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Nanotechnology-driven Fuel Additives for Improved Performance, Optimized Combustion, and Reduced Emissions

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ABSTRACT

Rising global energy demand, combined with the need to minimize environmental pollution, has driven the development of advanced fuel technologies. One such approach is the use of nanotechnology (particularly nanomaterials in the form of nano-additives) as an effective strategy for increasing fuel efficiency and reducing emissions. The present paper provides a comprehensive review of how nanotechnology-based fuel additives can be employed to optimize combustion in IC engines and reduce pollutant emissions into the environment. Nano-additives have a high surface area-to-volume ratio and are considered catalytic in nature; thus, they can significantly alter critical fuel properties such as cetane number, viscosity, and volatility. When added to traditional or bio-based fuels, nanoparticles such as Al_2O_3, TiO_2, CeO_2, and other carbon-based compounds enhance combustion by promoting faster and more complete oxidation, as well as by improving thermal conductivity. These effects result in increased thermal efficiency, shorter ignition delay, and significant reductions in carbon monoxide (CO), unburned hydrocarbons (HC), and particulate matter (PM) emissions. The fundamental processes through which nano-additives influence engine performance, including the enhancement of fuel atomization, improvements in combustion processes, and the ability to quench soot formation, were also examined. Overall, the application of nanotechnology in fuel design has the potential to be revolutionary, and this study outlines a pathway towards achieving greater efficiency and cleaner engine systems as part of the transition to green transportation solutions.

Keywords: Nano-additives; Performance; Emissions; Combustion.

1. INTRODUCTION

The transportation and energy industries worldwide have been struggling to find ways and means to balance increasing energy demands with the need to reduce environmental harm. Greenhouse gases are primarily produced by internal combustion (IC) engines, which still constitute the majority of the global vehicle fleet. These gases include carbon monoxide (CO), unburned hydrocarbons (HC), nitrogen oxides (NO_x), and particulate matter (PM). As traditional methods for improving engine efficiency and reducing emissions approach their technical limits, there is an urgent need to develop new solutions. In this context, nanotechnology has emerged as a groundbreaking field, offering advanced techniques to enhance fuel properties and combustion processes (Hamzah *et al.* 2024; Mofijur *et al.* 2024).

The distinctive nano-additives are very small in size, measured in nanometers, and have an extremely large surface area-to-volume ratio. This means they possess both catalytic and thermophysical properties, making them highly useful as fuel additives. Nanoparticles, including aluminum oxide (Al_2O_3), titanium oxide (TiO_2), cerium oxide (CeO_2), and carbon-based nanostructures, when added to conventional or alternative fuels such as biodiesel, significantly impact key fuel properties. The benefits include improvements in cetane number, viscosity, volatility, and ignition characteristics. Such changes have been proven to promote complete and efficient fuel combustion, thereby enhancing engine performance, reducing fuel consumption, and lowering emissions of CO, HC, and PM. However, their effect on NO_x emissions remains inconsistent and depends on factors like particle type, concentration, and engine operating conditions with nanoparticles (Modi *et al.* 2024).

This work provides an extensive review of nanotechnology-based fuel additives and their effects on enhancing the combustion process, improving fuel use, and reducing emissions in IC engines. The physicochemical processes by which nanoparticles influence atomization, combustion kinetics, and pollutant formation are examined. The introduction of two nano-additives, aluminum oxide and cerium oxide nanoparticles, in algae biodiesel, effectively reduced the brake-specific fuel consumption (Amala and Arunraj, 2024). Furthermore, the paper highlights some of the

most pertinent aspects of using nano-additives, including dispersion stability, economic viability, and possible health and environmental effects. The results highlight the potential of nanotechnology to restructure the fuel formulation procedures and support the global transition towards cleaner and more efficient energy systems.

Table 1. Nano-additives and their roles in fuels

Nanoparticle	Description and Role	Key Benefits	Reference
Cerium oxide (CeO_2)	Acts as an oxygen buffer and oxidation promoter, aiding in more complete fuel combustion	Significantly reduces PM and CO emissions, improves BTE, and supports cleaner and more efficient burning	(Caamal *et al.* 2025)
Aluminum oxide (Al_2O_3)	Acts as a combustion catalyst by improving heat transfer within the engine cylinder	Boosts thermal conductivity, enhances combustion efficiency, and helps lower HC and CO emissions	(Kumar *et al.* 2021)
Iron oxide (Fe_2O_3)	Known for both magnetic and catalytic effects, it supports more efficient combustion reactions	Helps reduce CO and HC emissions while enhancing overall combustion efficiency	(Nouri *et al.* 2021)
Zinc oxide (ZnO)	Functions as both a catalyst and an antioxidant, stabilizing fuel while promoting faster combustion	Improves fuel stability and accelerates the combustion process for better energy conversion	(Adawy, 2023)
Titanium dioxide (TiO_2)	Supports catalytic oxidation and controls soot formation, especially under high-temperature conditions	Reduces ignition delay and minimizes particulate emissions, leading to cleaner exhaust gases	(Khujamberdiev and Cho, 2024)
Carbon Nanotubes (CNTs)	Improves atomization and heat transfer due to their high surface area and thermal properties	Leads to finer fuel spray, better air–fuel mixing, and increased combustion rate	(Ninawe and Tariq, 2021)
Copper oxide (CuO)	Speeds up oxidation reactions during combustion, promoting quicker and more efficient fuel burn	Enhances combustion speed and reduces overall fuel consumption	(Muniyappan and Krishnaiah, 2024)

2. FUNDAMENTALS OF NANO-ADDITIVES IN FUEL APPLICATIONS

The integration of nano-additives into fuel systems marks a significant advancement in fuel technology, offering innovative solutions to long-standing issues of engine performance and emission control. Nano-additives are specially engineered materials with one or more dimensions smaller than 100 nm. Unlike conventional additives, their unique physicochemical properties, such as high surface area-to-volume ratios, enhanced catalytic activity, and quantum scale effects, allow them to mix more effectively with fuel components and combustion environments than traditional additives (Lv *et al.* 2022). Once incorporated into various fuel types, including fossil fuels like diesel and gasoline, as well as renewable fuels like biodiesel and ethanol blends, nano-additives play several important roles. They promote complete and uniform combustion, leading to increased brake thermal efficiency (BTE) and reduced emissions of harmful pollutants such as HC, CO, and PM. Some nanoparticles, such as cerium oxide (CeO_2), enhance these effects by acting as oxygen buffers, supplying oxygen during combustion to support more efficient oxidation (Mohan *et al.* 2023). Besides combustion improvement, nano-additives impact key fuel properties like viscosity, volatility, and cetane number, which facilitate better fuel atomization and spraying, especially in CI engines. Improved atomization results in more homogeneous air-fuel mixtures, reduced ignition delay, and smoother overall combustion. Adding nano-additives to fuel offers dual benefits: boosting engine efficiency while simultaneously reducing environmental emissions. However, their effectiveness depends on factors such as dispersion stability, compatibility with the base fuel, and performance under different engine conditions. Therefore, further research and development are essential to optimize their use in sustainable energy applications (Ul-Haq *et al.* 2024b). Table 1 lists the most commonly used nano-additives in fuels along with their respective functions.

3. CLASSIFICATION AND CHARACTERISTICS OF NANOPARTICLES

Nanoparticles used in the fuel industry can be classified based on their chemical composition, structural design, and activity properties. The main categories include metal oxide nanoparticles, carbon-based nanostructures, elemental metal nanoparticles, and composite nanoparticles. Each group provides unique benefits for improving combustion efficiency and reducing emissions in IC engines. This forms the fundamental basis for understanding how to classify their use in relation to the suitability for specific engine operating conditions and fuels (Sajid *et al.* 2025).

It is in the form of a metal oxide nanoparticle, which includes Al_2O_3, TiO_2, CeO_2, ZnO, and Fe_2O_3. The materials are involved in advancing combustion by enhancing the oxidation reaction, thereby reducing ignition delay and improving the overall conversion efficiency. Notably, cerium oxide is known for its ability to readily absorb and release oxygen, making the combustion process more complete and cleaner (Ghazaly and Abdulhameed, 2023).

Carbon-based nanomaterials have gained prominence because of their high thermal conductivity and excellent structural qualities (carbon nanotubes, graphene oxide, and fullerenes). These properties enhance atomization, spray formation, and heat transfer during combustion. As a result, they facilitate the creation of more homogeneous air-fuel mixtures and reduce soot formation. Less commonly used metal nanoparticles, such as copper (Cu), nickel (Ni), and silver (Ag), also exhibit significant catalytic activity, which accelerates combustion and minimizes ignition delay. Additionally, composite nanoparticles created from combining two or more materials, like CeO_2-ZrO_2, are designed to leverage synergistic effects, including improved heat resistance and extended catalytic activity at high temperatures (Elkelawy *et al.* 2023).

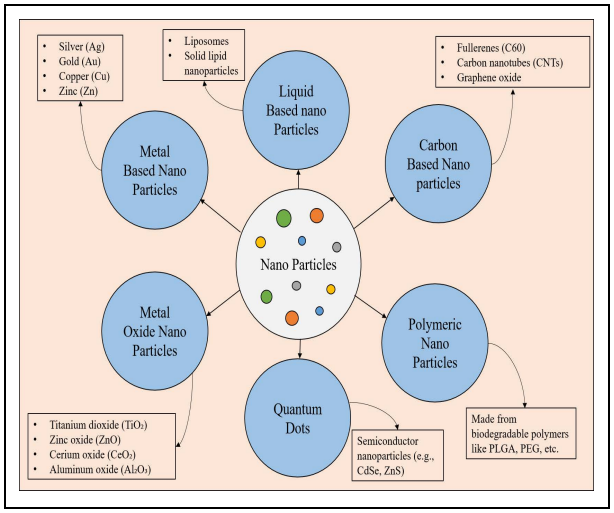


Fig. 1: Classification and characteristics of nanoparticles

Nanoparticles' inherent characteristics largely determine their effectiveness when used as a fuel additive. They have a much higher surface area-to-volume ratio than the typical engine vessel, which means they provide many active sites for chemical reactions, leading to more complete and efficient fuel combustion. The thermal conductivity of certain nanoparticles, particularly metal oxides and carbon-based particles, facilitates improved heat distribution in the combustion chamber, thereby enhancing the reaction rate. Additionally, the size and shape of the particles (spherical, rod-like, or tubular) affect the uniformity of dispersion in the fuel and reactivity. Smaller particles tend to distribute more evenly, providing consistent catalytic activity throughout the fuel medium (Dewangan *et al.* 2023).

In practical applications, the stability and compatibility of nanoparticles with base fuels must be ensured. The challenge with nanoparticles is poor dispersion, injection, or fouling, as well as inconsistent combustion operation. To address this, several stabilization methods are typically used, such as applying surfactants, surface functionalization, and ultrasonic dispersion. Ultimately, achieving optimal performance requires careful selection of nanoparticle type, size, concentration, and dispersion strategy to reduce emissions and ensure reliable engine operation (Das *et al.* 2024). Fig. 1 provides a visual overview of the classification and key characteristics of nanoparticles.

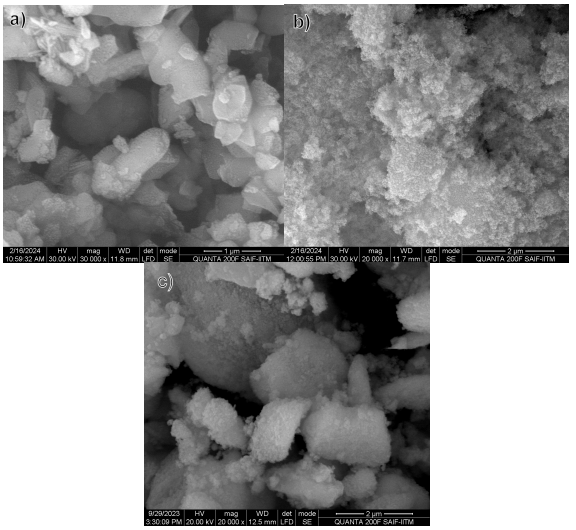


Fig. 2: SEM images of: (a) Al_2O_3, (b) TiO_2 and (c) CeO_2 nanoparticles

Scanning Electron Microscopy (SEM) is a form of imaging whereby the surface of a sample is scanned using a fine beam of high-energy electrons. These electrons combine with atoms on the material to start generating signals, which are trapped to form a highly magnified and most detailed image of the surface of the sample. Sample SEM images of Al_2O_3, TiO_2, and CeO_2 nanoparticles, as shown in Fig. 2, were taken by the authors in a separate study and are included here to illustrate the typical surface morphology and structural features of these additives. The images highlight particle shape, size distribution, and agglomeration tendencies, which are key factors influencing dispersion in fuel and subsequent combustion performance. Although not generated specifically for this paper, the SEM analysis provides relevant visual context for understanding how these nanoparticles function in biodiesel-diesel blends.

4. IMPACT OF NANO-ADDITIVES ON ENGINE CHARACTERISTICS

Incorporation of nanotechnology into fuel systems is an important innovation that takes the IC engines a notch higher. The use of nano-additives, the use of tiny nanoparticles, whose peculiar physicochemical features can be explained by their nano-size and a high surface-to-volume ratio, is among the most influential innovations. When added to conventional fuels, they have a significant impact on the engine performance,

combustion process, and emission behavior (Mofijur *et al*. 2024).

The comprehensive studies revealed that there are several different functions of nano-additives: they catalyze some sort of chemical reaction to make it faster, establish better fuel and air mixing, better ignition, and more efficient transfer of energy during the combustion. These effects result in higher engine power output, greater thermal efficiency, and improved fuel economy, while also addressing significant environmental concerns of reduced emissions of carbon monoxide (CO), unburned hydrocarbons (HC), particulate matter (PM), and nitrogen oxides (NO) (Hamzah *et al.* 2024).

Moreover, the nano-additives enhance complete and stable combustion through a short ignition delay and enrichment of flame propagation. Their potential to allow cleaner and more energy-efficient burning is an encouraging move to face the ever-stringent emission regulations, and all this can be achieved without needing to make the massive modifications needed to the established engine designs. It is thus necessary to know the nature and advantages of nano-additives to build a future generation of high-performance as well as environmentally friendly transportation technology (Gupta *et al.* 2024).

4.1 Impact on Performance

4.1.1 Brake Thermal Efficiency (BTE)

Through BTE, it is possible to determine the extent to which the chemical energy of fuel is converted to mechanical energy (Renish *et al.* 2022). Nano-additives like Al_2O_3, CeO_2, and TiO_2 have been found to give a boost to the properties of fuel combustion. They improve the oxidation processes by enhancing oxygen availability and act as catalysts for combustion. As a result, more of the fuel is completely burnt, releasing greater thermal energy. This increased heat production generates higher pressure inside the combustion chamber, which in turn raises engine torque and power output. Research consistently indicates that diesel or biodiesel mixtures supplemented with nano-additives can boost BTE by approximately 20.6%, depending on engine parameters and the specific additive used (Gad *et al*. 2024).

4.1.2. Brake-specific Fuel Consumption (BSFC)

Brake-specific Fuel Consumption (BSFC) is used as a reverse measure of the efficiency of the engine (Jaichandar and Annamalai, 2012). The installation of nano-additives assists in decreasing the BSFC by increasing the degree of combustion efficiency and advancement of fuel atomization. Nanoparticles ensure more efficient mixing with air and fuel, forming a smaller spray and a more even air-fuel mixture. This results in a higher degree of combustion and which results in less unburned gas overall and requires less fuel to produce the same amount of power. It has also been demonstrated that adding nano-additives can reduce BSFC by up to 12%, which would translate into considerable fuel savings—a factor of major importance in commercial and high-mileage vehicle applications (Guvenc *et al*. 2023).

4.1.3 Ignition Delay and Combustion Duration

Ignition delay refers to the period of time between the injection of the fuel and the start of combustion. Nano-additives greatly reduce this delay, particularly by facilitating the production of reactive species normally generated during ignition, such as hydroxyl (OH) radicals and oxygen (O) radicals, which accelerate flame propagation. Also, the life of the combustion process, that is, the time needed to burn all the fuel completely, is reduced (Rao *et al.* 2022). This can be attributed to improved fuel atomization, greater surface interaction, and enhanced heat transfer made possible by the presence of nanoparticles. A shorter combustion period results in more efficient and controlled combustion, with a reduced engine knock tendency and increased cycle stability, especially under low-temperature or lean-mixture conditions (Zheng and Cho, 2024).

4.1.4 Combustion Stability and Power Output

Stable combustion is a precondition of constant power and smooth engine operation. Nano-additives enhance the stability by promoting uniform mixing of fuel with air, as well as making the rapid heat liberation happen at the time of combustion. Highly ionized nanoparticles like CNTs and CuO can distribute temperature evenly faster inside the combustion chamber. This even heat distribution allows consistent movement of flame, and there are no cold spots or combustion profiles. Therefore, there is reduced cycling of the cylinder pressure, leading to more consistent handling of power and smoother operation of the engine, especially under part-load and variable operating conditions (Ramachandran *et al.* 2023).

4.2 Impact on Emissions

4.2.1 Carbon Monoxide (CO) Emissions

Carbon monoxide (CO) is a poisonous product of incomplete combustion, which is usually produced when oxygen is deficient or the fuel is burned poorly. Nano-additives (particularly CeO_2 and Fe_2O_3) have high catalytic oxidation potentials, which enhance the transformation of CO to carbon dioxide (CO_2) by providing active oxidation sites, even at low temperatures. In addition, nanoparticles promote fuel atomization and the combination of air with fuel, resulting in complete combustion and the natural reduction in the amount of CO produced. Research studies have reported up to a 45% reduction in the

emissions of CO in the engines using nano-additives (metal oxide) (Thirumal *et al.* 2015).

4.2.2 Unburned Hydrocarbons (HC) Emissions

Unburned hydrocarbons (HC) are created when part of the fuel does not go through combustion, which is common because of poor mixings, quenching by cooler parts of a flame, or subsequent incomplete burning cycles. The nano-additives address this by promoting effective combustion by enhancing the atomization of the fuel and increasing the rate of reaction. Such improvements make the flame spread more homogeneously and enable it to spread to lean or difficult-to-burn regions further; hence, about 31% of HCs are unburned. The subsequent decrease in HC emissions, on the one hand, contributes to the strict emissions regulation, and, on the other hand, increases the fuel efficiency, reducing energy losses of unburnt fuel (Zheng and Cho, 2024).

4.2.3 Nitrogen Oxides (NO_x) Emissions

The production of nitrogen oxide (NO_x) is usually higher as the temperatures in combustion increase and when the combustion is sustained in excess of oxygen. While nano-additives enhance the efficiency of combustion, their effect on forming NO_x is complicated. With improved combustion, there may be the possibility of a slight rise in flame temperature, which increases the production of NO_x. Nevertheless, some nanoparticles, especially cerium oxide, can overcome this effect, soaking the peak flame temperatures and controlling the release of oxygen. This decreases the concentrations of oxygen in hot zones, thus reducing the formation of NO_x. Through experimental evaluation, it has been determined that ideal conditions enable CeO_2 to curb the emission of NO_x to 26% levels (Pandey *et al.* 2018).

4.2.4 Particulate Matter (PM) and Soot Emissions

This is a result of incomplete combustion in oxygen-poor areas, which results in the formation of particulate matter (PM), which in large part is incombustible carbon or soot. Nano-additives support the reduction of the development of such zones due to better atomization of fuels and stimulated oxidation. Specifically, CeO_2 can react directly with soot, thereby facilitating its oxidation to CO_2 even at lower exhaust temperatures. This quality makes CeO_2 particularly useful in diesel engines, which are traditionally associated with high quantities of PM emissions. Experiments have demonstrated that nanoparticles can considerably reduce soot visibility and particulate concentration, with reductions of up to 52% observed in some nanoparticle–biodiesel–diesel blends (Sajith *et al.* 2010).

4.3 Impact on Combustion

4.3.1 Improved Combustion Completeness

Nano-additives, such as CeO_2, Fe_2O_3, and Pt, act as effective oxidation catalysts, which speed the breakdown of long-chain hydrocarbons into short-chain compounds. This catalyst effect facilitates fuller combustion by increasing the oxidation of short-chain oxidation products of incomplete combustion (CO and unburned HCs, which occur under incomplete combustion conditions. Consequently, this makes the fuel more efficient, and this leads to increased energy production and minimization of harmful emissions (Hameed and Muralidharan, 2023).

4.3.2 Accelerated Ignition and Shorter Delay Period

Increasing the radical formation rate of OH and O nano-additives helps reduce the ignition delay, which is the time between fuel injection and the onset of combustion. Their catalytic surfaces boost the chemical reactions involved in ignition so that the initiation of the flames happens more readily at all times, particularly during cold- or lean-burn scenarios (Mofijur *et al.* 2024).

4.3.3 Enhanced Flame Propagation

Nano-additives promote a more homogenized and rapid spreading of the flame through the combustion chamber. This has been attributed to better atomization and mixing of fuel and air in the improved fuel as the surface tension of the fuel reduces due to the presence of nanoparticles. The generated smaller droplets evaporate faster and burn more uniformly, letting the proper combustion even within the fuel-lean zones (Zheng and Cho, 2024).

4.3.4 Higher Peak Pressure and Heat Release Rate

Nano-additives improve the rate of heat release, making the combustion process more complete and faster. This occurs due to enhanced atomization and catalytic effects, which accelerate the combustion phase and increase energy output. This leads to an increase in the peak cylinder pressures nearer to the top dead center (TDC), which has the effect of improving the engine performance (Guo *et al.* 2024).

4.3.5 Improved Fuel Atomization

The nanoparticles suspended within the fuel act as a micro-nucleation site when injected into the fuel, which helps in breaking up the liquid fuel into smaller droplets. This increases the surface area of evaporation and burning. Nano-additives decrease the viscosity and surface tension of the fuel and hence enable finer atomization and better mixing of the air with fuel. Uniform spray distribution will reduce cold spots in the

combustion chamber, allowing more efficient and decisive combustion all over the engine cycle (Miglani and Basu, 2015).

4.3.6 Thermal Conductivity Effects

Nanoparticles such as Al_2O_3, CuO, and CNTs exhibit good thermal conductivity, which enhances heat transfer in the combustion chamber. This facilitates a more even distribution of temperature, particularly during the premixed combustion stage. Improved heat dissipation contributes to stable flame propagation, reduces the likelihood of local flame extinction, and promotes faster completion of combustion (Quadros *et al.* 2022).

Table 2. Impact of Nano-additives on performance, combustion, and emissions of IC engines

Mechanism Influenced by Nano-additives	Detailed Effect	Outcome	Common Nano-additives	References
Performance Characteristics				
Improved thermal conductivity	Enhances in-cylinder heat transfer, reducing thermal losses	Reduced BSFC	Al_2O_3, CuO, CNTs	(Ampah *et al.* 2022)
Enhanced fuel atomization	Produces finer droplets, better fuel-air mixing, and combustion uniformity	Smoother engine operation, reduced knocking	TiO_2, CNTs, Al_2O_3	(Fayad *et al.* 2023)
Catalytic activity enhances oxidation reactions	Lowers activation energy, leading to quicker and more efficient combustion	Higher BTE	CeO_2, Fe_2O_3, Pt	(Sulakhi *et al.* 2025)
Shortened ignition delay	Enables quicker combustion initiation; improves power generation	Increased engine responsiveness and torque	CeO_2, TiO_2, CNTs	(Celik and Uslu, 2023)
Emission Characteristics				
Soot oxidation and particulate matter reduction	Nanoparticles assist oxidation of carbonaceous soot, especially at lower temps	Significant reduction in PM (Particulate Matter)	CeO_2, TiO_2, CuO	(Borthakur, 2025)
Complete oxidation of CO and HC due to the catalytic surface	Converts harmful CO and HC to less toxic CO_2 and H_2O	Lower CO and HC emissions	CeO_2, Pt, Fe_2O_3	(Borthakur, 2025)
Controlled combustion temperature (especially for NO_x reduction)	Some nanoparticles modulate flame temperature by controlling burn rate	Lower NO_x formation due to moderated peak temperature	CeO_2, ZnO, Mn_3O_4	(Hossain *et al.* 2019)
Combustion Characteristics				
Enhanced homogeneity of fuel-air mixture	More consistent heat release due to finer spray; avoids local hotspots	Uniform pressure rise and reduced knocking	Al_2O_3, TiO_2, CeO_2	(Ul-Haq *et al.* 2024a)
Micro-explosion phenomenon	Superheating by nanoparticles causes droplet rupture, leading to secondary atomization and faster vaporization	Enhanced fuel burn rate and flame speed	CNTs, Al_2O_3, metal oxides	(Ul-Haq *et al.* 2024a)
Oxygen buffering capability	Stores and releases oxygen during lean/rich cycles, ensuring complete fuel oxidation	Complete combustion and better flame propagation	CeO_2, TiO_2	(Lv *et al.* 2022)

Table 3. Fundamental formulas used for the performance evaluation

S. No.	Parameter	Formula	Unit	Relevance
1	BTE	BTE = [BP / (m_fCV)] x 100	%	Measures how efficiently fuel energy is converted to useful work
2	BSFC	BSFC = mf/BP	kg/kWh	Indicates fuel economy; nano-additives reduce BSFC
3	Emission Reduction Efficiency	Reduction % = {(E_{base}−E_{nano})/ Ebase } × 100	%	Quantifies emission improvement with nano-additives
4	NO_x Formation (Zeldovich Mechanism)	Rate ∝ $[O_2]\cdot e^{-Ea/RT}$	–	Shows dependence of NO_x on flame temperature and oxygen concentration.
5	Heat Release Rate (HRR)	dQ/dθ = γ/(γ−1) P(dV/dθ) + 1/(γ−1)V(dPdθ)	J/°CA	Analyzes combustion speed and completeness
6	Combustion Duration	Duration = $\theta_{90\%}$-θ_{10}	°CA (crank angle)	Shorter duration implies faster, more efficient combustion
7	Cetane Number of Blend	CN_{blend} = $X_1\cdot CN_1+X_2\cdot CN_2+\Delta CN_{nano}$	–	Higher CN, influenced by nano-additives, reduces ignition delay
8	Effective Thermal Conductivity	k_{eff} = kf [kp+2kf+2ϕ(kp−kf)] / [kp+2kf−ϕ(kp−kf)]	W/m·K	Shows heat transfer improvement in nano-fuels
9	Surface Area of Nanoparticles	A = 6/ (ρ·d)	m²/kg	Higher area results in better catalytic activity in combustion

Where, BTE – Brake thermal efficiency; BP – brake power; mf – fuel mass flow rate; CV – calorific value; BSFC – brake specific fuel consumption; E_{base} & E_{nano} – emissions with base and nano fuels; NO_x - Oxides of Nitrogen; O_2 – Oxygen; Ea – activation energy; R – universal gas constant; T – flame temperature; P – cylinder pressure; V – cylinder volume; dQ/dθ – heat released per crank angle; dV/dθ & dP/dθ – volume and pressure derivatives w.r.t. crank angle; θ_{10} & θ_{90} – crank angles at 10% and 90% mass fraction burned; CN_{blend} – cetane number of blend; X1 & X2 – fractions of fuels 1 and 2; CN_1 & CN_2 – cetane numbers of fuels 1 and 2; ΔCN_{nano} – cetane number improvement due to nano-additives; kf & kp – thermal conductivity of fuel and particles; ϕ – nanoparticle volume fraction; A – specific surface area; ρ – particle density; d – particle diameter.

4.3.7 Micro-explosion Phenomenon

Some nanoparticles have caused micro-explosions during combustion. These occur when superheated fuel droplets form internal vapor pockets, which rapidly rupture and break the droplets into smaller secondary droplets. This secondary atomization greatly increases the surface area of the fuel in contact with air and heat, thereby enhancing the combustion rate (Miglani and Basu, 2015).

4.3.8 Flame Temperature Modulation

Depending on the properties of materials, nano-additives can affect and control peak flame temperatures. Even though enhanced combustion does tend to raise flame temperatures, which incidentally has an enhanced potential to increase NO_x emissions, the use of additives like CeO_2 is expected to counter this, as it gradually liberates oxygen. This delayed combustion facilitates the combustion to be even without sudden changes in temperature. In this way, the combustion efficiency can be improved and the emissions can be decreased at the same time, and the cleaner combustion can be accomplished without compromising the engine performance (Saraee *et al.* 2017).

4.3.9 Reduction in Combustion Duration

Greater ignition and quicker fuel consumption facilitated by nano-additives, result in a shorter overall combustion time. A reduced combustion period is favorable for engine cycles, as it allows more intense power strokes, efficient energy utilization, and decreased heat wastage. These developments lead to improved engine performance with reduced knocking and higher efficiency in both SI and CI engines (Mofijur *et al.* 2024).

The impact of nano-additives on performance, combustion, and emissions is outlined in Table 2, whereas Table 3 presents essential formulas used to assess the performance of nano-additives in combustion engines.

5. CHALLENGES IN USING NANO-ADDITIVES

5.1 Agglomeration and Stability Issues

One of the greatest challenges to making nano-additives useful is that they have a tendency to agglomerate, or clump, particularly during long-term storage in the fuel. Due to strong intermolecular forces (such as the van der Waals forces) and high surface

energy, nanoparticles may tend to cluster and precipitate at the bottom of fuel tanks or in the injectors. This distorts even combustion and causes irregular burning. Additions of surfactants or even ultrasonic mixing have to be used to achieve stable dispersion, which can be a difficult task in fuel preparation (Chen *et al.* 2024).

5.2 Cost and Commercial Viability

Some of the effective nanoparticles, especially those containing precious metals such as platinum or palladium, are expensive. Even more frequently employed ones, such as CeO_2 or CNTs, may become costly when manufactured on a large scale. Such expenses hinder large-scale implementation even in countries with cost-sensitive markets and in poor eastern and South Asian countries. Current research trends focus on developing less expensive methods of synthesis and recycling to enhance their commercial applicability (Chen *et al.* 2024).

5.3 Health and Environmental Risks

Although nanoparticles decrease engine emissions, they can be the source of health and environmental issues if not dealt with carefully. Handling, blending, or combustion may expose individuals to hazardous particles through inhalation or skin contact, potentially leading to respiratory or toxic effects. Their long-term environmental impact, such as their presence in exhaust or accumulation in lubricants, remains an active area of research and should be monitored with particular attention (Bakand and Hayes, 2016).

5.4 Engine Compatibility and Deposits

Prolonged application of nano-additives might result in the formation of deposits on engine parts such as injectors, valves, and combustion chambers. The deposits may disrupt the spray patterns, fuel-air mixing, and heat transfer. It is important to test how compatible the nano-additives are with the engine materials, filters, and after-treatment systems before they are used on a large scale (Gupta *et al.* 2024).

5.5 Lack of Standardization and Regulations

Presently, there are no regulatory principles and standards governing the use of nano-additives in fuels. Differences in particle size, concentration, dispersion, and engine type could also lead to inconsistent results, and it is difficult to establish benchmarks. Regulatory bodies have not yet established exposure limits or environmental safety standards for such materials (Modi *et al.* 2024).

6. FUTURE ASPECTS AND RESEARCH DIRECTIONS

6.1 Green and Low-cost Nano-additives

The value of future research lies in designing eco-friendly, biodegradable, and cost-effective nanoparticles through green synthesis methods. Researchers are exploring the use of agricultural waste, plant extracts, and even microorganisms to produce metal oxides or carbon-based nanoparticles, which are considered safer and more sustainable for fuel applications (Atofarati and Enweremadu, 2026).

6.2 Smart and Multi-functional Nanoparticles

Current research is progressing toward multifunctional nanoparticles, which not only catalyze combustion but also enhance lubrication, reduce wear, and clean engine components. Hybrid nanoparticles, made by the combination of various oxides or carbon-metal composites, are also under development to harness synergistic benefits for performance improvement and emission reduction (Sivamani and Salalah, 2025).

6.3 Real-time Monitoring and Control

Future IC engines might be equipped with sensors and AI algorithms to track real-time combustion features and vary the dosing of nano-additives to respond. The use of smart fuel injection technology would react to load, speed, and temperature data in optimizing the use of the nano-additives to maximize efficiency with minimum emissions (Daud *et al.* 2022).

6.4 Applications in Alternative Fuels

Nano-additives are also being explored for boosting the burning of alternative fuels like biodiesel, ethanol, hydrogen, and ammonia. They can be instrumental in overcoming the challenges associated with low-calorific and oxygenated fuels, making this a promising area for future research (Sivamani and Salalah, 2025).

6.5 Integration with Emission Control Technologies

Nanotechnology can also be incorporated into after-treatment mechanisms, such as catalytic converters, diesel particulate filters (DPFs), and exhaust gas recirculation (EGR) systems. Applying nanomaterials as coatings on filters or catalysts can increase their reactivity and enhance their durability, resulting in more efficient emission control under varying engine conditions (Daud *et al.* 2022).

7. CONCLUSION

The use of nano-additives in fuels has emerged as an innovative approach to achieve more efficient and cleaner IC engines. These nanoparticles, due to their greater surface area, catalytic and superior thermal characteristics, are deemed to influence the combustion process on a microscopic level. Various experimental studies have indicated that the addition of nanoparticles to diesel, biodiesel, or gasoline significantly influences engine performance, improving BTE, enhancing power output, and reducing BSFC. Nano-additives play a vital role in the combustion front in enhancing the ignition speed, flame spread, and fuel-air mixing. They help to form active radicals and can even cause micro-explosions in fuel droplets to promote faster combustion and better and more even burning of the fuel. Such an improved process is useful in reducing detrimental emissions like carbon monoxide, unburned hydrocarbons, and particulate matter. Among these metal oxides, CeO_2 is particularly notable, as it serves a dual function—enhancing the performance of the oxidation catalyst and supplying oxygen to support cleaner combustion.

However, there are some technical and environmental challenges in integrating nanotechnology into fuel systems; the difficulties include nanoparticle agglomeration, maintaining prolonged dispersion stability, potential abrasion of engine components, and the relatively high cost of nanoparticle production. Moreover, the environmental and health effects of emitted nanoparticles must be carefully considered. It is essential to implement strict standards for safe handling, dose optimization, and waste management to ensure responsible use.

The future of nano-additive fuels looks promising, with the emergence of greener and cheaper nanoparticle production methods. Combined with smarter combustion control systems, real-time fuel diagnostics, and hybrid powertrains, nano-enhanced fuels hold great potential, including compatibility with biofuels, hydrogen-rich fuels, and other sustainable alternatives.

Finally, nano-additives act as a comprehensive solution to enhance engine performance, lessen emissions, and extend engine life. With increased interdisciplinary research, innovation, and policy support, nanotechnology is poised to become a cornerstone in the development of clean and energy-efficient transportation systems.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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