

Review Paper

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

Udayakumar MOHAN*, Selvaraju SIVAMANI

*College of Engineering and Technology, Engineering Department,
University of Technology and Applied Sciences*

Salalah, Oman

*Corresponding Author e-mail: racudayakumar@gmail.com

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.



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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 impli-

cations 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.

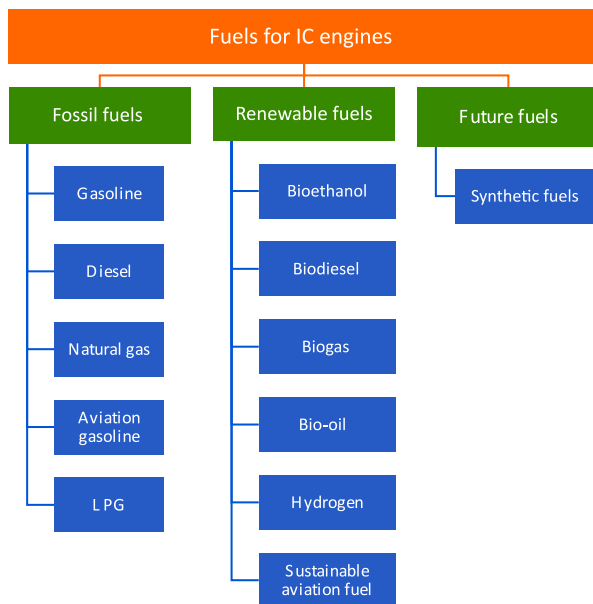


FIG. 1. Fuels for IC engines.

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
<i>Metal-based additives</i>		
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]
<i>Organic compounds</i>		
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]
<i>Polymeric compounds</i>		
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]
<i>Inorganic compounds</i>		
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]
<i>Organometallic compounds</i>		
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
<i>Plant-derived compounds</i>		
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]
<i>Microbial agents</i>		
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]
<i>Surfactants and emulsifiers</i>		
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]
<i>Nanomaterials</i>		
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].

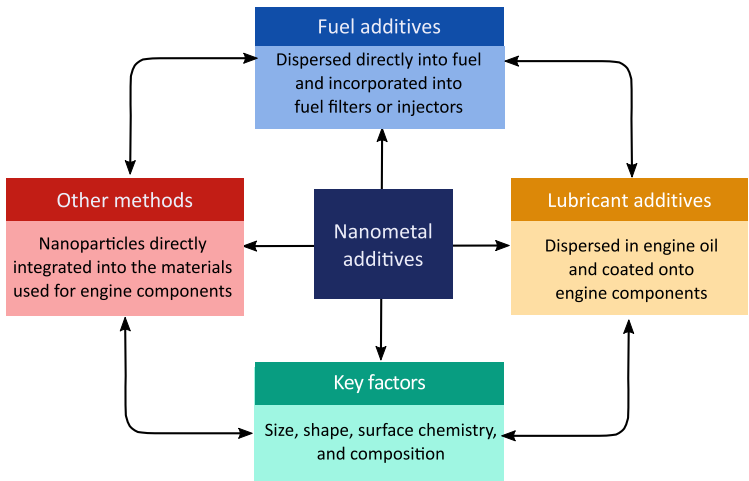


FIG. 2. Role of nanometal additives in fuels for IC engines.

Nanometal additives play a crucial role in modifying both the chemical and physical properties of fuels, offering opportunities for enhancing fuel perfor-

mance 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.

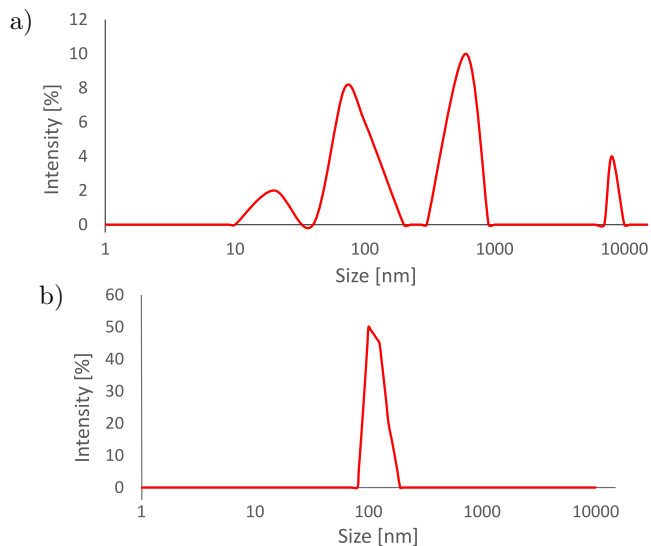


FIG. 3. Particle size distribution of TiO_2 nanoparticles: a) before milling, b) and after milling.

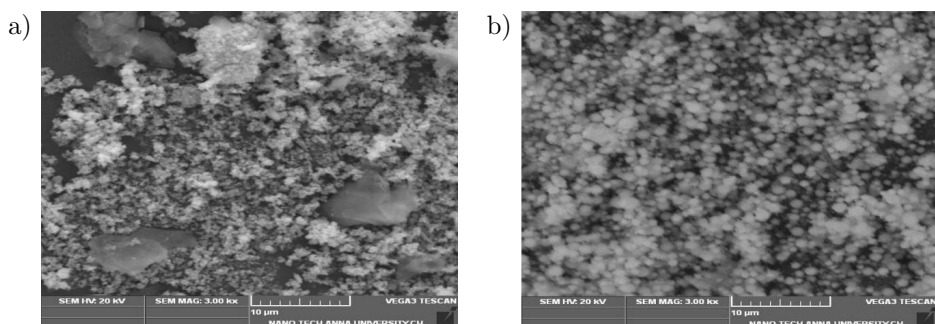


FIG. 4. SEM of TiO_2 nanoparticles: a) before milling, b) and after milling.

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 been 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.

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-

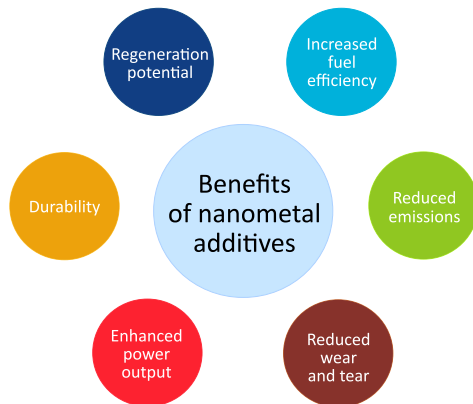


FIG. 5. Benefits of nanometal additives.

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:

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].

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].

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].

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].

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].

Exhaust gas recirculation (EGR). Utilizing exhaust gas recirculation systems reduce peak combustion temperatures and NO_x 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].

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].

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].

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.

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