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Investigate the Influence of Bi_2O_3 Nanoparticles in Diesel Fuel on the Emissions and Performance of a Diesel Engine

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ABSTRACT

This investigation explores the influence of incorporating bismuth oxide (Bi_2O_3) nanoparticles as fuel additives on the emission features and performance of a 4-stroke, single-cylinder, and compression ignition diesel engine. The experimental analysis was conducted using a biodiesel blend (B20) enhanced with varying concentrations of Bi_2O_3 nanoparticles—specifically 25, 50, 75, and 100 ppm—compared to the baseline diesel fuel. The introduction of Bi_2O_3 nanoparticles resulted in a marked improvement in brake thermal efficiency (η_{bth}) and a significant decrease in brake-specific fuel consumption (Bsfc), with the latter decreasing by approximately 11.4% relative to conventional diesel. In terms of emission behavior, increasing the nanoparticle concentration led to notable decreases in carbon monoxide (CO), unburned hydrocarbons (HC), and smoke opacity by 12.8%, 13.2%, and 16%, respectively. Among all tested concentrations, the B20 blend containing 100 ppm of Bi_2O_3 nanoparticles exhibited the most favorable performance and emission profile, outperforming pure diesel in all evaluated metrics.

1. INTRODUCTION

Diesel engines play a pivotal function in transportation and power generation industries due to their high thermal efficiency, robust power output, and ease of maintenance [1]. Nonetheless, the intensifying concerns surrounding global climate change and the ecological ramifications of greenhouse gas emissions have necessitated the pursuit of cleaner and more sustainable energy alternatives [2]. Biodiesel has emerged as a promising substitute for conventional petroleum-based diesel in compression ignition (CI) engines, driven by the depletion of fossil fuel reserves, escalating fuel costs, and the detrimental environmental impacts of engine exhaust emissions.

Structurally, biodiesel shares considerable similarities with petroleum diesel but is characterized by a higher oxygen content, facilitating more complete combustion and reducing carbon monoxide emissions, unburned hydrocarbons, and particulate matter. However, a notable drawback of biodiesel utilization is the elevated emission of nitrogen oxides (NOx) compared to traditional diesel fuels [3, 4].

Moreover, the sustainability of the current biodiesel feedstock supply chain has been scrutinized, particularly due to concerns over their implications for global food security and agricultural resource allocation. Consequently, researchers have reported conducting increasing studies to assess the feasibility of different alternative raw material sources. Researchers have studied plants that produce inedible oils, including castor, soapwort, and Jatropha curcas, as well as inedible fats and vegetable oils waste.

Additionally, soybean, cottonseed, sunflower, and rapeseed oils are proper vegetable oils for biodiesel manufacture [5, 6]. Combining combustible nanoparticles into biodiesel formulations has significantly enhanced the operational performance of CI engines. Unlike larger micron-sized additives, nanoparticles possess the distinct advantage of minimizing the risk of fuel injector blockage due to their ultra-fine scale and superior dispersion features [7, 8].

Recent advancements have demonstrated that incorporating optimized concentrations of metal oxide nanoparticles, such as Bi_2O_3, into biodiesel blends can effectively modify the physicochemical features of the fuel, resulting in improved combustion dynamics. Moreover, several investigations have extended the use of Nano and micro-sized added to conventional diesel fuel to achieve similar enhancements in performance metrics [9]. A critical observation in these studies is that nanoparticle dimensions must not exceed 100 nm to prevent adverse impacts such as agglomeration, increased viscosity, or incomplete combustion phenomena, particularly at elevated concentrations of Bi_2O_3 [10, 11].

Karthikeyan et al. [12] evaluated the performance and emission characteristics of a CI engine fueled with biodiesel derived from Caulerpa racemosa algae oil and doped with Bi_2O_3 nanoparticles. The findings demonstrated that the inclusion of Bi_2O_3 enhanced fuel reactivity and thermal efficiency while simultaneously reducing pollutant emissions under varying engine loads. Similarly, Sekharraj et al. [13] conducted an experimental evaluation on biodiesel synthesized from green microalgae oil, blended with Bi_2O_3 nanoparticles in a ratio of 20% biodiesel to 80% diesel. Their results indicated a significant improvement in engine performance and a substantial reduction in exhaust emissions compared to unmodified fuel blends.

The current study builds upon these insights by systematically investigating the influence of Bi_2O_3 nanoparticle additives on combustion features, engine efficiency, and exhaust emissions in a CI engine operated at a fixed speed to optimize nanoparticle-assisted fuel formulations for sustainable engine performance.

This study pioneers the incorporation of bismuth subsalicylate (Bi_2O_3) nanoparticles into pure diesel fuel and a biodiesel blend (B20) to enhance combustion efficiency and reduce emissions—marking a departure from previous research, which focused exclusively on biodiesel blends. By optimizing the concentration of Bi_2O_3 nanoparticles (25–100 ppm) and employing advanced dispersion techniques such as ultrasonication and magnetic stirring, this work uniquely addresses the inherent trade-offs in diesel engines between performance (Bsfc, η_{bth}) and emissions (NOx, CO, HC, and smoke). Bi_2O_3 nanoparticles were selected for their multifunctionality, relative safety, and high effectiveness in enhancing material properties. They offer distinct advantages over many other nanoparticles, including superior thermal and chemical stability, enhanced mechanical and physical properties of composites, and high ionic conductivity—characteristics that make them particularly valuable in electrochemical applications such as fuel cells and energy storage devices. The results demonstrate scalable and retrofit-compatible solutions for older diesel engines, contributing to more sustainable fuel engineering practices.

2. METHODOLOGY

The examinations in this study were executed in many stages, as shown below:

-Running the engine exclusively on pure diesel.

-As previously stated, the engine should run on diesel fuel and Bi_2O_3 mixtures. Table 1 illustrates the Thermal physical features of Nano-diesel: 0% Bi_2O_3+100% diesel fuel (Pure), (B20+25Bi_2O_3 ppm), (B20+50Bi_2O_3 ppm), (B20+75Bi_2O_3 ppm), and (B20+100Bi_2O_3 ppm). All tests were conducted in single-cylinder engines at a load ranging between 5 and 20, with constant speed.

Table 1. Nano-diesel thermal physical features

Features	Diesel	B20	B20+25Bi_2O_3 ppm	B20+50Bi_2O_3 ppm	B20+75Bi_2O_3 ppm	B20+100Bi_2O_3 ppm
Density (g/cm^3)	0.812	0.8302	0.8311	0.8316	0.8318	0.8318
Kinematic viscosity at 40 C^0 (mm^2/s)	4.7	4.73	5.21	5.69	5.67	5.65
Flashpoint C^0	168	176	177	178	179	181
Pour point C^0	-4	-4	-4	-4	-4	-4
Calorific value kJ/kg	44300	44645	45303	45750	45874	45943
Cetane	52	54	50	51	53	53

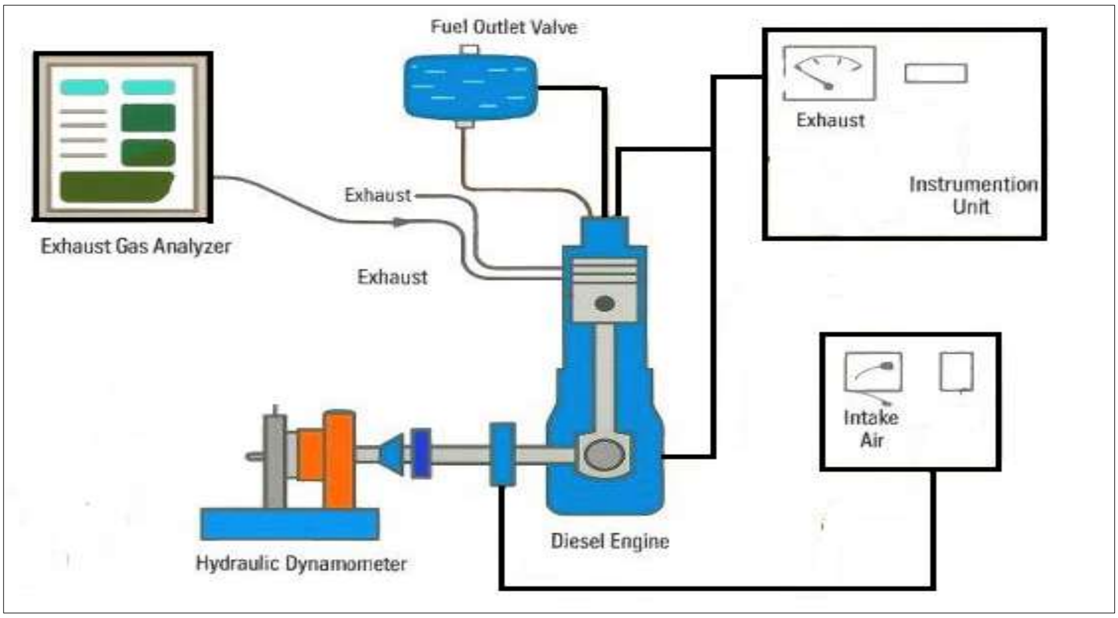

Figure 1. Schematic representation of the experimental test apparatus

3. EXPERIMENTAL SETUP

The experimental investigation assessed the impact of different fuel compositions on a 4-stroke diesel engine's performance and emission features operating at constant speed and subjected to variable load conditions. All experimental procedures were executed within the Internal Combustion Engines Laboratory, Department of Power Mechanics Engineering Techniques, at Al-Mussaib Technical College (TCM), affiliated with Al-Furat Al-Awsat Technical University (ATU), Kufa, Iraq. The test rig employed a single-cylinder, air-cooled, direct-injection diesel engine (model TD114) equipped with a hemispherical piston bowl-type combustion chamber, as depicted in Figure 1. The fundamental technical requirements of the engine are presented in Table 2. The engine was operated at a fixed rotational speed throughout the testing process, while four different fuel blends were evaluated to determine their influence on engine efficiency and exhaust emissions.

Table 2. Engine requirements

Engine Parameters	Specification
Model	TD111
General	Single-cylinder, 4-stroke, CI, Variable speed
Fuel	Diesel
Bore @ Stroke	70 mm @ 65 mm
Displacement volume	0.000250 m^3
Maximum speed	4000 rpm
Weight	45 kg

3.1 Experimental procedure

1. Starting the process by draining and flushing the fuel system before filling with the blend. In addition to that, unsure there is no fuel in the tank engine, because the influence of fuel remaining in the tank on may affect the values of the readings. Also must be certain that all the connections stiffened correctly.
2. Starting the engine after applying the pure diesel fuel, at four levels of loads (5-20), and constant speed (2000 rpm), then continue the engine to run at each load for (3-5) minutes to reach a stable operation condition.
3. After reaching a stable operating condition, the fuel consumption rate recorded by measuring the time taken the engine to consume 8 ml of fuel. Then the exhaust emissions (HC, CO, and NOx), were recorded by the exhaust gas analyzer and making sure that they maintain their stable values.
4. Each attempt was repeated three times under the same conditions to ensure consistency and reduce random error.
5. For each of the bismuth oxide -diesel blends (B20+25Bi_2O_3 ppm, B20+50Bi_2O_3 ppm, B20+75Bi_2O_3 ppm, and B20+100Bi_2O_3 ppm), the same steps (1, 2, 3 and 4) repeated at the same operating conditions.

4. Preparation of Bi_2O_3 Nanoparticles at ppm Concentration

This study involves the incorporation of Nano-Bi_2O_3 at varying concentrations of 25, 50, 75, and 100 ppm into diesel fuel. As seen in Figure 2, the nanoparticles and fuel were amalgamated using an electromagnetic stirrer for 45 min at a temperature between 70 and 80 degrees Celsius. The fuel specimens were utilized in the engine after they reached room temperature. The requirements for Nano-Bi_2O_3 are described in Table 3. As shown in Figure 3 their Energy Dispersive Spectrum (EDS).

Table 3. Nanoparticles features

Item	Requirements
Chemical Name	Nano Bismuth Oxide, (Bi_2O_3 - γ) 99.5%, America
Density	8.9 g/cm³
Mean Particle size	20-30 nm
Appearance	yellow Powder
Point of Melting	825°C
Point of Boiling	650°C

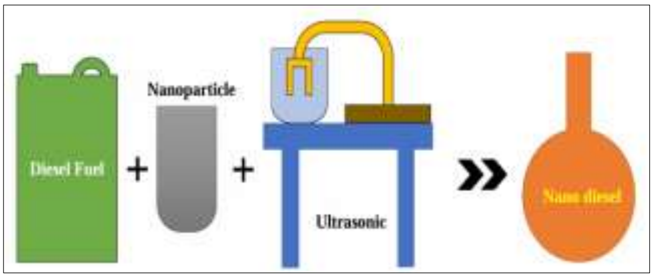

Figure 2. Schematic layout of the experimental setup

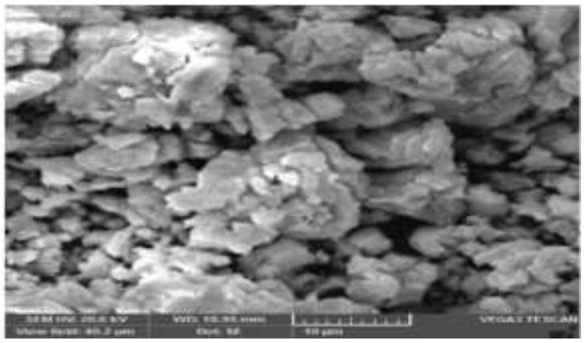

Figure 3. Bi_2O_3 nanoparticles

5. THE PERFORMANCE FEATURES

1. Braking-specific fuel consumption (Bsfc) represents the fuel's mass flow rate proportion ($\dot{m}_f$) to the braking power (wb) [14].

$$\text{Bsfc} = \frac{\dot{mf}}{\dot{wb}} \tag{1}$$

2. Brake thermal efficiency (η_{bth}) represents the ratio of the energy in braking power to the propelling fuel energy [15].

$$\eta_{bth} = \frac{BP}{\dot{mf} \times Q_{HV}} \tag{2}$$

6. RESULTS AND DISCUSSION

The primary objective of this investigation was to evaluate the impact of Nano Bi_2O_3 as fuel additives on the operational features of a CI diesel engine. The study systematically assessed the impacts of varying nanoparticle concentrations on key performance indicators, including Bsfc, η_{bth}, and exhaust emission factors—specifically smoke opacity, CO, HC, and NO_x.

Figure 4 demonstrates the difference in η_{bth} as a function of Bi_2O_3 nanoparticle concentration in biodiesel blends under different engine loads. The results indicate a progressive enhancement in η_{bth} with increasing nanoparticle dosage. The maximum η_{bth} was observed for the blend containing B20 and 100 ppm of Bi_2O_3, reaching a level comparable to that achieved with conventional diesel fuel. This enhancement in thermal efficiency at elevated loads is attributed to the catalytic action of Nano Bi_2O_3, which improve combustion kinetics by acting as an oxygen-donating agent. Consequently, the presence of these nanoparticles facilitates extended and more complete combustion, thereby contributing to higher thermal efficiency relative to the base fuel.

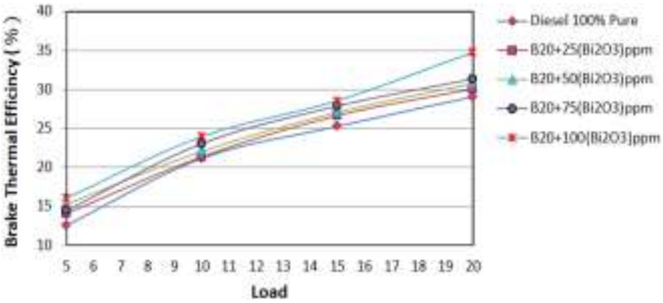

Figure 4. Impacts concentration of nanoparticles on η_{bth} at various engine loads

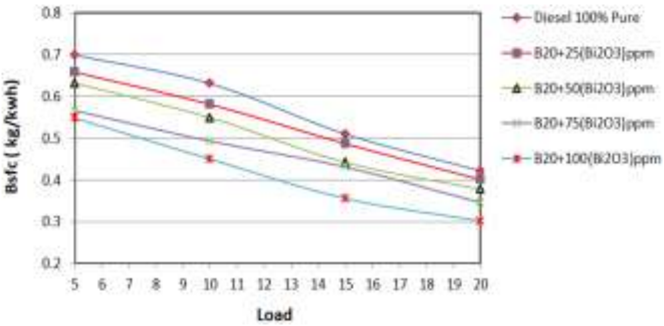

Figure 5. Impacts concentration of nanoparticles on Bsfc at various engine loads

Figure 5 represents the values of Bsfc at several concentrations of nanoparticle-diesel fuel concerning engine loads. It may be concluded that Bsfc is reduced with an increased concentration of nanoparticles in diesel fuel. Incorporating Bi_2O_3 into diesel fuel leads to a reduction in Bsfc comparisons to pure diesel. This significant enhancement might be recognized as the superior physical features, particularly the augmented proportion of surface area/volume of Nano-Bi_2O_3 compared with diesel fuel [16, 17]. The combination of (100% Bi_2O_3+B20) has the lowest Bsfc compared to all other fuel types. The most significant Bsfc decrease is 11.4% for the (100% Bi_2O_3+B20) compared to pure diesel fuel.

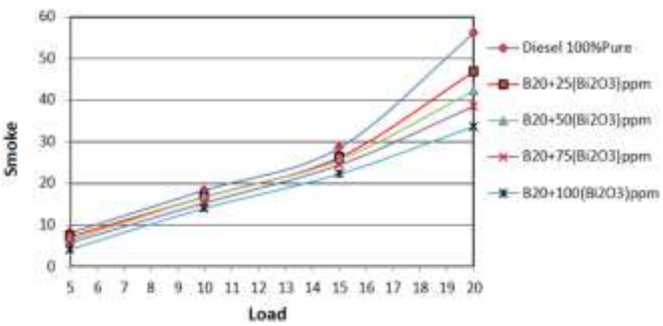

Figure 6. Impacts concentration of nanoparticles on smoke emissions at various engine loads

Figure 6 illustrates the correlation between smoke emissions and varying concentrations of Nano-Bi_2O_3 in diesel fuel under different engine loads. Indications indicate that Nano-Bi_2O_3 utilization in diesel fuel leads to decreased smoke emissions. Compared to pure diesel fuel, the minimum decrease in smoke emissions of 16% was observed for (100% Bi_2O_3+Di). This impact is recognized by the decreased ignition delay and enhanced combustion performance associated with an increased concentration of Bi_2O_3 in diesel fuel. It was projected that the reduction of soot formation and the promotion of reactant mixture will be due to the quick secondary atomization impacts in the presence of Bi_2O_3 nanoparticles.

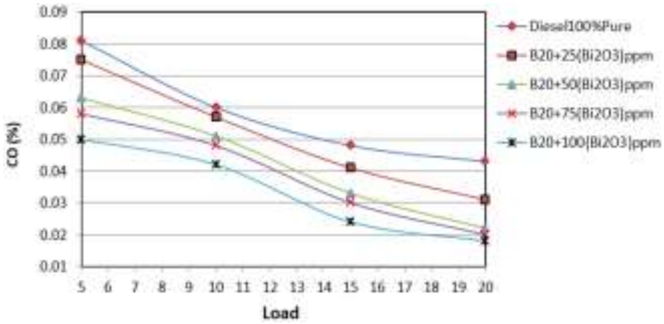

Figure 7. Impacts of concentration of nanoparticles on carbon monoxide (CO) at various engine loads

Figure 7 shows the impact of nanoparticle concentration on diesel fuel CO emissions. Evidence reveals that the Bi_2O_3 utilization of nano-Bi_2O_3 in diesel fuel decreases CO emissions. Under full load conditions, the most significant decrease in carbon monoxide emissions was documented at 13.2% for the (100% Bi_2O_3+B20) blend compared with pure diesel fuel. This enhancement is primarily attributed to the shortened ignition delay and the increased combustion characteristics resulting from the increased concentration of Nano-Bi_2O_3 in the diesel fuel blend.

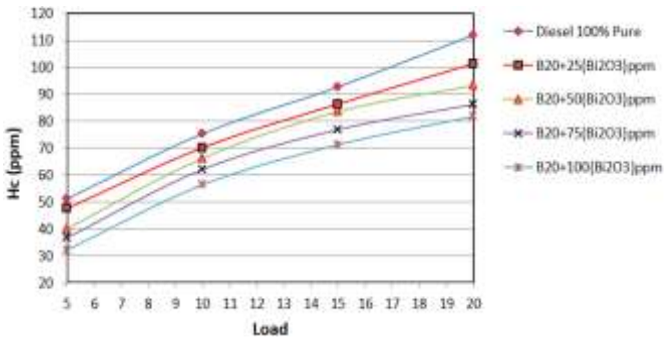

Figure 8. Impacts concentration of nanoparticles on hydrocarbon (HC) at various engine loads

Figure 8 shows the relationship between hydrocarbon emissions at different amounts of (Nano-Bi_2O_3) in diesel fuel and engine load changes. Unburned hydrocarbons (HC) in engine exhaust indicate incomplete combustion processes occurring during the combustion cycle. A negative correlation was observed between the amount of Nano-Bi_2O_3 in the diesel-biodiesel blend and the measured HC emissions. This reduction in HC levels can be attributed to the improved combustion efficiency facilitated by the nanoparticles, which likely lower the carbon ignition threshold during the activation phase. The catalytic nature of Bi_2O_3 promotes improved oxidation reactions, thereby minimizing the presence of unreacted hydrocarbons as nanoparticle concentration increases [18].

Figure 9 illustrates the association between NOx emissions and varying concentrations of Nano-Bi_2O_3 in diesel fuel concerning engine loads. At full load, the incorporation of (100% Bi_2O_3+Di) demonstrated the most significant reduction of 11.06% in Nitrogen oxide (NOx) emissions compared to pure diesel fuel, attributable to diminished ignition delays, which resulted in reduced early combustion, adiabatic flame temperatures, and thus, Nitrogen oxide (NOx) emissions [19, 20].

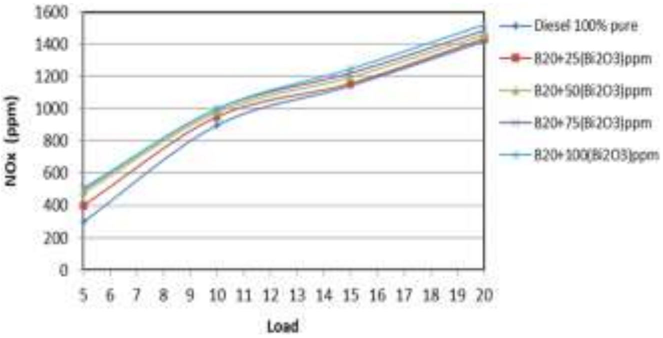

Figure 9. Impacts concentration of nanoparticles on Nitrogen oxide (NOx) at various engine loads

7. CONCLUSIONS

Bi_2O_3 nano-particles incorporated into diesel fuel affect emissions and engine performance. The subsequent conclusions were derived from the findings.

1. In Nanoparticle combustion, the higher surface area volume proportion enables more fuel for reacting with air, enhancing combustion efficiency.

2. Additionally, Nanoparticles improve the fuel's physical features and reduce ignition delay, leading to decrease in Bsfc.

3. It is seen that Bi_2O_3 blend fuels produce significantly lower emissions compared to diesel—specifically, CO, HC, and smoke emissions, while Bi_2O_3 blend fuels produce the most NOx emissions.

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NOMENCLATURE

Bi_2O_3	bismuth oxide
η_{bth}	brake thermal efficiency
Bsfc	brake specific fuel consumption
CO_2	carbon dioxide
CO	carbon monoxide
HC	hydrocarbon
NOx	nitrogen oxides
Temp	temperature
Di	diesel