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A Comprehensive Review on the Applications of Nanometal Additives in Fuels for Internal Combustion Engines

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Nanometal additives have emerged as promising candidates for enhancing the performance and efficiency of internal combustion (IC) engines. The present review provides an overview of their applications and benefits in IC engines. These additives, characterized by their nanoscale size and unique properties, offer advantages such as improved combustion kinetics, enhanced catalytic activity, and reduced emissions. By leveraging their high surface-to-volume ratios and tailored surface chemistry, nanometal additives facilitate more efficient fuel combustion, leading to higher engine efficiency and lower pollutant emissions. Also, this review highlights the importance of nanometal additives in addressing challenges related to fuel quality, combustion efficiency, and environmental impact in IC engines, paving the way for cleaner and more efficient engine technologies.

Keywords: internal combustion engines; fuels; fuel additives; nanometal additives.

1. Introduction

For over a century, internal combustion (IC) engines have dominated the automotive industry, serving as the primary driving force behind automobiles. These engines rely on combusting fuels such as gasoline or diesel within their cylinders to propel vehicles. This combustion generates pressure and heat that drive pistons downward, converting vertical motion into mechanical power [1–3]. The future of IC engines is uncertain. While they face increasing competition from electric vehicles (EVs), which offer greater efficiency and produce lower emissions, IC engines still retain several advantages. They provide longer driving ranges and quicker refueling times compared to EVs. Despite this, the market share of IC-powered vehicles, especially smaller ones, is expected to decline as EV technology advances [4]. Despite this shift, IC engines remain a time-tested technology that has propelled cars for over a century. They offer benefits such as high power density and fuel versatility. However, they suffer from drawbacks such as emissions and lower efficiency [5]. Despite uncertainty surrounding their future, IC engines are likely to continue to be used, particularly in situations where their advantages are significant [6]. Fuel additives improve the performance, efficiency, and longevity of IC engines by addressing various issues related to fuel quality, combustion, emissions, and engine operation. Advances in research and development have highlighted nanomaterials as potential fuel additives due to their unique properties and ability to modify fuel characteristics [7].

The motivation for using nanometal additives in fuels for IC engines stems from their potential to significantly enhance engine performance and reduce harmful emissions [8]. Improved combustion efficiency, increased fuel stability, and ability to mitigate emissions of pollutants such as carbon monoxide (CO), nitrogen oxides (NO_x), and hydrocarbons (HC) are achieved by incorporating nanometal particles into fuel formulations, such as iron, cerium oxide, platinum, or palladium nanoparticles. These additives act as catalysts, promoting more complete fuel combustion and facilitating the conversion of harmful exhaust gases into less harmful substances. Additionally, nanometal additives have the advantage of being lightweight and are effective when used in small quantities, minimizing any adverse impacts on engine mass or performance [9]. Their utilization holds promise for enhancing the efficiency, sustainability, and environmental impact of IC engines, contributing to advancements in automotive and transportation technology.

The literature on nanometal additives in fuels for internal combustion engines extensively discusses their potential benefits in terms of improving engine performance and reducing emissions [8, 10]. Studies have explored various nanometal additives such as iron, cerium oxide, platinum, and palladium nanoparticles, highlighting their catalytic properties and effectiveness in enhancing combustion efficiency and reducing pollutant emissions. However, a significant review gap in the existing literature often lies in the comprehensive evaluation and comparison of different nanometal additives in terms of their cost-effectiveness, mass impact, performance enhancement, and resource availability. While individual studies focus on specific nanometal additives, there is a lack of comprehensive reviews that systematically analyze and compare these additives across multiple dimensions, limiting valuable insights for researchers, industry stakeholders, and policymakers. Therefore, this paper aims to address this gap by offering a comprehensive analysis of nanometal additives in fuels, considering their cost, mass impact, performance enhancement, and resource availability. By doing so, it provides a holistic understanding of their potential applications and implications for internal combustion engine technology. Additionally, this review explores the applications of nanometal additives in IC engines by outlining the types of fuels and additives used.

2. Fuels for IC engines

The different types of fuels used in IC engines are classified as shown in Fig. 1.

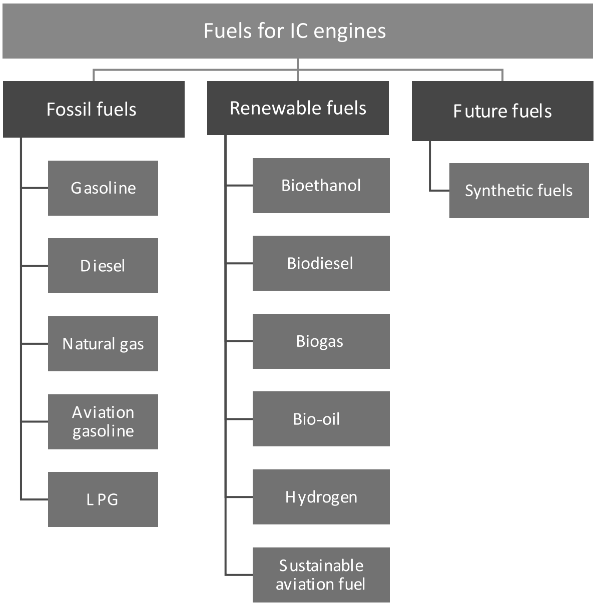

Fig. 1. Fuels for IC engines.

2.1. Fossil fuels

Gasoline, derived from crude oil, is a mixture of hydrocarbons and serves as the primary fuel for spark-ignition (SI) engines. Due to its high octane rating, it has the potential to offer higher compression ratios and greater power output while effectively preventing knocking or premature ignition [11]. However, its combustion releases greenhouse gases and other pollutants, rendering it a non-renewable resource [12].

Diesel fuel is a heavier, greasier liquid than gasoline and is used in compression-ignition (CI) engines. Despite having a lower octane rating, it does not require spark plugs because it ignites on its own when compressed [13]. Although diesel engines are renowned for their tremendous torque and fuel efficiency, they also emit more nitrogen oxides (NO_x) into the atmosphere than gasoline engines [14].

Natural gas is a subterranean blend of methane and other hydrocarbons that burn cleaner than gasoline and diesel [15]. It is becoming increasingly used in passenger vehicles, in addition to being utilized in buses and commercial vehicles. However, its infrastructure is less developed than that of gasoline and diesel, and due of its lower energy density, vehicles need larger tanks to travel the same distance [16].

Aviation gasoline and jet fuel are specialized fuels used in aircraft engines. Avgas is used in piston-engine aircraft, while jet fuel (such as Jet A or Jet A-1) is used in jet turbine engines. These fuels have specific properties tailored to the requirements of aviation engines, including high energy density and low volatility [17].

Propane, also known as liquefied petroleum gas (LPG), is a by product of natural gas processing and petroleum refining. It is commonly used as a fuel for IC engines in vehicles such as forklifts, buses, and taxis. Propane burns cleaner than gasoline or diesel and produces lower emissions.

2.2. Renewable fuels

Ethanol is an alcohol-based fuel that could be mixed with gasoline or utilized in engines that are specifically design for it. It is produced from fermented corn, sugarcane, or another biomass sources [18]. In comparison to gasoline, ethanol emits fewer greenhouse gases during combustion and is a renewable resource. However, if ethanol is not blended properly, it can damage older engines because it has lower energy density than gasoline [19, 20].

Biodiesel is a liquid fuel made from vegetable or animal fats that can be used in diesel engines without modification [21]. In comparison to petroleum diesel, it is a renewable resource whose combustion results in lower greenhouse gas emissions and particulate matter. However, the cost of producing biodiesel may be higher than that of petroleum diesel, and its production could compete with food production [22].

Bio-gas is a renewable energy source produced through the anaerobic digestion of organic materials such as agricultural residues, municipal waste, sewage sludge, and animal manure. It is primarily composed of methane (CH_4) and carbon dioxide (CO_2), with small amounts of other gases such as hydrogen sulfide (H_2S) and trace impurities [23].

Bio-oil, also known as pyrolysis oil or biocrude, is a liquid fuel derived from biomass through a process called pyrolysis [24]. Pyrolysis involves heating organic materials such as wood chips, agricultural residues, or algae, in the absence of oxygen to break them down into a mixture of gases, liquids, and solids. Bio-oil is the liquid fraction obtained from this process.

Hydrogen is an energy carrier rather than a fuel itself. Numerous sources, including renewable ones like solar and wind power, could be used to make it [25].

Vehicles running on hydrogen have no exhaust emissions; however, producing and storing hydrogen can be energy-intensive [26].

Sustainable aviation fuel (SAF) is produced from sustainable biomass feedstocks or renewable hydrogen and can be used as a drop-in replacement for conventional jet fuel in aircraft engines. Table 1 illustrates sources and properties of selected renewable fuels.

TABLE 1. Sources and properties of selected renewable fuels.

Renewable fuel	Sources	Properties
Biodiesel	Typically derived from vegetable oils or animal fats through a process called transesterification.	Biodiesel is biodegradable, non-toxic, and has a high cetane number, which indicates good ignition quality. It has lower sulfur content compared to conventional diesel fuel, reducing emissions of sulfur oxides (SO_x). Biodiesel also acts as a lubricant, potentially reducing engine wear.
Bioethanol	Primarily produced from biomass sources such as corn, sugarcane, or cellulosic materials through fermentation and distillation processes.	Ethanol is a high-octane, renewable fuel that could be blended with gasoline to reduce greenhouse gas emissions and enhance octane ratings. It has a higher oxygen content compared to gasoline, leading to more complete combustion and lower emissions of carbon monoxide (CO) and hydrocarbons (HC). However, ethanol has a lower energy density compared to gasoline, which leads to reduced fuel economy.
Bio-gas	Produced from the anaerobic digestion of organic materials such as agricultural waste, food waste, or sewage.	Bio-gas primarily consists of methane (CH_4) and carbon dioxide (CO_2), with small amounts of other gases such as hydrogen sulfide (H_2S) and nitrogen (N_2). It can be used directly as a fuel for heating, electricity generation, or as a transportation fuel in compressed natural gas (CNG) vehicles. Biogas combustion produces fewer greenhouse gas emissions compared to fossil fuels.
Hydrogen	Hydrogen can be produced through various methods, including electrolysis of water using renewable electricity, reforming of biogas or biomass, or through thermochemical processes.	Hydrogen is a clean-burning fuel that produces only water vapor when combusted in a fuel cell or internal combustion engine. It has a high energy-to-weight ratio, making it suitable for use in fuel cell vehicles or as a feedstock for industrial processes such as ammonia production. However, hydrogen production, storage, and distribution present technical and infrastructure challenges.

2.3. Future fuels

Fuels made from non-fossil fuels, such hydrogen or biomass, are known as synthetic fuels [27]. Synthetic fuels, such as synthetic gasoline, diesel, or jet fuel, can be produced from renewable sources using processes like Fischer–Tropsch synthesis or biomass-to-liquid (BTL) conversion. They can be designed to have desirable qualities, such as minimal emissions or a high-octane rating. However, they have not yet been released to the market and are remain in the early stages of development [28]. The kind of engine, the intended performance, the cost and availability of fuel, and the environmental impact all play a crucial role in the fuel selection process for an IC engine. Future fuel innovations are expected to introduce even more novel and inventive fuels as technology progresses [29, 30].

3. Additives for fuels in IC engines

Fuel additives for IC engines serve various purposes, such as improving fuel efficiency, reducing emissions, preventing corrosion, and enhancing engine performance [31]. Common types include detergents to clean fuel injectors, lubricants to reduce friction, stabilizers to prevent fuel degradation, and octane boosters to increase fuel's octane rating for better performance [32]. Table 2 highlights the various fuel additives used in IC engines.

Table 2. Fuel additives used in IC engines.

Additives	Inferences	Reference
Metal-based additives		
Lead	Used as an octane booster but phased out due to environmental concerns. Carbon monoxide emissions experienced a decrease of 25.6%, nitrogen oxide emissions saw a reduction of 1.4%, and hydrocarbon emissions witnessed a decrease of 0.6%.	[33, 37]
Manganese	Used as an octane enhancer or anti-knock agent in gasoline. Carbon monoxide emissions experienced a decrease of 37%, nitrogen oxide emissions saw a reduction of 4%, and hydrocarbon emissions witnessed a decrease of 1%.	[34, 38]
Iron	Found in some diesel fuel additives as a combustion catalyst or detergent. Carbon monoxide emissions experienced a decrease of 20.6%, nitrogen oxide emissions saw a reduction of 2.6%, and hydrocarbon emissions witnessed a decrease of 1.2%.	[37]
Organic compounds		
Alcohols	Ethanol and methanol are common examples used as oxygenates in gasoline or biodiesel blends. Carbon monoxide emissions experienced a decrease of 12.8%, nitrogen oxide emissions saw a reduction of 11.4%, and hydrocarbon emissions witnessed a decrease of 6.6%.	[38]

TABLE 2. [Cont.].

Additives	Inferences	Reference
Ethers	Methyl tert-butyl ether (MTBE) and ethyl tert-butyl ether (ETBE) are oxygenates used to increase octane and reduce emissions in gasoline. Carbon monoxide emissions experienced a decrease of 10.3%, nitrogen oxide emissions saw a reduction of 12.1%, and hydrocarbon emissions witnessed a decrease of 7.2%.	[39]
Esters	Found in biodiesel and some fuel stabilizers or lubricity improvers. Carbon monoxide emissions experienced a decrease of 11.1%, nitrogen oxide emissions saw a reduction of 10.6%, and hydrocarbon emissions witnessed a decrease of 7.1%.	[40]
Amines	Used in some diesel fuel additives as detergents or corrosion inhibitors. Carbon monoxide emissions experienced a decrease of 12.9%, nitrogen oxide emissions saw a reduction of 10.8%, and hydrocarbon emissions witnessed a decrease of 7.3%.	[41]
Polymeric compounds		
Polyisobutylene (PIB)	Found in some fuel system cleaners and octane boosters. Carbon monoxide emissions experienced a decrease of 14.3%, nitrogen oxide emissions saw a reduction of 12.6%, and hydrocarbon emissions witnessed a decrease of 8.1%.	[42]
Polyetheramine (PEA)	A detergent commonly used in gasoline fuel system cleaners. Carbon monoxide emissions experienced a decrease of 13.6%, nitrogen oxide emissions saw a reduction of 12.3%, and hydrocarbon emissions witnessed a decrease of 7.4%.	[43]
Inorganic compounds		
Nitrates	Used as cetane improvers in diesel fuel additives. Carbon monoxide emissions experienced a decrease of 16.5%, nitrogen oxide emissions saw a reduction of 14.3%, and hydrocarbon emissions witnessed a decrease of 8.1%.	[44]
Sulfur compounds	Found in some diesel fuel additives as lubricity improvers or combustion enhancers. Carbon monoxide emissions experienced a decrease of 15.3%, nitrogen oxide emissions saw a reduction of 14.2%, and hydrocarbon emissions witnessed a decrease of 7.9%.	[45]
Phosphorus compounds	Used as anti-wear agents in some lubricity additives. Carbon monoxide emissions experienced a decrease of 15.8%, nitrogen oxide emissions saw a reduction of 14.4%, and hydrocarbon emissions witnessed a decrease of 7.6%.	[46]
Organometallic compounds		
Ferrocene	Used as an octane booster and anti-knock agent in gasoline. Carbon monoxide emissions experienced a decrease of 13.4%, nitrogen oxide emissions saw a reduction of 12.2%, and hydrocarbon emissions witnessed a decrease of 8.2%.	[47]

TABLE 2. [Cont.].

Additives	Inferences	Reference
Plant-derived compounds		
Fatty acid methyl esters (FAME)	Found in biodiesel and some fuel stabilizers or lubricity improvers. Carbon monoxide emissions experienced a decrease of 16.2%, nitrogen oxide emissions saw a reduction of 13.9%, and hydrocarbon emissions witnessed a decrease of 8.3%.	[48]
Vegetable oils	Sometimes used directly as a fuel or blended with diesel fuel. Carbon monoxide emissions experienced a decrease of 18.2%, nitrogen oxide emissions saw a reduction of 14.1%, and hydrocarbon emissions witnessed a decrease of 8.6%.	[49, 50]
Microbial agents		
Biocides	Used to prevent microbial growth in fuel tanks and systems. Carbon monoxide emissions experienced a decrease of 13.7%, nitrogen oxide emissions saw a reduction of 12.2%, and hydrocarbon emissions witnessed a decrease of 6.7%.	[51]
Surfactants and emulsifiers		
Alkylphenol ethoxylates	Used in some fuel system cleaners and detergents. Carbon monoxide emissions experienced a decrease of 11.3%, nitrogen oxide emissions saw a reduction of 10.1%, and hydrocarbon emissions witnessed a decrease of 5.2%.	[52]
Nanomaterials		
Metal nanoparticles	Used as catalysts to improve combustion efficiency and reduce emissions in IC engines. Carbon monoxide emissions experienced a decrease of 18.5%, nitrogen oxide emissions saw a reduction of 14.3%, and hydrocarbon emissions witnessed a decrease of 8.2%.	[53, 54]
Carbon nanotubes	Studied for their potential to enhance fuel combustion kinetics and increase fuel efficiency. Carbon monoxide emissions experienced a decrease of 17.8%, nitrogen oxide emissions saw a reduction of 14.5%, and hydrocarbon emissions witnessed a decrease of 7.9%.	[34, 55–58]
Graphene	Similar to carbon nanotubes, graphene is researched for its potential to improve combustion efficiency and fuel economy. Carbon monoxide emissions experienced a decrease of 18.1%, nitrogen oxide emissions saw a reduction of 14.2%, and hydrocarbon emissions witnessed a decrease of 8.1%.	[59, 60]
Nanoparticles functionalized with catalytic coatings	Engineered to capture and remove harmful pollutants from exhaust gases. Carbon monoxide emissions experienced a decrease of 19.3%, nitrogen oxide emissions saw a reduction of 14.2%, and hydrocarbon emissions witnessed a decrease of 9.1%.	[61, 62]
Nanofluids	Suspensions of nanoparticles in a base fluid used to improve heat transfer and cooling in engines. Carbon monoxide emissions experienced a decrease of 16.3%, nitrogen oxide emissions saw a reduction of 12.5%, and hydrocarbon emissions witnessed a decrease of 7.3%.	[63]

Using metals in fuel additives offer benefits such as improved fuel efficiency and engine performance. While some metals, such as lead, have historically posed environmental and health risks, advancements in technology and regulatory oversight mitigate these concerns [33]. By exploring safer alternatives, implementing rigorous environmental assessments, and adhering to strict regulations, it is possible to utilize the advantages of metal additives while minimizing their negative impacts on the environment. Such measures ensure that any proposal to use metals in fuels is accompanied by thorough analysis and safeguards, promoting a balance between environmental protection and technological innovation [34].

In recent years, methylcyclopentadienyl manganese tricarbonyl (MMT) has been proposed as a fuel additive for octane improvement. Like other metal-based additives, MMT has the potential to enhance fuel performance [35]. However, concerns have been raised regarding its environmental and health impacts. Manganese emissions from MMT combustion contribute to air pollution and pose health risks, particularly for vulnerable populations. Therefore, any consideration of using MMT as a fuel additive must include a careful analysis of its potential environmental and health consequences, along with measures to effectively mitigate these risks. Despite its octane-boosting properties, the use of MMT must be approached cautiously to ensure that the benefits outweigh any adverse effects on public health and the environment [36].

The emission reductions listed in the Table 2 for each additive represent generalized findings based on average test conditions. In specific situations, the impact of additives may vary, and some additives may cause a temporary increase in emissions under certain engine conditions or in specific vehicle types. These results are based on studies where additives demonstrated beneficial effects in reducing CO, NO_x, and HC emissions, but variations may occur based on engine type, additive concentration, and operating conditions. Further research into the full spectrum of effects on emissions is warranted for a more comprehensive understanding of each additive's performance.

Nanomaterials offer unique advantages in fuel additive applications, including increased surface area, enhanced catalytic activity, and improved thermal and mechanical properties [64]. Their inclusion in fuel additive formulations leads to significant improvements in engine performance, emissions reduction, and fuel efficiency. These materials are used in various combinations and formulations to create fuel additives tailored to specific applications and performance requirements.

4. Nanometal additives in IC engines

Nanomaterials are increasingly being explored and utilized as fuel additives in various industries due to their unique properties and potential benefits. These materials, typically engineered at the nanoscale, offer advantages such as enhanced combustion efficiency, improved fuel stability, and reduced emissions [65]. They function as catalysts, combustion enhancers, or friction modifiers, depending on their specific composition and application. While research in this area is ongoing, some industries, particularly automotive and aviation sectors, are already incorporating nanomaterial-based additives into their fuel formulations to improve engine performance and meet increasingly stringent environmental regulations. However, challenges remain regarding scalability, cost-effectiveness, and potential environmental impacts, necessitating further research and development to optimize the use of nanomaterials as fuel additives on a broader scale.

Nanometal additives exhibit unique properties that make them valuable components in fuel formulations for IC engines. These nanoparticles possess high surface-to-volume ratios, allowing for efficient catalytic activity and enhanced reactivity in combustion processes. Their nanoscale size enables uniform dispersion within fuel matrices, ensuring optimal interaction with fuel molecules and combustion products. Additionally, nanometal additives offer tailored surface chemistry, allowing for precise control over catalytic performance and selectivity. Their exceptional thermal stability and mechanical properties make them resistant to harsh engine operating conditions, ensuring long-lasting effectiveness. Overall, nanometal additives play a vital role in improving combustion efficiency, reducing emissions, and enhancing engine performance in IC engines. Figure 2 illustrates the role of nanometal additives in fuels for IC engines [66].

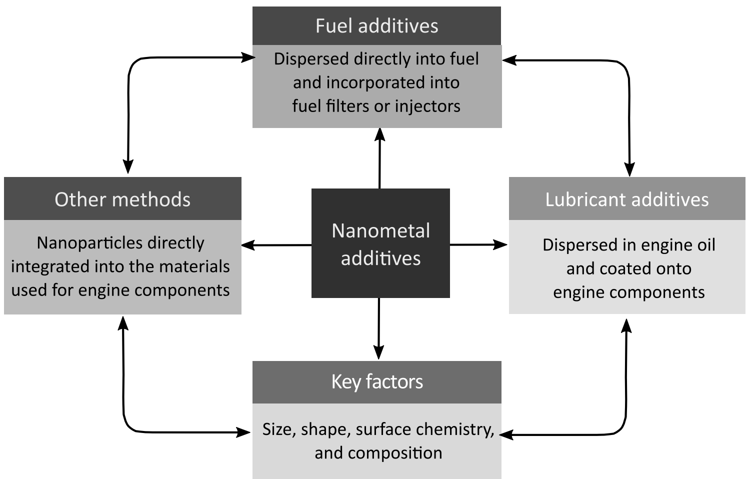

Fig. 2. Role of nanometal additives in fuels for IC engines.

Nanometal additives play a crucial role in modifying both the chemical and physical properties of fuels, offering opportunities for enhancing fuel performance and reducing emissions. Nanometal additives contribute to the following modifications:

Catalytic Activity. Nanometal additives, such as platinum, palladium, or cerium oxide nanoparticles, exhibit high catalytic activity due to their large surface area-to-volume ratio and unique surface properties. These nanoparticles facilitate various chemical reactions, including the oxidation of hydrocarbons, the reduction of nitrogen oxides (NO_x), and the decomposition of harmful pollutants. By promoting more efficient combustion and exhaust gas treatment, nanometal additives modify the chemical composition of fuels, leading to reduced emissions of pollutants and improved fuel efficiency [56, 67].

Combustion Enhancement. Nanometal additives modify the combustion characteristics of fuels by promoting more complete and uniform combustion. Iron nanoparticles, for example, act as combustion catalysts, accelerating the oxidation of fuel molecules and enhancing flame propagation. This results in more efficient energy release and reduced emissions of unburned hydrocarbons (HC) and carbon monoxide (CO). Additionally, nanometal additives improve ignition quality and reduce ignition delay, leading to smoother engine operation and improved overall performance [56].

Stabilization and Oxidation Resistance. Certain nanometal additives, such as cerium oxide nanoparticles, exhibit antioxidant properties that stabilize fuels and protect against oxidative degradation. These nanoparticles scavenge free radicals and reactive oxygen species, preventing the formation of gum, varnish, and other degradation products that impair fuel quality and engine performance. By enhancing fuel stability and oxidation resistance, nanometal additives extend the shelf life of fuels and improve their storage and handling properties [55, 65].

Particle Dispersion and Suspension. Nanometal additives also modify the physical properties of fuels by improving particle dispersion and suspension characteristics (Fig. 3). For example, nanoparticles act as surfactants or dispersants, preventing the agglomeration and settling of particulate matter in fuels. This ensures uniform distribution of additives throughout the fuel matrix, enhancing their effectiveness and ensuring consistent performance over time.

In total, nanometal additives offer a versatile and effective means of modifying the chemical and physical properties of fuels, enabling improvements in combustion efficiency, emission control, and overall fuel performance [68]. Their unique catalytic, stabilizing, and dispersing properties make them valuable tools for addressing challenges related to fuel quality, emissions reduction, and engine optimization in various applications. Uniform nanoparticle size is crucial for thermal efficiency. SEM is used to analyze particle size and crystal structure of titanium dioxide powder ball milled into nanometal additive, and size distribution by intensity is inferred [64] and is shown in Fig. 4.

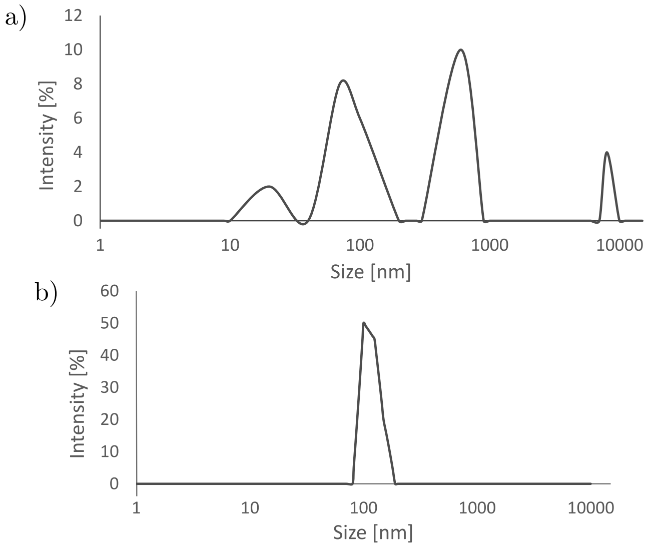

Fig. 3. Particle size distribution of TiO_2 nanoparticles: a) before milling, b) and after milling.

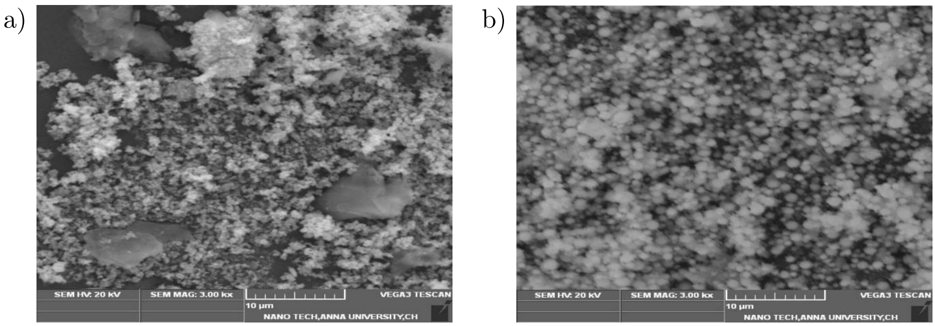

Fig. 4. SEM of TiO_2 nanoparticles: a) before milling, b) and after milling.

4.1. Fuel additives

- **Directly dispersed into fuel:** This is the most popular technique, which usually entails distributing the nanoparticles in an appropriate carrier fluid, such as gasoline or diesel [67]. During combustion, the additives enter the engine and interact with the fuel and air mixture to modify the combustion process [68].
- **Integrated into fuel filters or injector designs:** To introduce nanoparticles into the fuel stream gradually, fuel filters or injector designs might incorporate them. This allows for more regulated distribution and may lessen nanoparticle aggregation [58, 61].

The cost, mass, performance, resource availability and effects of nanometal additives is illustrated in Table 3.

TABLE 3. Cost, mass, performance, resource availability and effects of nanometal additives in fuels for IC engines.

Nanometal additive	Cost	Mass	Performance	Resource availability	Effects	References
Iron nanoparticles	Low cost due to abundant availability of iron.	Lightweight and can be used in small quantities.	Better than diesel fuel in terms of break-specific energy consumption (BSEC) by 3.3% and brake thermal efficiency (BTE) by 3%.	Iron is a widely available and inexpensive resource.	• Enhanced combustion efficiency • Improved fuel stability • Reduced emissions	[66]
Cerium oxide nanoparticles	Moderate to high cost due to limited availability and complex synthesis processes.	Lightweight and can be used in small quantities.	Thermal efficiencies are increased by 1.7 and 2.3%.	Cerium is moderately abundant, but extraction and processing are more complex.	• Catalytic activity for exhaust gas treatment • Reduction in emissions of carbon monoxide (CO) and hydrocarbons (HC) • Enhancement of fuel combustion	[67]
Platinum nanoparticles	High cost due to the scarcity and high demand for platinum.	Lightweight and used in small quantities due to high catalytic activity.	Increased heating value and cetane number slightly, but did not affect physicochemical characteristics. Additionally, cerium acetate hydrate nanoparticles and titanium dioxides significantly reduced pollutant emissions regardless of NO_x emissions.	Platinum is rare and primarily mined in a few regions, making it an expensive and limited resource.	• Catalytic conversion of harmful gases into less harmful substances • Improvement of engine performance and fuel efficiency • Reduction in emissions of carbon monoxide (CO), nitrogen oxides (NO_x), and hydrocarbons (HC)	[68]
Palladium nanoparticles	High cost similar to platinum due to its scarcity and high demand.	Lightweight and used in small quantities due to high catalytic activity.	Efficient in catalytic conversion of harmful gases, reduces emissions and enhances fuel efficiency.	Palladium is scarce and primarily sourced as a by product of platinum and nickel mining.	• Catalytic conversion of harmful gases in exhaust emissions • Reduction in emissions of carbon monoxide (CO), nitrogen oxides (NO_x), and hydrocarbons (HC) • Improvement of fuel efficiency	[59, 68]

4.2. Lubricant additives

Dispersed in engine oil. Nanoparticles can be added to engine oil, similar to how they are used in gasoline additives. In this form, they interact with engine parts, reducing wear and friction.

Coated onto engine components. Certain additives may be thinly coated and applied directly to engine parts, such as cylinder walls or piston rings, to provide wear protection and localized lubrication [69].

4.3. Other methods

Nanoparticles may be included directly into the materials that make up engine components for certain functions. Although it offers a more long-term solution, careful design and material compatibility considerations are needed [70].

4.4. Key factors influencing the effectiveness of nanometal additives

Nanoparticle properties. The way additives interact with fuels, lubricants, and engine parts is influenced by their size, shape, composition, and surface chemistry.

Dispersion and stability. For reliable performance and to minimize any side effects, it is crucial to ensure uniform distribution and avoid agglomeration of nanoparticles within the fuel or oil.

Engine running conditions. The type of gasoline, operating temperature, and pressure all affect how the additives behave and work.

5. Benefits of using nanometal additives

Research and development in the field of nanometal additives are still ongoing, so some of the many and intriguing potential benefits of employing nanometal additions in IC engines may not yet have be fully realized or may have downsides. Below is a summary of the main benefits under investigation, as shown in Fig. 5. Nanometal additives represent an important new technology that could boost IC engine efficiency and performance [62]. These minuscule particles, with a size of less than one hundred nanometers, have unique qualities that can help with some of the main problems encountered by traditional engines encounter.

Certain nanometal additives can act as catalysts, improving combustion and lowering emissions of pollutants such as NO_x and particulate matter. Both better public health and cleaner air may benefit from this. Moreover, nanometal additives can enhance fuel combustion, resulting in more complete fuel burning, which improves fuel efficiency and reduces fuel consumption [63–65]. By act-

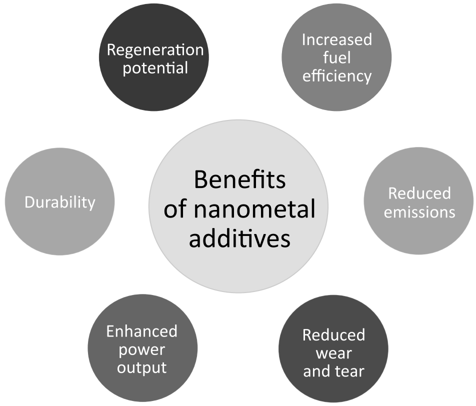

Fig. 5. Benefits of nanometal additives.

ing as lubricants and lowering friction between engine parts, some nanometal additives may be able to extend engine life and reduce maintenance costs [67]. Additionally, certain additives enhance the thermal conductivity of engine components, facilitating better heat transmission and increased power production [68, 69]. Table 4 shows the various nanometal additives used in fuels for IC engines.

Table 4. Nanometal additives used in fuels for IC engines.

Nanometal additives	Size [nm]	Functions	Reference
Aluminum oxide (Al_2O_3)	20	Engine emission testing reduced CO, HC, and smoke emissions by 83.3%, 40.9%, and 69.2%.	[70, 74]
Carbon nanotubes (CNTs)	6	Improves the engine parts' thermal conductivity, carbon nano tubes emit 58 PPM HC.	[71, 102]
Cerium oxide (CeO_2)	15	Compared to diesel, reduced brake specific fuel consumption by 2.5%, NO_x emissions by 15.7%, and smoke opacity by 34.7%.	[72, 65]
Cobalt nanoparticles	80	Catalyst for hydrogen production and combustion reactions.	[73]
Copper nanoparticles	40	Catalyst for CO and hydrocarbon oxidation, improving exhaust emissions.	[74]
Gold nanoparticles	20	Catalyst for CO oxidation, reducing emissions.	[75]

Table 4. [Cont.].

Nanometal additives	Size [nm]	Functions	Reference
Graphene and graphene oxide (GO)	150	Enhance thermal conductivity and provide extra features including adsorption of fuel additives and tribological enhancement, just as carbon nanotubes (CNTs).	[76]
Iron nanoparticles	130	There is a 3–6% volumetric reduction in HC emissions, 6–12% in CO, and 4–11.16% in NO_x.	[66, 79]
Nickel nanoparticles	8	Ni–O particles in base gasoline boost brake thermal efficiency by 6.3%.	[78]
Palladium nanoparticles	75	Catalyst for CO and hydrocarbon oxidation, improving exhaust emissions.	[79]
Platinum nanoparticles	15	Catalyst for NO_x reduction in diesel exhaust.	[80]
Rhodium nanoparticles	16	Catalyst for NO_x reduction in gasoline engines, improving emissions.	[81]
Silver nanoparticles	63	Have antibacterial qualities that may inhibit the growth of microorganisms in gasoline and engine oil, improving engine cleanliness and lowering wear. Nanoparticles reduce HC by 4.5% and NO_x by 13%.	[82, 45]
Titanium metal Oxide (TiO_2)	15	The maximum efficiency was 33.18% with 125 PPM titanium oxide nanoparticles, which is 3.01% greater than diesel.	[83]
Zinc nanoparticles	90	Reduce wear and friction as a lubricant additive and demonstrates photocatalytic qualities that may allow engine parts to self-clean. Anti-wear additive, reducing friction and extending engine life.	[84]

6. Engine modifications to improve diesel thermal efficiency due to nanometal additives

Improving diesel engine thermal efficiency involves various modifications aimed at increasing the engine's ability to convert fuel energy into mechanical work while minimizing energy losses with the help of nanometal additives [85, 86]. Here are some key modifications:

6.1. Higher compression ratio

Increasing the compression ratio of the diesel engine improves its thermal efficiency by maximizing the expansion ratio during the power stroke. This leads to better utilization of the fuel's energy and higher thermal efficiency [87–89].

6.2. Improved combustion chamber design

Optimal combustion chamber designs, such as re-entrant bowl or swirl chamber designs, promote more efficient fuel-air mixing and combustion [90]. This ensures more complete combustion of the fuel-air mixture, reducing unburned hydrocarbons and particulate matter emissions while improving thermal efficiency [91].

6.3. Advanced injection systems

Upgrading to advanced fuel injection systems, such as common rail injection or electronic unit injection, allows for finer control over fuel delivery timing, quantity, and pressure [92]. This enables more precise fuel metering and combustion control, resulting in improved thermal efficiency and reduced emissions [93].

6.4. Variable valve timing

Implementing variable valve timing (VVT) systems allows for optimal timing of intake and exhaust valve events based on engine operating conditions. This improves volumetric efficiency, reduce pumping losses, and enhance combustion efficiency, leading to higher thermal efficiency [94].

6.5. Turbocharging or supercharging

Adding a turbocharger or supercharger to the diesel engine increases the intake air pressure [95], allowing more air to be drawn in, compressed, and mixed with fuel during the combustion process. This results in higher power output and improves thermal efficiency [96].

6.6. Exhaust gas recirculation (EGR)

Utilizing exhaust gas recirculation systems reduce peak combustion temperatures and NOx emissions by recirculating a portion of exhaust gas back into the intake air [38, 97]. This improves thermal efficiency by reducing heat losses associated with high-temperature combustion [98].

6.7. Waste heat recovery

Implementing waste heat recovery systems, such as turbo-compounding or organic Rankine cycle (ORC) systems, allows for the capture and utilization of waste heat from exhaust gases or engine coolant for power generation or thermal management [99]. This improves overall system efficiency and reduces fuel consumption [100].

6.8. Friction reduction

Minimizing internal friction losses with low-friction materials, optimized lubrication systems, and improved bearing designs improves thermal efficiency by reducing mechanical losses within the engine [101–105].

6.9. Advanced engine control systems

Implementing advanced engine control systems with real-time monitoring and optimization algorithms allows for precise control of engine operating parameters, optimizing fuel-air mixture ratios, combustion timing, and other factors to maximize thermal efficiency under varying load and speed conditions [106].

Diesel engines achieve higher thermal efficiency, resulting in improved fuel economy, reduced emissions, and overall better performance with the addition of nanometal additives by incorporating these modifications [107].

7. Challenges and future prospects

Nanoadditives offer promising opportunities for improving the performance, efficiency, and environmental impact of IC engines [108–110]. However, they also present several challenges that need to be addressed for widespread adoption. Let us explore both the challenges and prospects.

7.1. Challenges

The manufacturing of nanoadditives could be expensive due to the complexity of production processes and the high cost of raw materials [111]. This limits their widespread adoption, especially in cost-sensitive industries such as automotive manufacturing [112–115].

Scaling up the production of nanoadditives to meet industrial demand could be challenging. Manufacturing processes may need to be optimized to ensure consistent quality and quantity of nanoadditives on a large scale [116, 117].

Regarding safety and environmental concerns, there is still limited understanding of the potential health and environmental impacts of nanoadditives [118].

Research is needed to assess their toxicity, biodegradability, and long-term environmental effects [119, 120].

Nanoadditives may interact with engine components or fuel systems in unpredictable ways, potentially causing damage or reducing performance. Compatibility testing is crucial to ensure that nanoadditives do not adversely affect engine operation or durability [121].

Additionally, nanoadditives may require regulatory approval before they could be used in commercial products. Meeting regulatory requirements for safety, emissions, and performance could be a lengthy and costly process [122].

Finally, nanoadditives tend to agglomerate or form clusters, which reduce their effectiveness and uniform distribution in fuel or lubricants. Developing effective dispersion techniques is essential to maximize the benefits of nanoadditives [123–125].

7.2. Future prospects

Nanoadditives have the potential to improve engine efficiency by reducing friction, enhancing combustion, and optimizing thermal management [119, 126]. These improvements lead to increased fuel efficiency and reduced emissions, contributing to sustainability goals.

Nanoadditives can help reduce harmful emissions such as particulate matter, nitrogen oxides, and greenhouse gases [116]. By promoting cleaner combustion and improving exhaust aftertreatment systems, nanoadditives contribute to cleaner air and reduced environmental impact [127].

Furthermore, nanoadditives enhance the durability and longevity of engine components by reducing wear, corrosion, and thermal degradation [121]. This results in longer service intervals, reduced maintenance costs, and an extended engine lifespan.

Nanoadditives can also be engineered to exhibit specific properties tailored to different applications and performance requirements [122]. This versatility allows for customized solutions to address specific challenges in IC engines, such as lubrication, heat transfer, or emissions control [128].

Ongoing research in nanomaterials science continues to yield new materials with novel properties and functionalities [129]. Future advancements may lead to the development of even more advanced nanoadditives with enhanced performance and versatility.

While nanoadditives hold great promise for improving IC engine performance and sustainability, addressing challenges such as cost, safety, and compatibility will be crucial for their successful implementation in real-world applications [130]. Continued research, innovation, and collaboration across disciplines will be essential to unlock the full potential of nanoadditives in IC engines [131].

8. Conclusion

Nanometal additives have emerged as promising enhancements for IC engines, offering unique catalytic properties and tailored surface chemistry to optimize combustion processes. This review provides an overview of the applications of nanometal additives in IC engines, focusing on their catalytic functions, dispersion mechanisms, and impact on engine performance. The following factors have been inferred from the detailed literature analysis.

- Compared to diesel, hydrogen production and combustion catalysts, as well as nanoparticles reduce CO, HC, NO_x, and smoke opacity.
- CNTs and Ni-O particles improve engine thermal conductivity, reducing fuel consumption and enhancing brake thermal efficiency.
- CO, hydrocarbons, and NO_x emissions are reduced by catalysts; this improves exhaust emissions and engine performance.
- Nanoparticles and additives minimize emissions and are antibacterial, improving engine cleanliness and durability. They have also self-cleaning and wear-resistant capabilities, thereby improving engine performance and longevity.
- The review concludes that incorporating sophisticated technology like carbon nano tubes, catalysts, and nanoparticles into engine systems significantly reduce pollutants, improve fuel efficiency, and extend engine lifespan. These advances may help solve environmental issues and boost engine performance.

Additionally, challenges and prospects associated with the utilization of nanometal additives in IC engines are discussed, paving the way for further research and development in this promising field.

Competing interests statement

The authors have no competing interests to declare.

References

1. Kalghatgi G., Is it really the end of internal combustion engines and petroleum in transport?, *Applied Energy*, **225**: 965–974, 2018, https://doi.org/10.1016/j.apenergy.2018.05.076

2. Kirkpatrick A.T., *Internal Combustion Engines: Applied Thermosciences*, John Wiley & Sons, New Jersey 2020.

3. Jessin J.C., Maheswaran P., Syed Abuthahir M., Vijayan K., Design and analysis of an internal combustion engine piston head to increase the torque on crankshaft,

International Journal of Innovative Research in Science, Engineering and Technology, **55**: 7898–7904, 2016, https://doi.org/10.15680/IJIRSET.2016.0505220.

4. Abdul-Manan A.F.N., Uncertainty and differences in GHG emissions between electric and conventional gasoline vehicles with implications for transport policy making, *Energy Policy*, **87**: 1–7, 2015, https://doi.org/10.1016/j.enpol.2015.08.029.

5. Faizal M., Feng S.Y., Zureel M.E., Sinidol B.E., Wong D., Jian G.K., A review on challenges and opportunities of electric vehicles (EVS), *Journal of Mechanical Engineering Research and Developments*, **42**(4): 130–137, 2019, https://doi.org/10.26480/jmerd.04.2019.127.134.

6. Sierzchula W., Bakker S., Maat K., Van Wee B., The competitive environment of electric vehicles: An analysis of prototype and production models, *Environmental Innovation and Societal Transitions*, **2**: 49–65, 2012, https://doi.org/10.1016/j.eist.2012.01.004.

7. Wolfram P., Lutsey N., Electric vehicles: Literature review of technology costs and carbon emissions, *International Council on Clean Transportation*, Washington, DC, 2016, https://theicct.org/wp-content/uploads/2021/06/ICCT_LitRvw_EV-tech-costs_201607.pdf (accessed September 4, 2024).

8. Hallegatte S., Shah A., Brown C., Lempert R., Gill S., Investment decision making under deep uncertainty – Application to climate change, *World Bank Policy Research Working Paper*, 6193, 2012.

9. Pollet B.G., Staffell I., Shang J.L., Current status of hybrid, battery and fuel cell electric vehicles: From electrochemistry to market prospects, *Electrochimica Acta*, **84**: 235–249, 2012, https://doi.org/10.1016/j.electacta.2012.03.172.

10. Awad O.I., Mamat R., Ibrahim T.K., Hammid A.T., Yusri I.M., Hamidi M.A., Yusop A.F., Overview of the oxygenated fuels in spark ignition engine: Environmental and performance, *Renewable and Sustainable Energy Reviews*, **91**: 394–408, 2018, https://doi.org/10.1016/j.rser.2018.03.107.

11. Felix A.V., Combustion of bio-fluids as an alternative energy source: prospects and challenges, *International Journal of Social Science and Humanities Research*, **8**(2): 150–178, 2020 (available at: www.researchpublish.com).

12. Das A.K., Sahu S.K., Panda A.K., Current status and prospects of alternate liquid transportation fuels in compression ignition engines: A critical review, *Renewable and Sustainable Energy Reviews*, **161**: 112358, 2022, https://doi.org/10.1016/j.rser.2022.112358.

13. Ahmad J., *Octane Requirement Increase Arising from the Use of Lead-Free Fuel*, Doctoral dissertation, Aston University,1989.

14. Westbrook C.K., Biofuels combustion, *Annual Review of Physical Chemistry*, **64**: 201–219, 2013, https://doi.org/10.1146/annurev-physchem-040412-110009.

15. Tyagi U., Aslam M., Sarma A.K., Green anti-knock agents for enhancement of gasoline performance, [in:] *Green Gasoline: A Green Spark Transportation Fuel*, Aslam M., Makteda, S., Sarma A.K. [Eds.], pp. 238–259, Royal Society of Chemistry, Cambridge, UK, 2023, https://doi.org/10.1039/BK9781837670079-00238.

16. Aljaberi H.A., Hairuddin A.A., Aziz N.A., The use of different types of piston in an HCCI engine: A review, *International Journal of Automotive and Mechanical Engineering*, **14**(2): 4348–4268, 2017, https://doi.org/10.15282/ijame.14.2.2017.17.0346.

17. Verma S., Sharma B., Ahmad J., Dwivedi G., Nandan G., Impact assessment of ethanol as fuel for engine operation, *Materials Today: Proceedings*, **52**(2, Part 1): 6115–6120, 2018, https://doi.org/10.1016/j.matpr.2017.12.217.

18. Niculescu R., Clenci A., Iorga-Siman V., Review on the use of diesel–biodiesel–alcohol blends in compression ignition engines, *Energies*, **12**(7): 1194, 2019, https://doi.org/10.3390/en12071194.

19. Yun Y., Alcohol fuels: current status and future direction, [in:] *Alcohol Fuels-Current Technologies and Future Prospect*, Yun Y. [Ed.], IntechOpen, Rijeka 2020, https://doi.org/10.5772/intechopen.89788.

20. Awad O.I., Mamat R., Ali O.M., Sidik N.A.C., Yusaf T., Kadirgama K., Kettner M., Alcohol and ether as alternative fuels in spark ignition engine: A review, *Renewable and Sustainable Energy Reviews*, **82**(Part 3): 2586–2605, 2018, https://doi.org/10.1016/j.rser.2017.09.074.

21. Kumar M., The performance analysis of an SI engine with various blends of ethanol-gasoline, *TD-317*, 2007.

22. Hill J., Nelson E., Tilman D., Polasky S., Tiffany D., Environmental economic and energetic costs and benefits of biodiesel and ethanol biofuels, *Proceedings of the National Academy of Sciences*, **103**(30): 11206–11210, 2006, https://doi.org/10.1073/pnas.0604600103.

23. Balat M., Potential alternatives to edible oils for biodiesel production – A review of current work, *Energy Conversion and Management*, **52**(2): 1479–1492, 2011, https://doi.org/10.1016/j.enconman.2010.10.011.

24. Luque R., Lovett J.C., Datta B., Clancy J., Campelo J.M., Romero A.A., Biodiesel as feasible petrol fuel replacement: A multidisciplinary overview, *Energy & Environmental Science*, **3**(11): 1706–1721, 2010, https://doi.org/10.1039/C0EE00085J.

25. Hasan M.M., Rahman M.M., Performance and emission characteristics of biodiesel–diesel blend and environmental and economic impacts of biodiesel production: A review, *Renewable and Sustainable Energy Reviews*, **74**: 938–948, 2017, https://doi.org/10.1016/j.rser.2017.03.045.

26. Mishra V.K., Goswami R., A review of production properties and advantages of biodiesel, *Biofuels*, **9**(2): 273–289, 2018, https://doi.org/10.1080/17597269.2017.1336350.

27. Hutchings G., Davidson M., Atkins P., Collier P., Jackson N., Morton A., Muskett M., Rosseinsky M., Styring P., Thornley P., Williams C., *Sustainable synthetic carbon-based fuels for transport, Policy Briefing*, The Royal Society, London 2019, http://royalsociety.org/synthetic-fuels.

28. Demirbas A., Biofuels securing the planet's future energy needs, *Energy Conversion and Management*, **50**(9): 2239–2249, 2009, https://doi.org/10.1016/j.enconman.2009.05.010.

29. Xing H., Stuart C., Spence S., Chen H., Alternative fuel options for low-carbon maritime transportation: Pathways to 2050, *Journal of Cleaner Production*, **297**: 126651, 2021, https://doi.org/10.1016/j.jclepro.2021.126651.

30. Grope N., Schröder O., Krahl J., Müller-Langer F., Schröder J., Matthess E., *Survey on Advanced Fuels for Advanced Engines*, *Task 52: Fuels for Efficiency*, *Project Report*, Advanced Motor Fuels, 2018, https:://www.iea-amf.org/app/webroot/files/file/Annex%20Reports/AMF_Annex_52.pdf (acessed September 6, 2024).

31. Abdellatief T.M., Ershov M.A., Savelenko V.D., Kapustin VM., Makhova U.A., Klimov N.A., Olabi A.G., Advanced progress and prospects for producing high-octane gasoline fuel toward market development: State-of-the-art and outlook, *Energy & Fuels*, **37**(23): 18266–18290, 2023, https://doi.org/10.1021/acs.energyfuels.3c02541.

32. Gibbs L., Schütze A., Motor gasoline, [in:] *Fuels and Lubricants Handbook: Technology Properties Performance and Testing*, Totten G.E, Shah R.J., Forester D.R. [Eds.], pp. 61–88, ASTM International, West Conshohocken, PA, 2003, https://doi.org/10.1520/MNL3720170009.

33. Badia J.H., Ramírez E., Bringué R., Cunill F., Delgado J., New octane booster molecules for modern gasoline composition, *Energy & Fuels*, **35**(14): 10949–10997, 2021, https://doi.org/10.1021/acs.energyfuels.1c00912.

34. Di Girolamo M., Brianti M., Marchionna M., Octane enhancers, [in:] *Handbook of Fuels: Energy Sources for Transportation*, Elvers B., Schütze A. [Eds.], pp. 403–430, Wiley Online Books, 2021, https://doi.org/10.1002/9783527813490.ch14.

35. Hoekman S.K., Leland A., Literature review on the effects of organometallic fuel additives in gasoline and diesel fuels, *SAE International Journal of Fuels and Lubricants*, **11**(1): 105–124, 2018, https://doi.org/10.4271/04-11-01-0005.

36. Yanowitz J., Christensen E., McCormick R.L., *Utilization of renewable oxygenates as gasoline blending components*, National Renewable Energy Lab. (NREL), Golden, CO, 2011, https://doi.org/10.2172/1024518.

37. Ribeiro N.M., Pinto A.C., Quintella C.M., Da Rocha G.O., Teixeira L.S., Guarieiro L.L., de Andrade J.B., The role of additives for diesel and diesel blended ethanol or biodiesel fuels: A review, *Energy & Fuels*, **21**(4): 2433–2445, 2007, https://doi.org/10.1021/ef070060r.

38. Agarwal A.K., Biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines, *Progress in Energy and Combustion Science*, **33**(3): 233–271, 2007, https://doi.org/10.1016/j.pecs.2006.08.003.

39. Yee K.F., Mohamed A.R., Tan S.H., A review on the evolution of ethyl tert-butyl ether (ETBE) and its future prospects, *Renewable and Sustainable Energy Reviews*, **22**: 604–620, 2013, https://doi.org/10.1016/j.rser.2013.02.016.

40. Hu J., Du Z., Li C., Min E., Study on the lubrication properties of biodiesel as fuel lubricity enhancers, *Fuel*, **84**(12–13): 1601–1606, 2005, https://doi.org/10.1016/j.fuel.2005.02.009.

41. Groysman A., Fuel additives, [in:] *Corrosion in Systems for Storage and Transportation of Petroleum Products and Biofuels: Identification Monitoring and Solutions*, pp. 23–41, Springer Netherlands, Dordrecht, 2014, https://doi.org/10.1007/978-94-007-7884-9_2.

42. Demirbas A., Balubaid M.A., Basahel A.M., Ahmad W., Sheikh M.H., Octane rating of gasoline and octane booster additives, *Petroleum Science and Technology*, **33**(11): 1190–1197, 2015, https://doi.org/10.1080/10916466.2015.1050506.

43. Wang W., Wang W., Zhu Z., Hu X., Qiao F., Yang J., Liu D., Chen P., Zhang Q., Quantitation of polyetheramines as the active components of detergent additives in gasoline by the ninhydrin reaction, *Fuel*, **338**: 127275, 2023, https://doi.org/10.1016/j.fuel.2022.127275.

44. Suppes G.J., Chen Z., Rui Y., Mason M., Heppert J.A., Synthesis and cetane improver performance of fatty acid glycol nitrates, *Fuel*, **78**(1): 73–81, 1999, https://doi.org/10.1016/S0016-2361(98)00126-4.

45. Hazrat M.A., Rasul M.G., Khan M.M.K., Lubricity improvement of the ultra-low sulfur diesel fuel with the biodiesel, *Energy Procedia*, **75**: 111–117, 2015, https://doi.org/10.1016/j.egypro.2015.07.619.

46. Peale L.F., Messina J., Ackerman B., Sasin R., Swern D., Evaluation of long-chain phosphorus compounds as lubricity additives, *ASLE Transactions*, **3**(1): 48–54, 1960, https://doi.org/10.1080/05698196008972386.

47. Fenard Y., Song H., Dauphin R., Vanhove G., An engine-relevant kinetic investigation into the anti-knock effect of organometallics through the example of ferrocene, *Proceedings of the Combustion Institute*, **37**(1): 547–554, 2019, https://doi.org/10.1016/j.proci.2018.06.135.

48. Geller D.P., Goodrum J.W., Effects of specific fatty acid methyl esters on diesel fuel lubricity, *Fuel*, **83**(17–18): 2351–2356, 2004, https://doi.org/10.1016/j.fuel.2004.06.004.

49. Sidibé S.S., Blin J., Vaitilingom G., Azoumah Y., Use of crude filtered vegetable oil as a fuel in diesel engines state of the art: Literature review, *Renewable and Sustainable Energy Reviews*, **14**(9): 2748–2759, 2010, https://doi.org/10.1016/j.rser.2010.06.018.

50. Franco Z., Nguyen Q.D., Flow properties of vegetable oil–diesel fuel blends, *Fuel*, **90**(2): 838–843, 2011, https://doi.org/10.1016/j.fuel.2010.09.044.

51. Bautista L.F., Vargas C., González N., Molina M.C., Simarro R., Salmerón A., Murillo Y., Assessment of biocides and ultrasound treatment to avoid bacterial growth in diesel fuel, *Fuel Processing Technology*, **152**: 56–63, 2016, https://doi.org/10.1016/j.fuproc.2016.06.002.

52. Ying G.G., Williams B., Kookana R., Environmental fate of alkylphenols and alkylphenol ethoxylates – A review, *Environment International*, **28**(3): 215–226, 2002, https://doi.org/10.1016/S0160-4120(02)00017-X.

53. Khan S., Dewang Y., Raghuwanshi J., Shrivastava A., Sharma V., Nanoparticles as fuel additive for improving performance and reducing exhaust emissions of internal combustion engines, *International Journal of Environmental Analytical Chemistry*, **102**(2): 319–341, 2022, https://doi.org/10.1080/03067319.2020.1722810.

54. Zhang X., Chi N.T.L., Xia C., Khalifa A.S., Brindhadevi K., Role of soluble nanocatalyst and blends for improved combustion performance and reduced greenhouse gas emissions in internal combustion engines, *Fuel*, **312**: 122826, 2022, https://doi.org/10.1016/j.fuel.2021.122826.

55. Mei D., Zuo L., Adu-Mensah D., Li X., Yuan Y., Combustion characteristics and emissions of a common rail diesel engine using nanoparticle-diesel blends with carbon nanotube and molybdenum trioxide, *Applied Thermal Engineering*, **162**: 114238, 2019, https://doi.org/10.1016/j.applthermaleng.2019.114238.

56. Ooi J.B., Kau C.C., Manoharan D.N., Wang X., Tran M.V., Hung Y.M., Effects of multi-walled carbon nanotubes on the combustion, performance, and emission characteristics of a single-cylinder diesel engine fueled with palm-oil biodiesel-diesel blend, *Energy*, **281**: 128350, 2023, https://doi.org/10.1016/j.energy.2023.128350.

57. Kumar S., Nehra M., Kedia D., Dilbaghi N., Tankeshwar K., Kim K.H., Carbon nanotubes: A potential material for energy conversion and storage, *Progress in energy and combustion science*, **64**: 219–253, 2018, https://doi.org/10.1016/j.pecs.2017.10.005.

58. Markov V., Kamaltdinov V., Zherdev A., Furman V., Sa B., Neverov V., Study on the possibility of improving the environmental performance of diesel engine using carbon nanotubes as a petroleum diesel fuel additive, *Energies*, **12**(22): 4345, 2019, https://doi.org/10.3390/en12224345.

59. El-Seesy A.I., Hassan H., Investigation of the effect of adding graphene oxide, graphene nanoplatelet, and multiwalled carbon nanotube additives with n-butanol-Jatropha methyl ester on a diesel engine performance, *Renewable Energy*, **132**: 558–574, 2019, https://doi.org/10.1016/j.renene.2018.08.026.

60. Ooi J.B., Ismail H.M., Tan B.T., Wang X., Effects of graphite oxide and single-walled carbon nanotubes as diesel additives on the performance, combustion, and emission characteristics of a light-duty diesel engine, *Energy*, **161**: 70–80, 2018, https://doi.org/10.1016/j.energy.2018.07.062.

61. Beni A.A., Jabbari H., Nanomaterials for environmental applications, *Results in Engineering*, **15**: 100467, 2022, https://doi.org/10.1016/j.rineng.2022.100467.

62. Xu H., Hong Q., Li J., Liao Y., Huang W., Qu Z., Yan N., Heterogeneous reaction mechanisms and functional materials for elemental mercury removal from industrial flue gas, *ACS ES&T Engineering*, **1**(10): 1383–1400, 2021, https://doi.org/10.1021/acsestengg.1c00180.

63. Kumar A., Subudhi S., Preparation, characterization and heat transfer analysis of nanofluids used for engine cooling, *Applied Thermal Engineering*, **160**: 114092, 2019, https://doi.org/10.1016/j.applthermaleng.2019.114092.

64. Kumar M.U., Sivaganesan S., Dhanasekaran C., Parthiban A., Analysis of performance, combustion and emission parameters in di diesel engine by using mahua methyl ester along with nano metal additives titanium dioxide, *Materials Today: Proceedings*, **37**(2): 3404–3410, 2021, https://doi.org/10.1016/j.matpr.2020.09.277.

65. Said Z., Assad M.E.H., Hachicha A.A., Bellos E., Abdelkareem M.A., Alazaizeh D.Z., Yousef B.A.A., Enhancing the performance of automotive radiators using nanofluids, *Renewable and Sustainable Energy Reviews*, **112**: 183–194, 2019, https://doi.org/10.1016/j.rser.2019.05.052.

66. Debbarma S., Misra R.D., Effects of iron nanoparticles blended biodiesel on the performance and emission characteristics of a diesel engine, *Journal of Energy Resources Technology*, **139**(4): 042212, 2017, https://doi.org/10.1115/1.4036543.

67. Jiaqiang E., Zhang Z., Chen J., Pham M.H., Zhao X., Peng Q., Zhang B., Yin Z., Performance and emission evaluation of a marine diesel engine fueled by water biodiesel-diesel emulsion blends with a fuel additive of a cerium oxide nanoparticle, *Energy Conversion and Management*, **169**: 194–205, 2018, https://doi.org/10.1016/j.enconman.2018.05.073.

68. Yaşar A., Keskin A., Yildizhan Ş., Uludamar E., Emission and vibration analysis of diesel engine fuelled diesel fuel containing metallic based nanoparticles, *Fuel*, **239**: 1224–1230, 2019, https://doi.org/10.1016/j.fuel.2018.11.113.

69. Candeia R.A., Silva M.C.D., Carvalho Filho J.R., Brasilino M.G.A., Bicudo T.C., Santos I.M.G., Souza A.G., Influence of soybean biodiesel content on basic properties of biodiesel–diesel blends, *Fuel*, **88**(4): 738–743, 2009, https://doi.org/10.1016/j.fuel.2008.10.015.

70. Wei J., Yin Z., Wang C., Lv G., Zhuang Y., Li X., Wu H., Impact of aluminium oxide nanoparticles as an additive in diesel-methanol blends on a modern DI diesel engine, *Applied Thermal Engineering*, **185**: 116372, 2021, https://doi.org/10.1016/j.applthermaleng.2020.116372.

71. Firrisa M.T., van Duren I., Voinov A., Energy efficiency for rapeseed biodiesel production in different farming systems, *Energy Efficiency*, **7**: 79–95, 2014, https://doi.org/10.1007/s12053-013-9201-2.

72. Dinesha P., Kumar S., Rosen M.A., Effects of particle size of cerium oxide nanoparticles on the combustion behavior and exhaust emissions of a diesel engine powered by biodiesel/diesel blend, *Biofuel Research Journal*, **8**(2): 1374–1383, 2021, https://doi.org/10.18331/BRJ2021.8.2.3.

73. Mosarof M.H., Kalam M.A., Masjuki H.H., Ashraful A.M., Rashed M.M., Imdadul H.K., Monirul I.M., Implementation of palm biodiesel based on economic aspects, performance, emission, and wear characteristics, *Energy Conversion and Management*, **105**: 617–629, 2015, https://doi.org/10.1016/j.enconman.2015.08.020.

74. Yang C.Y., Fang Z., Li B., Long Y.-F., Review and prospects of Jatropha biodiesel industry in China, *Renewable and Sustainable Energy Reviews*, **16**(4): 2178–2190, 2012, https://doi.org/10.1016/j.rser.2012.01.043.

75. Chauhan B.S., Kumar N., Cho H.M., A study on the performance and emission of a diesel engine fueled with Jatropha biodiesel oil and its blends, *Energy*, **37**(1): 616–622, 2012, https://doi.org/10.1016/j.energy.2011.10.043.

76. Datta A., Mandal B.K., Use of Jatropha biodiesel as a future sustainable fuel, *Energy Technology & Policy*, **1**(1): 8–14, 2014, https://doi.org/10.1080/23317000.2014.930723.

77. Thapa S., Indrawan N., Bhoi P.R., An overview on fuel properties and prospects of Jatropha biodiesel as fuel for engines, *Environmental Technology & Innovation*, **9**: 210–219, 2018, https://doi.org/10.1016/j.eti.2017.12.003.

78. Srinidhi C., Madhusudhan A., A diesel engine performance investigation fuelled with nickel oxide nano fuel-methyl ester, *International Journal of Renewable Energy Research*, **7**(2): 676–681, 2017, https://doi.org/10.20508/ijrer.v7i2.5566.g7046.

79. Bošnjaković M., Sinaga N., The perspective of large-scale production of algae biodiesel, *Applied Sciences*, **10**(22): 8181, 2020, https://doi.org/10.3390/app10228181.

80. Barua P., Chowdhury T., Chowdhury H., Islam R., Hossain N., Potential of power generation from chicken waste-based biodiesel, economic and environmental analysis: Bangladesh's perspective, *SN Applied Sciences*, **2**(3): 330, 2020, https://doi.org/10.1007/s42452-020-2113-9.

81. Liaquat A.M., Masjuki H.H., Kalam M.A., Fattah I.R., Hazrat M.A., Varman M., Mofijur M., Shahabuddin M., Effect of coconut biodiesel blended fuels on engine performance and emission characteristics, *Procedia Engineering*, **56**: 583–590, 2013, https://doi.org/10.1016/j.proeng.2013.03.163.

82. Sunil S., Chandra Prasad B.S., Kakkeri S., Suresha, Studies on titanium oxide nanoparticles as fuel additive for improving performance and combustion parameters of CI engine fueled with biodiesel blends, *Materials Today: Proceedings*, **44**(Part 1): 489–499, 2021, https://doi.org/10.1016/j.matpr.2020.10.200.

83. Ferreira M.I., Reinhardt C.F., Allelopathic weed suppression in agroecosystems: A review of theories and practices, *African Journal of Agricultural Research*, **11**(6): 450–459, 2016, https://doi.org/10.5897/AJAR2015.10580.

84. Kunz Ch., Sturm D.J., Varnholt D., Walker F., Gerhards R., Allelopathic effects and weed suppressive ability of cover crops, *Plant, Soil and Environment*, **62**(2): 60–66, 2016, https://doi.org/10.17221/612/2015-PSE.

85. Singh B., Kaur J., Singh K., Production of biodiesel from used mustard oil and its performance analysis in internal combustion engine, *Journal of Energy Resources Technology*, **132**(3): 031001, 2010, https://doi.org/10.1115/1.4002203.

86. Mitrović P.M., Stamenković O.S., Banković-Ilić I., Djalović I.G., Nježić Z.B., Farooq M., Siddique K.H.M., Veljković V.B., White mustard (*Sinapis alba L.*) oil in biodiesel production: A review, *Frontiers in plant science*, **11**: 299, 2020, https://doi.org/10.3389/fpls.2020.00299.

87. Aslan V., An overview of biodiesel produced from 2nd generation feedstock: Mustard seed types, *BioEnergy Research*, **16**(3): 1380–1400, 2023, https://doi.org/10.1007/s12155-022-10536-9.

88. Udayakumar M., Sivaganesan S., Sivamani S., One-factor-at-a-time approach for optimization of biodiesel synthesis from crude mahua oil, *International Journal of Mechanical Engineering*, **7**(1): 1577–1584, 2022.

89. Udayakumar M., Sivaganesan S., Sivamani S., Process optimization of KOH catalyzed biodiesel production from crude sunflower-mahua oil, *Biofuels*, **13**(8): 1031–1039, 2022, https://doi.org/10.1080/17597269.2022.2071068.

90. Antolín G., Tinaut F.V., Briceño Y., Castaño V., Pérez C., Ramírez A.I., Optimisation of biodiesel production by sunflower oil transesterification, *Bioresource Technology*, **83**(2): 111–114, 2002, https://doi.org/10.1016/S0960-8524(01)00200-0.

91. Thirumarimurugan M., Sivakumar V.M., Xavier A.M., Prabhakaran D., Kannadasan T., Preparation of biodiesel from sunflower oil by transesterification, *International Journal of Bioscience Biochemistry and Bioinformatics*, **2**(6): 441, 2012, https://doi.org/10.7763/IJBBB.2012.V2.151.

92. Udayakumar M., Sivaganesan S., Sivamani S., Performance and emissions of lemon peel oil biodiesel powered single cylinder direct injection diesel engine loaded with ceria nanoparticles additives and stabilized zirconia coating, *Materials Today: Proceedings*, **66**(Part 4): 1994–2000, 2022, https://doi.org/10.1016/j.matpr.2022.05.441.

93. Shanmugam M., Sathiyamurthy S., Rajkumar G., Saravanakumar S., Tamil Prabakaran S., Shaisundaram V.S., Effect of thermal barrier coating in CI engines fueled with Citrus Medica (Citron) peel oil biodiesel dosed with cerium oxide nanoparticle, *Materials Today: Proceedings*, **37**(Part 2): 1943–1956, 2021, https://doi.org/10.1016/j.matpr.2020.07.485.

94. Öztürk E., Performance emissions combustion and injection characteristics of a diesel engine fuelled with canola oil–hazelnut soapstock biodiesel mixture, *Fuel Processing Technology*, **129**: 183–191, 2015, https://doi.org/10.1016/j.fuproc.2014.09.016.

95. Ciubota-Rosie C., Ruiz J.R., Ramos M.J., Pérez Á., Biodiesel from *Camelina sativa*: A comprehensive characterisation, *Fuel*, **105**: 572–577, 2013, https://doi.org/10.1016/j.fuel.2012.09.062.

96. Ong H.C., Mahlia T.M.I., Masjuki H.H., Norhasyima R.S., Comparison of palm oil, *Jatropha curcas* and *Calophyllum inophyllum* for biodiesel: A review, *Renewable and Sustainable Energy Reviews* **15**(8): 3501–3515, 2011, https://doi.org/10.1016/j.rser.2011.05.005.

97. Arumugam A., Ponnusami V.J.R.E., Biodiesel production from *Calophyllum inophyllum* oil a potential non-edible feedstock: An overview, *Renewable Energy*, **131**: 459–471, 2019, https://doi.org/10.1016/j.renene.2018.07.059.

98. Demirbas A., Importance of biodiesel as transportation fuel, *Energy Policy*, **35**(9): 4661–4670, 2007, https://doi.org/10.1016/j.enpol.2007.04.003.

99. Ghanati S.G., Doğan B., Yeşilyurt M.K., The effects of the usage of silicon dioxide SiO_2 and titanium dioxide TiO_2 as nano-sized fuel additives on the engine characteristics in diesel engines: A review, *Biofuels*, **15**(2): 229–243, 2023, https://doi.org/10.1080/17597269.2023.2221882.

100. Ali Z.A.A.A., Takhakh A.M., Al-Waily M., A review of use of nanoparticle additives in lubricants to improve its tribological properties, *Materials Today: Proceedings*, **52**(Part 3): 1442–1450, 2022, https://doi.org/10.1016/j.matpr.2021.11.193.

101. Dhahad H.A., Hamadi A.S., Ali S.A., Effect of aluminum oxide nanoparticles fuel additives on the performance and emissions of diesel engine, *Engineering and Technology Journal*, **359**(Part A, No. 9): 956–960, 2017.

102. Tewari P., Doijode E., Banapurmath N.R., Yaliwal V.S., Experimental investigations on a diesel engine fuelled with multiwalled carbon nanotubes blended biodiesel fuels, *International Journal of Emerging Technology and Advanced Engineering*, **33**: 72–76, 2013.

103. Saxena V., Kumar N., Saxena V.K., A comprehensive review on combustion and stability aspects of metal nanoparticles and its additive effect on diesel and biodiesel fuelled CI engine, *Renewable and Sustainable Energy Reviews*, **70**: 563–588, 2017, https://doi.org/10.1016/j.rser.2016.11.067.

104. Giordano S., Adamo P., Spagnuolo V., Vaglieco B.M., Instrumental and biomonitoring of heavy metal and nanoparticle emissions from diesel engine exhaust in controlled environment, *Journal of Environmental Sciences*, **22**(9): 1357–1363, 2010, https://doi.org/10.1016/S1001-0742(09)60262-X.

105. Chacko N., Jeyaseelan T., Comparative evaluation of graphene oxide and graphene nanoplatelets as fuel additives on the combustion and emission characteristics of a diesel engine fuelled with diesel and biodiesel blend, *Fuel Processing Technology*, **204**: 106406, 2020, https://doi.org/10.1016/j.fuproc.2020.106406.

106. Afzal A., Ağbulut Ü., Soudagar M.E.M., Razak R.K.A., Buradi A., Saleel C.A., Blends of scum oil methyl ester alcohols silver nanoparticles and the operating conditions affecting the diesel engine performance and emission: An optimization study using Dragon fly algorithm, *Applied Nanoscience*, **11**: 2415–2432, 2021, https://doi.org/10.1007/s13204-021-02046-5.

107. Rajak U., Ağbulut Ü., Veza I., Dasore A., Saridemir S., Verma T.N., Numerical and experimental investigation of CI engine behaviours supported by zinc oxide nanomaterial along with diesel fuel, *Energy*, **239**(Part E): 122424, 2022, https://doi.org/10.1016/j.energy.2021.122424.

108. Canale L.C.F., Xu G., Liang H., Liu J., Totten G.E., Surface engineered coatings and surface additive interactions for boundary film formation to reduce frictional losses in the automotive industry: A review, *SAE Technical paper*, 2005-01-2180, 2005, https://doi.org/10.4271/2005-01-2180.

109. Kotia A., Chowdary K., Srivastava I., Ghosh S.K., Ali M.K.A., Carbon nanomaterials as friction modifiers in automotive engines: recent progress and perspectives, *Journal of Molecular Liquids,* **310**: 113200, 2020, https://doi.org/10.1016/j.molliq.2020.113200.

110. Xie S., Wang Z., Tan W., Zhu Y., Collier S., Ma L., Ehrlich S.N., Xu P., Yan Y., Xu T., Deng J., Liu F., Highly active and stable palladium catalysts on novel ceria–alumina supports for efficient oxidation of carbon monoxide and hydrocarbons, *Environmental Science & Technology*, **55**(11): 7624–7633, 2021, https://doi.org/10.1021/acs.est.1c00077.

111. Bae W.B., Kim D.Y., Byun S.W., Lee S.J., Kuk S.K., Kwon H.J., Lee H.C., Hazlett M.J., Liu C., Kim Y.J., Kim M., Kang S.B., Direct NO decomposition over Rh-supported catalysts for exhaust emission control, *Chemical Engineering Journal*, **475**: 146005, 2023, https://doi.org/10.1016/j.cej.2023.146005.

112. Ali M.K.A., Fuming P., Younus H.A., Abdelkareem M.A., Essa F.A., Elagouz A., Xianjun H., Fuel economy in gasoline engines using Al_2O_3/TiO_2 nanomaterials as nanolubricant additives, *Applied Energy*, **211**: 461–478, 2018, https://doi.org/10.1016/j.apenergy.2017.11.013.

113. Wozniak M., Batory D., Siczek K., Ozuna G., Changes in total friction in the engine friction in timing chain transmissions and engine emissions due to adding TiO_2 nanoparticles to engine oil, *Emission Control Science and Technology*, **6**: 358–379, 2020, https://doi.org/10.1007/s40825-020-00167-x.

114. Udayakumar M., Sivamani S., Devandiran E., Cerium oxide as an additive in biodiesel/diesel fueled internal combustion engines: A concise review, *International Journal of Mechanical Engineering*, **7**(1): 5954–5959, 2022.

115. Rohrer G., Predictive synthesis and characterization of oxide films with metastable structures, Plenary Lecture delivered on Room Town & Country – Session P.L. at 45th International Conference on Metallurgical Coatings and Thun Films, April 23–27, 2018, San Diego, CA.

116. Roy O., Sharif A., Industrial implementation of polymer-nanocomposites, [in:] *Advanced Polymer Nanocomposites. Science, Technology and Applications*, Hoque M.E., Ramar K., Sharif A. [Eds.], pp. 537–546, Woodhead Publishing, 2022, https://doi.org/10.1016/B978-0-12-824492-0.00005-2.

117. Rahman M., Islam K.S., Dip T.M., Chowdhury M.F.M., Debnath S.R., Hasan S.M.M., Sakib M.S., Saha T., Padhye R., Houshyar S., A review on nanomaterial-based additive manufacturing: Dynamics in properties, prospects, and challenges, *Progress in Additive Manufacturing*, **9**(4): 1197–1224, 2024, https://doi.org/10.1007/s40964-023-00514-8.

118. Bolan S., Sharma S., Mukherjee S., Zhou P., Mandal J., Srivastava P., Hou D., Edussuriya R., Vithanage M., Truong V.K., Chapman J., Xu Q., Zhang T., Bandara P., Wijesekara H., Rinklebe J., Wang H., Siddique K.H.M., Kirkham M.B., Bolan N., The distribution, fate, and environmental impacts of food additive nanomaterials in soil and aquatic ecosystems, *Science of the Total Environment*, **916**: 170013, 2024, https://doi.org/10.1016/j.scitotenv.2024.170013.

119. Ashraf S.A., Siddiqui A.J., Elkhalifa A.E.O., Khan M.I., Patel M., Alreshidi M., Moin A., Singh R., Snoussi M., Adnan M., Innovations in nanoscience for the sustainable development of food and agriculture with implications on health and environment, *Science of the Total Environment*, **768**: 144990, 2021, https://doi.org/10.1016/j.scitotenv.2021.144990.

120. Bumbudsanpharoke N., Ko S., Nano-food packaging: An overview of market migration research and safety regulations, *Journal of Food Science*, **80**(5): R910–R923, 2015, https://doi.org/10.1111/1750-3841.12861.

121. Liu Q., Ding X., Pang Y., Cao Y., Lei J., Wu J., Zhang T., New insights into the safety assessment of quantum dots: potential release pathways, environmental transformations, and health risks, *Environmental Science: Nano*, **9**(9): 3277–3311, 2022, https://doi.org/10.1039/D2EN00252C.

122. Fei L., Bilal M., Qamar S.A., Imran H.M., Riasat A., Jahangeer M., Ghafoor M., Ali N., Iqbal H.M.N., Nano-remediation technologies for the sustainable mitigation of persistent organic pollutants, *Environmental Research*, **211**: 113060, 2022, https://doi.org/10.1016/j.envres.2022.113060.

123. Ashraf A., Shafi W.K., Ul Haq M.I., Raina A., Dispersion stability of nano additives in lubricating oils – An overview of mechanisms, theories, and methodologies, *Tribology-Materials Surfaces Interfaces*, **16**(1): 34–56, 2022, https://doi.org/10.1080/17515831.2021.1981720.

124. Pownraj C., Valan Arasu A., Effect of dispersing single and hybrid nanoparticles on tribological, thermo-physical, and stability characteristics of lubricants: A review, *Journal of Thermal Analysis and Calorimetry*, **143**(2): 1773–1809, 2021, https://doi.org/10.1007/s10973-020-09837-y.

125. Soudagar M.E.M., Nik-Ghazali N.N., Kalam M.A., Badruddin I.A., Banapurmath N.R., Akram N., The effect of nano-additives in diesel-biodiesel fuel blends: A comprehensive review on stability, engine performance, and emission characteristics, *Energy Conversion and Management*, **178**: 146–177, 2018, https://doi.org/10.1016/j.enconman.2018.10.019.

126. Dhanola A., Gajrani K.K., Novel insights into graphene-based sustainable liquid lubricant additives: A comprehensive review, *Journal of Molecular Liquids*, **386**: 122523, 2023, https://doi.org/10.1016/j.molliq.2023.122523.

127. Kumar M.U., Sivaganesan S., Dhanasekaran C., Parthiban A., Analysis of performance, combustion, and emission parameters in DI diesel engine by using Mahua methyl ester along with nano metal additives titanium dioxide, *Materials Today: Proceedings*, **37**(Part 2): 3404–3410, 2021, https://doi.org/10.1016/j.matpr.2020.09.277.

128. Vickram S., Manikandan S., Deena S.R., Mundike J., Subbaiya R., Karmegam N., Jones S., Yadav K.K., Chang S.W., Ravindran B., Awasthi M.K., Advanced biofuel production policy and technological implementation of nano-additives for sustainable

environmental management – A critical review, *Bioresource Technology*, **387**: 129660, 2023, https://doi.org/10.1016/j.biortech.2023.129660.

129. Farid M.U., Kharraz J.A., Sun J., Boey M.-W., Riaz M.A., Wong P.W., Jia M., Zhang X., Deka B.J., Khanzada N.K., Guo J., An A.K., Advancements in nanoenabled membrane distillation for a sustainable water-energy-environment nexus, *Advanced Materials*, **36**(17): 2307950, 2023, https://doi.org/10.1002/adma.202307950.

130. Wu H., Fahy W.P., Kim S., Kim H., Zhao N., Pilato L., Kafi A., Bateman S., Koo J.H., Recent developments in polymers/polymer nanocomposites for additive manufacturing, *Progress in Materials Science*, **111**: 100638, 2020, https://doi.org/10.1016/j.pmatsci.2020.100638.

131. Zhang N., Song X., Jiang H., Tang C.Y., Advanced thin-film nanocomposite membranes embedded with organic-based nanomaterials for water and organic solvent purification: A review, *Separation and Purification Technology*, **269**: 118719, 2021, https://doi.org/10.1016/j.seppur.2021.118719.

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