**Review Article**

**The Role of Nanoparticles as Additives in Diesel/Biodiesel: A Review on Performance and Emission Enhancements**

**ABSTRACT**

This paper provides a comprehensive review of recent advancements in nanoparticles-enhanced diesel-biodiesel blends. It discusses the preparation methods, properties, and impacts of various nanoparticles on engine performance and emissions. Furthermore, the review highlights the potential and limitations of using nano-additives, such as their influence on engine life, environmental impact, and toxicity. Through this analysis, the study seeks to support the advancement of cleaner and more sustainable energy solutions that ensure a balance between performance, environmental responsibility, and cost-effectiveness.

***Key Words:*** *Nanoparticles, Diesel–Biodiesel Blends, Engine Performance, Emission Reduction, Combustion Efficiency, Nano-Additives*

**1. INTRODUCTION**

The global reliance on fossil fuels has led to significant environmental degradation and health concerns, primarily due to the release of harmful pollutants such as carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOₓ), and particulate matter (PM) during their combustion. These emissions contribute to climate change, smog formation, and respiratory ailments, posing a severe threat to ecosystems and human health. According to the Lancet Countdown on health and climate change, the greenhouse effect from excessive fossil fuel consumption has resulted in a dramatic rise in global average temperatures, surpassing pre-industrial levels by over four degrees. This alarming scenario has accelerated the search for renewable and sustainable energy alternatives to mitigate environmental impacts while addressing the growing global energy demands.

Among the many sustainable energy sources, biodiesel stands out as an environmentally friendly and practical replacement for petroleum-based diesel. It is derived through esterification processes involving animal fats, vegetable oils, and used cooking oils. Biodiesel offers notable benefits, including lower greenhouse gas emissions and compatibility with standard diesel engines. Research has shown that it helps reduce emissions of HC, CO, and PM without compromising engine performance. Feedstocks like rapeseed, jatropha, and sunflower methyl esters are commonly used and are blended with diesel in different proportions to enhance combustion and lower pollution. However, biodiesel still has drawbacks, such as relatively lower energy density, poor performance in cold conditions, and a tendency to increase NOₓ emissions, which hinders its widespread implementation.

To address these shortcomings, researchers have investigated various strategies, including the use of fuel additives. Among these, nanoparticles have attracted substantial interest due to their unique properties, such as a high surface area-to-volume ratio, catalytic activity, and enhanced energy density. Nanoparticles, when added to diesel-biodiesel blends, have shown promising results in improving fuel combustion, increasing thermal efficiency, and reducing harmful emissions. Metal-based nanoparticles like copper oxide (CuO), cerium oxide, and alumina, as well as carbon-based materials like graphene and carbon nanotubes, have been widely studied for their ability to optimize engine performance and emission profiles. These additives not only enhance fuel properties but also serve as secondary energy carriers, facilitating better combustion characteristics. However, challenges such as increased NOₓ emissions, potential engine wear, and environmental toxicity associated with unburned nanoparticles remain areas of concern.

Diesel engines, known for their high mechanical and thermal efficiency, are expected to continue playing a dominant role in global transportation and industrial sectors. Improving their combustion efficiency while reducing emissions has become a critical focus area for researchers and industry stakeholders. Integrating renewable fuels like biodiesel with advanced additives such as nanoparticles offers a promising pathway to achieve sustainable and efficient energy solutions.

This paper provides a comprehensive review of recent advancements in nanoparticle-enhanced diesel-biodiesel blends. It discusses the preparation methods, properties, and impacts of various nanoparticles on engine performance and emissions. Furthermore, the review highlights the potential and limitations of using nano-additives, such as their influence on engine life, environmental impact, and toxicity. By exploring these aspects, this study aims to contribute to the development of sustainable energy alternatives that balance performance, environmental sustainability, and economic feasibility for a cleaner and greener future.

**2. LITERATURE OF REVIEW**

Lai *et al*. (2023) optimized tribological performance in diesel engines using nanoparticle-enhanced tyre pyrolysis oil-biodiesel-diesel blends, employing response surface methodology (RSM) with Box-Behnken design. Parameters included load (20–60 kg), speed (1000–1400 RPM), and nanoparticle concentration (0–0.2 wt%). MgO, graphene, and Al₂O₃ nanoparticles significantly improved the coefficient of friction (COF), wear scar diameter (WSD), and surface roughness (Ra). Optimal conditions for MgO were 1000 RPM, 26.99 kg, and 0.0531 wt%; for graphene, 1161.73 RPM, 21.83 kg, and 0.105 wt%; and for Al₂O₃, 1109.3 RPM, 30.37 kg, and 0.0107 wt%, achieving the best performance at low cost and concentration. Al₂O₃ reduced COF and WSD under high loads, while graphene excelled in anti-wear properties at lower loads. Load was the most significant factor for COF and WSD, while nanoparticle concentration most influenced surface roughness. Al₂O₃ nano-fuel minimized COF, WSD, and Ra, improving surface texture and engine lubricity, thereby reducing wear and extending engine life. The study highlighted biodiesel blends' higher sulphur content, recommending desulfurization and increased biodiesel ratios for better compliance and performance. These findings demonstrate the effectiveness of nanoparticle additives in improving engine efficiency and sustainability.

Loo *et al*. (2023) analyzed the impact of nanoparticle additives on the tribological behaviour of FTPO-biodiesel-diesel blends using a four-ball tribometer under 40 kg load, 1200 RPM, and 75°C (ASTM-D4172). Magnesium oxide (MgO), graphene (G), and aluminium oxide (Al₂O₃) nanoparticles significantly improved lubricity. Al₂O₃-0.1 wt% reduced the coefficient of friction (COF) by 2.83%, while Al₂O₃-0.1 wt% and Al₂O₃-0.2 wt% decreased the wear scar diameter (WSD) by 22.09% and 18.33%, respectively. Surface roughness improved by 36.3% (MgO-0.1 wt%), 36.9% (MgO-0.2 wt%), 36.8% (G-0.1 wt%), and 35.5% (Al₂O₃-0.1 wt%). Lower concentrations formed protective films, reducing wear and friction, while higher concentrations caused agglomeration and surface damage. SEM and Alicona imaging confirmed reduced wear and smoother surfaces with 0.1 wt% nanoparticles. MgO-0.2 wt% excelled in surface roughness, and Al₂O₃-0.1 wt% provided the best friction and wear performance. Optimizing nanoparticle use could further enhance biofuel tribological properties.

Mofijur *et al*. (2024) conducted a study examining how nanoparticle (NP) additives influence biodiesel combustion, focusing on engine performance, emission levels, and combustion behaviour. The incorporation of titanium dioxide (TiO₂) nanoparticles led to significant reductions in exhaust emissions—smoke dropped by 32.98%, carbon monoxide (CO) by 30%, and hydrocarbons (HC) by 28.68%. Additionally, NOx, CO, HC, and smoke emissions showed respective reductions of 30%, 60%, 44%, and 38%. At the same time, improvements in brake power (BP) and brake thermal efficiency (BTE) were observed, both increasing by 12%. Nanoparticles such as cerium oxide (CeO₂) and aluminium oxide (Al₂O₃) enhanced the biodiesel's viscosity, thermal resilience, and atomization quality, resulting in more efficient combustion. For instance, copper oxide nanoparticles were effective in lowering NOx emissions while also enhancing fuel economy, whereas iron oxide nanoparticles contributed to shorter ignition delay, allowing for quicker combustion. These outcomes suggest that carefully adjusting nanoparticle size and concentration can further optimize these enhancements. The study also emphasized the need for future research to address long-term engine durability, the combined effects of different NP types, cost-efficiency, and environmental considerations through comprehensive lifecycle assessments. Moreover, the integration of nanoparticles with alternative fuels like hydrogen holds potential for advancing energy sustainability.

Alex *et al*. (2022) evaluated the influence of cerium oxide (CeO₂) nanoparticles mixed with orange peel oil methyl ester (OPOME) on the performance and emissions of a single-cylinder diesel engine. The research revealed that CeO₂ nanoparticles, due to their large surface area and strong oxidizing potential, significantly boosted fuel efficiency and cut emissions. Brake thermal efficiency (BTE) improved by 12% compared to diesel fuel, with BC15 achieving a 4% higher BTE and BC25 showing a 23% improvement over baseline values. Emission analysis revealed reductions in nitrogen oxides (NOₓ) by 27%, carbon monoxide (CO) by 6.5%, and smoke by 7% for nanoparticle-blended fuels. The improved combustion characteristics of OPOME blends resulted in reduced carbon monoxide emissions at part load but increased NOₓ emissions by 22% at full load for BC25 due to better cetane ratings. Additionally, brake-specific fuel consumption (BSFC) decreased with higher OPOME blends, enhancing fuel economy. The findings highlight the potential of CeO₂ nanoparticle-enhanced OPOME as a renewable and efficient alternative fuel, with recommendations for further studies on environmental impacts and optimization for direct injection systems.

Xu *et al*. (2015) investigated the tribological performance of pyrolysis bio-oil enhanced with nano-Lanthanum oxide (La₂O₃) additives. Using a four-ball tribometer, the study compared the effects of nano-La₂O₃, micro-La₂O₃ (m-La₂O₃), and un-additized bio-oil. Results showed that nano-La₂O₃ significantly improved the tribological properties, with optimal concentrations at 1% by weight, where both friction and wear were minimized. At lower concentrations of m-La₂O₃ (less than 1%), wear had little effect, while higher concentrations (over 1%) led to particle aggregation and abrasive wear. Nano-La₂O₃ reduced corrosive wear due to the acidic components in bio-oil and provided stable transient friction properties. At a 1% nano-La₂O₃ concentration, the wear and friction coefficients increased with load and speed, but the specific wear rate decreased, indicating excellent lubrication performance under various conditions. Tribological mechanisms for nano-La₂O₃ were attributed to a combined effect of adsorbed bio-oil films on contact surfaces and the bearing properties of the particles. Adhesive wear predominated under high loads, while abrasive wear became the main mechanism at high rotational speeds due to particle agglomeration.

Mohammed (2023) explored how zinc oxide (ZnO) nanoparticles influence diesel engine performance and combustion traits when used with diesel and second-generation biodiesel fuel blends. The study used six fuel blends: B0, B20, B40, B0ZnO, B20ZnO, and B40ZnO, with ZnO nanoparticles added at 50 ppm via ultrasonication. Key findings include a 6.74%, 4.95%, and 3.69% improvement in engine torque for B0ZnO, B20ZnO, and B40ZnO at 2300 RPM compared to their respective blends without ZnO. Brake-specific fuel consumption (BSFC) decreased by 5.6%, 6.44%, and 2.5% for B0ZnO, B20ZnO, and B40ZnO, respectively. The brake thermal efficiency (BTE) improved by 4.34% for B0ZnO and 3.28% for B20ZnO at 2600 RPM. Combustion attributes also showed enhancements, with cumulative heat release rates (CHR) increasing by 4.1%, 3.46%, and 1.72% for the ZnO blends. Ignition delay periods decreased by 18.18%, 8.32%, and 7.13% for B0ZnO, B20ZnO, and B40ZnO. ZnO nanoparticles compensated for biodiesel's poor combustion characteristics, improving fuel combustion and engine performance, though the study suggests further research on cost-effectiveness and sustainability assessments.

Prabu (2018) assessed the effects of adding nanoparticles to biodiesel–diesel mixtures on the performance, combustion, and emission metrics of a single-cylinder direct injection (DI) diesel engine. The test fuels included a standard B20 blend, a B20 blend with nanoparticle additives (B20A30C30), and a pure biodiesel blend containing nanoparticles (B100A30C30), with 30 ppm of Alumina (Al₂O₃) and Cerium oxide (CeO₂) nanoparticles uniformly dispersed via ultrasonication. The inclusion of nanoparticles led to a 12% rise in brake thermal efficiency (BTE) for B20A30C30 and a 9% increase for B100A30C30, in comparison to the unmodified B100 blend. Nanoparticle addition shortened ignition delay, enabling earlier combustion, which in turn reduced both heat release rates and peak cylinder pressures under full-load conditions. Emissions were also significantly lower—NO reduced by 30%, CO by 60%, unburned hydrocarbons (UBHC) by 44%, and smoke opacity by 38% for B20A30C30. The study concluded that incorporating Al₂O₃ and CeO₂ nanoparticles can significantly enhance biodiesel-diesel fuel blends without the need for modifications to existing diesel engines.

ul Haq *et al*. (2024) investigated the influence of nanoparticles (NPs) as additives in diesel–biodiesel blends on engine spray characteristics, performance, and emissions. The addition of 50 ppm CeO₂ improved spray characteristics by increasing the spray cone angle by 4.3% and reducing penetration length by 2.16% compared to 25 ppm. Performance tests showed a boost in brake thermal efficiency (BTE), with Fe₂O₃ nanoparticles enhancing BTE by 1.58%, 1.62%, and 2.34% at concentrations of 40, 80, and 120 ppm, respectively, in Mauha biodiesel. The highest BTE, 39.04%, was achieved with B20CSME + ZnO80, 36% higher than diesel at peak load. Emission reductions were notable, with CO emissions decreasing by 9.78% (TiO₂), 21.84% (Al₂O₃), 17.10% (CuO), and 6.38% (CeO₂) in B10 blends, while HC and smoke emissions also showed significant reductions. However, the impact of NPs on NOx emissions was variable. The study highlighted the potential of NPs to enhance fuel properties and combustion, though challenges like long-term fuel stability and production costs remain critical for their widespread adoption.

Ansari *et al*. (2023) examined how aluminium oxide (Al₂O₃) nanoparticles affect the performance and noise emissions of a diesel engine when added to a JB30 fuel blend, comprising 30% Jatropha biodiesel and 70% diesel. The investigation was conducted using a 4-stroke, single-cylinder engine running at a steady speed of 1350 rpm. The nanoparticle-enriched JB30 blend, with 50 ppm Al₂O₃, was prepared using an ultrasonicator to ensure even dispersion. The results indicated a 6.1% drop in brake-specific fuel consumption (BSFC) for the DF67JB30Al₂O₃ blend relative to diesel, while DF70JB30 showed a 3.65% reduction. Brake thermal efficiency (BTE) improved by 3.77% for DF70JB30 and 3.82% for DF67JB30Al₂O₃. All nanoparticle-blended fuels produced less noise than diesel, with DF67JB30Al₂O₃ showing the greatest reduction-attributed to lower rates of pressure rise during combustion. These findings suggest that DF67JB30Al₂O₃ delivers enhanced fuel economy and reduced noise, making it a suitable candidate for unmodified diesel engine application.

Sabarish *et al*. (2018) carried out experimental research to evaluate the influence of nanocrystalline cobalt oxide (Co₃O₄) on Jatropha biodiesel blends using a single-cylinder, air-cooled Kirloskar diesel engine operating at constant speed. The primary goal was to cut fuel use and emissions while boosting combustion efficiency. Adding Co₃O₄ improved brake thermal efficiency (BTE) by 1% for B10 biodiesel at 75% engine load, largely due to the enhanced oxygen availability promoting better combustion. Emission studies showed a nearly 60% reduction in NOx, HC, and smoke emissions for 100% biodiesel at full load, attributed to better mixing and secondary atomization. Brake-specific energy consumption (BSEC) was reduced by 7.95% for B20-Co₃O₄ and 2.10% for B100-Co₃O₄ at full load. The findings highlight that adding Co₃O₄ nanoparticles to biodiesel blends enhances combustion efficiency and significantly reduces harmful emissions.

Sivaram *et al*. (2018) investigated how blending cerium oxide and aluminium oxide nanoparticles with Pongamia pinnata biodiesel influences emission characteristics in diesel engines. Their findings showed that diesel fuel exhibited the highest NOx emissions due to elevated exhaust temperatures. In contrast, incorporating nanoparticles into biodiesel led to notable NOx reductions, with the extent of reduction increasing alongside the nanoparticle concentration. Carbon monoxide (CO) emissions also declined progressively with higher nanoparticle content in biodiesel when compared to both diesel and emulsion fuels. Additionally, unburnt hydrocarbon (UBHC) emissions were highest for emulsion fuel due to incomplete combustion caused by water content. However, nanoparticle additives improved combustion efficiency, reducing UBHC emissions effectively. This study highlights the potential of nanoparticle-infused biodiesel blends to lower automotive emissions significantly.

Bitire *et al*. (2023) reviewed the impact of CuO nanoparticles as fuel additives in biodiesel-blended diesel engines. Biodiesel, a renewable and biodegradable alternative to petro-diesel, faces challenges such as poor engine efficiency, higher NOx emissions, and reduced effectiveness in cold climates. CuO nanoparticles were identified as potential additives to address these issues. Their inclusion enhanced engine performance, combustion characteristics, and emission profiles. Specifically, CuO nanoparticles improved heat release rate (HRR), in-cylinder pressure, brake thermal efficiency (BTE), and brake-specific fuel consumption (BSFC). Emission reductions were significant, with decreased CO, HC, and NOx levels due to catalytic oxidation, micro-explosions, higher oxygen concentration, and better atomization. CuO's role as an oxidation agent also contributed to lower CO and HC emissions. While these findings highlight the benefits of CuO nanoparticles, further studies are needed to explore their environmental and health impacts.

Sharma *et al*. (2023) explored the application of titanium oxide (TiO₂) nanoparticles (NPs) in reducing emissions from diesel engines powered by waste cooking oil biodiesel (WCOB). The study tested three fuel blends: B1 (100% diesel), B2 (80% diesel + 20% WCOB), and B3 (80% diesel + 20% WCOB + 200 mg/L TiO₂ NPs) on a 3.2 kW single-cylinder water-cooled CI engine with a compression ratio of 17.5 and injection timing of 23° BTDC. The addition of TiO₂ NPs significantly improved emission characteristics. Compared to diesel (B1), carbon monoxide (CO) emissions decreased by 8.92% for B2 and 25% for B3. Similarly, hydrocarbon (HC) emissions dropped by 5.6% for B2 and 16.6% for B3. The B3 blend also achieved a 3.75% reduction in nitrogen oxide (NOx) emissions compared to B2. The findings suggest that nano-enhanced biodiesel blends, such as B3, offer a promising solution for mitigating diesel engine emissions. However, further optimization of operational parameters is required to achieve efficiency comparable to conventional diesel fuel.

Sivaprakash and Ganesh (2015) investigated the impact of zirconium oxide nanoparticles (ZrO₂ NPs) on the performance and emissions of diesel engines fueled with biodiesel derived from Jatropha oil. The biodiesel was prepared using a transesterification process, where Jatropha oil was preheated to 60°C and treated with 5 g potassium hydroxide dissolved in 250 mL methanol, stirred for 60 minutes, and allowed to settle for 24 hours. Zirconium nanoparticles were synthesized using a sol-gel method by mixing zirconium oxide and urea in deionized water, adjusting the pH to 8 with sodium hydroxide, and drying the solution. The addition of ZrO₂ NPs improved combustion at the molecular level without obstructing fuel injectors, making them more effective than micron-sized additives. These nanoparticles enhanced the combustion process and optimized fuel performance, demonstrating potential for reducing emissions and improving fuel efficiency in diesel engines fueled with biodiesel. This study highlights the significance of integrating nanoparticles to address challenges associated with biofuels.

Lv *et al*. (2022) reviewed the role of nano-additives in enhancing diesel engine performance and reducing harmful emissions when added to diesel-biodiesel fuel blends. The study highlighted that nanoparticles such as CuO, Al₂O₃, CeO₂, MWCNT, TiO₂, GO, and GNPs improve combustion efficiency due to their catalytic activity, high heat of combustion, and large surface area. CeO₂ reduced brake-specific fuel consumption (BSFC) by 30%, while MWCNT enhanced brake thermal efficiency (BTE) by 36.81%. In terms of emissions, TiO₂ reduced NOx by 22.57%, GNPs reduced CO by 65%, and GO decreased HC by 70%. The review emphasized cost-effective preparation methods like sol-gel and mechanical grinding for stable nanoparticle suspensions. However, the release of residual nanoparticles post-combustion poses risks to human health and the environment, underscoring the need for a life cycle assessment (LCA) approach to evaluate the benefits and hazards comprehensively. Despite certain limitations, the use of nano-additives demonstrates substantial potential to enhance diesel engine performance and reduce exhaust emissions.

Zheng and Cho (2024) presented a detailed review of the overall influence of nanoparticle additives on biodiesel-fueled engines, particularly focusing on performance enhancements and emission control. Their findings suggest that nanoparticles improve fuel attributes by increasing energy content (calorific value), cetane number, and flash point, thus aiding in more efficient and safer combustion. However, the rise in fuel density due to nano-additives may negatively impact combustion. Nanoparticles facilitate secondary atomization and micro-explosions, leading to increased cylinder pressure, heat release rate, brake thermal efficiency, and reduced brake-specific fuel consumption. Emission reduction is significant, with TiO₂ nanoparticles reducing CO and HC emissions by up to 41.19% and 31.89%, respectively. However, better combustion conditions increase CO₂ emissions, although low concentrations of TiO₂ (50–100 ppm) showed a CO₂ reduction of up to 12.57%. Variations in NOₓ emissions were observed; TiO₂, CNT, and ZnO nanoparticles reduced NOₓ emissions by 8.8%, 3.92%, and 27.1%, respectively, while other nanoparticles increased NOₓ due to higher combustion temperatures. The review concluded that TiO₂ nanoparticles show the most significant improvements in engine performance and emission reduction. The authors recommended exploring the synergistic effects of multiple nanoparticles to optimize their benefits further. Such advancements can aid in achieving cleaner fuels while addressing challenges like CO₂ and NOₓ emissions.

Sorunmu *et al*. (2019) reviewed the upgrading of pyrolysis bio-oil into drop-in fuels, focusing on production costs, scalability, and environmental impacts. Using life cycle assessment (LCA), techno-economic analysis (TEA), and technology readiness level (TRL) evaluations, they identified trade-offs among economic feasibility, environmental compliance, and technological readiness. While pilot-scale testing has been conducted, no technology has achieved full commercialization. The study emphasized the importance of consistent LCA and TEA frameworks and integrating multiple metrics to guide the development and scalability of these technologies, ensuring adherence to greenhouse gas standards and energy policy goals.

Hameed and Muralidharan (2023) investigated the impact of aluminium oxide (Al₂O₃) and cerium oxide (CeO₂) nanoparticles on the performance and emission characteristics of diesel engines operating on a 20% mahua biodiesel blend (MAH B20). Tests conducted at an engine speed of 1500 rpm revealed that incorporating 100 ppm of both nanoparticles significantly enhanced combustion efficiency and decreased pollutant emissions. These improvements were attributed to the nanoparticles’ high surface-area-to-volume ratios and catalytic behaviour. The optimal formulation, MAH B20 AL100 CE100, resulted in a 3.25% decrease in brake-specific fuel consumption (BSFC), a 1.39% rise in brake thermal efficiency (BTE), and notable reductions in hydrocarbon (HC), nitrogen oxides (NOx), and carbon monoxide (CO) emissions by 30.73%, 1.27%, and 44.13%, respectively. The study underscores the viability of using mahua biodiesel in conjunction with nano-additives to achieve cleaner and more efficient engine operation. The authors recommend further research into optimizing combustion chamber designs for maximizing these benefits.

Karthikeyan *et al*. (2023) studied the influence of zinc oxide (ZnO) nanoparticles on the performance, combustion behaviour, and emission output of a single-cylinder diesel engine running on a B20 fuel blend composed of 80% diesel and 20% canola oil methyl ester. The tests were carried out at 1500 rpm under full load conditions, with ZnO added at concentrations of 50 ppm and 100 ppm. The inclusion of ZnO nanoparticles led to improved combustion, evident through shortened ignition delay, higher in-cylinder pressures, and increased brake thermal efficiency (BTE). Compared to the B20 baseline, the ZnO-enriched blends exhibited marginally better calorific values and kinematic viscosities. The presence of ZnO also helped lower BSFC, CO, and HC emissions due to enhanced mixing and combustion facilitated by the nanoparticles’ large surface area. However, NOx emissions rose with ZnO use, likely due to the elevated combustion temperature from improved burn rates. Overall, the study highlights the effectiveness of ZnO nanoparticles in boosting engine efficiency and minimizing some emissions, although the trade-off in NOx output must be carefully managed.

Mahgoub (2023) reviews the use of nano-biodiesel blends in diesel engines, focusing on improving fuel properties, combustion efficiency, and reducing emissions. The study highlights the impact of various nano-metallic additives such as Al2O3, CeO2, CNTs, CuO, GO, and TiO2 on fuel quality and engine performance. Notable improvements were observed in brake thermal efficiency (BTE), with up to 24.7% improvement for Jatropha biodiesel (B20) with 50 ppm Al2O3, and a 25% reduction in brake-specific fuel consumption (BSFC) for Acacia concinna biodiesel with 150 ppm TiO2. Emissions also showed significant reductions, including up to 70.94% for hydrocarbons (HC), 80% for carbon monoxide (CO), and 30% for nitrogen oxides (NOx). Despite promising results, the study highlights the need for more research on the optimal combinations and dosages of nanoadditives for biodiesel blends. Future studies may focus on hybrid nanoparticles, which combine multiple nanoadditives, to explore their potential in improving engine outputs and emissions further.

Bidir *et al*. (2021) conducted a review examining the application of nanoparticles (NPs) in biofuel production and their impact on engine performance, combustion efficiency, and emissions when used in biodiesel–diesel fuel mixtures. The study outlines the limitations of using pure biodiesel in diesel engines, including its higher density, reduced cetane number, and lower energy content. To overcome these drawbacks, blending biodiesel with conventional diesel is proposed, and the addition of nanoparticles is recommended to further enhance engine operation. Findings indicate that incorporating NPs can lead to a 20–23% decrease in brake-specific fuel consumption (BSFC) and a 2.5–4% rise in brake power output. Emission analysis revealed notable reductions in hydrocarbons (HC), carbon monoxide (CO), and particulate matter (PM); however, an increase in nitrogen oxides (NOx) emissions—up to 55%—was also observed. The review concludes that integrating nanoparticles into biodiesel–diesel and bioethanol fuel blends can significantly improve overall engine performance and emission profiles. Nonetheless, the effectiveness of this approach depends heavily on selecting the right type, size, and concentration of nanoparticles. Furthermore, combining advancements in nanotechnology with biofuel production methods may help lower production costs and enhance fuel quality.

Elkelawy *et al*. (2023) reviewed the use of nanoparticle additives in diesel/biodiesel fuel blends to enhance engine performance and reduce emissions in direct injection diesel engines. Nanoparticles like copper oxides, titanium oxides, and aluminium oxides improve combustion, reduce brake-specific fuel consumption (by 20-23%), and increase brake power (by 2.5-4%) due to their high thermal conductivity. Emission tests showed reduced HC, CO, and PM emissions, but NOx increased by up to 55%. The study highlights that adding nanoparticles, such as alumina and cerium oxide, to biodiesel-diesel blends improves performance and emissions without engine modifications, while also lowering biofuel production costs. Proper nanoparticle selection and dosage are essential for optimal results.

Norhafana *et al*. (2019) presented a comprehensive review on the impact of nanoparticle additives on the performance and emission behaviour of diesel engines. The analysis showed that incorporating nanoparticles into diesel and biodiesel fuels enhanced combustion processes and improved overall engine efficiency. These nano-additives contributed to higher calorific values and cetane numbers of the fuel blends, while also causing slight increases in viscosity, flash point, and density. Enhanced combustion efficiency led to a noticeable reduction in brake-specific fuel consumption (BSFC), mainly due to better catalytic oxidation. Additionally, brake thermal efficiency (BTE) improved with increased nanoparticle concentrations, with several studies reporting substantial gains. Emission data demonstrated reductions in nitrogen oxides (NOx) and hydrocarbons (HC), which were attributed to elevated cetane numbers and improved ignition properties. Some findings also indicated lower smoke emissions as a result of better evaporation characteristics, although the effects on carbon monoxide (CO) emissions were mixed—higher nanoparticle concentrations occasionally led to increased CO output. Furthermore, the use of nanoparticles resulted in elevated in-cylinder pressure and heat release rates, both of which contributed to improved engine performance.

Egbosiuba (2022) investigated the influence of nickel nanoparticles on the pyrolysis of cassava peels to produce biochar, bio-oil, and biogas. The study found that at a lower pyrolysis temperature of 300°C, biochar yield was higher, with 68.59%, 62.55%, and 56.92% at heating rates of 10, 20, and 30°C/min, respectively. At 600°C, the carbon content of biochar increased to 52.39%, 53.30%, and 55.44% for the same heating rates. The optimum bio-oil yield (24.35%, 17.69%, and 18.16%) and biogas yield (31.35%, 42.03%, and 46.12%) were achieved at 600°C. The biochar produced at 600°C had a high heating value (HHV) of 28.70 MJ/kg, while the bio-oil exhibited a higher HHV of 42.68 MJ/kg at 600°C and a flash point of 53.85°C. The study also showed that the thermal stability of biochar increased with temperature, and the fuel properties of the bio-oil met or exceeded conventional diesel standards. Overall, cassava peels, when pyrolyzed at high temperatures, demonstrated significant potential as a renewable energy source in the form of biochar and bio-oil.

Suhel *et al*. (2023) investigated the impact of ZnO nanoparticles as an additive in waste plastic oil (WPO20) on the performance and emissions of a diesel engine. The study aimed to enhance the oxidation reaction and heat transfer during combustion. ZnO nanoparticles were synthesized using the sol-gel technique and added to WPO20 in concentrations of 50, 100, and 150 ppm. The engine tests revealed that incorporating ZnO nanoparticles significantly improved the engine's performance by reducing smoke, CO, UHC, and NOx emissions, while enhancing brake thermal efficiency (BTE) and reducing brake-specific fuel consumption (BSFC). The optimal results were achieved with a 100 ppm ZnO nanoparticle concentration, leading to a reduction in smoke (11.86%), CO (5.7%), UHC (28%), and NOx (14.93%) emissions, along with a 2.47% improvement in BTE at maximum load. The inclusion of ZnO nanoparticles also improved the fuel properties of WPO20, such as flash point, cetane index, and calorific value. However, beyond 100 ppm, the BTE slightly decreased, and emissions increased due to nanoparticle agglomeration. Overall, ZnO nanoparticles proved to be a promising additive for improving the performance and emissions of WPO blends, although further studies are needed to evaluate their impact on engine wear and corrosion.

Praveena *et al*. (2018) reviewed the effects of nano additives on biodiesel fuels used in internal combustion engines (ICEs). They found that nano additives like Al2O3, CeO2, CuO, ZnO, Ag, CNT, and MWCNT improve engine performance and lower emissions. For instance, Al2O3 reduced brake-specific fuel consumption (BSFC) by 7.66% and increased brake thermal efficiency (BTE) by 1.58%. CNT reduced NOx emissions by 35%, while MWCNT helped reduce NOx, CO, and smoke emissions, improving performance. The review emphasizes that the improved surface area and catalytic properties of nano additives lead to better combustion. However, the high cost of MWCNT needs to be addressed for broader use.

Mikky *et al*. (2024) explored the optimization of biodiesel–nanoparticle blends to enhance diesel engine performance and reduce emissions. Biodiesel, derived from waste cooking oil, is a sustainable alternative fuel but faces challenges like increased nitrogen oxide emissions, incompatibility with cold climates, and lower calorific value. The study tested nanoparticles (cerium oxide, silicon dioxide, and aluminium oxide) as additives to improve biodiesel properties. Using LINGO optimization software, they found that cerium oxide nanoparticles at 100 ppm improved engine performance and emissions, with a biodiesel blend ratio of 24.892%. This blend reduced brake-specific fuel consumption (BSFC) by 24%, smoke opacity by 52%, and CO emissions by 30%. The optimal blend consisted of 25% biodiesel, 75% conventional diesel, and 100 ppm CeO2 nanoparticles, resulting in improved performance and reduced emissions. The study highlights the potential of CeO2 nanoparticles in increasing biodiesel ratios and enhancing fuel performance.

Sule *et al*. (2022) reviewed the use of nano-additives in diesel-biodiesel blends to improve engine performance and reduce emissions. They found that nano-additives, particularly metallic and oxygenated ones, help reduce CO and particulate emissions by enhancing combustion. However, they may increase NOx emissions at higher loads due to "oxygen overdosing." Metal-based additives like magnesium and nickel can reduce flash point, viscosity, and density, but can also lead to higher brake-specific fuel consumption (BSFC) and lower thermal efficiency. The study highlights challenges like the instability of nano-additives over time and the lack of consistent trends across different biodiesel feedstocks.

El-Fakharany *et al*. (2024) investigated TiO₂ nanoparticles added to B20 biodiesel from waste cooking oil (WCO) and exposed to a magnetic field. They found that TiO₂ at 25 and 50 mg/L combined with the magnetic field improved engine efficiency and lowered emissions: brake-specific fuel consumption (BSFC) dropped by 1.2–6%, brake thermal efficiency (BTE) increased by 1–6.5%, CO emissions decreased by 5–15%, NOx by 7.5–26%, and hydrocarbons (HC) by 8–32%, although CO₂ emissions rose by 7–29%. The best results came from B20 + 50 mg/L TiO₂ + magnetic field, enhancing catalytic reactivity, heat transfer, and combustion.

Soudagar *et al*. (2020) studied zinc oxide (ZnO) nanoparticles and diethyl ether (DEE) additives in diesel and 20% Mahua biodiesel blends using a CRDI engine with a 7-hole injector and toroidal reentrant combustion chamber (TRCC). At optimized injection parameters, ZnO and DEE raised brake thermal efficiency by 7.3% (diesel + ZnO) and 18.7% (biodiesel + ZnO), while BSFC dropped by 17.1% and 3.2%, respectively. Emissions of smoke, CO, HC, and NOx decreased significantly. Cylinder pressure and heat release rates also improved, indicating enhanced combustion.

Rajesh *et al*. (2024) tested alumina (Al₂O₃) nanoparticles at 25, 50, and 100 ppm in biodiesel from coconut fatty acid distillate (BCFAD). With 100 ppm Al₂O₃, brake thermal efficiency increased by 6.5%, HC and CO emissions dropped by 29.3% and 34%, but NOx emissions rose due to higher combustion temperatures. Combustion characteristics like cylinder pressure and heat release rate approached those of diesel, showing nanoparticle-enhanced combustion. Strategies such as emulsification or injection modification were suggested to manage NOx.

Gad *et al*. (2024) evaluated hybrid nano additives—TiO₂ and Al₂O₃ at 25 mg/L each—in B20 WCO biodiesel blends. Hybrid blends outperformed single additives, reducing BSFC by 11%, increasing BTE by 12.5%, and lowering HC, CO, and smoke emissions by up to 20%, 30%, and 21%, respectively. NOx emissions increased by 23%. Cylinder pressure and heat release rate rose, reflecting improved combustion and thermal conductivity. The study recommended B20 with hybrid nano additives as a promising alternative fuel, especially in cold climates.

Bhan *et al*. (2022) assessed Al₂O₃ nanoparticles at 25–100 ppm in a B20 blend from mixed waste cooking oils in a CRDI diesel engine. B20 + 100 ppm Al₂O₃ showed a 13.5% rise in BTE and 20.9% reduction in specific fuel consumption (SFC). Peak cylinder pressure and heat release rate were highest for this blend due to shorter ignition delay. CO and HC emissions decreased significantly, while NOx rose slightly at high loads. The blend was considered a viable fuel alternative with improved efficiency and emissions profile.

Kumar *et al*. (2021) examined 50 ppm alumina nanoparticles in a 25% rubber seed biodiesel blend (B25). Nanoparticle addition improved BTE by 4.8%, reduced BSFC by 8.5%, and cut HC, CO, and smoke emissions by 36%, 20%, and 44%, respectively. Cylinder pressure and heat release rate increased, indicating enhanced combustion through reduced ignition delay and better fuel oxidation. NOx emissions increased, consistent with higher combustion temperatures.

Kaushik *et al*. (2022) investigated the impact of alumina (Al2O3) nanoparticles on diesel engine performance and emissions using diesel–neem biodiesel blends. Fuel samples included diesel (B0) and a 20% biodiesel blend (B20) with 25 ppm and 50 ppm nanoparticles (B0A25, B0A50, B20A25, B20A50). Testing at CR 18 and 8 kg load revealed that B0A50 improved BTE by 4.5%, reduced BSFC by 11%, CO by 12%, and HC by 16% compared to pure diesel. Similarly, B20A50 enhanced BTE by 5% and reduced BSFC by 11%, CO by 16%, and HC by 12% compared to B20 alone. The inclusion of nanoparticles improved combustion, reduced harmful emissions, and mitigated the performance losses associated with biodiesel blending, making B20A50 a favorable option for sustainable diesel engine operation.

**3. CONCLUSION**

This review provides an extensive analysis of the role of nano-additives in addressing the limitations of diesel-biodiesel fuel blends while enhancing engine performance and reducing emissions. Biodiesel's promise as a sustainable fuel alternative is tempered by challenges such as high viscosity, poor cold flow properties, and increased NOx emissions. The incorporation of nanoparticles has emerged as an effective approach, significantly improving in fuel properties, combustion efficiency, and emission profiles.

Key findings reveal that metal-based nano-additives (e.g., Mn, Ni, Mg, Co) and oxygenated additives effectively reduce viscosity and flash point while increasing the oxygen content, improving combustion efficiency. Nanoparticles like TiO2 and CNTs have demonstrated remarkable performance enhancements, including reduced ignition delay, higher calorific value, and complete combustion. For instance, TiO₂ significantly boosts engine power, and metallic nanoparticles reduce brake-specific fuel consumption (BSFC) along with harmful emissions like CO, HC, and smoke.

Stability remains a critical factor, as the effectiveness of nanoparticles is contingent upon preventing agglomeration and maintaining uniform dispersion in the fuel. Techniques such as optimizing surfactant selection and particle size distribution are vital to achieving consistent performance. Moreover, nanoparticles help mitigate biodiesel’s inherent drawbacks, particularly by enhancing oxidation stability and reducing cold flow issues.

The review emphasizes the importance of optimizing nanoparticle properties—size, shape, concentration, and stability to maximize their benefits. Future research should focus on improving nanofluid formulations, developing cost-effective preparation techniques, and evaluating the long-term impact of nano-additives on engine components and durability.

In conclusion, the integration of nano-additives into diesel-biodiesel blends holds immense potential to improve fuel performance and reduce environmental impact, making it a promising pathway toward sustainable and efficient energy solutions.

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