficiency as it allows for a longer duration of preparing the fuel-air combination (Basha and Anand, 2011; T. T. Bui *et al.*, 2022; Venu and Madhavan, 2016).

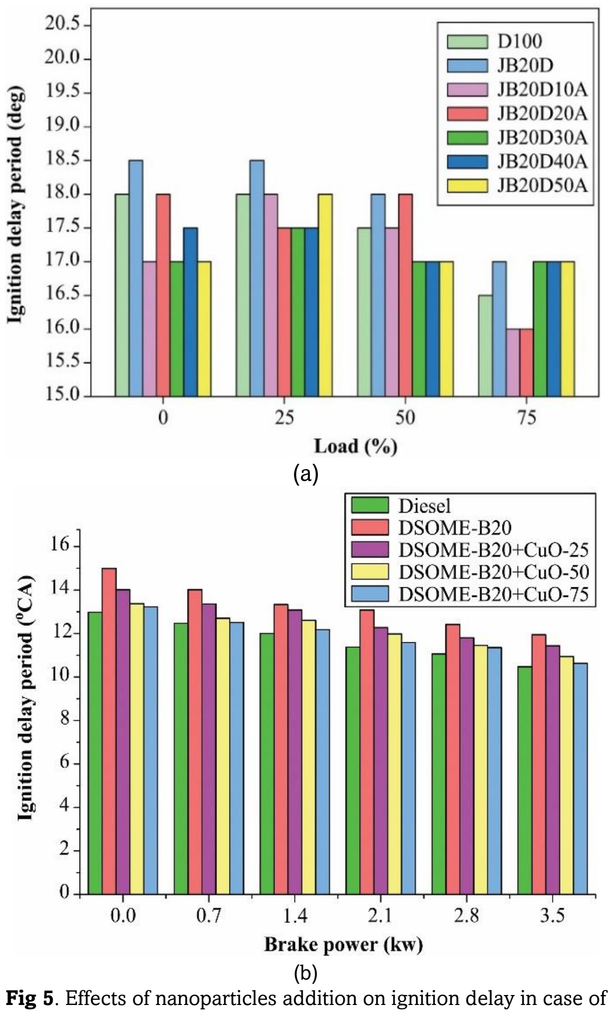


Fig 5. Effects of nanoparticles addition on ignition delay in case of (a) Alumina-based nanoparticles added to Jajoba biodiesel blends (El-Seesy *et al.*, 2018), (b) CuO-based nanoparticles added to Dairy scum biodiesel blends (Channappagoudra and Channappagoudra, 2021)

The distribution of nanoparticles inside the fuel droplets facilitated greater absorption of radiative heat, resulting in an enhanced rate of evaporation (Küçükosman *et al.*, 2022). Furthermore, the increased oxygen content available also had a significant impact on the combustion of the fuel blends by improving the mixing of fuel, air, and nanoparticle oxides. El-Seesy *et al.* (El-Seesy *et al.*, 2018) showed that the addition of Al_2O_3 nanoparticles led to a decrease in ID. The authors highlighted that the rise in the surface-area-to-volume ratio and improved heat conductivity were the factors responsible for the heightened evaporation rate and decreased ID. Similar findings were also reported by other research studies (Huzayyin *et al.*, 2004; Venu and Madhavan, 2016). The effects of different nanoparticles on the ID in biodiesel-diesel blend powered engines are depicted in Figure 5.

Alumina (Al_2O_3) nanoparticles, when added to diesel or a mixture of diesel and biodiesel, can effectively decrease the ID due to their enhanced thermal conductivity and greater surface-area-to-volume ratio. These improvements eventually result in an increased evaporation rate and reduced ID (Mostafa *et al.*, 2023). Al_2O_3 nanoparticles, when combined with the base fuel, can enhance combustion quality and optimize heat transmission (El-Seesy *et al.*, 2018)(Huzayyin *et al.*, 2004). The Al_2O_3 nanoparticles added to the fuel mix exhibited a rapid increase in HRR at a crank angle position of 6.5° to 1° before reaching the top dead center position, despite its lower calorific value. The significant impact of Al_2O_3 nanoparticles on enhancing combustion quality is evident from the greater peak pressure and combustion rate observed in the case of D80SBD15E4S1 and Al_2O_3 nanoparticles fuel blend. For JB20D, the highest recorded gross heat release rate (HRR) was somewhat lower than that of pure diesel, as described in the reference (El-Seesy *et al.*, 2018). The explanation for this phenomenon can be attributed to the blend's increased molecular weight and decreased laminarly burning speed (Huzayyin *et al.*, 2004; Prabakaran and Udhoji, 2016). Shaafi *et al.* (Shaafi and Velraj, 2015) found that the combination of D80SBD15E4S1 and Al_2O_3 nanoparticles had the maximum heat release rate (HRR) at 62 J/CA. In comparison, plain diesel and B20 blend had HRR values of 51.60 J/CA and 53.12 J/CA, respectively. However, the use of Al_2O_3 nanoparticles in the JB20D fuel mixture was shown to elevate the overall heat release rate (HRR) beyond that of pure diesel. The Al_2O_3 nanoparticles have a greater surface-area-to-volume ratio and improved ignition characteristics. This leads to a higher combustion quality, as evidenced by a

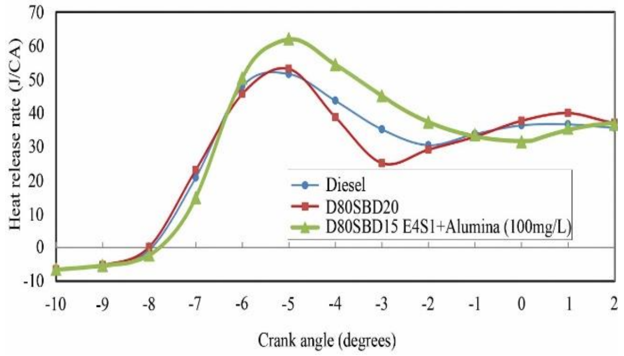


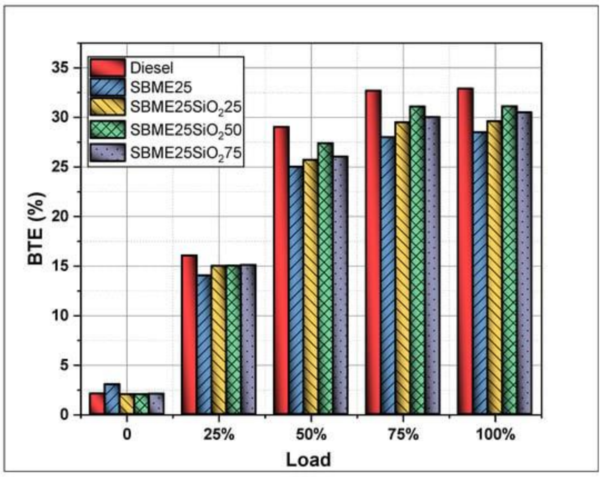
Fig 6. Effects of nanoparticle addition on HRR (Shaafi and Velraj, 2015)

reduction in ID and an increase in peak gross HRR compared to unaltered JB20D. The effects on HRR are depicted in Figure 6 from a study by Shaafi *et al.* (Shaafi and Velraj, 2015).

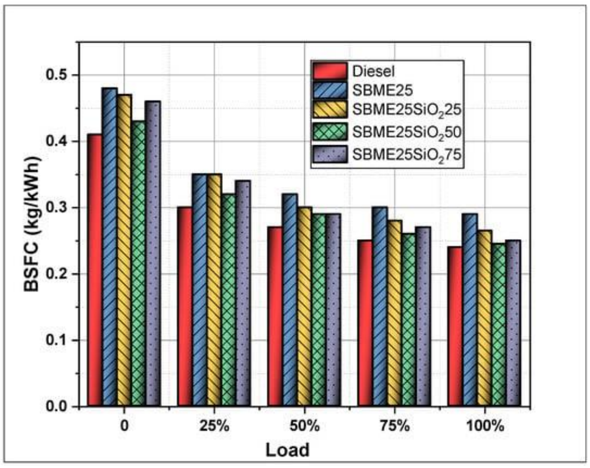
By adjusting the amount of ethanol, a pilot study that was conducted to investigate the impact of ethanol on an SC-4S diesel engine operating at variable speed while under full load discovered that raising the ethanol ratio led to an increase in the amount of hydrocarbon and carbon monoxide emissions, as well as the HRR and in-cylinder pressure. As well as shorter oxidation times and greater ignition delay, Mirzajanzadeh *et al.* (Madiwale *et al.*, 2018) reported significant decreases in CO_2 and NO levels. Additionally, they reported increases in ignition delay. The quantity of oxygen is the most critical factor in significantly boosting the efficiency of combustion. Due to the higher oxygen content, biodiesel-alcohol produces higher quantities of nitrogen oxides (NOx), which can reach up to 22 percent, as a result of the higher combustion temperature. When compared to diesel fuel, it reduces carbon monoxide emissions by as much as 33 percent, the formation of hydrocarbons by 90 percent, and particulate matter emissions by about 76 percent (Bidir *et al.*, 2021; Jiaqiang *et al.*, 2017).

The exhaust gas temperature (EGT) is a vital parameter used to determine the combustion temperature inside the engine cylinder (Atasoy *et al.*, 2022). Prabakaran *et al.* (Prabakaran and Udhoji, 2016) found that ZnO nanoparticles demonstrated higher catalytic activity, leading to an increase in the average combustion temperature due to improved combustion acceleration. The graph clearly showed an upward trend in EGT levels when the engine load reached or exceeded 50% for the ethanol/biodiesel blend with nanoparticles, as opposed to the unmodified version. Similarly, EL-Seesy *et al.* (EL-Seesy and Hassan, 2019) noted a reduction in EGT when JME40B was mixed with nanoparticles. By leveraging the higher cetane number of biodiesel and the surface-area-to-volume ratio of MNP, the addition of nanoparticles has the potential to improve the combustion efficiency of the base fuels. Hence, the increased interaction between the air and fuel in the combustion chamber resulted in a higher combustion acceleration rate [14]. El-Seesy *et al.* (El-Seesy *et al.*, 2018) noted a reduction in the exhaust gas temperature upon the initial addition of Al_2O_3 nanoparticles to JB20D, irrespective of the engine's operational circumstances. An inverse relationship was noted between higher levels of nanoparticle concentration and a decrease in EGT. However, this relationship was only statistically significant until a certain threshold of nanoparticle concentration was reached. Upon exceeding this limit, EGT was observed to increase again. As previously mentioned, the inclusion of Al_2O_3 nanoparticles resulted in reduced BSFC values. The main factor behind the decrease in EGT was resulting in a decrease in energy content (Shaafi and Velraj, 2015). The effects of nanoparticles on BTE and BSFC are depicted in Figure 7.

In a study by Kumar *et al.* (Kumar *et al.*, 2017a), the investigators explored the variance of BTE with different concentrations of CeO_2 nanoparticles. By adding cerium oxide nanoparticles to diesel, the BTE increased by 6%. Ceria nanoparticles convert into an oxygen buffer, releasing and storing oxygen in response to oxygen partial pressure. As a result, its addition to fuel promotes longer and more efficient burning than base fuel. CeO_2 may efficiently transition from a +4-valence state to a +3-valence state using low-energy processes. Increasing the treatment amount of CeO_2 nanoparticles above 35 ppm led to a modest drop in effectiveness. Higher loads result in the most effective nanoparticle dosing to diesel. Basha (Sadhik Basha, 2018) in another study used CNTs and di-ethyl ether blended with diesel to test the performance of a diesel engine. The 91% Jatropha biodiesel + 9% water (JME5W) mixture increased the volume of the fuel-air mixture, resulting in greater peak pressure and higher fuel consumption owing to longer ignition delay. It is also deduced that additive blended biodiesel emulsion fuels had higher BTE than pure diesel, plain biodiesel, and JME5W fuel. The use of additives such as CNT and DEE in emulsion fuel has increased combustion. The blend having CNTs with biodiesel-water emulsion fuel outperformed plain biodiesel emulsion fuel owing to the superior burning properties of the CNTs included



(a)



(b)

Fig 7. (a) Influences of SiO_2 NPs on BTE (Gavhane *et al.*, 2021); (b) Influences of SiO_2 NPs on BSFC (Gavhane *et al.*, 2021)

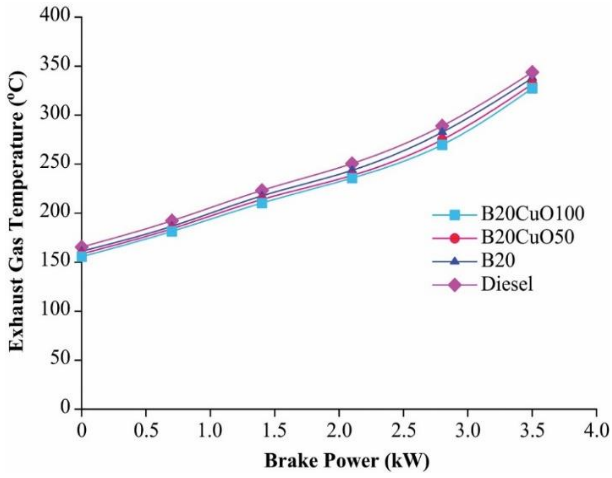


Fig 8. Effects of adding nanoparticles on EGT (Perumal and Ilangkumaran, 2018)

in the fuel (Atarod *et al.*, 2021). The addition of CNTs in the JME5W fuel increased combustion and, as a result, collected less fuel (due to shorter ignition delay), resulting in lower fuel consumption than pure JME5W fuel. However, the test fuel sample 91% Jatropha Methyl Esters+5% Water+50 ppm CNT+50 ml DEE showed significantly better performance characteristics. This might be attributed to the presence of CNT and DEE in the biodiesel emulsion fuel. Both additives (CNT and DEE) enhanced combustion properties due to secondary atomization and micro-explosion effects.

The combustion, performance, and emission characteristics of the fuel blend samples were investigated by Kalaimurugan *et al.* (Kalaimurugan *et al.*, 2023) through the utilization of experimentally derived criteria such as cloud point, viscosity, calorific value, density, and pour point. They did not make any modifications to the engines. Exhaust emissions, smoke opacity, BSFC, BTE, HC, CO NOx, and other metrics were used to assess the engine's performance. Adding a biodiesel mixture containing CuO_2 nanoparticles to an existing CI engine enhanced combustion, significantly increased performance characteristics, and reduced exhaust pollutants (Fayad *et al.*, 2022). On the other hand, in light of the growing concern regarding nanoparticle exposure, it is of the utmost importance to conduct a comprehensive investigation into the potential health and environmental implications of introducing CuO_2 nanoparticles into diesel-powered engines. Recently other studies in this domain reported similar results (Mofijur *et al.*, 2024). The influences of nanoparticles on EGT are depicted in Figure 8.

There is a large and multifaceted impact that nanoparticles have on the performance of engines and the characteristics that are associated with them, such as braking power, brake-specific fuel consumption (BSFC), and brake thermal efficiency (BTE). The combustion of engines, the efficiency with which fuel is used, and the reduction of pollution are all significantly influenced by nanoparticles due to their distinctive characteristics, which include a high surface area-to-volume ratio. It has been demonstrated that the use of nanoparticles such as Al_2O_3 and CeO_2 in fuel blends, such as mixtures of biodiesel, diesel, and nanoparticles, can increase the brake power (Venu *et al.*, 2021; Venu and Appavu, 2020; Yusuf *et al.*, 2022b). The majority of this improvement was owed to improved combustion properties and higher chemical reactivity that nanoparticles provide. One of the most important indicators of fuel economy is the BSFC, which is affected by nanoparticles. Even though diesel fuel typically has a higher BSFC than biodiesel due to the latter's lower heating value, the introduction of NPs into the fuel can enhance its lower heating values, hence lowering the BSFC as well as indicating an increase in fuel efficiency. In addition, the utilization of nanoparticles enhances BTE. By enabling finer fuel atomization, nanoparticles like titanium dioxide and aluminum oxide (Al_2O_3) contribute to an increase in combustion efficiency. This, in turn, leads to a more complete burning process. Not only does this strengthen BTE, but it also reduces the amount of harmful contaminants (Jit Sarma *et al.*, 2023; Singh Pali *et al.*, 2023). The utilization of ZnO nanoparticles in CI engines is a prevalent method owing to its capacity to mitigate engine wear and protect against corrosion. The manufacturing of ZnO nanoparticles is characterized by their antioxidant property and may be achieved through a straightforward and cost-effective technique. The augmentation of ZnO nanoparticles in CI fuel has culminated in improved combustion characteristics, as indicated by the greater BTE (Hussain Vali *et al.*, 2022; Ooi *et al.*, 2017).

Furthermore, the incorporation of water molecules in the fuel emulsion enhanced the effective blending of fuel and air particles, leading to accelerated evaporation of the mixture. The higher surface-area-to-volume ratio in the case of nanoparticles might potentially enhance the evaporation and atomization of fuel droplets (Kannaiyan *et al.*, 2019; Kannaiyan and Sadr, 2017). Moreover, these nanoparticles have demonstrated the ability to assimilate hydrogen atoms from water molecules, hence enabling enhanced combustion efficiency (Soukht Saraee *et al.*, 2016). Nanoparticles were employed to increase the surface-area-to-volume ratio, facilitating a more effective blending of air and fuels in blends of biodiesel with elevated viscosity, hence leading to improved BTE (Selvaganapthy *et al.*, 2013). Nevertheless, the BTE levels were lower compared to those of regular diesel. Moreover, the BTE values observed in these fuel blends exhibited a favorable correlation with the quantity of CuO nanoparticles utilized in the investigations. Greater concentrations of nanoparticles enhanced the accessibility of active contact surfaces and amplified the catalytic influence of the nanoparticles. Utilizing CuO nanoparticles enables an accelerated and elevated heat release rate (HRR) while concurrently augmenting oxygen concentration, hence facilitating the combustion process (Annamalai *et al.*, 2016; Tamilvanan *et al.*, 2019). Increasing fuel economy while simultaneously lowering emissions is a difficult balance that must be maintained. Different nanoparticles have different effects on emissions, even though they improve engine performance and efficiency. To give an example, the combination of SiO_2 nanoparticles with biodiesel has the potential to reduce emissions, but it may also increase levels of NOx. There is a wide range of effects that nanoparticles can have on the efficiency of the engine. The BTE of diesel-ethanol fuel is improved by CeO_2 to a moderate degree, whereas the BTE of TiO_2 is significantly improved and emissions are reduced. There is a possibility that the usage of biodiesel that is composed entirely of particles will result in higher particle emissions. Diesel, on the other hand, typically has a lower BSFC and a greater BTE, but it is less conducive to environmental preservation (Sathish *et al.*, 2023a).

The introduction of nanoparticles with engine fuels is an intriguing strategy with the possibility to enhance engine performance while also reducing emissions (Pandian *et al.*, 2017; Saxena *et al.*, 2017). However, the outcomes are significantly influenced by many factors, including nanoparticle types, the

Table 1
Performance characteristics of engine running on nanoparticles-based biodiesel

Biodiesel types	Nanoparticles type	Nanoparticles dosage	BTE	Fuel consumption	Ref
25% Pongamia biodiesel/75% diesel fuel	Al_2O_3	50-100 ppm	↑1.91% for 50 ppm of Al_2O_3, ↑2.7% for 100 ppm of Al_2O_3	↓ 0.015 kg/kWh 50 ppm of Al_2O_3, ↓ 0.025 kg/kWh for 100 ppm of Al_2O_3	(Sivakumar *et al.*, 2018)
20%Jatropha biodiesel/80% diesel fuel		50 mg/l	↑ 15%	↓ 12%	(El-Seesy *et al.*, 2018)
10% Waste cooking oil/ 90% diesel fuel	MgO	30ppm	↑4.8% compared to B10;	↑ 2.64% compared to B10	(Ranjan *et al.*, 2018)
Calophyllum Inophyllum biodiesel	ZnO	100 ppm	↑4.7% for 100 ppm ZnO	↑0.025 kg/kWh for 100 ppm ZnO	(Ashok *et al.*, 2017)
50% Calophyllum Inophyllum diesel/50% diesel fuel	CeO_2	40 ppm	↑2% for 40 ppm CeO_2	↓ for 40 ppm CeO_2	(Vairamuthu *et al.*, 2016)
20% of Calophyllum Inophyllum biodiesel/80% diesel fuel	TiO_2	40ppm	↑ 3.1%	↓	(Praveen *et al.*, 2018)
25% Neem oil biodiesel/75% diesel fuel	NiO	100 ppm	↑31.8% with 100 ppm NiO;	↓	(Srinidhi *et al.*, 2019)
20% *Ricinus communis* biodiesel/80% diesel fuel	Sr@ZnO	60 ppm	↑ 45.36%	↓21.47%	(Soudagar *et al.*, 2021)
20% jojoba biodiesel/80% diesel	CuO	75 ppm	↑ 4.94%	↓13.17%	(Rastogi *et al.*, 2021)
30% waste cooking oil biodiesel/70% diesel	Fe-CeO_2	90 ppm	↑	↓	(Hawi *et al.*, 2019)
5% Waste cooking oil/95% diesel	Fe_2O_3	100 ppm	↑	↓	(Jumaa and Mashkour, 2021)
Waste orange peel oil biodiesel	TiO_2	50 ppm	↓4.5%	↑0.045 kg/kWh	(A. M. Kumar *et al.*, 2020)
20% Mahua biodiesel/ 80% diesel	ZnO	30 ppm	↑ 3%	↓35 g/kWh	(Soudagar *et al.*, 2020)
20% Pongamia biodiesel/80% diesel	Ag-doped ZnO	25mg	↑8%	↓ 0.09 kg/kWh	(Sam Sukumar *et al.*, 2020)
25% Soybean biodiesel/75% diesel	Cu-ZnO	75 ppm	↑ 11.5%	↓14.8%	(Gavhane *et al.*, 2020)
Jatropha biodiesel	Al_2O_3/ CeO_2	100 ppm	↑3%	↓6%	(Hossain and Hussain, 2019)
10% Aloe vera biodiesel/90% diesel	Al_2O_3	30 ppm	↑3%	↓0.12 kg/kWh	(Prabu *et al.*, 2019)

fuel that serves as the foundation, the design of the engine, and the operating conditions (Bitire *et al.*, 2023; Yusof *et al.*, 2020). Each type of nanoparticle has its own set of benefits and drawbacks that are distinct from the others. It is necessary to conduct additional in-depth studies to ascertain the optimal equilibrium between nanoparticle type, fuel mixture, and engine settings to maximize either the performance or the environmental benefits (Bidir *et al.*, 2021; Kumar *et al.*, 2017b).

Furthermore, to fully achieve the potential of nanoparticle-enhanced fuels, any possible negative consequences must be addressed and mitigated, particularly those impacts that are related to emissions. Concentrating on environmentally friendly and sustainable methods of producing nanoparticles may increase the environmental benefits offered by the technology as scientific research continues to advance (El-Adawy *et al.*, 2023; Kohli *et al.*, 2023; Sathish *et al.*, 2023b). In general, the effect of nanoparticles on engine performance can be given in Table 1.

5. Effects of nanoparticles-blended biodiesel on engine emission

In the last several decades, scientists have come to a unanimous conclusion: nano-additives are to blame for the shift in our energy consumption habits. Diesel engines have discovered extensive use for diesel-biodiesel fuel blends that contain nanoparticles. Nanoparticles significantly alter fuels' physical characteristics, such as their thermal conductivity and heat transfer rate, by acting as a catalyst and an effective secondary energy transporter (Manigandan *et al.*, 2020; Radhakrishnan *et al.*, 2018). Premixing in combustion also resulted in more dominating reaction rates owing to a quicker oxidation process and a higher surface volume ratio, either of which improved fuel combustion efficiency (Hosseini *et al.*, 2017). Fuel consumption is reduced with the same amount of engine brake power, higher operating pressure, and enhanced heat release rates compared to diesel fuel, with no discernible effect on engine emission features (Kishore and Gugulothu, 2022). Experiments have shown that adding nanoparticles to fuel used for diesel engines reduces chemical reaction time even further, which in turn shortens the ignition delay period and ultimately results in fewer pollutants (Feroskhan *et al.*, 2019; Ganesan *et al.*, 2020). The size of the nanoparticles and the extra concentration of fuel are also major factors in the significant reduction of engine emissions.

Regardless, this isn't the only thing that matters; additional elements include oxygen availability, combustion temperature, response time, and their local complex interface, among others. The effects of TiO_2 nanoparticles on engine emission are depicted in Figure 9 (Mujtaba *et al.*, 2020). The use of nanoparticles in biodiesel-diesel blends has emerged as a potentially fruitful technique for improving the efficiency in lowering the emissions of diesel engines. This novel strategy makes use of the unique qualities of nanoparticles to maximize the characteristics of fuel and the kinetics of combustion. The employment of dispersed nanoparticles in biodiesel-diesel mixes improved the fuel atomization, increased the surface area for combustion, and reduced the generation of pollutants (Karthikeyan *et al.*, 2016). The combustion kinetics are altered as a result of the interaction between nanoparticles and fuel molecules, this results in a more complete oxidation of fuel and a reduction in emissions of hazardous pollutants such as nitrogen oxides (NOx), particulate matter (PM), and carbon monoxide (CO) (Debbarma and Misra, 2018; M. V. Kumar *et al.*, 2019). Investigating the amount of carbon monoxide that is emitted in the exhaust of a diesel engine can be of use in determining the degree to which incomplete combustion takes place during the combustion cycle.

The introduction of CNT led to a considerable reduction in NOx emissions. The study attributed this to the water-emulsified CNT's capacity to swiftly absorb heat during combustion, resulting in a rapid fall in in-chamber temperature and lower NOx levels (Ghojel *et al.*, 2006). The Al_2O_3 nano additive considerably increased NOx levels, probably due to an increase in the in-cylinder pressure and temperature from rapid

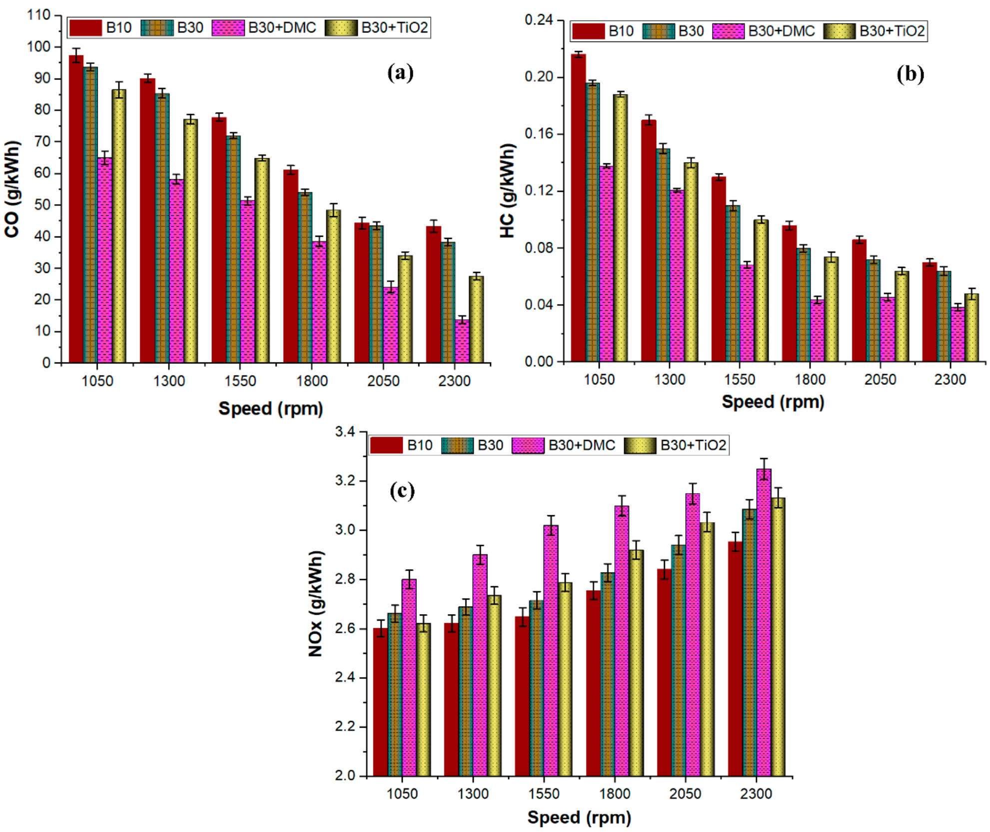


Fig 9. Influence of TiO2 nanoparticles on (a) CO (b) HC (c) NOx emissions (Mujtaba *et al.*, 2020)

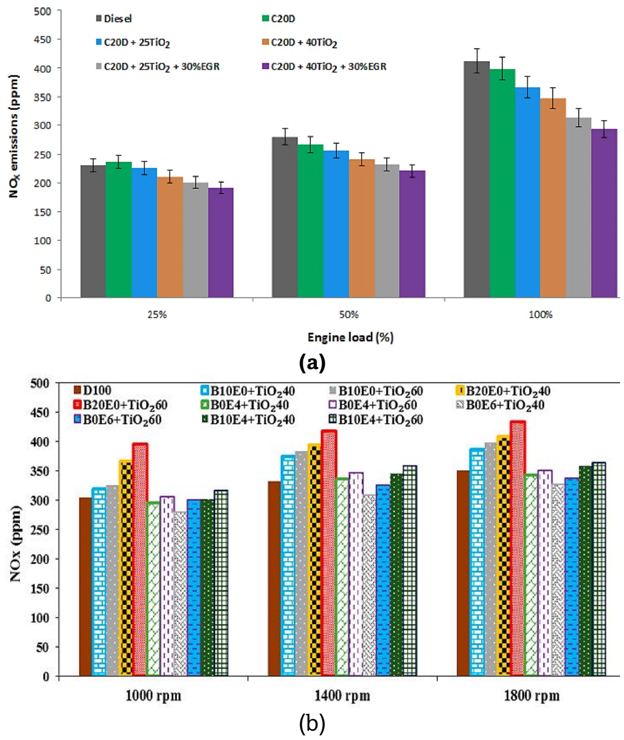


Fig 10. (a) - Effects of TiO_2 nanoparticles and EGR on NO_x emission (Fayad *et al.*, 2023); (b) - Effects of TiO_2 - 40 and 60 ppm nanoparticles on NO_x emission (Mobasheri *et al.*, 2023)

fuel burning. The increasing chamber temperature resulted in greater NOx production (Barboza *et al.*, 2023; Gupta *et al.*, 2024). It has also been demonstrated by chemical equilibrium tests that a significant amount of nitrogen oxides is produced at the last stage of the combustion process (Kowalski and Tarelko, 2009b). Furthermore, it has been demonstrated that rich fuel-air mixtures produce a lower quantity of these oxides compared to lean fuel-air mixtures. The burning of biodiesel fuel results in the production of more nitrogen oxides (NOx) than diesel fuel does. This is because biodiesel fuel contains a higher quantity of oxygen. As a result of this highly oxygenated biodiesel's ability to burn more efficiently and produce more heat, the temperatures inside the cylinder are improved. Furthermore, for the reason that biodiesel has a larger bulk modulus, sophisticated fuel injection was utilized, which resulted in an even greater increase in NOx emissions (Chandrasekaran *et al.*, 2016; Manimaran *et al.*, 2023; Shelare *et al.*, 2023).

Fayad *et al.* (Fayad *et al.*, 2023) used TiO_2 nanoparticles with a higher rate of exhaust recirculation (EGR) to improve the combustion performance and reduce emission from a common rail direst injection (CRDi) engine. Figure 10a depicts the NO_X emissions levels vs engine loads generated from EGR and the incorporation of TiO_2 concentrations into castor oil blends. The overall trend across all fuels reveals that NO_X emissions increased with higher engine loads compared to medium and reduced engine loads owing to a rise in combustion temperature within the combustion chamber. In comparison to the other evaluated fuels, the castor oil mix produces slightly greater NOX emissions during low-load burning. In contrast, introducing TiO_2 nanoparticles resulted in a significant 13.42% decrease in NO_X when compared to the fuel without nanoparticles. This is due to a reduced level of active radicals, which increases the capacity to limit NO_X generation. Similar results were reported by Mobasheri *et al.* (Mobasheri *et al.*, 2023) as depicted in Figure 10b.

CO emissions are significant since they represent lost chemical energy that cannot be used in the engine. In diesel engines, incomplete combustion is typically brought on by a lack of combustion time, which is required for the oxidation of carbon monoxide into carbon dioxide, an insufficient amount of oxygen, and an insufficient amount of fuel-air mixing in the combustion area (Aalam and Saravanan, 2017; Khan *et al.*, 2020). Evidence demonstrated that elevated concentrations of CuO nanoparticles significantly decreased carbon monoxide emissions (Naik and Kumar, 2018). The enhanced catalytic efficacy of these nanoparticles, uniformly dispersed throughout the liquid fuel, permitted the proper amalgamation of air and fuel, resulting in an overall enhancement of the combustion process (Prabakaran *et al.*, 2017; Yusuf *et al.*, 2022a). Fuel quality, engine load, spray characteristics, and air-fuel ratio are all important elements in CO generation (Flamarz Al-Arkawazi, 2019; Hoang *et al.*, 2018). CO emissions are created by the incomplete oxidation of carbon atoms in the combustion chamber's rich mixture sections at temperatures less than 1180°C (Deheri *et al.*, 2020; Sarıdemir *et al.*, 2024). In a study by Zhang *et al.* (Zhang *et al.*, 2022) it was reported that hydrogen incorporated with nanoparticles results in a decrease in CO levels. Because the quantity of biofuel utilized raises the oxygen concentration, this is the case. The oxygen content of the biofuel, the addition of nanoparticles to reduce viscosity, and the supply of hydrogen to increase diffusivity and flame speed all contribute to an increased rate of pure combustion with no unburned fuel (Ettefaghi *et al.*, 2018). The unburned fuel components are also contributing to CO emissions. Moreover, the absence of a carbon structure in hydrogen leads to reduced CO_2 emissions. TiO2's substantial energy surface area is an additional prerequisite for complete combustion. However, as velocity increased, so did carbon monoxide emissions. Due to the partial combustion of the mixture in the combustion chamber, carbon monoxide (CO) emissions are generated. However, the addition of alumina nanoparticles to diesel fuel helps decrease these emissions. The concentration of CO emissions is shown to decrease as the dosage of nanoparticles increases. Alumina nanoparticles are evenly distributed owing to their catalytic activity, resulting in improved contact between air and fuel, as well as combustion (Soudagar *et al.*, 2018; Soukht Saraee *et al.*, 2016).

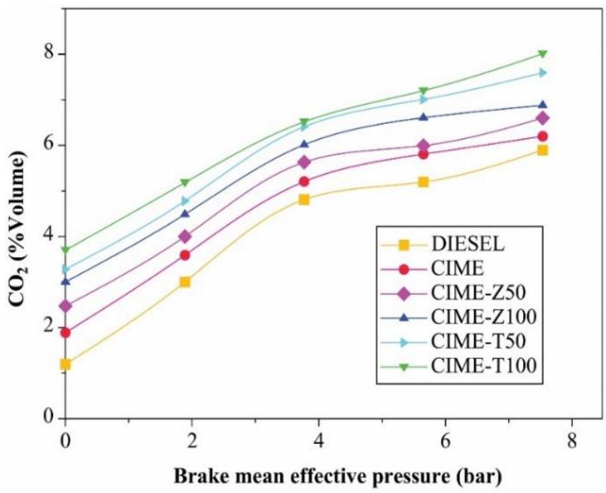


Fig 11. Effects of TiO_2 nanoparticle addition on CO_2 emission (Nanthagopal *et al.*, 2017)

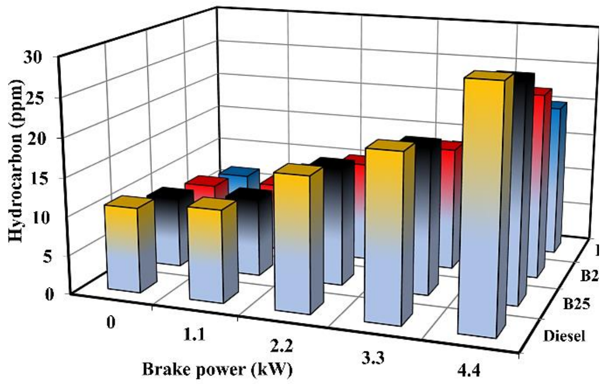


Fig 12. Effects of Al_2O_3 nanoparticle addition on HC emission (S. S. Kumar *et al.*, 2021)

CO_2 emissions in a CI engine indicate that the test fuel has been thoroughly burned. There was a link between engine load and CO_2 emissions for all evaluated fuels. Because of its increased oxygen content, biodiesel was shown to emit more CO_2, as shown in Figure 11. The use of CuO nanoparticles in blended fuels leads to a higher oxygen availability as well as a surface area-to-volume ratio. This, in turn, improves the oxidation of carbon monoxide (CO) and hydrocarbons (HC), resulting in greater temperatures in the combustion chamber and improved combustion efficiency. CuO Nano addition increases CO_2 emissions somewhat when compared to JB20 gasoline. The event is the outcome of an enhanced combustion process triggered by Nano additions. This process maintains an equilibrium between CO and CO_2 emissions since an increase in CO_2 emissions causes a reduction in CO emissions (Rastogi *et al.*, 2021; Venu *et al.*, 2022).

Hydrocarbon (HC) emissions are always referred to as unburned HC since they are the product of incomplete combustion (Balasubramanian *et al.*, 2022). The presence of HC emissions in exhaust fumes is generated by insufficient oxygen atoms in fuels and high ignition temperatures (Dehhaghi *et al.*, 2021; Gharehghani *et al.*, 2019). These produce non-oxidized and/or semi-oxidized casings for testing fuels. In such cases, HC production begins to increase. It was noticed that HC fluctuated with engine speed. At all engine speeds, 1000-CuO and 2000-CuO produce fewer HC emissions than diesel fuel. It is clear that the oxygen content increased with the addition of metal-oxide nanoparticles to the mixture; hence, HC is larger for DF under all conditions (Ağbulut *et al.*, 2021; S. Kumar *et al.*, 2020). In a similar study by Kumar T *et al.* (Deepak Kumar *et al.*, 2020) it was reported that at higher loads ZnO nanoparticles helped in the reduction of HC emission. The catalytic impact of nano-additives improves the process of combustion, resulting in reduced HC concentrations. The use of ZnO nanoparticles minimizes CO emission generation owing to the catalyst throughout combustion, the increased surface area, and the quicker combustion rate. Furthermore, it was proven that augmenting the dose of ZnO nanoparticles in the diesel-water emulsion resulted in a proportional decrease in HC emissions. The secondary atomization of nano-additives, together with improved fuel-air blending and increased reactivity, speeds up the oxidation of HC, resulting in reduced HC emissions. Nanomaterials enhance combustion efficiency by the incorporation of oxygen molecules (Dhahad and Chaichan, 2020; Gad *et al.*, 2023). Kumar *et al.* (S. S. Kumar *et al.*, 2021) reported that the fuel quality, spray actions, and air-fuel ratio are the most important parameters influencing HC emissions; HC emissions are produced owing to the lack of oxygen present during combustion. Figure 12 depicts the change in HC emissions with braking power for diesel, biodiesel blends, and nanoparticle combinations. The graph shows that at peak load, the HC emission for the B25 is 28 ppm, whereas the diesel emission is 32 ppm. The inclusion of an additional O_2 molecule in the chemical structure improves oxidation, which leads to enhanced combustion and fewer HC emissions. For tested fuels, HC emissions ranged from 7 to 32 ppm between no load and peak load. From no load to peak load, diesel HC emissions vary from 11 to 32 ppm, whereas B25 emissions range from 9 to 28 ppm. The application of 25 and 50 ppm of alumina nanoparticles reduces B25 HC emissions from 8 to 24 ppm and 7 to 20 ppm, respectively. Alumina nanoparticles acted as oxidation catalysts, which increased HC oxidation and reduced HC emission.

Smoke formation is observed in the fuel-rich zone during the burning process, indicating advanced timing during full engine load (Adam *et al.*, 2017; Debbarma and Misra, 2017). Scientists have highlighted the positive impacts of adding nanoparticles in reducing smoke generation and improving combustion properties (Attia *et al.*, 2014; Ramakrishnan *et al.*, 2019). This is attributed to the enhanced catalytic activity and increased surface-area-to-volume ratio of the nanoparticles (Murugan *et al.*, 2022; Suhel *et al.*, 2021). Utilizing nanoparticles enhances the oxygen content in nano-fuel mixes, facilitating complete combustion while decreasing smoke emissions. Significantly, there was a reduction in smoke emissions seen when burning a fuel mixture that included nanoparticles (Shrivastava *et al.*, 2018; Srinivasan *et al.*, 2021). The engine's improved emissions performance is attributed to its enhanced ignition characteristics, decreased ignition delay, and accelerated evaporation rate (Le *et al.*, 2023, 2021). As stated by Balaji *et al.* (Balaji and Cheralathan, 2017), the use of Al_2O_3 nanoparticle fuel additives led to reduced smoke emissions at all engine loads. The researchers discovered that using neem oil biodiesel with a concentration of 200ppm of Al_2O_3 and neem oil biodiesel with a concentration of 300ppm of Al_2O_3 resulted in a reduction in smoke intensity by 3.11%, 8.58%, and 5.84%, respectively. The data were compared to the burning of undiluted biodiesel at

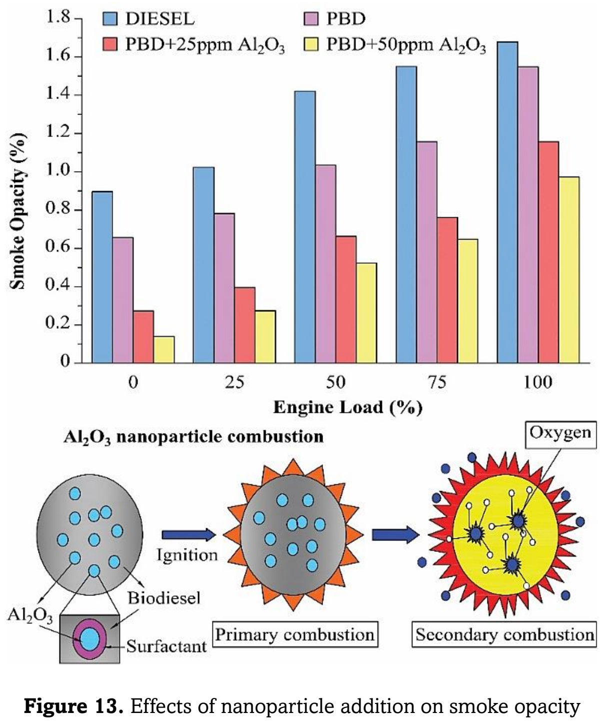


Figure 13. Effects of nanoparticle addition on smoke opacity (Venu and Appavu, 2020)

maximum engine load. The enhanced combustion of the uniform fuel-air mixture led to reduced smoke emissions. Moreover, the utilization of Al_2O_3 nanoparticles has been discovered to enhance emissions performance, and the combustion of fuel has been enhanced due to the improved surface-area-to-volume ratio of the nanoparticle fuel additives, as shown in Figure 13 (Venu and Appavu, 2020).

PBD with a 25 ppm Al_2O_3 concentration consistently yielded reduced smoke opacity and particulate matter levels across all load settings. Kalaimurugan *et al.* (Kalaimurugan *et al.*, 2020) discovered that the combustion of biodiesel blends with additional CeO_2 resulted in lower levels of smoke opacity compared to B20. Consequently, the introduction of ceria nanoparticles led to a reduction in smoke emissions by

Table 2
Emission characteristics of engine running on nanoparticles-based biodiesel

Fuel types	Nanoparticles type	Nanoparticles dosage	Engine emissions				Ref
			CO	HC	NOx	PM/Smoke	
25% Pongamia biodiesel/75% diesel fuel	Al_2O_3	100 ppm	↓ 0.9 %vol	↓21 ppm	↑270 ppm	↓23 HSU	(Sivakumar *et al.*, 2018)
10% Waste cooking oil/90% diesel fuel	MgO	30 ppm	↓ 5.88%	↓ 22.52%	↓ 4.06%	↓ 1.59%	(Ranjan *et al.*, 2018)
20% jojoba biodiesel/80% diesel fuel	Al_2O_3	40 mg/l	↓70%	↓60%	↓ 60%	↓20%	(El-Seesy *et al.*, 2018)
Calophyllum Inophyllum biodiesel	ZnO	100 ppm	↓max. 18.4%	↓13%	↓ 12.6%	↓	(Ashok *et al.*, 2017)
20% canola oil biodiesel/80% diesel fuel	Pd and Fe	25 ppm	↓60.07% for Pd and ↓57.89% for Fe	-	↑7.02% for Pd ↓4.84% for Fe	↓22.04% for Pd, ↓ 24.27% for Fe	(Keskin *et al.*, 2018)
20% of Calophyllum Inophyllum biodiesel/80% diesel fuel	TiO_2	40ppm	↓23%	↓12%	↑ 63 ppm	↓	(Praveen *et al.*, 2018)
Manhua oil biodiesel	TiO_2	200 ppm	↓ 9.3%	↓ 3.8%	↓ 6.6%	↓ 2.7%	(Pandian *et al.*, 2017)
B10 (10% waste cooking oil+ 90% diesel fuel)	Al_2O_3, TiO_2, SiO_2	100 ppm	↓	↓80.98% for SiO_2	↓	-	(Ağbulut *et al.*, 2020)
25% Neem oil biodiesel/75% diesel fuel	NiO	100 ppm	↓	↓11%	↑6.1%	-	(Srinidhi *et al.*, 2019)
20% neochloris overabundant algae oil/80% diesel fuel	CeO_2	25, 50, 75, 100 ppm	↓	↓	↑	↓	(Kalaimurugan *et al.*, 2020)
20% palm biodiesel/80% diesel fuel	Fe	50, 75 ppm	↓ 56%	↓	↓ 4%	-	(Debbarma and Misra, 2017)
20% waste cooking oil biodiesel/80% diesel	TiO_2	0.01% by mass	↓ 10.83%	↓ 6.33%	↑ 6.95%	↓ 3.71%	(Örs *et al.*, 2018)
10% corn oil/ 90% diesel)	CeO_2	50 ppm	↓16.6%	↓13.63%	↑ 5.8%	-	(P *et al.*, 2021)
10% Karanja biodiesel/90% diesel	TiO_2	80 mg	↓21.52%	↓18.47%	↓1.54%	-	(Parida *et al.*, 2020)
Palm oil biodiesel	Ag_2O	10 ppm	↓ 30.55%	↓25%	↓30.3%	↓25%	(Devarajan *et al.*, 2018)
Mahua oil biodiesel	CuO	100 ppm	↓4.9%	↓ 5.6%	↓3.9%	↓2.8%	(Devarajan *et al.*, 2019)
20% algae biodiesel/80% diesel	RuO_2	100 ppm.	↓ 22.9%	↓32.5%	↑11.3%	↓ 4.4%	(Kalaimurugan *et al.*, 2019)
Jatropha biodiesel	Al_2O_3	150 mg/L	↓ 22.5%;	↓19%;	↓5.9%;	↓13.5%;	(Shrivastava *et al.*, 2018)
20% corn oil/70% neat diesel	TiO_2 and ZnO.	50, 100 ppm.	↓ 39%	↓39%	↓10%	↓13%;	(Manigandan *et al.*, 2020)
80% Diesel/20% poultry litter biodiesel	Ce_2O	80 ppm	-	↓20%	↓23%	↓14%	(S. Kumar *et al.*, 2019)
80% diesel/20% Botryococcus braunii algae biodiesel	CuO_2	100 ppm.	↓	↓	↑	↓	(Dharmaprabhakaran *et al.*, 2020)
75% diesel/25% soybean biodiesel in diesel)	Ce-ZnO	50 ppm	↓30%	↓21.5 %	↑11.46%	↓18.7%	(Hussain *et al.*, 2020)

decreasing the time it takes for ignition to occur and enhancing the quality of combustion (Hoang, 2021b). Sajeevan *et al.* (Sajeevan and Sajith, 2013) employed a TPR analysis method to examine the impact of Zr – Ce-O nanoparticles on fuel combustion and soot emissions in their study on catalysis. Upon reaching temperatures ranging from 300 to 400°C, the researchers observed that the nanoparticles supplied sufficient oxygen to facilitate the oxidation of the soot particles at high temperatures. Therefore, they observed a decrease in soot emissions ranging from 3.5% to 26.3% in comparison to conventional diesel. In general, the effect of nanoparticles on engine performance can be given in **Table 2**.

6. Challenges and future perspectives

During this phase of our exploration into the domain of nano-based biodiesel production and consumption, it is of the utmost importance to recognize the obstacles that are now being faced and to envisage the prospects that will pave the way for improvements in this sector. In my capacity as your professor, I will elaborate on the difficulties and constraints that are now being faced, as well as the possibilities for more research and development, as well as the opportunity for the commercialization and expansion of nano-enhanced biodiesel technology.

6.1. Currently existing obstacles and restrictions

Efficient use of resources: The high cost of nanomaterials and production procedures remains a significant obstacle, even though nano-based approaches have proven promising outcomes. Therefore, to address this difficulty, developing novel techniques that can cut manufacturing costs without sacrificing quality or efficiency is necessary (Zhong *et al.*, 2020).

Scalability and Production Scale-Up: Although research conducted in the laboratory has yielded positive results, the process of scaling up nano-enhanced biodiesel production methods for use in commercial applications presents several daunting hurdles. To satisfy the demand for nano-enhanced biodiesel on a wider scale, it is necessary to make considerable efforts to create production procedures that are both scalable and cost-effective.

Impact on the Environment: The environmental repercussions of nanomaterial production, as well as their long-term consequences on ecosystems and human health, call for a comprehensive evaluation and the development of mitigating solutions (Bin Rashid, 2023). To assure the environmental sustainability of nano-based biodiesel technologies, it is essential to use environmentally friendly synthesis processes and sustainable manufacturing practices respectively.

6.2. Further research and development opportunities

The Optimization of Nanomaterials: Ongoing research efforts are required to optimize the design and synthesis of nanomaterials that are specifically specialized for specific uses in the manufacturing of biodiesel materials. The investigation of innovative nanocatalysts, nanocomposites, and nanocarriers offers the potential to improve the level of efficiency and selectivity of the processes involved in the production of biodiesel.

Process Integration and Engineering: The integration of nanotechnology with other fields of study, such as biotechnology, chemical engineering, and materials science, has the potential to generate synergistic advantages and novel solutions. The development of integrated processes and nanomaterials with multiple functions has the potential to result in biodiesel manufacturing methods that are more efficient and environmentally friendly.

Characterization and Evaluation of Performance To evaluate the performance and stability of nano-enhanced biodiesel fuels, it is necessary to employ comprehensive characterization methodologies. To gain a better understanding of the physicochemical parameters and combustion behavior of nano-enhanced biodiesel, advanced analytical approaches such as spectroscopic, microscopic, and rheological techniques can be utilized.

5.3. Potential commercialization and scaling-up

There is a possibility of commercialization, scaling up, market penetration, and adoption. Efforts to raise awareness and encourage market acceptance of nano-enhanced biodiesel are becoming increasingly important as the technologies behind these fuels advance. To support the commercialization and widespread acceptance of nano-enhanced biodiesel technology, it is vital to collaborate with industry stakeholders, legislators, and regulatory bodies.

Establishing infrastructure and supply chains for the manufacturing, distribution, and storage of nano-enhanced biodiesel fuels is essential for assuring market readiness and scalability. This is because the infrastructure is essential for the development of the infrastructure. Accelerating the process of commercialization and enabling extensive market penetration may be accomplished through investments in the construction of infrastructure and other forms of logistical assistance.

The policies, incentives, and regulations that are implemented by the government play a crucial part in encouraging innovation and providing financial incentives for investments in nano-enhanced biodiesel technology. To fully realize the promise of nano-enhanced biodiesel technologies, it is necessary to have policy frameworks that encourage research and development, provide incentives for adoption, and guarantee environmental sustainability.

In summary, to successfully navigate the hurdles and seize the potential in the production and consumption of nano-based biodiesel, it is necessary to engage in collaborative efforts across several disciplines, conduct new research, and form strategic alliances. We can pave the road for a future that is sustainable, efficient, and commercially viable for nano-enhanced biodiesel technologies if we overcome these problems and embrace the possibilities that lie ahead.

7. Conclusions

The present review provides a comprehensive analysis of nano-additives and their impact as a blended additive in biodiesel-powered engines. Utilizing nanoparticles in liquid fuel offers numerous benefits, such as reduced exhaust emissions and improved performance. Here are the key findings from the comprehensive literature study, along with a suggestion for future research on nanoparticles as a potential additive for CI engines:

- It has been shown that the inclusion of metallic additives in diesel-biodiesel blends can effectively reduce exhaust emissions, including HC and CO. Thanks to the improved combustion properties of biodiesel fuel with NP additives, enhanced ignition is achieved.

- Research on incorporating different NPs into biodiesel feedstocks is limited. Numerous studies have investigated the combination of metallic nanoparticles.
- A comparative analysis of nanoparticles and diesel/biodiesel blends, along with the optimization of NP dosage rate, is required.
- Metallic and CNT nano-additives improved engine performance and decreased pollutants. Observations have shown that the addition of TiO2 additives greatly enhances engine power.
- Using metal-based nanoparticles has shown promising results in reducing ignition delay duration, improving the lower heating value, and accelerating the rate of oxidation. This leads to a more efficient and cleaner combustion process.

It is important to establish the appropriate dosage and assess the compatibility of nanoparticles in the fuel blend over time. In addition, it is crucial to find an affordable way to produce nanoparticles and tackle the potential health and environmental issues associated with human consumption of these particles.

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