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Experimental Investigation of Fe_2O_3 Nanoparticle Additives on Diesel Engine Performance and Emissions

Ameer Hasan Hamzah[1*], Batool Najm Khudhair[2], Amer Khudhair Idan[1]

[1] Al-Mussaib Technical Institute, Al-Furat Al-Awsat Technical University, Babylon 51009, Iraq
[2] Technical College Al-Mussaib, Al-Furat Al-Awsat Technical University, Babylon 51009, Iraq

Corresponding Author Email: ameer.hassan@atu.edu.iq

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ABSTRACT

The aim of this research is to study the impact of Fe_2O_3 (hematite) nanoparticles as a fuel additive on the performance and emissions of a diesel engine. The aim is to find the optimum nanoparticle concentration in pure diesel fuel (D100) and assess its effect at full engine load. Fe_2O_3 nanoparticles (20–40 nm, 99% pure) were added at 50, 75, and 100 ppm by ultrasonic homogenization. Tests were performed on a single-cylinder, four-stroke diesel engine under varying loads, from 0% to 100%. Findings demonstrate that the 100 ppm mixture performed the best, with a 6% increase in brake thermal efficiency (BTE) and a 2% decrease in brake specific fuel consumption (BSFC) over diesel. Emission tests showed a 5% decrease in NOx, 10% in HC, and 5% in CO, with the highest decrease in CO (9%) at 50 ppm. This study is the first to quantify the optimal concentration of Fe_2O_3 nanoparticles in pure diesel fuel under full load engine conditions, showing its potential as a drop-in additive to enhance combustion efficiency and emissions under unmodified engine conditions. The next step will be to study long-term engine performance and compatibility of nanoparticles with engine parts, as well as the effect under variable operating conditions (transient loads, variable environment).

1. INTRODUCTION

1.1 Global context and environmental imperative

IC is still, to date, used as the primary source of power in the world, with transportation, agricultural, as well as industrial sectors particularly appreciating the usage of diesel engines due to their high thermal efficiency and reliability [1]. Nevertheless, the burning of conventional fossil fuels in these engines has a serious effect on environmental degradation by releasing nitrogen oxides (NOx), unburned hydrocarbons (HC), carbon monoxide (CO), and particulate matter [2]. This is because of the dire need to alleviate climate change and lessen reliance on petroleum-based fuels, that have prompted the speedy pace of alternative and complementary fuel technologies research [3]. Recent detailed surveys point out that NP fuel additives are one of the brightest future solutions to the problem of efficient fuel combustion without the necessity to change the engine hardware components [4, 5].

1.2 Development and continuing limitations of biodiesel

Biodiesel is also a promising renewable option because of its lubricity, biodegradability, and its possible carbon neutrality [1, 2, 6]. There are many non-edible forms of oil feedstock, such as linseed [1], Karanja and Jatropha [2], Pongamia [6], and waste cooking oils, which have been studied broadly as sources of biodiesel. These analyses indicate that despite the fact that the use of biodiesel cuts down on net CO_2 and the amount of particulate matter, there are issues that exist concerning the phenomenon of a higher viscosity index, lower calorific value, and higher emission of NOx in comparison to the standard diesel fuel [2, 7]. Most recent studies have also indicated that the increased surface tension of biodiesel has a negative influence on the atomization of spray, forcing the need to include countermeasures to enhance the fuel and air mixing [8].

In their experiment, Prakash et al. [9] tested the idea of vegetable oil as a renewable diesel substitute to demonstrate its effectiveness. The research was carried out on brake thermal efficiency (BTE), fuel consumption, and exhaust emissions. The findings showed that despite its viability, renewable oils still face increased viscosity and incomplete combustion that still have to be overcome through further modification of the fuel or addition of other additives. The paper by Prakash et al. [10] established the performance and emission characteristics of a diesel engine propelled on fish oil methyl ester. Their findings showed that the CO and HC emissions are lower than those in conventional diesel, but there were some slight NOx increases. The experiment established the viability of the marine-based biodiesel as a renewable alternative energy to mitigate environmental impacts. Aboelazayem et al. [11] conducted intensive research on the production of castor oil biodiesel, which covered kinetics modeling of the process, process optimization, and engine performance. They obtained better combustion properties and tolerable emission profiles. The experiment was useful as it helped to understand how to optimize the parameters of biodiesel production while simultaneously evaluating the actual engine operation.

1.3 Nanoparticle additives as combustion enhancers

Nanotechnology has recently developed metallic and metal oxide nanoparticles as fuel additives to overcome the shortcomings of conventional diesel and biodiesel fuels [12, 13]. These nanoparticles have interesting physicochemical properties, including a large surface-to-volume ratio and high thermal conductivity, enhancing combustion efficiency. Critical elements for successful performance are their dispersion stability at effective concentrations and the synergetic effect with the fuel [4, 5]. Hamzah et al. [12] proved that the presence of aluminum oxide nanoparticles in the water hyacinth biodiesel diesel blends increased the BTE by 6.4 percent and also reduced CO and HC emissions by 18.5% and 22.1 percent, respectively. 2024 findings have validated that CeO_2 at a 75 ppm dose can reach a 22.2 percent maximum thermal efficiency increase in biodiesel blends, and a 11.56 percent soot optical light reduction [14]. Studies that are more recent have shown that ternary nano-hybrid additives (CeO_2-TiO_2-Al_2O_3) at 50 ppm improve calorific value by 8% and reduce PM generation by 30, which is superior to single-component additives [15].

1.4 Vacuity of research and iron oxide nanoparticles

The iron oxides (Fe_2O_3 and Fe_3O_4) are also under consideration as one of the most common metal oxides because of their abundance, cost efficiency, and the two properties of being a combustion catalyst as well as being able to be recovered magnetically after their use [original paper]. In particular, Fe_2O_3 (hematite) nanoparticles have a high specific surface area (4060 m^2/g) that favours contact between the fuel-oxidizer, catalytic reduction of ignition delay, and high heat release rates due to better mixing attributes. Nonetheless, literature in systematic thermal analysis shows that the current research on Fe_2O_3 mainly concentrates on biodiesel mixes, and lacks any significant characterization of the catalytic mechanism in pure HC fuels [16]. This is a crucial difference, with the chemistry of combustion and the mechanisms of emission formation being very different between biodiesel that is oxidized and the all-HC diesel fuels.

1.5 Laundry technologies and drop-in solutions

Similar studies have examined alternatives to engine optimization, including thermal barrier coating (TBC) for combustion chamber components and exhaust gas recirculation (EGR) for emission control [17, 18]. While TBC and EGR improve thermal efficiency and reduce NOx emissions, they necessitate extensive engine redesign. In contrast, fuel-based nanoparticle additives offer a drop-in solution without requiring mechanical changes to existing engine infrastructure, supported by recent research on enhanced secondary atomization [5, 8].

When investigating diesel engine performance, Odibi et al. [19] considered waste cooking biodiesel and triacetin additive, noting enhanced exergy efficiency and lower irreversibility in comparison to diesel. Second law analysis was noted as important for advanced biofuels. Nabi et al. [20] evaluated non-edible biodiesels, reporting improved exergy efficiency and reduced CO emissions, with variations in NOx values, showing the advantages of different biodiesel blends in terms of both exergy and emissions.

1.6 Research gaps and study objectives

In spite of the fact that the literature on the use of nanofuel is increasing, there are still notable gaps in the knowledge. Although there has been a mass of investigation on CeO_2, Al_2O_3, and hybrid nanoparticles, the optimization of Fe_2O_3 in pure diesel (D100) over full working operational regions has not been systematically investigated. Moreover, the union of ultrasonic dispersion programs and quantitative stability results is a major hindrance in displaying laboratory outcomes and business utilization [8]. The analyzed gaps are fulfilled by a systematic characterization of the dosage of Fe_2O_3 nanoparticles (50 100 ppm) into standard diesel fuel throughout the entire engine loading cycle, enabling a reproducible methodology and mechanistic understanding of catalytic combustion enhancement.

2. MATERIALS AND METHODS

In this research, iron (III) oxide (Fe_2O_3) nanoparticles, which are approximately spherical in shape, with an average diameter of about 10 nm, and 99% purity, were supplied, specified, and manufactured in the United States. The morphology and approximate particle size of the Fe_2O_3 nanoparticles are shown in Figure 1. Their physical and chemical properties are listed in Table 1. The chemical and mechanical properties were evaluated by the average size of the nanoparticles. Three concentrations of 50, 75, and 100 ppm of each nanoparticle were used to evaluate the effect of nanoparticles on the performance and gas emissions of the CI engine.

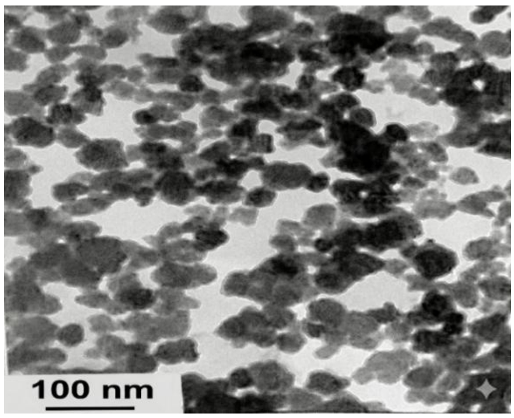

Figure 1. Fe_2O_3 nanoparticle

Table 1. Nanoparticle properties used in the current study

Type	Size	Purity	SSA	Color	Bulk Density	True Density	Product Number
(Fe_2O_3, alpha)	20–40 nm	+99%	40–60 m^2/g	Dark brown	1.20 m^2/g	5.24 m^2/g	3310DX

2.1 Preparation of fuel mixtures

The most commonly used method for stabilizing nanoparticle additives in fuel is the use of surfactants and engine performance measurement [20]. This results in proper distribution of nanoparticles in the fuel, and thus better stability. In the present research, surfactants were used to establish the relative stability of D100 fuel. In order to mix the nanoparticles with the fuel, an ultrasonic bath at a frequency of 45 kHz and a power of 245 W was used for 40 min to ensure homogeneity of the nanoparticles with pure diesel fuel, as shown in Figure 2. A slight amount of nanoparticle agglomeration was observed after 30 h. To re-homogenize, the fuel mixture was placed under ultrasonic waves before being used in the engine. The engine was fed with different fuel mixtures during the tests: pure diesel, D100 + $Fe_2O_3$50, D100 + $Fe_2O_3$75, D100 + $Fe_2O_3$100. The characteristics of the fuel mixtures and the photographs of the prepared fuel mixtures are given in Table 2. It should be noted that the hybrid fuel mixture is black because the color of the Fe_2O_3 nanoparticles is predominant.

The change in the calorific value of the fuel with the addition of Fe_2O_3 nanoparticles is inconsistent with the concentration. There is a slight increase in the calorific value at 50 ppm and 100 ppm, but a slight decrease at 75 ppm. The variations are minor and can be explained by measurement errors and the low concentrations of nanoparticles used. Thus, it is evident that the addition of Fe_2O_3 nanoparticles has no significant impact on the calorific value. The performance improvements observed in the engine are likely a result of improved combustion properties, including better atomization, catalytic activity and air-fuel mixing.

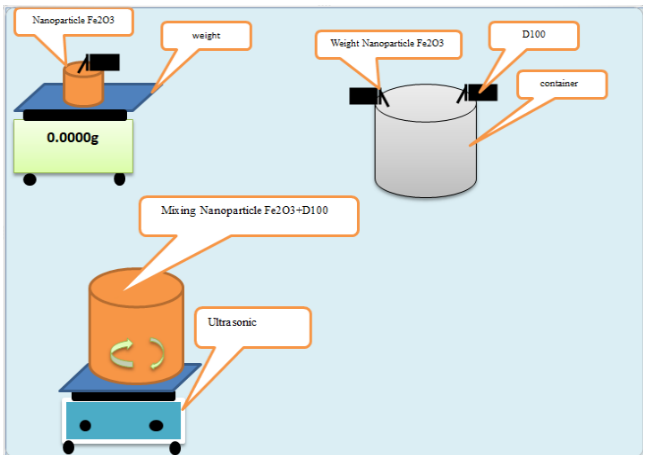

Figure 2. Preparation of pure diesel fuel using nanoparticles Fe_2O_3

Table 2. Properties of test fuels

Sample	Caloric Value (kJ/kg)	Kinematic Viscosity (cSt)	Density at 40 °C (g/ml)	Flash Point (°C)
D100	34408	9.02	0.866	115
D100 + $Fe_2O_3$50 ppm	35370	4.30	0.911	118
D100 + $Fe_2O_3$75 ppm	34250	4.40	0.908	119
D100 + $Fe_2O_3$100 ppm	34932	4.35	0.906	118

2.2 Experimental test engine

A diesel single-cylinder engine of Italian origin connected to an engine dynamometer was employed in the present analysis. A schematic representation of the test engine is illustrated in Figure 3. The necessary apparatus was calibrated and tested prior to measuring the engine performance parameters and CO, hydrogen, and nitrogen oxide emissions. The engine was run for 15 minutes and the preparation bath checked for the absence of pure diesel fuel. The complete operating conditions of the test engine are presented in Table 3. The gasoline engine exhaust parameters, including CO, hydrogen, and nitrogen oxides, were measured using a Chinese-type gas analyzer, while the smoke opacity from the tailpipe was determined using an AVL-437 smoke meter. The engine was operated initially on neat diesel, followed by a blend of neat diesel with the 1st dose of copper oxide at 50, 75, and 100 ppm and D100. 50, 75, and 100 at three loads to examine engine performance across the entire load range (0–100%) and at a constant speed of 1900 rpm (at 25% increments). Experiments were performed in triplicate, and data were averaged for calculations. The experimental results were discussed and compared with those of a diesel engine.

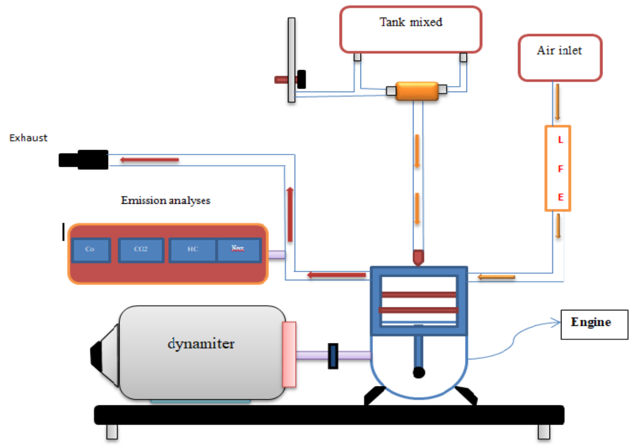

Figure 3. Preparation of pure diesel fuel using nanoparticles Fe_2O_3

Table 3. Properties of test fuels

Parameter	Specification
Engine kind	Injection pump, four stroke
Number of cylinders	Single cylinder diesel
Bore × stroke	81 mm × 64 mm
Compression ratio	8.3:1
Cooling	Air cooling
Maximum speed	2000 RPM
Output power	11 kW
Swept volume	0.000329 m^3
Manufacturer	Italian

2.3 Performance characteristics

(1) Brake Power (BP) is the power obtained from the crankshaft; also, the BP of the engine is calculated using Eq. (1) [11].

$$BP = \frac{2\pi NT}{60.000} \quad (1)$$

where, BP is in KW, T refers to the engine's torque in N·m, measured using a dynamometer, and N denotes engine speed in rpm.

(2) The thermal efficiency of the brake is the amount of work produced from the fuel energy that can be obtained from Eq. (2) [9].

$$\text{BTE (\%)} = \frac{\text{BP}}{\text{mf} * \text{LCV}} \quad (2)$$

where, mf is the mass flow rate of the fuel in kg/hr.

(3) Brake specific fuel consumption (BSFC) refers to the rate at which the engine consumes fuel and can be calculated using Eq. (3) [19].

$$\text{BSFC (kg. Kw. h)} = \frac{m^\circ f}{\text{BP}} \quad (3)$$

3. RESULTS AND DISCUSSION

3.1 The brake specific fuel consumption

As shown in Figure 4, the model determined by the fuel consumption rate with the brake force, the higher the load, the higher the fuel consumption. There is a decrease in the fuel consumption rate in the mixture of diesel fuel and nanoparticles in the biofuel D100 + Fe_2O_3 N100, compared to pure diesel fuel, where the fuel consumption was 2% for pure diesel fuel and nanoparticles. The reason is the presence and abundance of nanoparticles; all types recorded a decrease in the specific consumption value. With the addition of the nanomaterial, the fuel brake increased the injection angle and reduced the diameters of the fuel droplets. In addition, combustion was improved by creating smaller fuel droplets and increasing the surface area of the fuel, which leads to better mixing with air and works to oxidize the fuel and reduce viscosity. The effect of the ultrasonic device was that it contributed to improving combustion and reducing the amount of fuel needed to generate the required power, as well as working to reduce the attractive force between the fuel particles, which helps to quickly dissolve the fuel, mix it with the air, and obtain the best mixing and best combustion.

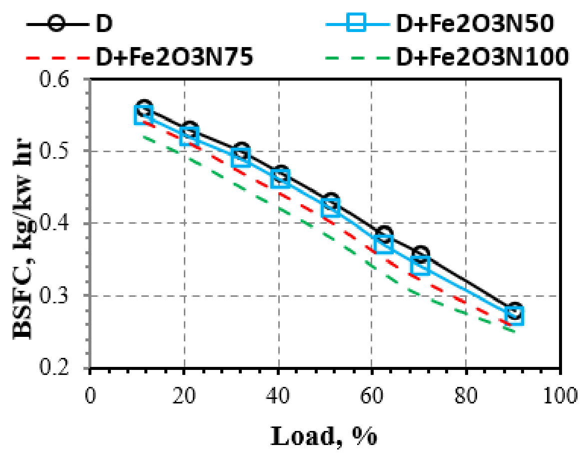

Figure 4. Brake specific fuel consumption (BSFC) at different loads for three tests of pure diesel fuel with nanoparticles

3.2 Brake thermal efficiency

It can be concluded from Figure 5 that indicates that, increasing engine performance by blending the pure diesel fuel with Fe_2O_3 nanoparticles improves it thermal efficiency of the engine BTE. The greatest engine performance was obtained by the D100 + Fe_2O_3N100 composition. The addition of Fe_2O_3 nanoparticles improved the combustion process, resulting in a 6% increase in BTE at peak load compared to pure diesel fuel at peak BP output (7.53 kW). A lower thermal efficiency was also determined when diesel fuel was blended. Lower braking effectiveness compared with the diesel blend containing nanoparticles. The addition of nanoparticles also leads to a rise in thermal efficiency. For this reason, inclusion of iron trioxide nanoparticles decreases the ignition delay and fuel evaporation time. It also improves the fuel and combustion characteristics. Nanomaterials possess a high surface-area-to-volume ratio, which enhances air–fuel mixing and promotes more efficient combustion reactions.

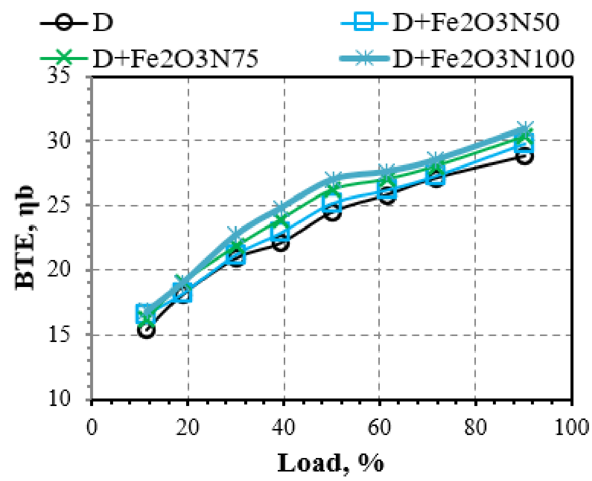

Figure 5. Brake thermal efficiency (BTE) at different loads for three tests of pure diesel fuel with nanoparticles

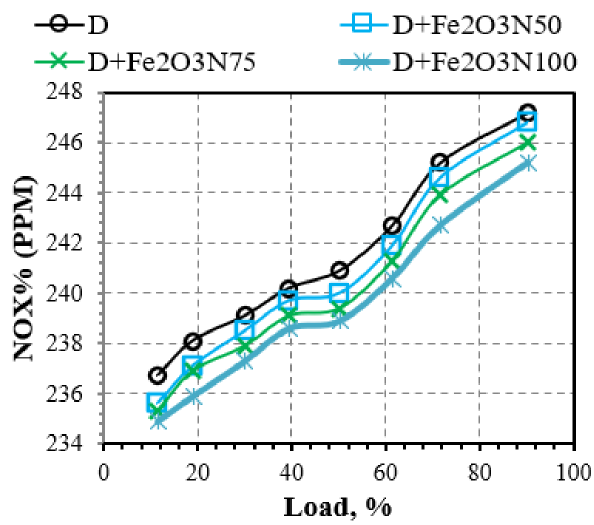

Figure 6. NOx at different loads for three tests of pure diesel fuel with nanoparticles

3.3 Emission characteristics

As shown in Figure 6, with the presence of nanoparticles, pure diesel fuel, high temperature, and abundant oxygen, it was observed that the emissions of nitrogen oxides D + Fe_2O_3N100 ppm Pure diesel nitrogen oxides decreased when using diesel fuel with nanoparticles, where the diesel ratio reached 5%, 90 kN/m^2; this is a good indicator. The main reason for the increase in the oxygen ratio is the increase in the mixing rate and the use of an ultrasonic device, which also affects the amount of oxides. The residual nitrogen in the exhaust gases and the fuel temperature here; the Fe nanoparticles increase the combustion surface area and release heat during complete combustion. The nanomaterial helps improve the heat transfer rate formed inside the combustion chamber, as the formation of nitrogen oxides is affected by the cylinder temperature, which helps it to decompose and mix with air better.

3.4 Hydrocarbon

As shown in Figure 7, when biodiesel was added with nitrous oxide trioxide, it was observed that the HC emission was 4% lower compared to pure diesel. HC emissions were 10% lower than D100 + Fe_2O_3N100 with pure diesel fuel at a maximum load of 90 kW N/m2. The reason is the presence of a large percentage of oxygen, which enhances the completion of the combustion process. Adding nanoparticles to diesel fuel leads to an increase in combustion efficiency, as well as the tendency of nanomaterial has to better reduce viscosity, spread the fuel during injection into the cylinder, and mix it well with air and combustion in a good way. It is clear that the effect of the load is to increase the percentage of emissions. Unburned HCs.

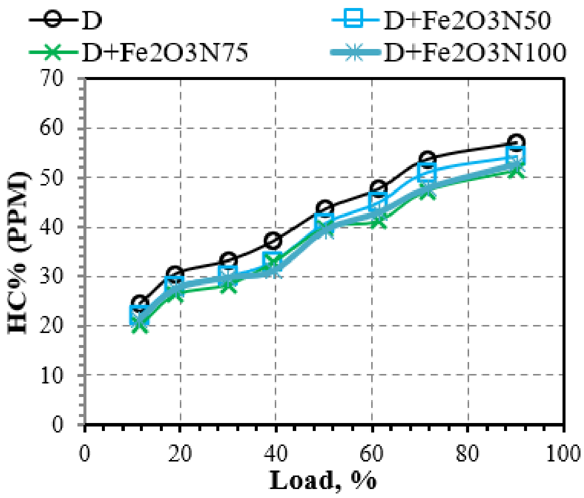

Figure 7. Hydrocarbon (HC) at different loads for three tests of pure diesel fuel with nanoparticles

The decrease in unburned HCs is mainly due to improvements in combustion efficiency rather than a reduction in combustion temperature. Fe_2O_3 nanoparticles enhance fuel atomization and provide more surface for reaction to occur, facilitating better mixing of air and fuel. This facilitates enhanced oxidation of HCs and hence a reduction in HC emissions.

3.5 Carbon monoxide

Figure 8 shows that CO decreases when pure diesel is added with nanoparticles in D100+ Fe_2O_3N100, where the maximum load is 90 kW, and the ratio is less than 5% pure diesel fuel. On the other hand, D100 + Fe_2O_3N50 fuel was much lower than pure fuel, where the ratio reached 9%, which is considered a good indicator. Adding nanomaterials and mixing them with fuel would improve fuel combustion due to a slight decrease in viscosity, an increase in combustion surface area, and a shorter ignition period of the fuel mixture. Adding nanomaterials to fuel leads to higher homogeneity and formation of rich zone fuel that helps in better combustion. The use of an ultrasonic device also helped in mixing and homogenizing the fuel to increase atomization inside the combustion chamber and thus achieve good mixing with air and complete fuel combustion.

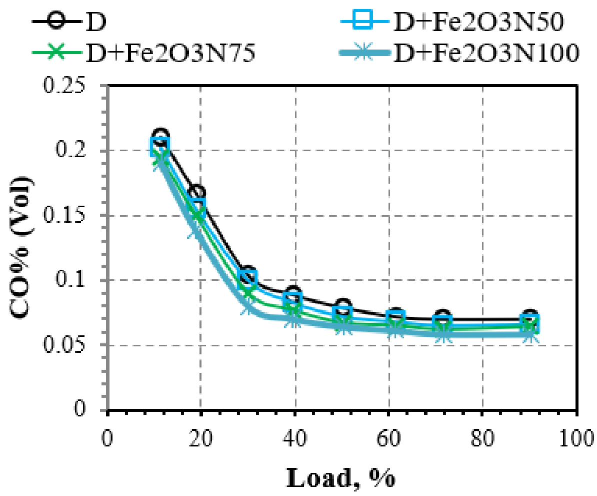

Figure 8. Carbon monoxide (CO) at different loads for three tests of pure diesel fuel with nanoparticles

Reduced CO emissions are linked to improved carbon oxidation. Fe_2O_3 nanoparticles play an important role in buffering the oxygen supply during combustion, promoting oxidation of CO to CO_2. Moreover, enhanced fuel mixing and reduced ignition delay lead to better combustion, which minimizes locally rich regions where CO is produced.

The decrease in NOx emissions, even with improved combustion, can be attributed to a thermal and catalytic effect. Though improved combustion usually leads to higher flame temperatures (which favor NOx formation), Fe_2O_3 nanoparticles promote more uniform heat release and reduce the time of combustion, thereby reducing peak temperatures. In addition, the reduction in ignition delay, due to improved combustion, results in reduced heat release rates, which inhibits NOx formation.

Table 4 presents the comparison of Fe_2O_3 nanoparticles with other popular nano-additives such as CeO_2 and Al_2O_3. It is evident that although CeO_2 nanoparticles tend to show a higher improvement in BTE owing to their high oxygen-storage capacity, Fe_2O_3 nanoparticles show comparable results, especially for HC and CO emissions. The current study differs from many other investigations that use biodiesel blends in assessing Fe_2O_3 nanoparticles in pure diesel (D100), which is a more relevant and direct application for diesel engines. This underlines the potential of Fe_2O_3 as a cost-effective and viable alternative nano-additive.

Table 4. Comparison of engine performance and emission improvements using nanoparticle additives

Additive	Fuel Type	Concentration (ppm)	BTE Improvement (%)	BSFC Reduction (%)	NOx Reduction (%)	HC Reduction (%)	CO Reduction (%)	Reference
Fe_2O_3 (this study)	Diesel (D100)	100	**+6%**	**−2%**	**−5%**	**−10%**	**−5%**	Present work
Fe_2O_3 (this study)	Diesel (D100)	50	+3–4%	−1–2%	−3–4%	−6–8%	**−9% (max)**	Present work
Cerium dioxide (CeO_2)	Biodiesel blend	75	+8–22%	−5–10%	−5–15%	−10–20%	−8–18%	Recent studies
Aluminum oxide (Al_2O_3)	Biodiesel blend	50–100	+4–7%	−3–6%	−3–10%	−15–22%	−10–18%	Hamzah et al. [12]

4. CONCLUSIONS

This study experimentally examined the impact of Fe_2O_3 nanoparticles in pure diesel fuel (D100) on diesel engine performance and emissions. This study showed that the optimal nanoparticle concentration (100 ppm) led to a 6% improvement in BTE, a 2% decrease in BSFC, and significant emission reductions of 5% in NOx, 10% in HC, and 5% in CO at high loads.

The significance of this study is the systematic investigation of Fe_2O_3 nanoparticles with pure diesel fuel at varying engine loads, including controlled dispersion and stability studies. This work, in contrast to many studies using biodiesel blends, demonstrates the efficacy of Fe_2O_3 nanoparticles as a direct additive for diesel engines without engine modifications.

Pragmatically speaking, the results show that Fe_2O_3 nano-additives can be an affordable and practical approach to enhance combustion performance and emissions control in the current fleet of diesel engines, especially in applications where retrofitting may not be an immediate option.

Researchers should conduct further studies to understand the durability of the engine, agglomeration of nanoparticles under practical conditions, and detailed combustion analysis (in-cylinder pressure and heat release). In addition, future research should be conducted to examine hybrid multi-nanoparticles and advanced modelling techniques to improve efficiency further.

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NOMENCLATURE

Fe_2O_3	Iron(III) oxide (hematite)
Fe_3O_4	Iron(II,III) oxide (magnetite)
CeO_2	Cerium(IV) oxide (ceria)
Al_2O_3	Aluminum oxide (alumina)
CuO	Copper(II) oxide
D100	pure diesel fuel (100% diesel)
D100+Fe_2O_3N50	diesel with 50 ppm Fe_2O_3 nanoparticles
D100+Fe_2O_3N75	diesel with 75 ppm Fe_2O_3 nanoparticles
D100+Fe_2O_3N100	diesel with 100 ppm Fe_2O_3 nanoparticles
BP	Brake Power, kW
BTE	brake thermal efficiency, %
BTHE	brake thermal efficiency *(alternative abbreviation used in paper),* %
BSFC	brake specific fuel consumption, kg/(kW·h)
N	engine rotational speed, rpm
T	engine torque, N·m
ṁ°f	mass flow rate of fuel, kg/h
LCV	lower calorific value, kg/h
mf	mass flow rate of fuel, kg/h
ηth	thermal efficiency, %
NOx	nitrogen oxides (NO + NO_2), ppm or g/kWh
HC	unburned hydrocarbons, ppm or g/kWh
CO	carbon monoxide, % or ppm or g/kWh
CO_2	carbon dioxide, % or g/kWh
PM	particulate matter, g/kWh
EGR	exhaust gas recirculation
H	hydrogen