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INVESTIGATION OF EMISSION PROPERTIES OF A COMPRESSION IGNITION ENGINE USING WATER – DIESEL EMULSION FUEL

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Abstract

The growing environmental problems linked to regular diesel fuel, like greenhouse gas emissions and particulate matter, people are looking for cleaner, more sustainable options. Water-Diesel Emulsion (WDE) fuel has become a promising option because it can cut down on harmful pollutants without needing to change the structure of current engines. A study examined the emission profiles of a single-cylinder, four-stroke compression ignition engine utilising water-diesel emulsion fuels with different water concentrations. The findings indicated that elevating the water concentration in diesel fuel markedly influences combustion dynamics and emission characteristics. With 10 % WDE under full load conditions, NOx emissions went down by as much as 30 %. This was mostly because water cools things down. The smoke opacity went down by 10 %, which means that the combustion was more complete and the air-fuel mixing was better because of the micro-explosion effect. But there was a small rise in carbon monoxide and unburned hydrocarbon emissions, especially at lower loads. With neat diesel the 10 % water–diesel emulsion (WDE10) reduced NOx emissions by 30 % at full load and decreased smoke opacity by 10 % across the tested load range. However, CO and unburned hydrocarbons (HC) increased at certain operating points (CO rose 15 % for WDE10 under selected loads), while CO_2 showed an increase of 8% at high loads, indicating measurable trade-offs. The results indicate that WDE is a feasible and effective method for improving combustion efficiency and decreasing significant emissions in CI engines, providing an immediate and economic transition strategy towards cleaner fuels while utilising current diesel infrastructure.

1.0 INTRODUCTION

The need for internal combustion engines, especially diesel-powered compression ignition (CI) engines, is growing around the world because they are more fuel-efficient, last longer, and work better in hot weather [1]. These engines are used a lot in farming, building, transportation, and making electricity [2]. But the widespread use of diesel engines has raised serious environmental concerns because they release harmful pollutants like nitrogen oxides (NOx), particulate matter (PM), unburned hydrocarbons (HC), carbon monoxide (CO), and carbon dioxide (CO_2) [3; 4]. These emissions make smog, acid rain, and other health problems for people with breathing problems, and they also change the climate around the world [5].

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Engineers and scientists are looking into alternative fuels and combustion enhancement techniques that can lower emissions without hurting engine performance [6]. This is because environmental regulations are getting stricter and there is an urgent need to cut down on harmful emissions [7]. One promising way to do this is to use Water-Diesel Emulsion (WDE) fuel. To make a stable emulsion, this fuel mix uses surfactants to spread tiny droplets of water throughout diesel fuel [8]. Using water in diesel combustion is not brand new, but recent improvements in surfactant chemistry and emulsification methods have made it a more effective and manageable way to cut down on emissions [9].

When WDE fuel burns, it causes micro-explosions, which happen when water droplets quickly turn into vapour at high temperatures, causing diesel droplets to break apart again [10]. This makes the mixing of fuel and air better, encourages complete combustion, and lowers peak flame temperatures [11]. This lowers the amount of NOx that is formed because it stops thermal NOx pathways [12]. WDE can reduce particulate emissions and smoke opacity by facilitating more uniform and efficient combustion [13]. The presence of water also slows down the combustion rate, providing extended ignition delay, which further improves mixing and contributes to cleaner exhaust emissions [14; 15].

Many paper have explored the influence of WDE on engine performance and emissions, and results consistently demonstrate significant decreases in NOx and smoke emissions [16]. The increases in CO and HC have been reported under low-load situations, primarily because of the quenching effect of water and reduced combustion temperatures [17]. These outcomes are achievable without the need for any hardware modifications to the engine, making WDE a cost-effective and retrofittable solution for existing diesel infrastructure [18].

In India, the shift from Bharat Stage (BS)-IV to BS-VI emission norms has created a pressing need for innovative emission control solutions that can be quickly adopted by the automotive and power sectors [19]. In this context, WDE offers an attractive pathway toward cleaner combustion. The simplicity of its preparation and the use of commercially available surfactants further enhance its applicability [20].

This research papers objectives are to comprehensively evaluate the **emission effects of a single-cylinder, four-stroke CI engine** fuelled with WDE containing 5 % and 10 % water by volume [21]. The investigation focuses on key emission parameters—namely, carbon monoxide (CO), carbon dioxide (CO_2), unburned hydrocarbons (HC), nitrogen oxides (NOx), and smoke opacity—under various engine loading conditions at a steady speed of 1500 RPM. This outcomes contribute to the growing body of knowledge that support WDE as a sustainable and effective emission reducing strategy for diesel engines [22].

The study systematically evaluates water-diesel emulsions (0 %, 5 %, and 10 %) across five engine load points and constant speed, reporting emissions of CO, CO_2, HC, NOx, and smoke, with created measurement uncertainty and replicate measurements. It quantifies emission reductions, particularly NOx and smoke, while analysing trade-offs in CO/HC and CO_2 behaviour, facilitating comparison with other studies. Limitations include the absence of in-cylinder pressure and heat-release-rate data, experiments conducted on a single engine with short-term tests, and testing limited to only two water fractions (5 % and 10 %). Future work should involve high-resolution diagnostics, transient duty cycles, further water-fraction optimization, particulate morphology analysis, injector wear studies, and life-cycle assessments to better understand real-world applicability and trade-offs between NOx emissions, particulate emissions, and fuel consumption.

[23]presents Water-Emulsified Diesel (WDE) as an effective method for cutting emissions from compression ignition engines by mixing water with diesel fuel [24]. This process utilizes surfactants to create a stable colloidal mixture suitable for existing diesel engines [25]. WDE significantly reduces nitrogen oxides, cooling the fuel during combustion, and lowers smoke emissions. Nevertheless, there are performance trade-offs, including higher carbon monoxide and unburned hydrocarbon emissions at low loads due to lower combustion temperatures [26]. Optimal water content (5-20%) is crucial for achieving a balance between emissions and performance, with 10% WDE showing notable improvements in NOx and smoke under full load [27]. Despite the reported advantages, gaps persist, such as the lack of standardized protocols for emulsion preparation, limited repeatability in emission data, and insufficient studies on in-cylinder diagnostics and engine durability, which hinder

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reliable assessments and practical deployment of WDE [28].

2.0 MATERIALS AND METHODS

This research paper examines the emission characteristics of a Diesel/CI engine using WDE fuels containing varying proportions of water (0 %, 5 %, and 10 % by volume). The research methodology encompasses fuel preparation, characterisation of fuel properties, and description of the test rig, instrumentation utilized for data acquisition, and the procedure followed during experimentation.

2.1 Fuel Preparation and Emulsification Process

The preparation of the WDE fuel was carried out using mechanical stirring for emulsification was performed using a high-shear laboratory homogenizer (Model: IKA T25 Ultra-Turrax) operated at 2500 rpm to ensure homogeneity and stability [29; 30]. The continuous phase was made up of diesel fuel from Bharat Petroleum Corporation Limited (BPCL) in India, which is available for sale. The dispersed phase was made up of double-distilled water, which was used to reduce impurities that could affect combustion or emulsion stability.

To keep the emulsion stable, a non-ionic surfactant mix of Span 80 (sorbitan monooleate) and Tween 80 (polyoxyethylene sorbitan monooleate) was used [31]. These surfactants were chosen because they are well-known to work well with each other and to keep water-in-oil emulsions stable. A 5% of fuel volume concentration was used, which kept the Hydrophilic-Lipophilic Balance (HLB) at 9, which is best for W/O emulsions [32].

Mechanical stirring for emulsification was performed using a high-shear laboratory homogenizer (Model: IKA T25 Ultra-Turrax) operated at 2500 rpm. To stop sudden phase separation and encourage even droplet distribution, water was added to the diesel slowly, dropwise, over the course of about 20 minutes. This method made sure that a thermodynamically metastable emulsion was made that could be used for engine testing for a short to medium amount of time without the need for co-solvents or high-pressure mixing systems [33]. Fuel samples were prepared as follows:

- Pure Diesel (0% water) – reference fuel
- 5% WDE – 5% water, 95% diesel with surfactant system
- 10% WDE – 10% water, 90% diesel with surfactant system

Each sample was subjected to physical property testing before engine trials. The surfactant system consisted of a Span-80-Tween-80 blend prepared to give an overall HLB = 9 and was added at **5 %** of the total fuel volume (50 ml surfactant per 1 litre of fuel); to achieve HLB = 9 the surfactant blend ratio was Span-80: Tween-80 = 56.1: 43.9**,** corresponding to 28.1 ml Span-80 + 21.9 ml Tween-80 per litre of fuel**.**

2.2 Fuel Property Characterization

To evaluate the influence of water content on fuel properties, each prepared fuel sample was analysed for calorific value, density, flash point, and kinematic viscosity. Standardized testing protocols conforming to ASTM and EN590:2009 specifications were followed [6; 34] All values listed in Table 1 were determined experimentally in the laboratory. Properties were measured following standard ASTM test methods as follows: net calorific value — ASTM D240; density — ASTM D4052 (or ASTM D1298 where applicable); kinematic viscosity — ASTM D445; flash point — ASTM D93 (Pensky-Martens); cetane number — ASTM D613; sulfur content — ASTM D4294 (XRF) / ASTM D5453 (UV fluorescence) as appropriate for concentration; water content — ASTM D6304 (Karl-Fischer); pour point — ASTM D97; and distillation characteristics — ASTM D86. Each reported property value is the mean of three independent measurements; the uncertainty reported is ±1 standard deviation.

Table 1 presents the physical and chemical properties of various test fuels (neat diesel, WDE-5 %, and WDE-10 %), highlighting systematic changes in density, viscosity, and lower heating value (LHV) with increasing water content. The increased density and altered viscosity influence injection mass per pulse and spray momentum, which enhances fuel penetration under constant injection pressure and affects spray breakup. The lower LHV of emulsions necessitates a greater fuel mass to achieve equivalent brake power, impacting observed brake-specific fuel consumption (BSFC) trends [35].

Dispersed water droplets provide evaporative cooling, which reduces peak local temperatures, thereby decreasing thermal-NOx and soot formation. Contrarily, micro-explosion effects lead to finer droplets that enhance local mixing, resulting in increased CO_2 emissions at elevated loads [36]. This

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balance between charge dilution and cooling effects versus improved atomization illustrates the trade-offs observed in emission data, notably the reductions in NOx and soot as opposed to increases in CO and hydrocarbons (HC). All Table 1 values are expressed as mean ±1 standard deviation based on three independent measurements.

Table 1: Properties of fuel sample

Fuel Property	Diesel	5% WDE	10% WDE	EN590:2009 Specification
Calorific Value (MJ/kg)	42.02	39.81	37.71	—
Density (kg/m³)	823.4	831.85	840.7	820–845
Flash Point (°C)	62	68	73	>55
Viscosity (cSt @ 40°C)	3.05	3.29	3.58	2.0 – 4.5

2.3 Engine Test Setup

The experiments used a Kirloskar AV-1 — a single-cylinder, four-stroke, direct-injection compression-ignition (CI) engine rated at 3.5 kW (5 HP) and operated at 1500 rpm (Figure 1). The engine is cooled by water and connected to an eddy current dynamometer with a built-in load cell that can measure torque and power very accurately. The engine ran at a steady speed of 1500 RPM during the tests, but the load conditions changed. Table 2 shows the specifications of engine setup used for experimentation.

Figure 1: Engine test setup photo (Kirloskar AV-1)

Table 2: Engine specifications

Parameter	Details
Engine Make	Kirloskar AV-1
Type	4-Stroke, Single Cylinder, Vertical, CI Engine
Cooling System	Water-Cooled
Rated Power	3.5 kW (5 HP)
Speed	1500 RPM
Bore × Stroke	87.5 mm × 110 mm
Compression Ratio	17.5:1
Swept Volume	661 cm³
Injection Type	Direct Injection

The engine was interfaced with a computerized data acquisition system, which enabled real-time monitoring and recording of various parameters.

2.4 Emission Measurement Instruments

To capture exhaust gas concentrations and smoke opacity, two high-precision devices were utilized:

Table 3: Instrumentation specifications

Parameter	Range	Resolution	Accuracy
CO (%)	0 – 10	0.01	± 0.10
CO_2 (%)	0 – 20	0.10	± 0.30
O_2 (%)	0 – 22	0.01	± 0.20
HC (PPM)	0 – 20,000	1 PPM	± 12 PPM

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Parameter	Range	Resolution	Accuracy
NO (PPM)	0 – 5,000	1 PPM	± 22 PPM
Smoke Opacity (%)	0 – 100	0.1%	± 1–2% Full Scale

1. **AVL 444 Five-Gas Analyser** used for measuring carbon monoxide (CO), carbon dioxide (CO_2), unburned hydrocarbons (HC), nitric oxide (NO_x) and oxygen (O_2).
2. **AVL 437 Smoke Meter** used for determining **smoke opacity (% opacity)** using the light absorption method.

Table 3 shows the specifications of instruments used to analyse the results. All instruments were calibrated before each set of experiments using manufacturer-recommended standard gases and calibration kits.

2.5 Experimental Procedure

The engine was initially operated on **pure diesel** to establish baseline emission values under several load conditions (no load, 25%, 50%, 75%, and full load). After each test, the engine was allowed to cool down, and the next fuel blend was introduced after flushing the fuel lines. For each fuel type (diesel, 5% WDE, 10% WDE), the engine was operated at steady speed and varying loads. After stabilization, the emission data were recorded thrice at each load point, and the average value was considered for analysis to minimize measurement error. Safety protocols were followed to avoid any contact with the emulsion fuel and to prevent overheating of the engine. No modifications were made to the engine hardware during the experimentation, thereby demonstrating the **plug-and-play** potential of WDE in conventional CI engines.

2.6 Repeatability, Averaging and Uncertainty Analysis

For each engine operating point (speed 1500 rpm; loads 0, 25, 50, 75 and 100% of full load) we performed **three independent test runs**. For each run emissions (CO, CO_2, HC, NOx, smoke opacity) and performance quantities (fuel flow, torque/power) were recorded after the engine reached steady thermal conditions. Reported data points in the Results are the **arithmetic mean** of the three independent runs.

3.0 RESULTS AND DISCUSSION

3.1 Emissions of Carbon Monoxide (CO)

Carbon monoxide results from incomplete combustion, generally occurring when there is inadequate oxygen or low combustion temperatures that prevent the complete oxidation of carbon into carbon dioxide. Figure 2 illustrates the fluctuation of CO emissions in relation to engine load for diesel, 5 % WDE, and 10 % WDE. At low engine loads, all three fuels exhibited comparatively low CO emissions owing to sufficient time for air-fuel mixing and combustion. Nonetheless, when the load intensified, CO emissions escalated, particularly for 10 % WDE. This phenomenon may be ascribed to the latent heat of vaporisation of water inside the emulsion, which absorbs considerable combustion heat and reduces in-cylinder temperature. The reduced flame temperature impedes the full oxidation of carbon to CO_2, hence elevating CO production. The micro-explosion phenomenon facilitates atomisation but does not guarantee full combustion, particularly under high water content and rapid combustion cycle requirements. The 10 % WDE fuel demonstrated the greatest CO emissions, followed by 5 % WDE and neat diesel.

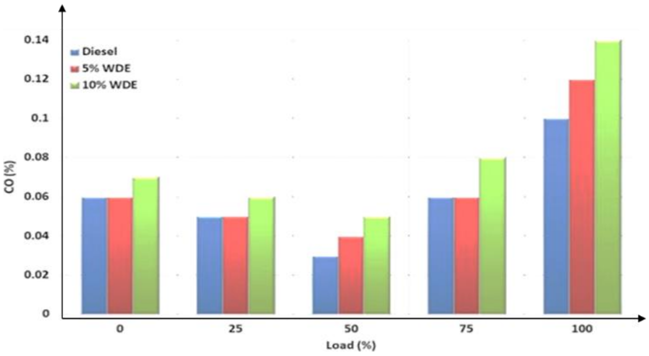

Figure 2: Load versus carbon monoxide CO (%) emission

Water content increases CO emissions, with 10% WDE resulting in 12-15% increase over diesel at full load, and higher water loading increases combustion quenching near cylinder walls.

3.2 Carbon Dioxide (CO_2) Emissions

CO_2 is a key indicator of complete combustion. It is formed when carbon in the fuel is fully oxidized. Figure 3 shows CO_2 emission trends across various load conditions. At lower and medium engine loads, WDE fuels showed **slightly reduced CO_2 emissions** as compared to diesel. This is consistent with the increased CO levels observed and indicates partial combustion due to cooling effects and lower reaction rates.

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However, at higher loads, both 5 % and 10 % WDE exhibited higher CO_2 emissions than diesel, with 10 % WDE showing the maximum. This rise is attributed to secondary atomization via micro-explosions, which enhances air-fuel mixing and allows more of the fuel to burn completely, especially under high-temperature, high-pressure conditions. The micro-explosions fragment fuel droplets into smaller sizes, increasing the surface area for combustion.

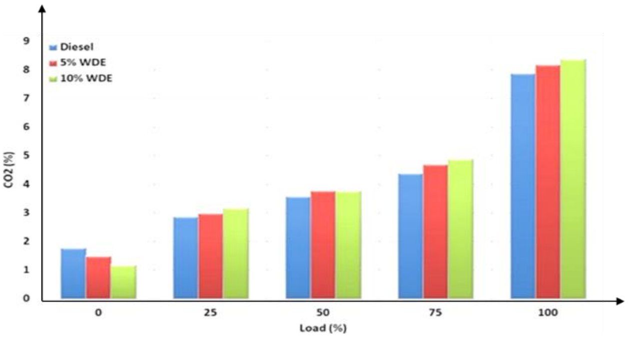

Figure 3: Load versus carbon dioxide (CO_2) emissions

10 % WDE produces 8 % higher CO_2 than diesel at full load, but improved micro-explosion mixing enhances combustion completeness at higher loads, while low-load CO_2 reduction is offset by increased CO and HC emissions.

Several physical and chemical mechanisms explain emission trends observed with Water-Diesel Emulsions (WDE) [37]. These include: (i) micro-explosions of emulsified droplets leading to finer droplet spectra, enhancing fuel-air mixing and combustion completeness at higher loads, resulting in increased CO_2 and reduced soot; (ii) charge dilution and evaporative cooling from water vapour lowering peak combustion temperatures, thus reducing thermal-NOx formation; [38; 39] (iii) at high temperatures, water dissociation increases OH radical concentrations, promoting soot oxidation while potentially increasing CO and HC emissions at low-load conditions; (iv) the stability and microstructure of surfactants influence atomization and combustion behaviour, necessitating accurate reporting of surfactant metrics; and (v) WDE alters lower heating value (LHV), density, and viscosity, affecting injection and ignition characteristics, correlating performance diagnostics with emissions and in-cylinder processes [40; 41].

3.3 Unburned Hydrocarbons (HC) Emissions

Unburned hydrocarbons represent fuel that escapes combustion either due to quenching near cold engine surfaces or due to insufficient oxygen. Figure 4 displays HC emissions for different fuels. At low engine loads, HC emissions were slightly higher for both 5 % and 10 % WDE compared to diesel. This is due to the suppression of flame propagation by evaporative cooling from water, which slows the reaction rate and increases the tendency of flame quenching—especially in boundary layers and crevice volumes. As engine load intensified, HC emissions from WDE progressively decreased, becoming equivalent to those from diesel at full capacity. This results from elevated temperatures and intensified combustion caused by micro-explosions under high loads.

The study found that HC emissions increased by 12 % with 10 % WDE at low load, nearly matching diesel emissions under full load. Higher water content increased quenching but offset better atomization at higher load. The diesel performed better than the 5 % and 10 % WDE in HC emissions.

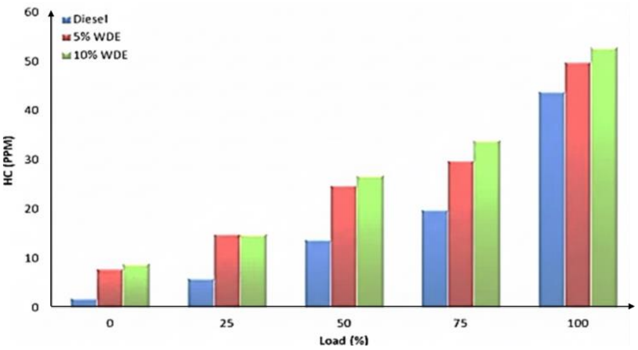

Figure 4: Unburned hydrocarbons (HC) emissions

3.4 Nitrogen Oxides (NOx) Emissions

NOx generation in diesel engines mostly transpires via the thermal NOx mechanism, which is acutely responsive to maximum flame temperature and oxygen supply. Figure 5 illustrates NOx emissions under different loading circumstances. A significant decrease in NOx emissions was recorded for WDE fuels, with the peak reduction (30 %) attained using 10 % WDE under full load circumstances. The principal process involves the absorption of combustion heat by water, which reduces the local adiabatic flame temperature, so directly influencing the thermal NOx production pathway. The delay in ignition and longer premixed phase induced by WDE also allow more uniform combustion, further reducing peak temperature zones where NOx would typically form. The reduction in NOx emission aligns well with findings from other researchers such as [3;

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42], who reported similar NOx reductions in water-emulsified fuels.

Water deposition (WDE) significantly reduces NOx by 20 % at full load, with a 30 % reduction at full load, with NOx reduction being more prominent at medium and high loads.

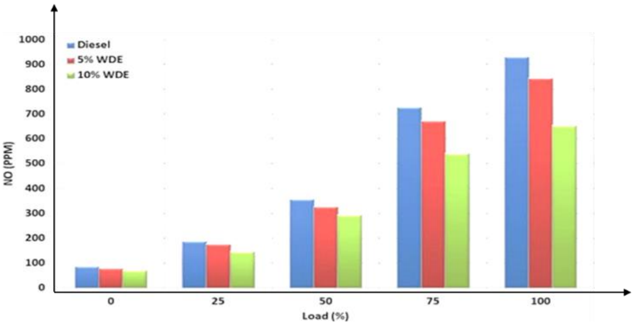

Figure 5: Nitrogen oxides (NOx) emissions

3.5 Smoke Opacity

Smoke or soot emissions arise from **incomplete combustion and fuel-rich zones** in the cylinder, where insufficient oxygen leads to the formation of carbon particles. Figure 6 illustrates smoke opacity variations across load conditions. The results show that both 5 % and 10 % WDE significantly reduced smoke opacity compared to diesel at all load levels. Water micro-explosions improve atomization, reducing droplet size. Mixing air and fuel makes pockets of fuel-rich air, and oxygen in water molecules helps partial oxidation. Previous studies have shown that lower flame brightness and soot formation temperature make smoke less opaque. This is because the air and fuel mix better and there is oxygen in water molecules.

The study found that 5 % WDE reduce smoke opacity by 10 %. This was because the air-fuel mix was better and the temperature at which soot forms was lower. Table 4 shows the parameters and effect of 5 % and 10 % WDE.

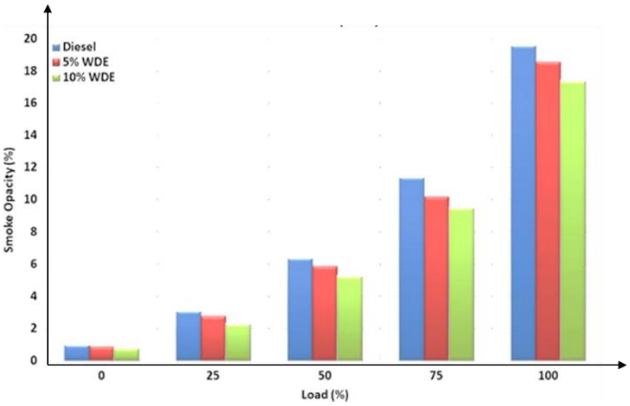

Figure 6: Load versus smoke opacity

Table 4: Summary of results obtained

Emission Parameter	**Effect of 5% WDE**	**Effect of 10% WDE**
CO	Slight increase	Moderate increase
CO_2	Similar at low load, increase at high load	Higher at high load
HC	Slight increase at low load	Higher at low load, reduces at full load
NOx	15 % reduction	30 % reduction
Smoke Opacity	8 % reduction	10 % reduction

4.0 CONCLUSION

The experimental study demonstrates that water–diesel emulsions (WDE) are a feasible mitigation strategy for combustion-temperature–driven pollutants in compression-ignition engines: specifically, WDE with 10 % water (WDE-10) reduced NOx by 30 % at full load and decreased smoke opacity by 10 % across tested loads, while CO increased by 15 % at some operating points and CO_2 rose by 8 % at high loads (all values are means of three independent runs; error bars ±1 standard deviation). These results indicate WDE can meaningfully lower thermal-NOx formation and soot without hardware modification, making it attractive for high-load traction applications (heavy trucks, buses, off-road machinery) where steady high-load operation maximizes NOx/soot benefits and can reduce after-treatment burden; however, the observed CO/HC penalties under low-load conditions caution against unqualified use in urban stop–start duty cycles without calibration or after-treatment adjustments. For practical deployment we recommend optimizing water fraction and surfactant formulation for the target duty cycle, pairing WDE with suitable after-treatment (oxidation catalyst, SCR and DPF strategies), and conducting comprehensive

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durability and fuel-system compatibility tests (injector wear, deposits, corrosion). Limitations of this work include absence of in-cylinder pressure/heat-release diagnostics, tests on a single research engine, and only two water fractions (5 % and 10 %) evaluated; future work should therefore add high-resolution combustion diagnostics, broader water-fraction optimization, transient/real-drive testing, particulate morphology analysis, and long-term durability studies to validate fleet-level applicability.

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