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

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ABSTRACT

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

Introduction

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

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Nomenclature

Acronyms

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

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

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

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

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

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

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

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

Nanoparticles

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

Types of nanoparticles

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

Organic-based nanoparticles

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

Inorganic-based nanoparticles

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

Carbon-based nanoparticles

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

Composite-based nanoparticles

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

Synthesis of nanoparticles

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

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

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

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

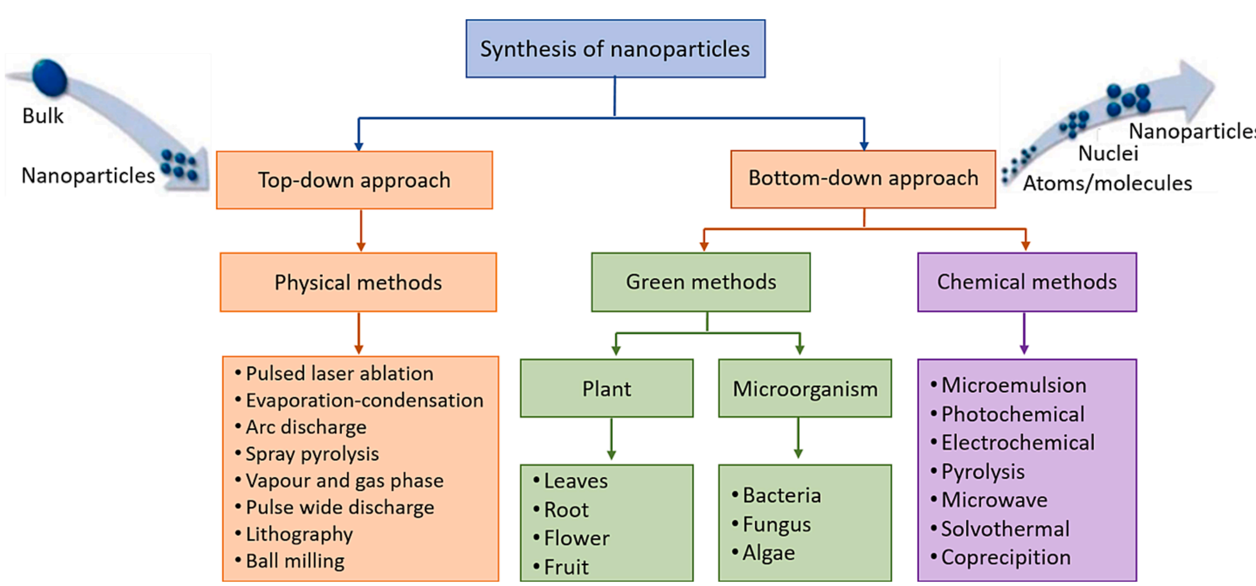

Fig. 1. Methods of synthesising nanoparticles, modified from Ahmed et al. [9].

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

Properties of nanoparticles

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

Mechanical properties

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

Magnetic properties

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

Thermal properties

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

Electrical and optical properties

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

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

Applications of nanoparticles

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

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

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

Effect of nanoparticles on biodiesel properties

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

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

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

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

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

Effect of nanoparticles on engine performance

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

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

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

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

Brake power

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

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

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

Brake-specific fuel consumption

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

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

Brake thermal efficiency

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

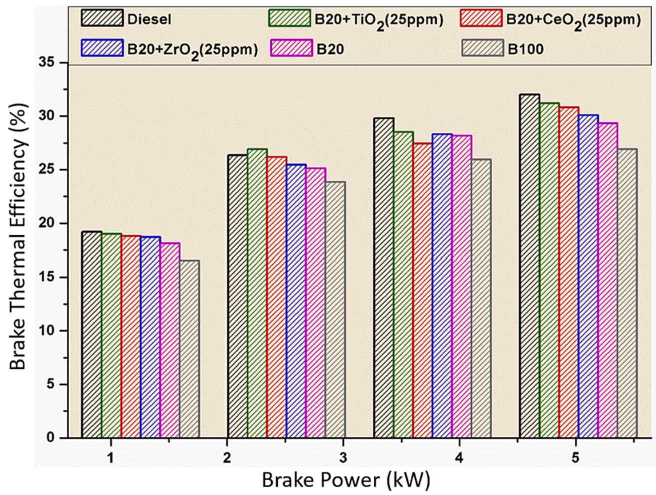

Fig. 2. BTE variation in relation to brake power across various fuel blends, reprinted with permission of Elsevier from Janakiraman et al. [58].

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

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

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

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

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

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

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

Effect of nanoparticles on engine emission

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

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

Carbon monoxide

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

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

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

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

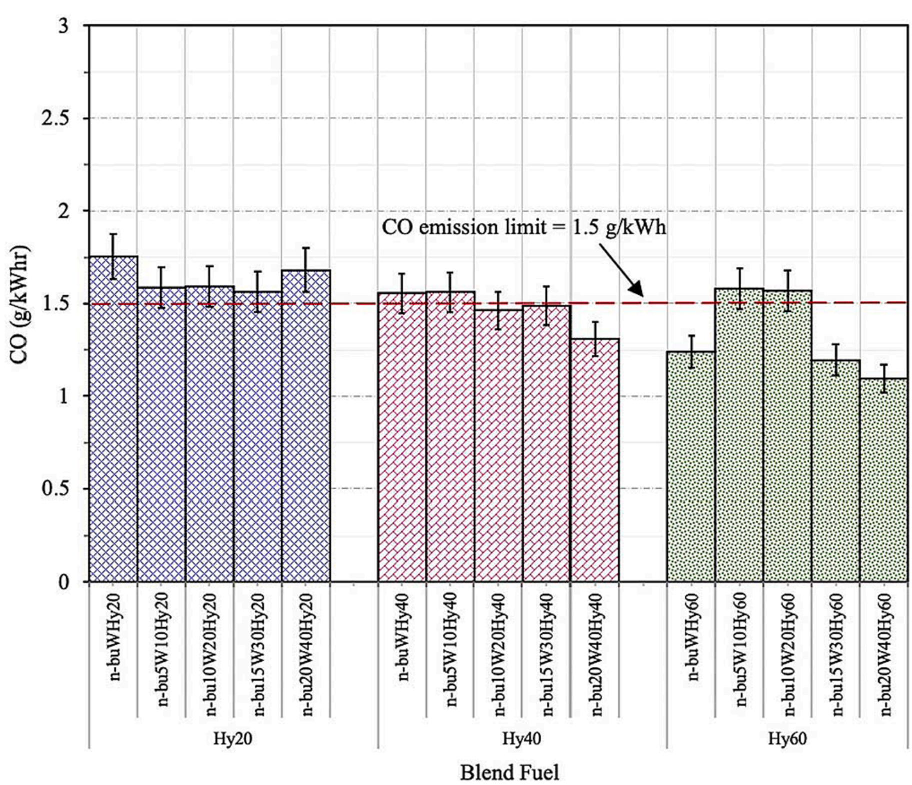

Fig. 3. Variation in CO emissions across various test fuels incorporating hybrid nanoparticles, reprinted with permission of Elsevier from Yusuf et al. [141].

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

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

Hydrocarbon emissions

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

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

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

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

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

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

Nitrogen oxide emissions

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

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

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

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

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

Soudagar et al., [116] conducted a study where magnetic ferrofluid was combined with MEMO (methyl esters of mustard oil) to examine the latter's impact on the performance and emission behaviour of diesel engines. The biodiesel engine's speed was steady for the duration of the experiment. This study demonstrated that increasing the proportion of magnetic ferrofluid in a combustion mixture results in a greater quantity of heat produced at higher combustion temperatures, which helps to shorten the ID (ignition delay) time and reduce NO_x emissions. By adding 1 % of magnetic ferrofluid (by volume) to MEMO, this study observed a total reduction in NO_x emissions of 7.74 %. Nevertheless, the results presented here conflict with those of a different study by Srinivasan et al. [118] where the authors used Al_2O_3 and TiO_2 nanoparticles with neat biodiesel at 25 and 50 ppm to evaluate the impact on the function, combustion, and exhaust emission behaviour of a CI engine. A sol–gel method was employed to synthesize the nanoparticles. The results demonstrated that the incorporation of aluminium oxide and titanium oxide in a blended biodiesel revealed a negative impact on the reduction of NO_x and an increase in NO_x emissions of 21 %. A similar

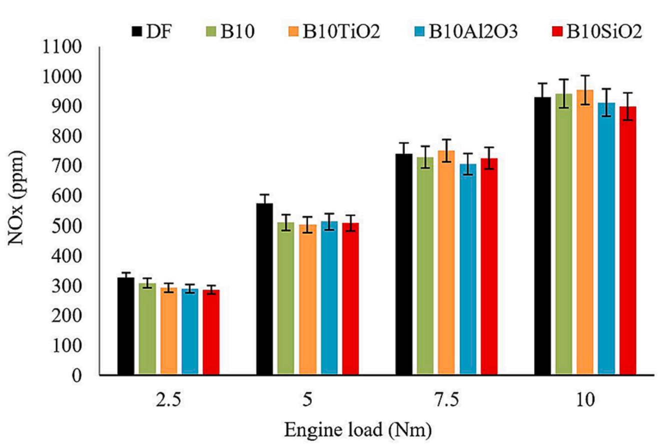

Fig. 4. Fluctuations in NO_x emissions occur as a result of different test fuels and engine loads, reprinted with permission of Elsevier from Ağbulut et al. [6].

result was also found in a study cited by Heydari-Maleney et al., [50] when using CNTs as an additive to diesohol-B2fuels (diesel + ethanol) at concentrations of 20, 60, and 100 ppm. The results of this study showed that the incorporation of CNTs increases NO_x emissions by 12.22 %. This might be explained by a shortage of oxygen causing an incomplete reaction and ultimately increasing the NO_x output.

Particulate matter emissions

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

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

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

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

Biodiesel particulate matter emissions were also studied by Verma et al., [132], who looked at the impact of biodiesel alcohol and nanoadditive blends. They assessed different oxygenated additives such as DME (dimethyl ether), DMF (2,5-dimethylfuran), DMC (dimethyl carbonate), triacetin and so on. After doing a comprehensive analysis, this study concluded that the absorption of triacetin can dramatically eliminate the emissions of PM. The findings achieved from the above studies revealed consistent trends with those reported by Dobrzyńska et al. [30]. The authors utilized two types of nanoparticles such as CeO_2 and ferrocene ($Fe(C_5 H_5)_2$) as nanocatalysts with the aim of exploring the effect of nanoadditives in reducing the emission of harmful components into the environment. Different emissions were measured using a chassis dynamometer and the NED (New European Driving) Cycle. The significant efficiency of CeO_2 in reducing emissions means it can be used to reduce PM emissions by as much as 7 %.

Carbon dioxide emissions

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

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

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

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

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

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

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

Smoke emissions

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

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

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

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

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

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

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

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

Effect of nanoparticles on engine combustion

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

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

Exhaust gas temperature

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

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

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

Table 1
The effectiveness of various nanoadditives in engine emissions.

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

(*continued on next page*)

Table 1 (*continued*)

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

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

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

Cylinder pressure

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

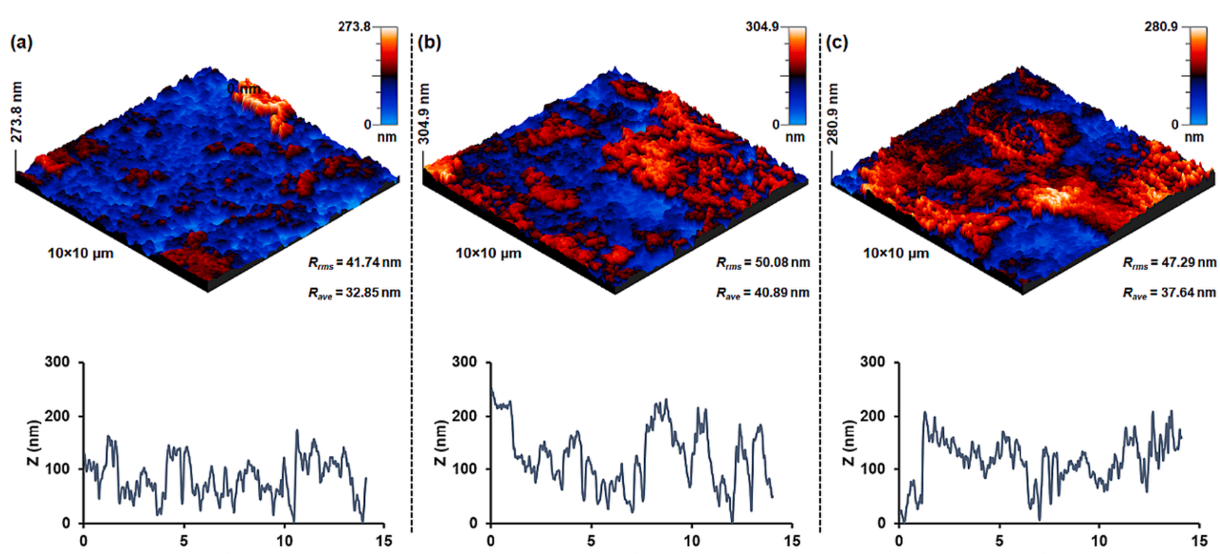

Fig. 5. 3D micrographs with surface profiles illustrating the roughness of surface morphology, and topography of sensitive element–$ZnFe_2O_4$ NPs processed at (a) 600 °C, (b) 800 °C, and (c) 1000 °C [5].

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

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

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

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

Heat release rate (HRR)

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

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

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

Ignition delay

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

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

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

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

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

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

Conclusions and further research

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

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

Prospects and recommendations for future development:

Table 2
Effects of different nanoparticles on engine combustion.

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

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Table 2 (*continued*)

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

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

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CRediT authorship contribution statement

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

Declaration of competing interest

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

Data availability

Data will be made available on request.

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