



Experimental Study on the Impact of Using Fe₂O₃ Nanoparticles on the Emissions and Performance Characteristics of a Diesel Engine

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ABSTRACT

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This study investigates the influences of adding iron oxide (Fe₂O₃) nano-particles to traditional diesel fuel on engine performance and emissions. Three Nano-particle amounts (25, 50, and 75 mg/L) were tested and compared with neat diesel fuel under variable engine speeds and constant load. The results showed improvements in brake thermal efficiency (η_{Bth}), and brake power (BP) by 17.6% and 11.4%, respectively, while brake specific fuel consumption (BSFC) was improved by 22.8%. The findings demonstrated that BP and η_{Bth} improved by 11.4% and 17.6%, respectively, while BSFC was reduced by 22.8%. Emissions of CO₂, NO_x, and Hc were reduced by 21.9%, 24.9%, and 14.4% respectively. Additionally, the fuel containing 75 mg/L nanoparticles at 2000 rpm performed better than pure diesel fuel.

1. INTRODUCTION

Diesel fuel finds widespread applications in many fields, including agriculture, industry, and transportation. It is used in buses, trucks, and trains, as well as for equipment in power plants-all of which are very important to the economy [1]. Combustion of diesel oil continues to have significant environmental effects. The combustion of diesel emits particulate matter and nitrogen oxides (NO_x) into the atmosphere, while carbon dioxide (CO₂) emitted during combustion contributes to global warming. Development of renewable energy sources of energy is afoot, and so are setting higher standards for emissions. The path forward to sustainable development has to marry the economic importance of diesel with its serious environmental impacts [2, 3].

Rising petroleum prices, increasing air pollution, and the alarming effects of global warming have revitalized global interest in the development of alternative engine fuels. Of the many, Nano-diesels have received considerable attention, with various formulations having been tried over the years as viable alternatives to conventional petroleum-based fuels. Nano-additives in fuel are one promising solution to both environmental and energy problems. Metal oxide nanoparticles like Fe₂O₃, TiO₂, CO₃O₄, CeO₂, and Al₂O₃ were used for reducing the exhaust emissions and specific fuel consumption [4-6].

The inclusion of Nano-particles enhances the performance of the engine by increasing (η_{Bth}) and reducing the amount of Bsf since a high surface-to-volume ratio also lowers pollutant emissions and accelerates the rate of reactions. The accelerated

combustion is a result of a shorter ignition delay compared with neat diesel [7, 8]. The combustion efficiency of diesel fuel is enhanced when Iron-oxide (Fe₂O₃) nanoparticles are combined with it, since their oxygen-rich molecular structure [9]. Enhancing combustion leads to reduced emissions of nitrogen oxides (NO_x) and particulate matter compared with pure diesel engines. The added Fe₂O₃ also promotes a more homogeneous fuel-air mixture, which reduces incomplete combustion and enhances engine performance. Furthermore, the higher cetane number of these additives contributes to improving engine smooth operation and fuel efficiency [10, 11].

Nouri et al. [12] focus on the added Fe₂O₃ Nano-particles (30, 60, and 90 mg/L) to pure diesel fuel on the combustion characteristics, enactment, and emissions of diesel engines. The effects of Fe₂O₃ fuel mixtures on (Bp), η_{Bth} , and CO₂ releases have been detected to be greater than those of neat diesel fuel blends, with increased thermal efficiency (η_{Bth}) and power, reduced BSFC by 7.40%, 14%, and 8.2%, respectively, and decreased CO₂ releases by 21.2% compared with pure diesel fuel. Saxena et al. [13] added G and Fe₂O₃ nanoparticles to the fuel at mass amounts of 50, 100, and 150 ppm. It found indicate a positive correlation between nanoparticle dosage and the enhancement of η_{Bth} . This improvement is likely attributed to the increased reactivity and surface area of the nanoparticles. Also, the presence of nanoparticles enhanced the thermal conductivity of the fuel. The maximum (η_{Bth}) was enhanced by 26.1% at the highest dosage level (D150G). Ahmed et al. [14] reported that adding graphite (G) and iron oxide (Fe₂O₃) nano-particles to neat diesel can reduce the brake specific fuel consumption Bsf since

the engine. The highest reductions in Bsf_c were found to be 2.6 and 2.2% at 150 mg/L for G and Fe₂O₃, respectively. The findings also reveal that raising the dosages of G and Fe₂O₃ in diesel decreases CO releases and increases NO_x releases. Maximum CO reductions of 14.2 and 9.8% at 150 mg/L for G and Fe₂O₃, respectively, were reported. Besides, the maximum NO_x increases were 29.2 and 34.7% at 150 mg/L of G and Fe₂O₃, respectively. This might be because, at higher velocities, the engine does not have sufficient time to accomplish the process of combustion. Zhang et al. [15] paid attention to the impact of a Fe₂O₃-based selective decrement catalyst on the emission and combustion performance of a biofuel-fueled diesel engine that was investigated. The findings demonstrated an average increase in Bsf_c of 10.60, 5.35, and 5.22% for the diesel, RME, and CSME catalysts, respectively. Additionally, the use of biodiesel led to an average reduction in (CO) by 35%, (HCl) by 64%, and smoke by 45%. However, nitrogen oxide (NO_x) releases increased by 11% under medium and high engine loads. Jumaa and Mashkour [16] focus on the effect of humidification of the air on the performance of CI engine operating on diesel, biodiesel with added Fe₂O₃ Nano-particles (10, 30, 50 ppm, 70, and 100 mg/L). The experiment was carried out on a single-cylinder, 4-stroke, direct injection (E6/US) diesel engine under varying loads and a constant speed of 1800 rpm. Taguchi Method by DOE was used for the optimization in this investigation. The results manifested that BTE improved by 17.62% and BSFC decreased by 12.72%, while NO_x and PM reduced by 8.45%, 24.17%, respectively.

The aim of this research is to present a comprehensive analysis that explores and compares the impacts of various amounts of Fe₂O₃ with pure diesel fuel, at amounts of 25, 50, and 75 mg/L in diesel engine combustion on the emission and performance behaviors with variable speed and constant load.

2. NOVELTY IN CURRENT WORK

This work incorporates Iron oxide Fe₂O₃ Nano-particles into conventional diesel fuel for the dual purpose of improving combustion efficiency and reducing emissions, distinctly different from the earlier works, which were mainly biodiesel-based. This work, through optimization of Fe₂O₃ quantities of 25, 50, and 75 mg/L and using sophisticated dispersion methods like ultrasonic and magnetic agitation, tries to address the innate diesel engine trade-offs between performance parameters-Bp, η BT, Bsf_c, and emission releases, NO_x, CO, and HC. The novelty of this work is in demonstrating both the catalytic and thermodynamic roles of Fe₂O₃ within diesel systems, hence bridging the knowledge gap on the synergy of nanoparticles with diesel. These findings provide scalable and retrofit-compatible solutions for legacy diesel engines and, therefore, are important contributions toward the advancement of sustainable fuel technologies.

3. METHODOLOGY

In this study, iron oxide (Fe₂O₃) Nano-particles, which originated from Arej Al-Furat Office, were used to test the effect of using such particles on the performance as well as releases of a compression ignition (CI) engine. Experiments were conducted using a single-cylinder TD111 diesel engine at (1000, 1250, 1500, 1750, and 2000 rpm) speeds for a

constant load condition. Three quantities (20, 50, and 75 mg/L) of each of the Nano-particles were employed to examine their effects on engine performance as well as releases.

3.1 Preparation of various fuel mixtures

The usual procedure to stabilize the fuel additives in Nano-sized particles is ultra-sonication, which helps in evenly dispersing nanoparticles in fuel, besides increasing fuel blend stability. For this study, an ultrasonic bath having a power of 240W, a frequency of 40 KHz, and a temperature (temp) of 50°C is used to mix nanoparticles in diesel fuel for at least 30-40 minutes. A slight aggregation of nanoparticles is observed after 48 hours. Re-homogenation of fuel for testing is facilitated by further subjecting fuel to ultrasonic waves for a period of an additional 15 minutes; this is ascertained by two ways, namely, visual verification of tests and further spectroscopic verification, which is strong confirmation of the readiness of the fuel samples for tests to proceed as scheduled. During the experiments, the engine was fueled with various mixtures: pure diesel (Di+25mg/L Fe₂O₃, Di+50mg/L Fe₂O₃, and Di+75mg/L Fe₂O₃) as shown in Figure 1. The specifications of the Nano-sized and Fe₂O₃ particles are provided in Table 1.

Table 1. Features of diesel fuel mixed with nanoparticles

Features	Diesel	Di + 25mg/L Fe ₂ O ₃	Di + 50mg/L Fe ₂ O ₃	Di + 75mg/L Fe ₂ O ₃
Flash Point °C	58	63	64	67
Cloud Point °C	-3	-4	-4	-5
Kinematic viscosity (Mm ² / sec)	3.5	3.6	3.7	3.8
Density (g/cm ³)	0.816	0.817	0.821	0.823
Heating Magnitude (Kj/Kg)	42929	43442	43657	43729
Cetane number	51	55.3	55.9	56.4



Figure 1. Pure diesel, (Di +25 mg/L Fe₂O₃, Di +50 mg/L Fe₂O₃, and Di + 75 mg/L Fe₂O₃)

3.2 The features of the nanoparticles

The features of the Nano-particles utilized in this investigation are listed in Table 2. Figure 2 displays the TEM and SEM analyses, which confirm the Nano-particle sizes. Additionally, Figure 2 demonstrates the uniformity in the shape and size of the Nano-particles an important and

desirable characteristic.

Table 2. Nanoparticles features utilized in the present investigation

Kind	Size	Purity	Surface Area SSA	Appearance
Iron-oxide Nano-particle (Fe ₂ O ₃ , alpha) USA	20-40 m	99%	40–60 m ² /g	Red Powder

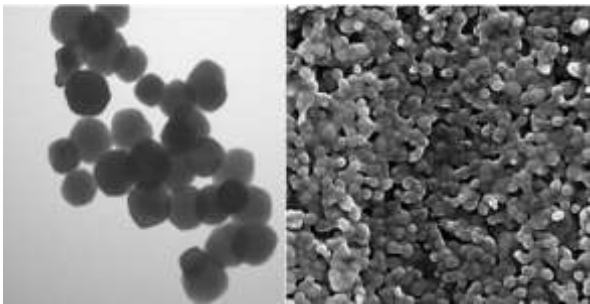


Figure 2. SEM and TEM analysis of Fe₂O₃ Nano-particles

3.3 Experimental setup

The experiments evaluated the various kinds of fuel influence on the performance and emissions of four-stroke diesel engines operating under flexible speed at a constant load condition. All tests have been performed at the (ICE- Lab) in the PME Techniques Department at Al-Mussaib Technical College (TCM), a branch of (ATU) in Kufa, Iraq. The experimental setup featured a single-cylinder, air-cooled diesel engine model TD111 equipped with a direct-injection system and a piston bowl combustion chamber, as shown in Figure 3. Key engine specifications are provided in Table 3. Three different fuels were tested at variable engine speeds to determine their effects on engine emissions and performance.

Table 3. Diesel engine requirements

Engine Factors	Requirements
Engine model	TD111
Manufacturer	TQ Education and Training Limited.
Type	Air-cooled, 4-stroke, and Single-cylinder
Fuel	Diesel
Bore@Stroke	70@65 mm
Swept volume	250 cm ³
Maximum speed	4000 rpm

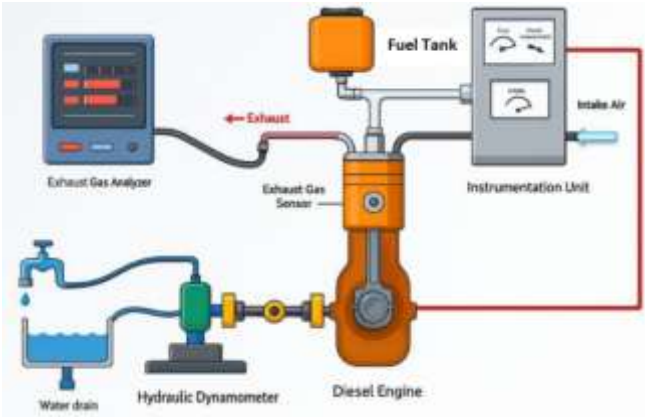


Figure 3. The engine test set-up

3.4 The performance characteristics

The braking power at the output shaft represents the brake power, whereas τ represents torque and N denotes engine speed in rpm [17].

$$Bp = \frac{2\pi N\tau}{60} \tag{1}$$

Brake specific consumption of fuel - Bsfc - is the quotient obtained by the division of the fuel mass flow rate ($\dot{m}_f$), by the Brake Pressurization - BP [18].

$$Bsfc = \frac{\dot{m}_f}{Bp} \tag{2}$$

The brake thermal efficiency (η_{bth}) itself presents the ratio of the energy in braking power to the propelling fuel energy [19].

$$\eta_{bth} = \frac{BP}{\dot{m}_f \times Q_{HV}} \tag{3}$$

4. RESULTS AND DISCUSSION

This study aims to explore how engine speed and fuel type independently affect engine emissions and performance characteristics.

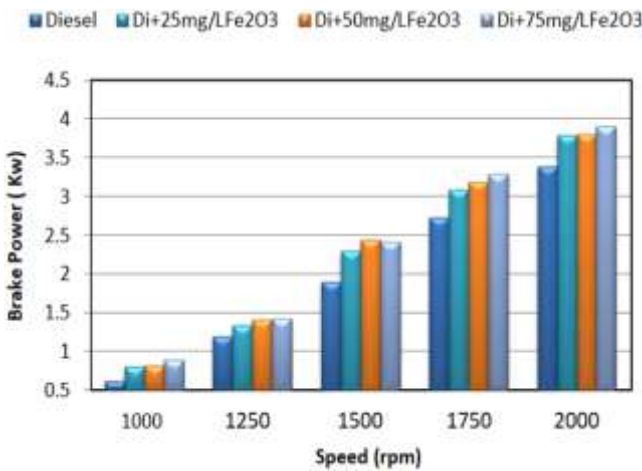


Figure 4. Brake power magnitudes against rotating speed for various diesel fuel and Nano-Fe₂O₃ mixtures

Figure 4 shows the relationship between engine speed and brake power. Braking power increases for all fuel types utilized when engine speed is gradually increased: pure diesel, and with the addition of Nano-Fe₂O₃ at 25, 50, and 75 mg/L. It was seen that the highest magnitude of braking power during a test using a 75 ppm amount gave a value of 3.9 kW at 2000 rpm, compared to 3.5 kW for pure diesel, an improvement of $\approx 11.4\%$. Other improvements also show a different percentage, reaching $\approx 5.7\%$ at 25 mg/L and 8.6% at 50 ppm. This is due to the catalytic role that Nano-Fe₂O₃ plays in the combustion process, enhancing power and thermal performance in diesel engines [20].

Figure 5 shows the relationship between engine speed and BSFC when using pure diesel fuel combined with iron oxide (Fe₂O₃) Nano-particles at different amounts (25, 50, and 75 mg/L). The Bsfc magnitude decreases significantly with the

added Fe_2O_3 comparison with pure diesel at all speeds. The results showed that at 2000 rpm, the BSFC for pure diesel was approximately 310 kg/kW.hr, while it decreased to approximately 240 kg/kW.hr with the added 75 mg/L Fe_2O_3 Nano-particles, a decrease of $\approx 22.8\%$. At 50 mg/L Fe_2O_3 , the decrease was $\approx 19\%$, and at 25 mg/L, it decreased by $\approx 16\%$. This reduction in fuel consumption is because of the effective catalytic role of nanoparticles, which improves the process of combustion inside the engine chamber by mitigating combustion delay, enhancing fuel atomization, and increasing flame temperature, causing a lowering of fuel usage and highly efficient combustion. Previous studies indicate that mixing fuel with nanoparticles metals as Fe_2O_3 , contributes to enhancing the fuels thermal and physical features [21].

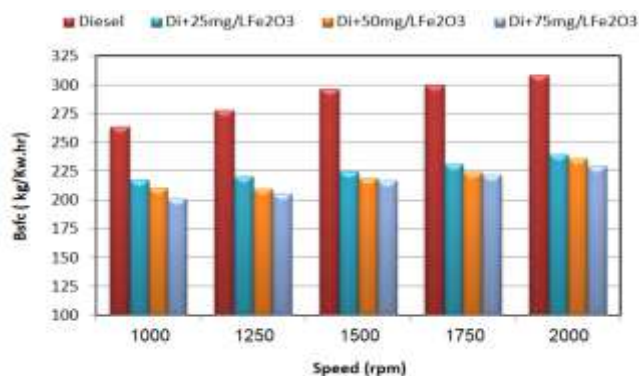


Figure 5. Bsfrc magnitudes against rotating speed for various diesel fuel and Nano- Fe_2O_3 mixtures

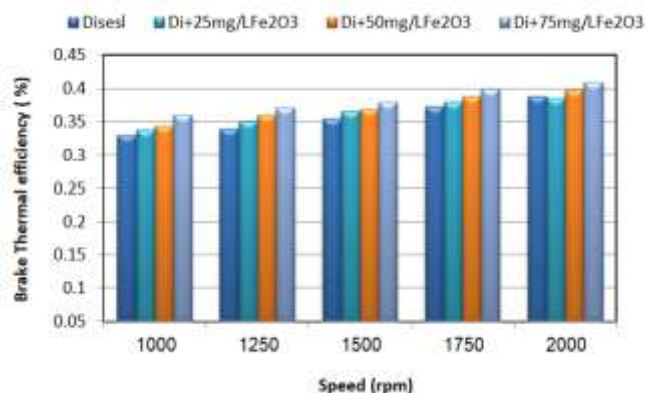


Figure 6. η_{BT} magnitudes against rotating speed for various diesel fuel and Nano- Fe_2O_3 mixtures

The mixing of pure diesel fuel with iron oxide Nano- Fe_2O_3 shown in Figure 6, significantly improved the thermal efficiency (η_{Bth}). The results showed that at an amount of 75 mg/L, the η_{Bth} reached 0.42% compared with 0.25% for pure diesel fuel at 2000 rpm, an improvement of 17.6%. This is because the role of the nanoparticles is as catalysts that accelerate the fuel oxidation rate and reduce the ignition delay time. They also enhance thermal conductivity within the combustion chamber, enhancing combustion completeness and reducing thermal energy. Fe_2O_3 nanoparticles have the potential to improve combustion efficiency and reduce carbon deposits, and thereby enhance engine durability. Over time, these benefits may extend service life and lower maintenance costs [22].

Figure 7 shows the effect of adding Nano- Fe_2O_3 at different amounts (25, 50, and 75 mg/L) to pure diesel fuel on carbon

monoxide (CO) releases at different engine speeds (1000–2000 rpm). It can be observed that CO releases decreased with increasing Fe_2O_3 amount at all speeds compared with pure diesel. The results showed that at 1000 rpm, CO releases decreased from 1.85% in pure diesel fuel to 1.45% with the added 75 mg/L Fe_2O_3 , an improvement of $\approx 21.9\%$. At 2000 rpm, CO releases decreased from 1.05% to 0.9% with the same additive, an improvement of $\approx 14.3\%$. The main reason for this improvement is that the catalytic features of Nano-iron oxides contribute to enhancing the process of combustion inside the combustion chamber by providing additional reaction surface and increasing oxidation efficiency, thus reducing the formation of carbon monoxide resulting from incomplete combustion [23, 24].

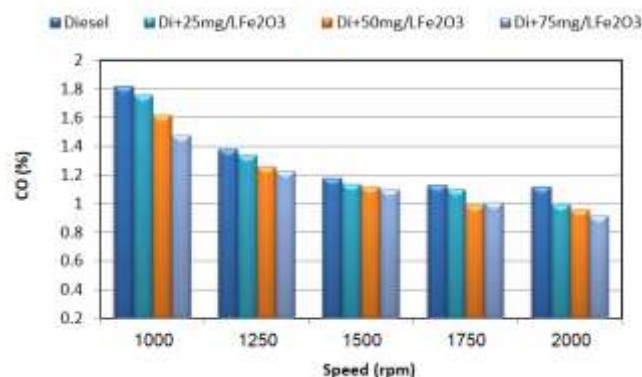


Figure 7. The differences in the CO releases versus engine speed for various combinations of Nano-particle-diesel fuel

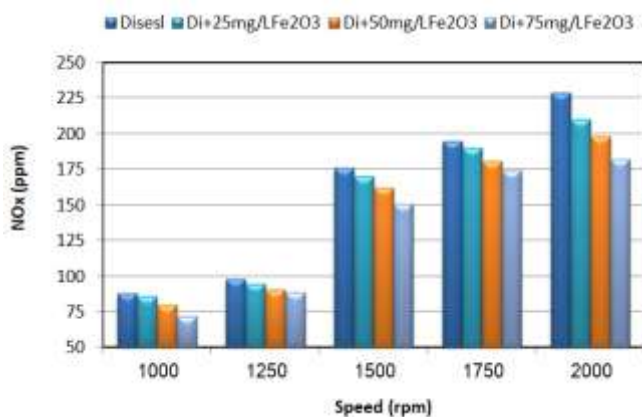


Figure 8. The differences of the NOx releases versus engine speed for various combinations of Nano-particle-diesel fuel

Figure 8 shows the changes in nitrogen oxide (NOx) releases after adding Nano- Fe_2O_3 to diesel fuel at different engine speeds. It can be viewed that NOx releases are reduced with Fe_2O_3 added ratio, especially at the highest amount (75ppm). At 2000 rpm, NOx releases decreased from ≈ 235 ppm using pure diesel to 180 ppm using 75 mg/L of Fe_2O_3 , an improvement of $\approx 24.9\%$. At 1,500 rpm, the decrease occurred from 175 ppm to 150 ppm, a reduction of $\approx 14.3\%$. The reduction in NOx releases caused by Nano- Fe_2O_3 leads to a reduction in the peak temperature inside the combustion chamber because of enhancing the process of combustion and reducing the duration of violent combustion, which leads to reducing the chances of forming nitrogen oxides that are primarily formed at high temperatures [25, 26].

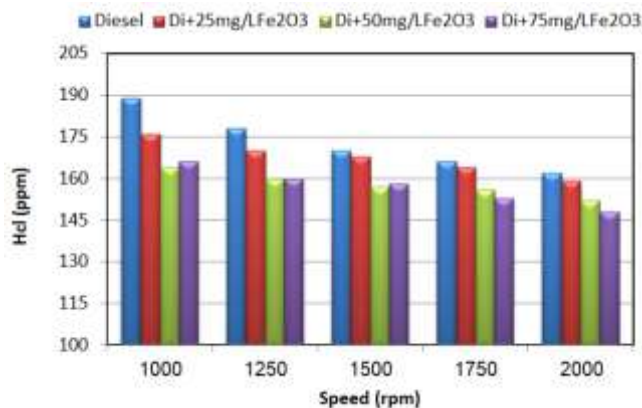


Figure 9. The differences in the HCl releases versus engine speed for various combinations of Nano-particle-diesel fuel

Figure 9 shows the relationship between engine speed and hydrocarbons and the impact of adding Nano-Fe₂O₃ to diesel fuel on hydrocarbon (HCl) emissions at different engine speeds (from 1000 to 2000 rpm). HCl release decreased significantly with increasing Fe₂O₃ amount in the fuel. At 1000 rpm, HC emissions decreased from 188 ppm for pure diesel to 160 ppm using 75 mg/L Fe₂O₃, representing an improvement of $\approx 14.4\%$. At 2000 rpm, HC emissions decreased from 162 ppm to 140 ppm for the same addition, representing an improvement of $\approx 13.6\%$.

5. SUMMARY AND CONCLUSIONS

This study conducted engine experiments to assess the impact of Fe₂O₃ nanoparticle additions at amounts of 25, 50, and 75 mg/L on the performance (Bp, η_{Bth} , BSFC) and release (CO, NO_x, and HC) features of a compression ignition engine. The main conclusions of this research are:

1. Fuel mixes with elevated amounts of nanoparticles in the fuel combination enhanced brake thermal efficiency and power by 17.6 and 11.4%, respectively, while reducing Bsfc by 22.8% in comparison to pure diesel fuel at 2000 rpm engine speeds.

2. Carbon monoxide emissions decreased from 1.05% to 0.9% with the addition of 75 mg/L Fe₂O₃ to pure diesel, an improvement of approximately 14.3%, at 2000 rpm.

3. Increasing the mixing amount of the Nano-particles Fe₂O₃ (25-75 mg/L) by weight, an improvement of approximately 24.9% of NO_x, and 14.4% HC releases at 2000 rpm.

6. FUTURE WORK

1. Testing the effectiveness of Fe₂O₃ nanoparticles when blended with biodiesel or diesel/biodiesel blends to evaluate their feasibility in enhancing the combustion of renewable fuels.

2. Conducting long-term research to analyze the effects on real engines, such as the effect of Fe₂O₃ solid nanoparticles on the wear of injection system components and piston rings.

3. Developing innovative additives or dispersion methods to enhance the stability of the mixture for longer periods and reduce costs, paving the way for commercial applications.

4. Testing Fe₂O₃ Nanoparticles under different loads or temperatures.

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NOMENCLATURE

η_{Bth}	brake thermal efficiency, %
BP	brake power, Kw
QHv	higher heat value, kj/kg
m _f	mass fuel rate, Kg/sec
BSFC	brake specific fuel consumption, kg/kw.h
CO	carbon monoxide, %
CO ₂	carbon dioxide, %
HC	hydrocarbon, ppm
NO _x	nitrogen oxides, ppm
Di	diesel fuel
Fe ₂ O ₃	iron oxide
CO ₃ O ₄	cobalt oxide
FeO ₃	iron oxide
TiO ₂	titanium dioxide
CeO ₃	cerium oxide
PME	power mechanics engineering