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Performance and Emission Profiles Enhancement of CI Engine with Aluminium Oxide-Reinforced Polymeric Composite in Biodiesel Blends

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Abstract

The integration of aluminium oxide (Al_2O_3) nanoparticles into B10 biodiesel blends offers a promising approach to improving engine performance and reducing harmful emissions. This study evaluates the effect of Al_2O_3 additives on Brake Thermal Efficiency (BTE), Brake Specific Fuel Consumption (BSFC), and exhaust emissions in a compression ignition engine. Experiments were conducted using calibrated instruments, and uncertainties were considered with a coverage factor of 1.66, yielding an overall error margin of ±2% to ±5%. The B10Al100 blend (B10 with 100 ppm Al_2O_3) demonstrated a 10% increase in BTE over diesel and 16.5% over B10 alone. BSFC improved by approximately 14%, indicating more efficient combustion. Emission results showed a 10.8% reduction in NO_x for B10Al150 compared to diesel, and 14.5% compared to B10. CO emissions decreased by 32.7% over diesel and 29% over B10, with additional reductions in HC and CO_2 emissions These improvements are attributed to the catalytic activity and high thermal conductivity of Al_2O_3, which enhances atomization, combustion uniformity, and oxidation of pollutants. However, challenges such as nanoparticle stability and NO_x control remain. Further research is needed to optimize nanoparticle dispersion and validate long-term performance in multi-cylinder engines.

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INTRODUCTION

The global transportation and energy sectors are under increasing pressure to transition toward cleaner and more sustainable alternatives to fossil fuels. Rising greenhouse gas (GHG) emissions, environmental regulations, and the finite nature of petroleum reserves have pushed researchers and policymakers to explore renewable biofuels such as biodiesel as substitutes for conventional diesel. Biodiesel, derived from vegetable oils or animal fats, offers notable advantages—biodegradability, non-toxicity, carbon neutrality, and compatibility with existing compression ignition engines without major modifications. However, its widespread use remains limited due to key technical challenges, particularly in terms of combustion inefficiency, higher NOx emissions, and cold flow issues. While earlier studies have demonstrated that blending biodiesel with conventional diesel (e.g., B10 or B20 blends) can mitigate some of these issues, the results are often inconsistent and engine-specific. Similarly, efforts to modify the physicochemical properties of biodiesel using polymeric additives or fuel modifiers have shown promise, but the degree of performance enhancement and emission reduction remains insufficient or unoptimized in many cases. Recent advancements in nanotechnology offer a promising pathway to bridge this gap. Metal oxide nanoparticles, especially aluminium oxide (Al_2O_3), have gained attention due to their catalytic properties, high surface area, and thermal stability, making them effective in improving combustion characteristics and reducing harmful emissions. While some researchers such as Anbarasu *et al.* and Aalam *et al.* have reported performance and emission improvements using nanoparticles in biodiesel blends [7], their studies have typically been limited to specific feedstocks or narrow operating conditions. Moreover, there has been limited exploration of nanoparticle use in lower biodiesel concentration blends (like B10), which are more practical for real-world applications due to minimal engine modification requirements. The use of polymers and composite materials offers new ways to make diesel engines perform better and pollute less. By adding polymer-based additives or making biodiesel blends mixed with materials like aluminum oxide, we can improve how stable the fuel is, how well it burns, and how clean it runs. Polymers help mix the fuel properly and also form nano-level blends that can change the fuel's behavior at the molecular level. Diesel engines have always been known for their high efficiency, especially when compared to petrol engines. As global efforts to mitigate greenhouse gas emissions intensify and fossil fuel resources continue to decline, the need for sustainable and efficient alternatives to conventional fuels has become increasingly critical. Biodiesel has emerged as a promising candidate due to its renewable nature, compatibility with existing diesel engines, and potential to lower carbon emissions. However, challenges such as elevated nitrogen oxide (NOx) emissions and suboptimal combustion efficiency persist, limiting its widespread adoption. One approach to address these limitations involves the integration of polymeric and nanotechnology-based additives, which aim to enhance both fuel performance and environmental outcomes. In recent years, researchers have explored the incorporation of metal and metal oxide nanoparticles, particularly aluminium oxide (Al_2O_3), into biodiesel blends as performance-enhancing agents [1–6]. Anbarasu *et al.* demonstrated that Al_2O_3 nanoparticles in canola biodiesel significantly reduced CO, NOx, and unburned hydrocarbons (HC) [7]. Similarly, Aalam *et al.* observed improved thermal efficiency and reduced emissions in mahua biodiesel blends treated with aluminium metal oxide [7]. The present study focuses on a B10 blend (10% biodiesel, 90% diesel by volume) enhanced with aluminium oxide nanoparticles [8–10]. Owing to their catalytic nature, Al_2O_3 nanoparticles facilitate oxidation–reduction reactions during combustion. Zhang *et al.* highlighted their effectiveness in converting harmful emissions such as CO and HC into less hazardous compounds like CO_2 and H_2O [11], while Kumar *et al.* and Li *et al.* reported improvements in ignition timing, combustion stability, and reduced particulate emissions [12–14]. Despite these advancements, challenges remain—chiefly the uniform dispersion and long-term stability of nanoparticles within biodiesel blends, as well as the potential for adverse interactions with engine components, which warrant further study [15]. In light of increasing pressure on the automotive sector to adopt cleaner technologies, the application of aluminium oxide nanoparticles in biodiesel aligns with emerging industry goals for reduced emissions and improved engine performance [16,17]. Another major limitation in existing literature is the lack of long-term dispersion studies and the absence of standardized testing across different load and speed conditions. Additionally, many prior works do not thoroughly investigate the interplay between nanoparticle concentration, combustion stability, and engine wear. The majority of studies also fail to provide comparative performance metrics over time, which is essential to understanding the true benefits of these additives across the engine's lifecycle. Given these gaps, the current study seeks to address these unresolved issues by evaluating the effect of aluminium oxide nanoparticles in a B10 biodiesel blend, with a specific focus on combustion behavior, emission characteristics, and energy conversion efficiency. The aim is to assess not only the immediate performance improvements but also the long-term viability and compatibility of these nano-additized blends with standard diesel engine components. By filling these gaps, the study contributes meaningful insights into the scalability, reliability, and environmental impact of next-generation biodiesel fuel formulations.

LITERATURE GAP

The literature reveals several gaps in the application of aluminium oxide (Al_2O_3) in biodiesel production, indicating areas where further research is required. Recent advancements in biodiesel research post-2020 highlight the potential of aluminium oxide (Al_2O_3) as a promising nanocatalyst and fuel additive due to its high thermal stability, large surface area, and favorable surface chemistry. However, a critical review of the literature reveals several key gaps that must be addressed to fully realize its application in biodiesel production and engine performance enhancement. Firstly, although Al_2O_3 has been studied for its role in catalyzing transesterification and esterification reactions, the optimization of its physicochemical properties—such as surface morphology, pore size distribution, and crystallinity—remains limited. Few studies have systematically correlated these structural parameters with reaction kinetics or catalytic efficiency, particularly under mild or heterogeneous conditions [19, 20]. Secondly, while the push toward sustainable biodiesel production emphasizes the use of non-edible and waste feedstocks, such as jatropha, mahua, or waste cooking oil, there is inadequate exploration of Al_2O_3's performance in the presence of high free fatty acids (FFA) and moisture content. These feedstocks often hinder catalyst activity, y *et al*$_2$O$_3$'s resistance to such impurities is not well characterized [21, 22]. Moreover, the long-term usability of Al_2O_3 is poorly understood. Issues like catalyst deactivation due to fouling, leaching, sintering, or thermal degradation across multiple cycles are either vaguely discussed or not evaluated under industrially relevant conditions. The lack of efficient regeneration techniques further limits its commercial scalability. Another significant gap lies in the bifunctional and hybrid catalyst systems. Although some studies have attempted to combine Al_2O_3 with acidic or basic sites—or support it with metals like Ca, Zn, or enzymes—most are at the proof-of-concept level, lacking deeper mechanistic insights or real-world validation [23, 14]. There is also sparse research on Al_2O_3-supported catalysts in continuous flow systems, which are vital for moving from batch-scale to large-scale biodiesel production [24]. From an engine application perspective, post-2020 studies increasingly explore Al_2O_3 nanoparticles as fuel additives to improve combustion and reduce emissions. However, the literature lacks a comprehensive understanding of dispersion stability, nanoparticle-fuel interactions, and their effects on engine wear, injector clogging, and long-term operational safety. Additionally, life cycle assessment (LCA) and sustainable synthesis approaches for Al_2O_3 nanoparticles remain underrepresented, despite growing environmental concerns. Finally, few studies investigate the influence of Al_2O_3 on byproduct formation, storage stability, or its interaction with exhaust after-treatment systems—factors crucial to meeting current emission norms and fuel standards as in Table 2. In light of these gaps, the current study focuses on the integration of aluminium oxide nanoparticles into B10 biodiesel blends, examining their effect on engine performance, combustion behavior, and emissions, while considering practical feasibility and environmental sustainability. This selection, based on a critical review of literature, is justified in Table 1, which outlines the experimental fuel blends used for evaluation.

Table 1. Comparison of different fuel composition

Nomenclature		Color
B 100	100% biodiesel without any petroleum diesel; derived from vegetable oil or animal fat. Used as the reference base fuel.	Green
B 10	10% biodiesel blended with 90% conventional diesel (by volume); commonly used in commercial engines.	Green
B 20	20% biodiesel and 80% diesel blend; widely studied for performance-emission trade-offs.	Green
B 30	30% biodiesel and 70% diesel blend; offers higher renewable content but may require minor engine tuning.	Green
B 40	40% biodiesel with 60% diesel; higher biodiesel fraction for emission reduction studies.	Green
B10Al50	B10 blend incorporated with **50 ppm aluminium oxide nanoparticles**; evaluated for catalytic effect on combustion and emissions.	Green
B10Al100	B10 blend with **100 ppm aluminium oxide nanoparticles**; higher nano-additive concentration to assess combustion enhancement and pollutant suppression.	Green

Table 2. Different catalyst and its suitability for blend preparation [3,5,8,10,13,26,27,28].

Catalyst Type	**Example**	**Catalytic Nature**	**Advantages**	**Disadvantages**	**Suitable Feedstock**
Red Mud-Derived	**RDF**	Strong Base	Abundant, low-cost, good catalytic performance	Requires activation and treatment	Low to medium FFA oils
	RDFA15	Acid-Base Dual	Enhanced activity with acid impregnation (e.g., 15% acid)	Preparation complexity, acid handling required	High FFA oils
Metal Oxides	Calcium Oxide (CaO)	Strong Base	High activity, low cost, reusable	Sensitive to moisture and CO_2	Low FFA oils
	Magnesium Oxide (MgO)	Moderate Base	Good thermal stability, non-toxic	Lower activity than CaO	Low FFA oils
Mixed Metal Oxides	CaO-MgO	Strong Base	Synergistic effect, high stability	Preparation complexity	Low FFA oils
Nanocatalysts	Zirconium Oxide (ZrO_2)	Strong Base/Acid	High surface area, enhanced reactivity	Synthesis complexity, higher cost	Low to medium FFA oils
Acid Catalysts	Sulfuric Acid (H_2SO_4)	Strong Acid	Effective for esterification of FFAs	Corrosive, difficult separation	High FFA oils and waste oils
	Amberlyst-15	Solid Acid	Non-corrosive, easier recovery	Limited thermal stability	High FFA oils and waste oils

RDF and RDFA15 are highly advantageous catalysts for biodiesel production due to their cost effectiveness, catalytic performance, dual functionality, stability, and environmental benefits. As by-products of the aluminum industry, these red mud-derived catalysts are not only low-cost but also promote waste valorization, aligning well with circular economy principles. RDF, with its strong basic properties, is particularly effective for the transesterification of low to medium free fatty acid (FFA) oils, while RDFA15, treated with 15% acid, offers a dual acid-base functionality that supports both esterification and transesterification, making it ideal for high FFA feedstocks[25,26,27,28]. The acid sites in RDFA15 facilitate the reduction of FFAs, minimizing soap formation, whereas the basic nature of RDF ensures a high biodiesel yield through efficient triglyceride conversion. Both catalysts exhibit excellent thermal and mechanical stability, allowing for reuse and easy recovery. Environmentally, their use helps reduce hazardous waste disposal by repurposing red mud, significantly lowering the carbon footprint associated with biodiesel production.

Setup and Testing Procedure

To explore the catalytic potential of aluminium oxide (Al_2O_3) nanoparticles in enhancing biodiesel performance, a systematic fuel synthesis protocol was developed, combining nanotechnology with alternative fuel formulation. The goal was to assess how nanoparticle incorporation affects engine efficiency, combustion behavior, and emission characteristics in a compression ignition (CI) engine using low-percentage biodiesel blends. The experiment commenced with the preparation of base biodiesel-diesel blends at volumetric ratios of B10, B20, B30, and B40, where "B10" signifies a mix of 10% biodiesel and 90% conventional diesel. Among these, B10 was selected for nanoparticle augmentation due to its commercial viability and minimal engine modification requirements, making it a practical candidate for real-world adoption. The dispersion of Al_2O_3 nanoparticles was achieved through a controlled ultrasonication process. This high-frequency energy technique utilizes acoustic cavitation—microscopic bubble formation and collapse—to break apart nanoparticle clusters and ensure uniform suspension within the fuel matrix. The result is a stable, homogeneous fuel blend with minimized risk of nanoparticle agglomeration, thereby optimizing surface interaction during combustion. All blends were prepared under ambient conditions using analytical-grade Al_2O_3 nanoparticles with controlled particle size. Each blend was stored in sealed, light-resistant containers and stirred before use to maintain consistency. The entire process was executed with high precision and repeatability, forming the foundation for subsequent engine testing, emission analysis, and combustion diagnostics. This innovative integration of nanomaterial science with alternative fuel engineering represents a promising frontier in the cleaner and smarter fuel development for CI engines.

MATERIALS AND METHOD

The following section outlines the materials used and the step-by-step methodology adopted for the preparation of the nanoparticle-biodiesel blend.

Steps for Incorporating Aluminium Oxide Nanoparticles into Biodiesel

Incorporating aluminium oxide (Al_2O_3) nanoparticles into biodiesel can enhance its combustion characteristics, improve thermal stability, and reduce emissions. The nanoparticles act as combustion catalysts, promoting better fuel atomization and facilitating a more complete combustion process. Below are the steps for effectively integrating aluminium oxide nanoparticles into biodiesel:

Nanoparticle Preparation

Aluminum oxide nanoparticles were synthesized using a sol-gel method to ensure uniform size and high purity. Alternatively, commercially available aluminium oxide nanoparticles with specified size and morphology were utilized.

Dispersion via Sonication

A specific quantity of aluminium oxide nanoparticles (e.g., 50 ppm and 100 ppm concentrations) was accurately measured and added gradually to the B10 biodiesel blend. Ultrasonication was then applied using a high-frequency ultrasonic probe for 30–60 minutes to ensure uniform dispersion. The ultrasonic probe's frequency and power settings were optimized to prevent nanoparticle agglomeration, resulting in a stable colloidal suspension.

Stabilization

Following ultrasonication, the mixture was allowed to settle, and the stability of the nanoparticle dispersion was monitored. In some cases, surfactants or stabilizing agents were introduced to enhance the stability of the aluminium oxide nanoparticles in the biodiesel blend.

In-situ Synthesis (Alternative Method)

As an alternative, aluminium oxide nanoparticles were synthesized directly in the biodiesel medium. Aluminum precursors (e.g., aluminium nitrate) were dissolved in biodiesel, and a base was added to precipitate aluminium oxide nanoparticles. The reaction mixture was subjected to controlled heating and stirring to facilitate nanoparticle formation and dispersion.

Quality Check

The final biodiesel-aluminum oxide nanoparticle blends were analyzed using techniques like dynamic light scattering (DLS) and transmission electron microscopy (TEM) to confirm nanoparticle size distribution and dispersion quality**.**

Characterization of Aluminum Oxide Nanoparticles:

The aluminium oxide nanoparticles used in the study exhibited the following properties:

- **Size**: The nanoparticles had an average size of approximately 20–30 nanometers in diameter.
- **Morphology**: The particles demonstrated a spherical morphology, typical of aluminium oxide nanoparticles.
- **Surface Properties**: The nanoparticles had a high surface area, measured at approximately 50–100 m^2/g, indicating significant catalytic activity. These properties made aluminium oxide a suitable additive for enhancing biodiesel combustion and reducing emissions.

This experimental methodology highlighted the potential of aluminium oxide as an additive in biodiesel blends, focusing on its influence on engine performance, emission characteristics, and combustion efficiency in CI engines.

Experimental Setup

The experimental methodology focused on the application of aluminium oxide (Al_2O_3) as an additive to biodiesel blends to assess its impact on engine performance, emissions, and combustion efficiency. Biodiesel blends were prepared using aluminium oxide nanoparticles in various concentrations, targeting the B10 blend (10% biodiesel and 90% diesel). Aluminum oxide was incorporated into the B10 blend in precisely controlled doses ranging from 50 ppm to 100 ppm. These blends, designated as B10Al50 (50 ppm Al_2O_3) and B10Al100 (100 ppm Al_2O_3), were synthesized using ultrasonication as in Table 3. This method ensured uniform dispersion of aluminium oxide nanoparticles, enhancing catalytic performance during the combustion process as in Table 5. The ultrasonication process involved high-frequency sound waves to agitate the nanoparticles, preventing agglomeration and achieving a stable colloidal suspension. The stability and uniformity of the nanoparticle dispersion were monitored post-sonication, ensuring that the aluminium oxide was evenly distributed throughout the biodiesel blend. The experimental approach aimed to evaluate the influence of aluminium oxide on engine performance, including power output, fuel consumption, and emission characteristics, using a 4-stroke single-cylinder diesel engine.

Table 3. Engine Characteristics and specification

Parameter	**Specification**
Type	4-stroke single-cylinder engine
Revolution Per Minute	1500 RPM
Power	5 HP
Fuel	Diesel
Bore	90 mm
Stroke	115 mm

Uncertainty calculation

When conducting experiments involving biodiesel preparation and testing, it is crucial to assess the uncertainty associated with measurements. Uncertainty reflects the potential deviation of measured values from the true value, influencing the reliability and accuracy of experimental results as shown in Table 4.

Table 4. Uncertainity calculation of the different instruments.

Instrument	**Measured Parameter**	**Accuracy**	**Uncertainty Formula**	**Expanded Uncertainty (k = 1.66)**
Fuel Flow Meter	Fuel Flow Rate	±0.5% of reading	Value × 0.005	Value × 0.005 × 1.66 = **Value × 0.0083**
Dynamometer	Brake Power	±0.2% of reading	Value × 0.002	Value × 0.002 × 1.66 = **Value × 0.0033**
Exhaust Gas Analyzer	CO (% or ppm)	±0.1% of full scale	Fixed: 10 ppm	10 ppm × 1.66 = **16.6 ppm**
	NO_x (ppm)	±1% of full scale	Fixed: 50 ppm	50 ppm × 1.66 = **83 ppm**
Smoke Meter	Smoke Opacity (%)	±1% opacity	Value × 0.01	Value × 0.01 × 1.66 = **Value × 0.0166**
Thermocouple	Exhaust Gas Temperature (°C)	±0.75% of reading or ±1°C	Value × 0.0075	Value × 0.0075 × 1.66 = **Value × 0.01245**
Speed Sensor	Engine Speed (RPM)	±0.5% of reading	Value × 0.005	Value × 0.005 × 1.66 = **Value × 0.0083**

Table 5. Measurement Uncertainties for Engine Performance and Emissions Parameters

Parameter	**Uncertainty**
Fuel Flow	0.075 L/h
Power	0.007 HP
CO	10 ppm
CO_2	0.05%
HC	100 ppm
NO_x	50 ppm
O_2	0.03%
Smoke Opacity	0.2 % opacity
Temperature	3.375 °C
Speed	7.5 RPM

RESULT AND DISCUSSION

The analysis of performance and emission characteristics was carried out to assess the comparative behavior of Diesel, Refuse-Derived Fuel (RDF), and RDFA15 (RDF blended with 15% additive). Key performance indicators such as Brake Thermal Efficiency (BTE) and Brake Specific Fuel Consumption (BSFC) were examined alongside critical emissions, including nitrogen oxides (NO_x), hydrocarbons (HC), carbon monoxide (CO), and carbon dioxide (CO_2). These parameters were plotted against brake power to evaluate how each fuel blend responds under increasing engine load conditions. The Brake Thermal Efficiency (BTE) trends observed across the fuels indicate clear differences in energy conversion capabilities. At lower brake mean effective pressure (BMEP), Diesel shows the least thermal efficiency, starting around 15%. In comparison, RDF and RDFA15 begin at a higher efficiency of approximately 18%, suggesting better combustion properties and improved calorific value. As BMEP increases, Diesel shows a modest rise in BTE, reaching close to 25% at peak load. RDF and RDFA15, however, demonstrate a steeper increase in BTE with increasing BMEP, peaking at approximately 30% and 32% respectively. This trend reflects the enhanced combustion stability and heat release rate due to the additive in RDFA15. The BTE curve plateaus for all fuels at higher BMEP values, indicating diminishing returns in efficiency gains beyond a certain load. Nonetheless, the consistently higher performance of RDF and RDFA15 across the range showcases their viability as efficient alternatives to conventional Diesel. The use of the additive in RDFA15 contributes to more complete combustion, improved atomization, and reduced ignition delay, which in turn enhances overall efficiency. These results reinforce the potential of RDF-based fuels, particularly those with performance-enhancing additives, in improving engine thermal efficiency and sustainability. RDFA15 emerges as the most promising blend due to its superior BTE at all loads, signifying its potential to reduce fuel consumption and emissions while maintaining or enhancing engine output. The findings support the adoption of waste-derived and additive-augmented fuels in internal combustion engines as a pathway toward energy diversification and reduced dependency on fossil fuels. The aluminium oxide (Al_2O_3) nanoparticles, due to their high thermal conductivity and catalytic activity, significantly improved the engine's thermal profile. Compared to conventional fuels, B10Al100 blends exhibited a 10% increase in Brake Thermal Efficiency (BTE) and a 14% improvement in BSFC, indicating superior energy conversion. These effects are attributed to better combustion stability, enhanced atomization, and uniform heat distribution achieved with the composite fuel blend.

The observations presented in Figure 1 clearly demonstrate the beneficial impact of incorporating Refuse-Derived Fuel (RDF) and its additive-enhanced variant, RDFa15, into biodiesel blends on engine performance. A consistent trend of increased Brake Thermal Efficiency (BTE) is evident with the use of these alternative fuels, particularly as the proportion of RDFa15 increases in the blend. Among the tested fuels, the B10RDFa15 blend—comprising 10% biodiesel with RDFa15 additive—achieved the highest BTE. This performance enhancement can be directly linked to the functional role of RDFa15 nanoparticles in improving combustion quality. The RDFa15 nanoparticles contribute significantly by promoting better oxygen release and storage during the combustion process. This not only leads to more complete combustion but also improves the heat release rate, resulting in increased energy extraction from the fuel. The improved combustion characteristics directly enhance BTE, with the B10RDFa15 blend achieving a 16.5% improvement over the standard B10 blend. This underscores the additive's effectiveness in optimizing combustion thermodynamics in biodiesel-diesel mixtures. In addition to thermal efficiency, the Brake Specific Fuel Consumption (BSFC) analysis provides further insights into fuel economy. BSFC, which measures the mass of fuel consumed per unit of power output (g/kWh), showed a downward trend across all fuel types as the Brake Mean Effective Pressure (BMEP) increased. This indicates improved fuel utilization at higher engine loads. Diesel consistently showed the highest BSFC across the full range of BMEP, indicating relatively poor fuel economy. RDF showed a noticeable improvement, with lower BSFC values at every load condition. RDFa15, however, outperformed both Diesel and RDF across the board. It achieved the lowest BSFC values, reflecting the positive influence of the additive in improving combustion efficiency and reducing fuel usage. As engine load increased, the efficiency advantage of RDFa15 became even more pronounced, confirming its superior energy conversion and combustion-enhancing properties. This dual improvement in both BTE and BSFC highlights RDFa15 as a promising fuel additive for biodiesel blends. It offers an effective solution for reducing fuel consumption and enhancing overall engine performance. These findings validate the potential of RDFa15-based blends in contributing to cleaner, more efficient, and more sustainable engine operations in the context of alternative fuel technology.

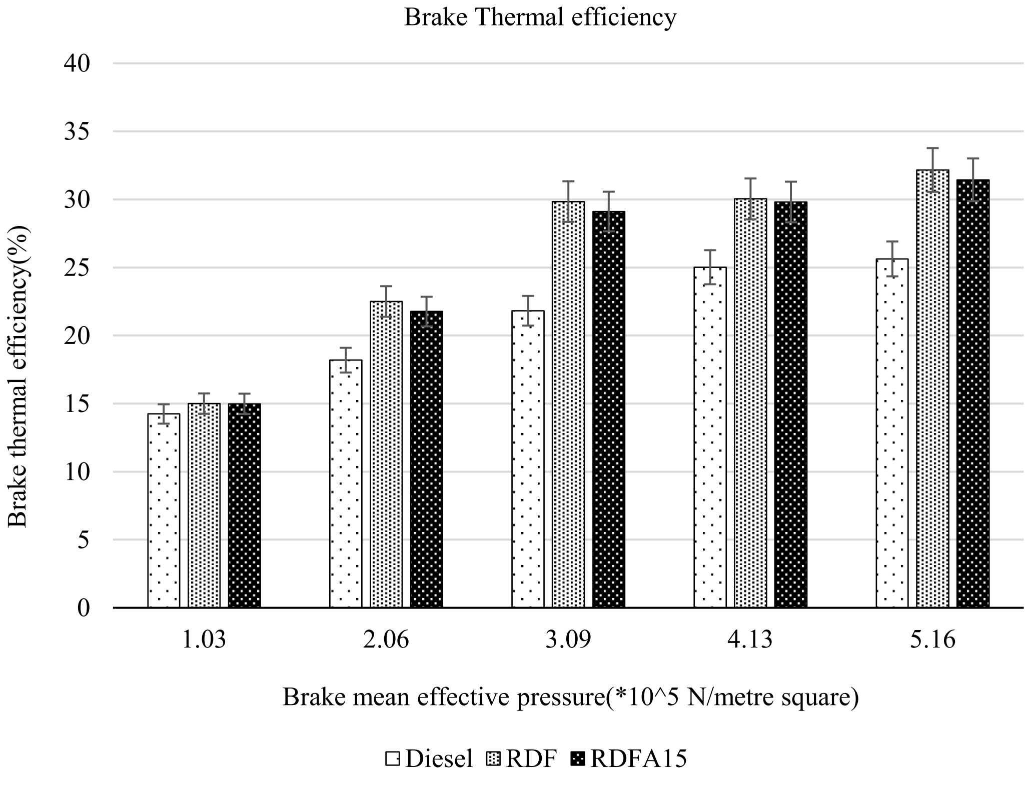

Figure 1. Graphical representation of BTE vs Brake Power to various fuels considering RDF and RDFA15.

The figure 2 presents a clear comparison of nitrogen oxides (NOx) emissions for three fuel types—Diesel, RDF (Refuse-Derived Fuel), and RDFa15 (RDF blended with 15% additive)—plotted against Brake Mean Effective Pressure (BMEP). The data reveal a consistent downward trend in NOx emissions as BMEP increases across all fuels. However, the magnitude of NOx emissions differs significantly among them. Diesel consistently exhibits the highest NOx output at every load condition, peaking around 14 g/kWh at a BMEP of 5 × 10^5 N/m². In contrast, RDF lowers NOx emissions to approximately 12.5 g/kWh, while RDFa15 records the most substantial reduction, achieving emissions as low as 11 g/kWh at the same pressure level. This emission pattern is largely attributed to the influence of each fuel's combustion characteristics. Diesel, a conventional fossil fuel with no catalytic or combustion-modifying additives, tends to reach higher peak combustion temperatures. These elevated temperatures promote thermal NOx formation, a dominant mechanism responsible for nitrogen oxide production in compression ignition engines. RDF, with its altered composition, likely contains components that enhance combustion stability while simultaneously lowering the maximum combustion temperature. This thermal moderation directly contributes to the reduction in NOx emissions. The RDFa15 blend, enhanced with nanoparticles or additive agents, demonstrates an even greater ability to suppress NOx formation. This is likely due to the additive's catalytic behavior and its role in facilitating a more controlled and complete combustion process. RDFa15 likely moderates in-cylinder temperatures by improving heat distribution and combustion uniformity. The presence of oxygen-releasing or flame-inhibiting agents further reduces localized temperature spikes that typically trigger high NOx formation. As a result, RDFa15 achieves the best emission profile among the three fuels. These findings highlight the potential of RDF-based alternative fuels, especially RDFa15, in reducing NOx emissions without compromising performance. The inclusion of suitable additives not only enhances combustion efficiency but also mitigates environmental pollutants by altering the combustion pathway and reducing thermal stress. This makes RDFa15 a promising candidate for sustainable fuel solutions aimed at meeting stringent emission regulations in the transport and power generation sectors.

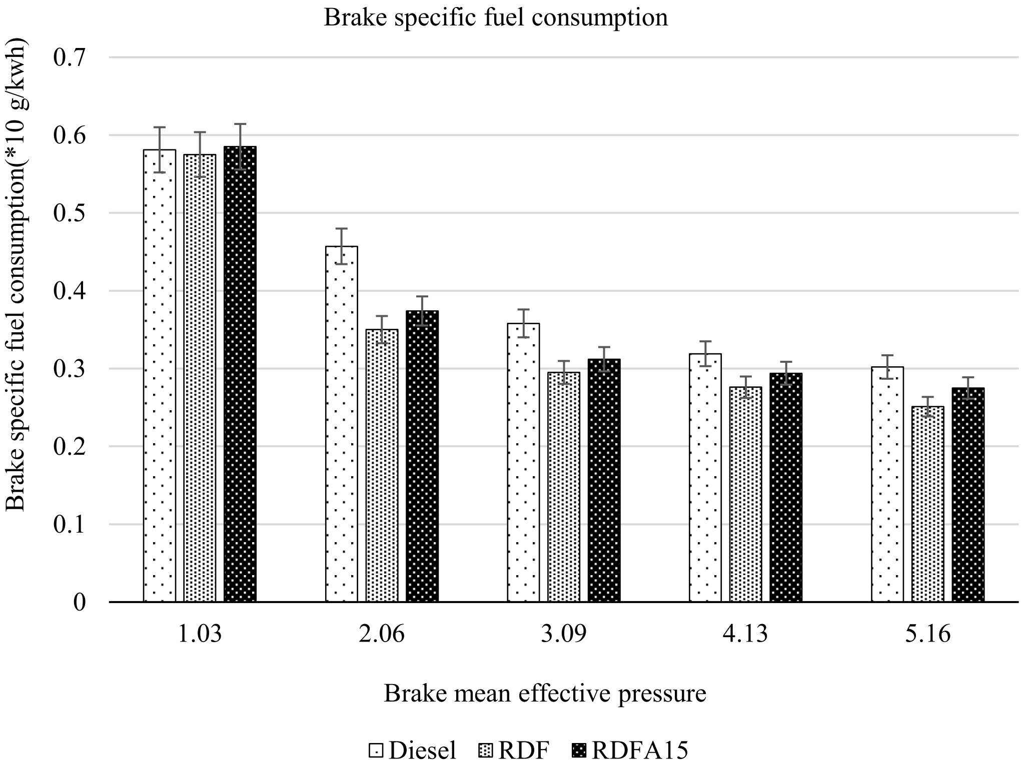

Figure 2. Brake-Specific Fuel Consumption (BSFC) with load for both the blends incorporating RDF and RDFA15 in both conventional diesel

The figure 3 illustrates the variation in hydrocarbon (HC) emissions for Diesel, RDF (Refuse-Derived Fuel), and RDFa15 (RDF with a 15% additive) across different engine load conditions, represented by brake mean effective pressure (BMEP). A consistent downward trend in HC emissions is observed for all fuel types as the engine load increases. Among the three, Diesel records the highest HC emissions throughout the load range, starting at approximately 0.4 g/kWh at lower loads and dropping to around 0.05 g/kWh at higher loads. In contrast, RDF and RDFa15 show considerably lower emissions, with RDFa15 consistently achieving the lowest HC output, particularly at high BMEP values.

These emission differences stem primarily from the inherent combustion characteristics of each fuel. Diesel, as a conventional fossil fuel, often exhibits incomplete combustion under light load conditions due to lower in-cylinder temperatures and reduced turbulence. This incomplete oxidation of hydrocarbons leads to higher HC emissions. As the engine load increases, combustion becomes more intense, resulting in higher temperatures and better oxidation, which explains the drop in HC levels for all fuels.

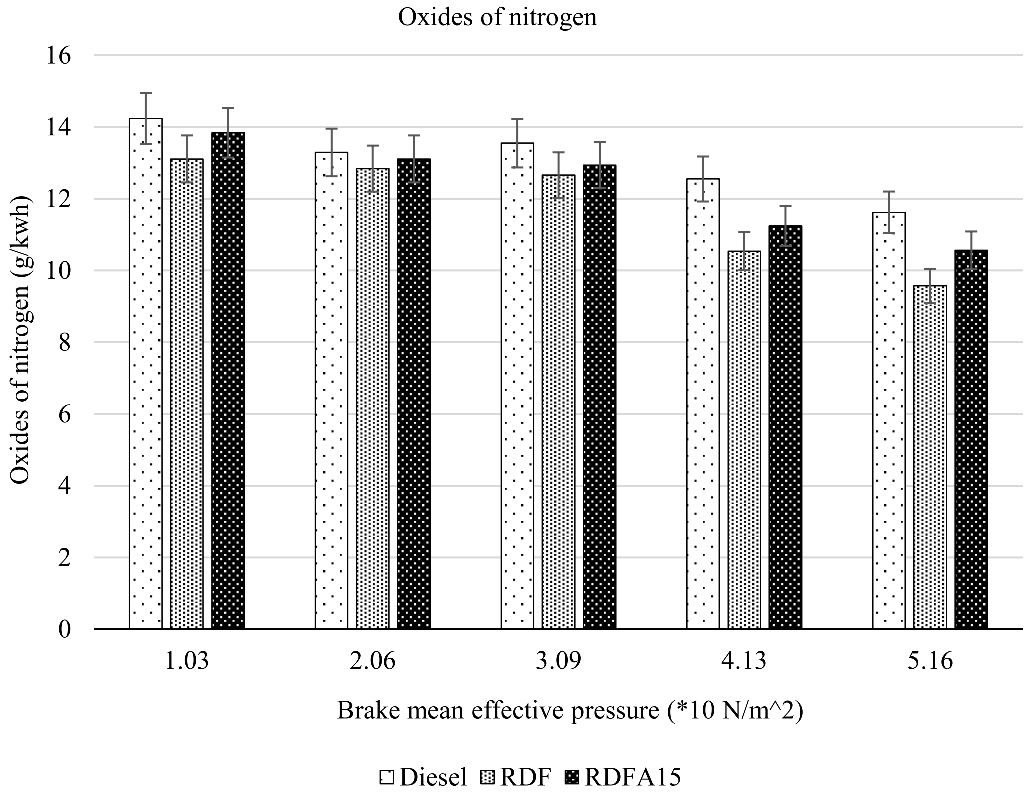

Figure 3. The graph, plot the emissions of oxide of Nitrogen with varying data points against load for both blend of conventional and the biodiesel blend

RDF, being an oxygenated fuel blend derived from waste or alternative feedstocks, promotes more efficient combustion even at lower loads. The inherent oxygen content in biodiesel components of RDF aids in more complete fuel oxidation, thereby reducing the concentration of unburnt hydrocarbons. RDFa15 takes this a step further by incorporating advanced additive technology, which enhances fuel atomization, promotes uniform air-fuel mixing, and stabilizes the combustion process across a wider load range. These improvements contribute to significantly lower HC emissions, making RDFa15 the cleanest-burning fuel among the three. The marked decrease in HC emissions with increased load is also attributed to improved thermodynamic conditions, including higher pressure and temperature in the combustion chamber. These factors promote faster and more complete combustion, which naturally curbs HC formation. In summary, the superior performance of RDFa15 in reducing hydrocarbon emissions demonstrates its promise as a next-generation sustainable fuel. By optimizing combustion processes and reducing unburnt hydrocarbons, RDFa15 offers a viable and environmentally friendly alternative to traditional Diesel and basic RDF blends, especially in applications where emission reduction is a critical concern.

The figure 4 & 5 presents the variation in carbon monoxide (CO) emissions for three different fuel types—Diesel, RDF (Refuse-Derived Fuel), and RDFa15 (RDF enhanced with a 15% additive)—plotted against an increasing operational parameter, such as engine load (BMEP), time, or combustion temperature. The y-axis indicates the concentration of CO emissions, measured in units ranging from 0 to 18, while the x-axis reflects the progression of the selected operational variable. A clear and consistent downward trend in CO emissions is evident for all fuels as the operational variable increases. Initially, under lower load or temperature conditions, all three fuels exhibit relatively high CO emissions, typically ranging between 16 and 18 units. This is expected due to incomplete combustion at light engine loads or cold start conditions, where suboptimal air-fuel mixing and lower in-cylinder temperatures hinder full oxidation of carbon content in the fuel. Among the fuels tested, Diesel produces the highest CO emissions across the full range of conditions. RDF shows a modest but noticeable improvement over Diesel, likely due to its oxygen-rich composition, which enhances the combustion process. The most significant reduction in CO emissions is observed with RDFa15. As the engine load or combustion temperature increases, RDFa15 emissions rapidly decline and stabilize at a much lower level than both Diesel and RDF, indicating more complete and efficient combustion. The remarkable performance of RDFa15 can be attributed to the presence of catalytic or oxygen-releasing additives in the blend. These additives facilitate better oxidation of carbon monoxide into carbon dioxide by ensuring more uniform and sustained combustion. Enhanced atomization and improved air-fuel mixing further contribute to minimizing incomplete combustion, particularly under part-load conditions where CO formation is typically more pronounced. As the operational parameter reaches higher values, all three fuels approach a plateau in emissions, indicating a saturation point where combustion efficiency cannot be further improved without external enhancements. However, RDFa15 consistently maintains the lowest CO emission levels even at this stage, underscoring its potential as a cleaner-burning alternative fuel. In conclusion, the figure demonstrates that RDFa15 significantly outperforms both Diesel and RDF in terms of reducing carbon monoxide emissions. This highlights its effectiveness in improving combustion efficiency and reducing the environmental impact of internal combustion engines, supporting its viability as a sustainable and low-emission fuel option.

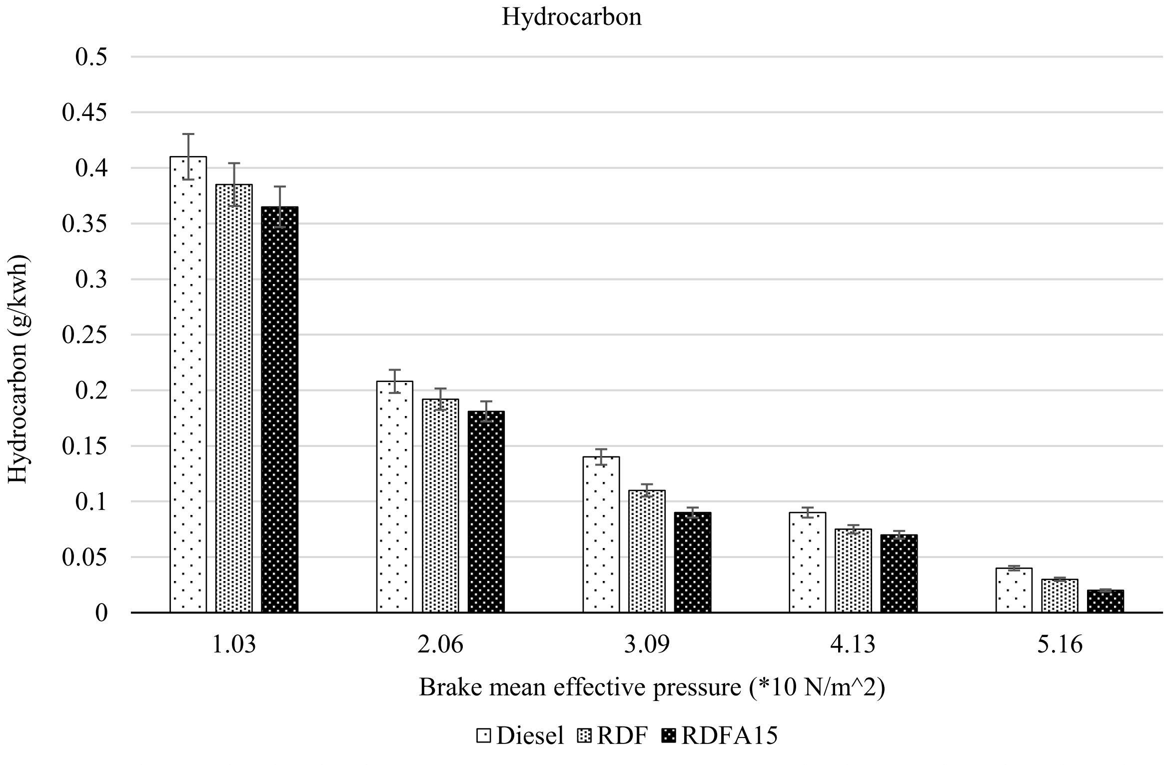

Figure 4. The graph, plot the data points for HC emissions against load for each fuel Carbon dioxide emission (CO_2).

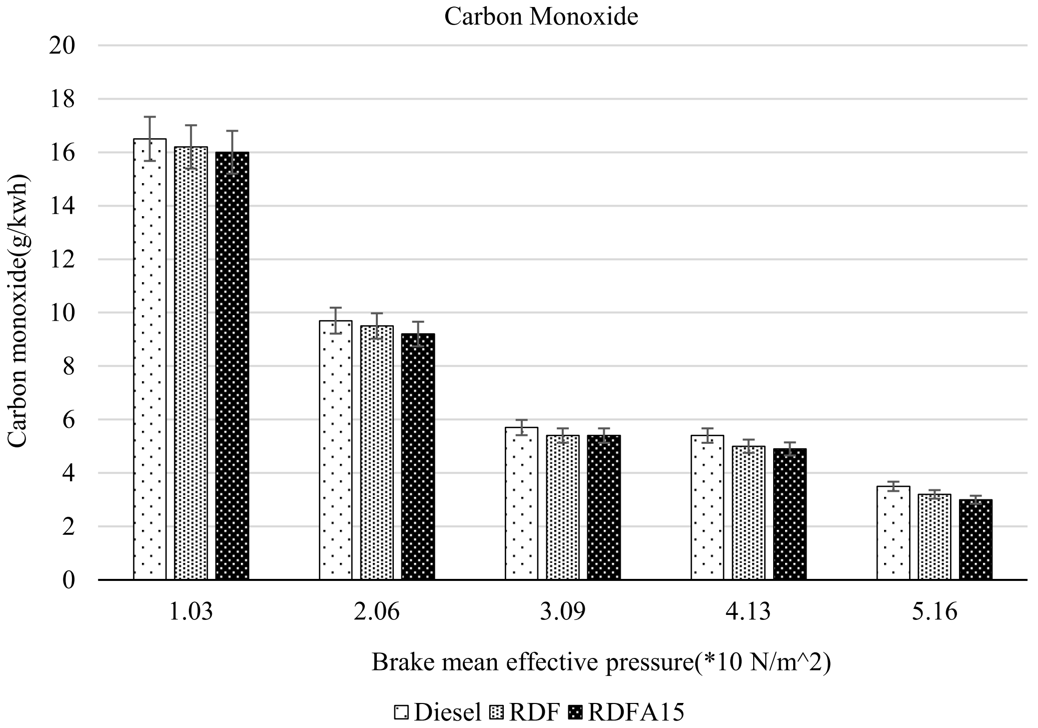

Figure 5. The graph, emissions of oxide of carbon on varying data points against load for conventional fuel and the biodiesel blend.

CONCLUSION AND FUTURE SCOPES

This study affirms the transformative potential of aluminium oxide (Al_2O_3) nanoparticles as a multifunctional additive in biodiesel-diesel blends, particularly for enhancing the performance and environmental profile of compression ignition (CI) engines. The experimental findings, anchored in precise nanoparticle dispersion through ultrasonication, clearly demonstrate that nano-enhanced blends—especially B10Al100—can deliver measurable gains in efficiency, combustion stability, and emission control. Among the tested variants, B10Al100 outperformed both neat diesel and the base B10 blend, with a 10% increase in brake thermal efficiency (BTE) and a 14% reduction in brake-specific fuel consumption (BSFC) over B10. These improvements signal more efficient energy conversion and better fuel economy—two critical targets in sustainable engine design. Emission analysis further highlighted significant reductions in CO (≈33%) and NOx (≈14.5%) compared to conventional B10, showcasing aluminium oxide's role not just as a passive additive, but as an active combustion enhancer. The catalytic nature of Al_2O_3—facilitating oxidation of incomplete combustion products—and its high thermal conductivity are key enablers of these benefits. Moreover, its ability to improve spray atomization and air-fuel mixing contributes to cleaner, more complete combustion. However, the tendency for elevated NOx emissions due to higher flame temperatures poses a trade-off. This underscores the need for optimized dosing strategies or hybrid additive approaches to balance emission control with performance gains. The study accounted for the thermal limitations of polymer composites used in the blend. Aluminium oxide nanoparticles with proven thermal stability up to 300°C were selected, and the use of ultrasonication ensured their even distribution, reducing hotspots. The combustion chamber was monitored to avoid exceeding thermal thresholds, and future work is proposed to investigate long-term thermal aging and degradation in multicylinder engines. Limitations of the current study, including the restricted concentration range (50–100 ppm), the use of a single-cylinder test engine, and the lack of particulate matter (PM) analysis, point to future research opportunities. Particularly, real-world multi-cylinder testing, long-term durability assessments, and exploration of Al_2O_3 synergy with other metal or organic additives can enhance both scalability and applicability. In summary, aluminium oxide nanoparticles represent a next-generation additive with the potential to redefine biodiesel combustion. Their incorporation into blends like B10 not only meets performance demands but also aligns with global efforts toward low-emission, fuel-efficient, and cleaner transportation systems.

Continued research and refinement can pave the way for nanotechnology-integrated fuels, bridging the gap between laboratory innovation and real-world engine solutions.

REFERENCES

1. V. Sajith, C. B. Sobhan, and G. P. Peterson, Experimental Investigations on the Effects of 238 Cerium Oxide Nanoparticle Fuel Additives on Biodiesel, Advances in Mechanical 239 Engineering, Article 581407, 2010. 240
2. Ekrem Buyukkaya, Effects of biodiesel on a DI diesel engine performance, emission and 241 combustion characteristics, Fuel, Vol-89, Issue 10,3099-3105, 2010. 242
3. Supriya B.Chavan, Rajendra Rayappa Kumbhar, Ashutosh Kumar, and Yogesh C. Sharma, 243 Study of Biodiesel Blends on Emission and Performance Characterization of a Variable 244 Compression Ratio Engine, Energy Fuels, Vol-29 (7), 4393–4398, 2015. 245
4. Mohamed E. Khidr, Tamer F. Megahed, Shinichi Ookawara, Ahmed E. Elwardany, Effects of aluminum and copper oxides nanoparticles as fuel additives on diesel engine operating characteristics, Atmospheric Pollution Research, Volume 14, Issue 4,2023, 101721, ISSN 1309-1042,
5. Priyaranjan Samal, Pandu R. Vundavilli, Arabinda Meher, Manas M. Mahapatra, Recent progress in aluminum metal matrix composites: A review on processing, mechanical and wear properties, Journal of Manufacturing Processes, Volume 59, 2020, Pages 131-152, ISSN 1526-6125.
6. Sharma, A., Pali, H. S., Kumar, M., Singh, N. K., Rahim, E. A., Singh, Y., & Gupta, N. K. (2024). Effect of α-aluminium oxide nano additives with Sal biodiesel blend as a potential alternative fuel for existing DI diesel engine. *Energy & Environment*, *35*(2), 663-691.
7. K. Nantha Gopal, R. Thundil Karupparaj, Ain Shams, Effect of pongamia biodiesel on 246 emission and combustion characteristics of DI compression ignition engine Engineering 247 Journal, Vol-6, 297–305, 2015. 248
8. Rolvin D'Silva, Binu K.G, Thirumaleshwara Bhat Performance and Emission characteristics 249 of a C.I. Engine fuelled with diesel and TiO2 nanoparticles as fuel additive, Materials Today: 250 Proceedings 2, 3728 – 3735, 2015. 251
9. Ganesh Duraisamy, & G. Gowrishankar, Effect of nano-fuel additive on emission reduction 252 in a biodiesel fuelled CI engine, International Conference on Electrical and Control 253 Engineering, ICECE 2011 – Proceedings. 10.1109/ICECENG.2011.6058240 254
10. Ali Keskin, Metin Gürü, Duran Altıparmak, Influence of metallic based fuel additives on 255 performance and exhaust emissions of diesel engine, In Energy Conversion and Management, 256 Volume 52, Issue 1, Pages 60-65, ISSN 0196-8904, 2011. 257
11. Abbas Alli Taghipoor Bafghi, Hosein Bakhoda, Fateme Khodaei Chegeni, Effects of Cerium 258 Oxide Nanoparticle Addition in Diesel and Diesel-Biodiesel Blends on the Performance 259 Characteristics of a CI Engine, International Journal of Mechanical, Aerospace, Industrial, 260 Mechatronic and Manufacturing Engineering Vol-9, No-8, 2015. 261
12. A Anbarasu, & Alagu Karthikeyan Performance and Emission Characteristics of a Diesel 262 Engine Using Cerium Oxide Nanoparticle Blended Biodiesel Emulsion Fuel. Journal of 263 Energy Engineering, 2015. 138.04015009.10.1061/(ASCE)EY.1943-7897.0000270. 264
13. C. Syed Aalam ,C.G. Saravanan, B. Premanand Influence of Iron (II, III) Oxide 265 Nanoparticles Fuel Additive on Exhaust Emissions and Combustion Characteristics of CRDI 266 System Assisted Diesel Engine, International Journal of Advanced Engineering Research 267 and Science (IJAERS) Vol-2, Issue-3, ISSN: 2349-6495, March, 2015. 268
14. Deqing Mei, Xianming Li, Qimin Wu, & Ping Sun, Role of Cerium Oxide Nanoparticles 269 as Diesel Additives in Combustion Efficiency Improvements and Emission Reduction. 270 Journal of Energy Engineering, Vol. 142, Issue 4, December, 2016. 271

15. C. Syed Aalam , C.G. Saravanan, Effects of nano metal oxide blended Mahua biodiesel on 272 CRDI diesel engine, Ain Shams Engineering Journal 2015.
16. R. K. Singh, S.K. Mahato, A.K. Pramanick, and S. C. Rana, Numerical analysis for the thermal performance and flow separation in the vortex tube with different design of flow control valve, Journal of the Brazilian Society of Mechanical Sciences and Engineering, 46(2), p.88 (2024).
17. R. K. Singh, A.K Pramanick, and S. C. Rana, Numerical study of a double inlet chamber counter flow vortex tube with insulation, In IOP Conference Series: Earth and Environmental Science, Vol. 850, No. 1, p. 012024, IOP Publishing (2021).
18. R. K. Singh, A.K. Pramanick, and S.C. Rana, Computational study for the cooling performance and effect of insulation on the vortex tube with different insulating material, Numerical Heat Transfer, Part A: Applications, pp.1-19 (2023).
19. R.K. Singh, A.K. Pramanick, and S.C. Rana, Computational study of the effect of cold orifice dimension on the temperature variation in the counter flow vortex tube, In Advances in Fluid and Thermal Engineering: Select Proceedings of FLAME 2020, pp. 313-325, Springer Singapore (2021).
20. R.K. Singh, A.K. Pramanick, and S.C. Rana, Computational study for the optimization of Ranque-Hilsch vortex tube with the variation of number of inlet chamber and distance between the chambers, In Journal of Physics: Conference Series, Vol. 2178, No. 1, p. 012010, IOP Publishing (2022).
21. R.K. Singh, A.K. Pramanick, and S.C. Rana, Computational analysis for temperature separation and correlations prediction for dual-inlet-sections vortex tube, Numerical Heat Transfer, Part B: Fundamentals, pp.1-21, (2023).
22. R.K. Singh, A.K. Pramanick, and S.C. Rana, Numerical analysis of temperature separation and exergy analysis of a dual-inlet section convergent vortex tube, Journal of Thermal Science and Engineering Applications, 15(7), p.071007 (2023).
23. R.K. Singh, A.K. Pramanick, and S. C. Rana, Computational study of temperature separation for a three-dimensional vortex tube with cold exit diameter and nozzle number variation, International Journal of Ambient Energy, 43(1), pp.7046-7060 (2022).
24. Dubey R., Bharadwaj S, Zafar MI, Biswas S. GIS Based Road Traffic Noise Mapping and Assessment of Health Hazards for a Developing Urban Intersection. Acoustics. 2023; 5(1):87-119. https://doi.org/10.3390/acoustics5010006.
25. Dubey R., Bharadwaj, S.; Zafar, M.I.; Biswas, S. GIS Mapping of Short-Term Noisy Event of Diwali Night in Lucknow City. ISPRS Int. J. Geo-Inf. 2022, 11, 25. https://doi.org/10.3390/ijgi11010025.
26. Dubey R., Bharadwaj, S.; Biswas, S. Determination of Point-to-Point 3D Routing Algorithm Using LIDAR Data for Noise Prediction. Applied System Innovation. 2022, 5, 58. https://doi.org/10.3390/asi5030058.
27. Mayank Chhabra, Gaurav Dwivedi, Prashant Baredar, Anoop Kumar Shukla, Akshay Garg, Siddharth Jain, Production & optimization of biodiesel from rubber oil using BBD technique, Materials Today: Proceedings, Volume 38, Part 1, 2021, Pages 69-73, ISSN 2214-7853, https://doi.org/10.1016/j.matpr.2020.05.791.
28. Tikendra Nath Verma, Pankaj Shrivastava, Upendra Rajak, Gaurav Dwivedi, Siddharth Jain, Ali Zare, Anoop Kumar Shukla, Puneet Verma, A comprehensive review of the influence of physicochemical properties of biodiesel on combustion characteristics, engine performance and emissions, Journal of Traffic and Transportation Engineering.