

## EMISSIONS EVALUATION OF A DIESEL ENGINE FUELED BY A WATER-DIESEL EMULSION

*Jawaher Ahmed Salman, Naseer Salman Khadhim*

*Department of Agricultural Machines and Equipment, College of Agricultural Engineering Sciences,  
University of Baghdad, Iraq*

*Jawaher.ahmed1603c@coagri.uobaghdad.edu.iq<sup>1</sup>*

*Water–diesel (W/D) emulsions have emerged as a promising for reducing harmful exhaust emissions while maintaining diesel engine performance, particularly emissions of nitrogen oxides (NO<sub>x</sub>) and smoke opacity (SO). This study investigated the effects of two (W/D) emulsion ratios containing 7% and 17% water by volume on the exhaust emissions of a water-cooled, 4-cylinder, direct-injection diesel engine operating at a constant speed of 1600 rpm under various load conditions. The experimental results demonstrated that the 7% (W/D) emulsion reduced NO<sub>x</sub> and SO emissions by 27% and 82%, respectively, compared with neat diesel fuel. The 17% (W/D) emulsion achieved greater reductions, lowering NO<sub>x</sub> and SO emissions by 38% and 89%, respectively. Nevertheless, both emulsions increased emissions of carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>), and unburned hydrocarbons (HC). For the 7% emulsion, CO, CO<sub>2</sub>, and HC emissions increased by 20%, 8%, and 30%, respectively, whereas the corresponding increases for the 17% emulsion were 33%, 24%, and 50%. Overall, although the 17% (W/D) emulsion provided superior reductions in NO<sub>x</sub> and SO emissions, the 7% W/D emulsion offered a more favorable compromise between the reduction of regulated pollutants and the increase in other exhaust emissions under the investigated operating conditions.*

*Key words: Diesel engine; emission; alternative fuel; water/diesel emulsion; Nitrogen Oxide; Smoke Opacity*

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### 1. Introduction

The diesel engine remains a predominant source of mechanical power, extensively utilized across essential sectors such as transportation, agriculture, construction, electricity generation, and maritime transport. Its significance stems from its capacity to convert the chemical energy in fuel into mechanical energy through combustion within the engine. Factors such as fuel availability, cost, and combustion characteristics are critical considerations for users. Consequently, while fuel combustion provides valuable energy, it also results in substantial exhaust emissions. Diesel engines significantly contribute to environmental pollution, emitting nitrogen oxides (NO<sub>x</sub>), carbon monoxide (CO), particulate matter (PM), and unburned hydrocarbons (HC), all of which pose health risks [1,2].

The pursuit of alternative and sustainable energy sources has become crucial for suitable alternatives to mitigate global warming is an important topic that has received attention within the global Sustainable Development goals given its role in reducing environment impacts and improving the sustainability of energy sources [3].

Many research efforts have focused on developing renewable alternatives to fossil fuels, with the aim of reducing harmful environmental impacts and providing sustainable fuel that can be used efficiently in internal combustion engines [4].

Recent studies have explored diverse alternative fuels for conventional diesel engines to reduce harmful emissions and enhance engine performance. Similarly, the potential of diesel–biodiesel–water emulsions as a substitute for traditional diesel was demonstrated [5], re-

ducing harmful emissions and increasing engine efficiency. Biodiesel derived from trans esterification of various feedstocks can serve as a sustainable transportation fuel, positively affecting engine performance and emission reduction [6]. Additionally, hydrogen-diesel dual fuel technology was systematically reviewed, revealing that hydrogen enrichment enhances engine performance and significantly lowers emissions like CO, CO<sub>2</sub>, and HC, although they noted an increase in NO<sub>x</sub> emissions at high loads [7]. A pilot study was conducted [8] to evaluate the performance of a diesel engine running on a butanol-acetone mixture with diesel fuel at two different fuel levels. They concluded that the butanol-acetone mixture shows a it did demonstrate a significant reduction in carbon dioxide, hydrocarbon, and nitrogen oxide emissions.

Based on these studies, water-in-diesel emulsions have attracted considerable attention because of their potential to reduce harmful exhaust emissions. The presence of water in the emulsion lowers the combustion temperature, thereby reducing nitrogen oxide (NO<sub>x</sub>) formation. In addition, water promotes soot reduction and enhances oxidation reactions, leading to lower exhaust smoke opacity. Therefore, water-in-diesel emulsions are considered a promising approach for mitigating diesel engine emissions and helping engines comply with increasingly stringent environmental regulations [9].

Studies show that the use of water emulsions in diesel engines influences engine emissions in various ways. Most studies concur that water emulsions reduce smoke opacity and nitrogen oxide (NO<sub>x</sub>) emissions, as demonstrated by Alahmer et al [10], Mahdi et al [11], and

Oliveira et al [12]. However, some studies, such as Mostafa et al [13], have indicated the opposite effect. Mahmood et al [14] found that adding water might increase emissions of unburned hydrocarbons (HC) and carbon monoxide (CO). In contrast, Alahmer et al [10] observed a decrease in these emissions, while Oliveira et al [12] reported an increase in carbon dioxide (CO<sub>2</sub>) emissions with higher water content in diesel. In addition, Nguyen and Nguyen [15] found that the use of a (WD) emulsion in a marine diesel engine installed on an actual ship reduced NO<sub>x</sub> and CO emissions compared with conventional diesel fuel, demonstrating the feasibility of applying water–diesel emulsions in practical marine diesel engines.

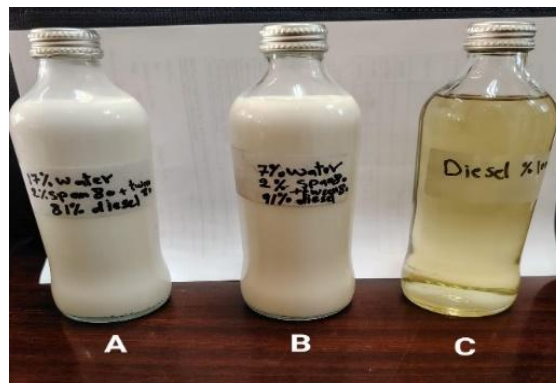
Although diesel–water emulsions have been extensively investigated for transportation and diesel engine applications, the present study focuses on diesel–water emulsions containing 7% and 17% water prepared using a surfactant blend with a required HLB value of 6. The stability of the prepared emulsions and their exhaust emissions were evaluated under different engine loads. The results contribute to a better understanding of the effect of these emulsions on exhaust emissions.

## 2. Materiel and methods

### 2.1. Fuel

Diesel fuel was obtained from local fuel stations in Baghdad. Deionized water and the surfactants Span 80 and Tween 80 were procured from Loba Chemie Pvt. Ltd (India) for emulsion preparation. Two distinct emulsions were formulated in the laboratory through mechanical homogenization, a low-energy mixing technique designed to produce relatively stable emulsions with varying water ratios at room temperature [12]. To prepare the emulsion, the oil phase (diesel + Span 80) was mixed for one minute before adding the aqueous phase (water + Tween 80). The aqueous phase was then incorporated into the oil phase and mixed using a mechanical homogenizer for three minutes. Two emulsions were produced: one composed of 91% diesel, 7% deionized water, and 2% surfactants (84% Span 80 and 16% Tween 80), and the other composed of 81% diesel, 17% deionized water, and 2% surfactants. All emulsion compositions are reported on a volume basis (vol.%). The fuel types in the present study are shown in Figure 1.

Surfactant percentages were calculated on volume basis. The stability of the emulsions was monitored over the first 24 hours, during which no separation occurred. The emulsion remained stable for 30 days without any component separation. Minor separation or surfactant precipitation was observed after 35 days. Surfactants with HLB values ranging from 3 to 6 are generally suitable for stabilizing water-in-oil (W/O) emulsions [16]. Since diesel-based emulsions are classified as W/O emulsions and the required HLB value for diesel has been reported to be approximately 6.0 [17], an HLB value of 6 was selected in the present study.



**Fig 1.** Fuel types used in the present study: (A) water diesel emulsion 17%, (B) water diesel emulsion 7%, (C) Pure diesel

The percentage of Tween 80 in the surfactant blend was calculated using the following formula [18]:

$$C_{\text{Tween80}} = 100(x - \text{HLB}_{\text{Span}}) / (\text{HLB}_{\text{Tween80}} - \text{HLB}_{\text{Span80}}) \quad (1)$$

Where

$x$  is the required HLB value ( $x=6$ ),

$\text{HLB}_{\text{Tween80}} = 15$

$\text{HLB}_{\text{Span80}} = 4.3$

The prepared emulsions were characterized in terms of stability and physicochemical properties prior to engine testing. Emulsion stability was evaluated by visual observation of phase separation during storage, while viscosity, density, flash point, pour point, and calorific value were measured and are presented in Table 1.

**Table 1** Properties of tested fuels.

Property	Pure Diesel	WDE 7%	WDE 17%
Density @ 15°C (g/cm <sup>3</sup> )	0.8275	0.8365	0.84771
Viscosity @ 40 °C (mm <sup>2</sup> /s)	2.765	3.7142	5.18425
Pour point (°C)	-15	-15	-18
Flash point (°C)	63	64	67
Calorific value (kJ/kg)	42889.5	39996.5	35319.8

### 2.2. Engine

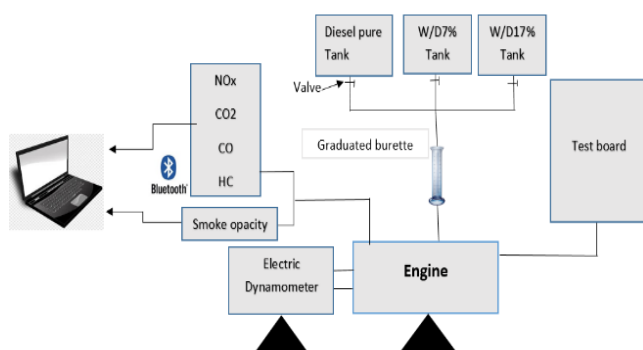
The engine used was a Korean-made, four-cylinder, four-stroke water cooled, Table 2 presents the engine specifications engine after engine preparation, and it was started at 1600 rpm using pure diesel fuel under 0%, 50%, and 100% loads. Readings were taken at each load, including fuel consumption, exhaust temperature, and emissions. The experiment was repeated with 7% and 17% emulsified fuels, taking into account changing the fuel filter with each fuel type.

TEXA GASBOX exhaust gas analyzer (Italy) was used to measure carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>), nitrogen oxides (NO<sub>x</sub>), and unburned hydrocarbons (UHC). Exhaust smoke opacity was measured using a TEXA smoke opacity meter and was used as an indicator of particulate matter (PM) emissions.

**Table. 2** Engine specifications.

Engine Type	Kia Bongo (Korean)
Engine Model	J2 2701
Displacement	2694 cm <sup>3</sup>
Stroke	95 mm
Cooling System	Water-cooled
Bore	95 mm
Rated Power	80 hp at 4000 rpm
Maximum Torque	16.8 N.m at 2400 rpm
Injection system	Direct Injection (ID)
Exhaust aftertreatment	None

Figure 2 illustrates the schematic diagram of the engine testing setup.

**Fig 2** Schematic diagram of engine testing

## 2.2. Test procedure

The engine was first tested with pure diesel fuel, with the speed set to 1600 rpm and the engine allowed to run for 15 minutes to reach stabilization. After stability was achieved, fuel consumption and exhaust-temperature readings were taken with no load applied, and exhaust emissions were recorded. A 50% load was then applied, exhaust emissions, current, the procedure was repeated at 100% load, with all measurements recorded again. When (7% and 17%) emulsified fuels were used, the fuel filter was changed and the engine was run for 10 minutes to purge the previous fuel. The entire sequence was then repeated for each fuel type.

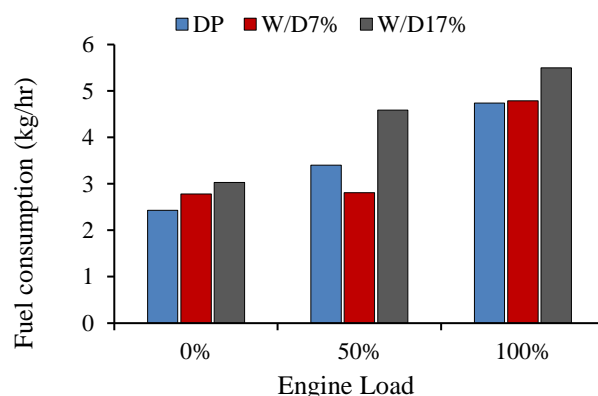
The Statistical Analysis System (SAS) (2018) [19] was used to analyze the data to study the effect of fuel type and load, and their interaction, on the studied characteristics at a speed of 1600 rpm. A 3 x 3 factorial experiment was conducted using a completely randomized design (CRD). Analysis of variance (ANOVA) was performed. Significant differences between means were compared using the Least Significant Difference (LSD) test at  $P \leq 0.05$ .

## 3. Results and discussion

This research initiated by evaluating the performance metrics of a diesel engine utilizing various ratios of water-diesel emulsions, with a particular focus on emissions and fuel consumption. The result indicated noticeable changes in several indicators as the water content increased, highlighting the emulsion's influence on combustion. The subsequent sections will delve into these findings, connect them with previous research, and provide interpretations of the observed phenomena.

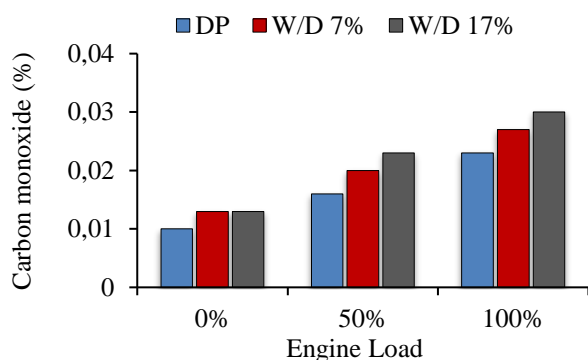
### 3.1. Fuel Consumption

The results indicate that fuel consumption increased with the use of the emulsified fuels compared with pure diesel. (W/D) 7% showed an average increase of approximately 7%, while (W/D) 17% exhibited an increase of about 24% compared with pure diesel. This increase may be attributed to the lower heating value of the emulsified fuels due to the presence of water, which requires a greater amount of fuel to produce the same engine output. Similar observations have been reported by Hamid et al. [20]. Regarding engine load, fuel consumption increased progressively with increasing load because a greater amount of fuel was required to satisfy the higher power demand. Figure 3 illustrates the effect of fuel type and engine load on fuel consumption.

**Fig 3** Fuel consumption at various engine load.

### 3.2. Carbon Monoxide (CO)

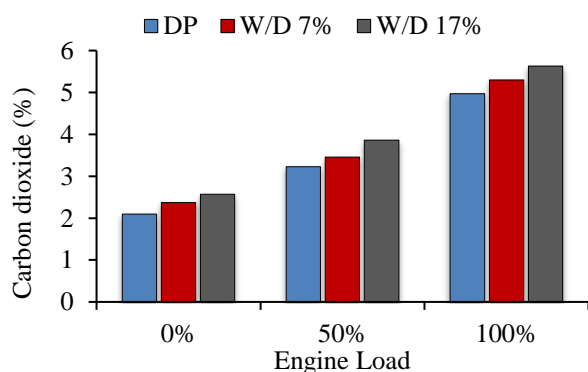
The results show that carbon monoxide emissions from pure diesel are lower than those from emulsified diesel. The CO emissions increased by 20% and 33% for (W/D)7% and (W/D)17%, respectively. This increase is attributed to some fuel molecules due to lower combustion chamber temperature and fuel heterogeneity, as reported Oliveira et al [12]. Additionally, engine load resulted in higher CO emissions due to increased fuel consumption and incomplete combustion under high load conditions. These findings are consistent with previous studies (Oliveira et al; Scarpete et al [12,21]). Figure 4 illustrates the impact of fuel type and load on carbon monoxide emissions.



**Fig 4** Content of CO in exhaust gas at various engine load.

### 3.3. Carbon dioxide (CO<sub>2</sub>)

The results indicate that CO<sub>2</sub> emissions were lower with pure diesel compared to the emulsified fuels. (W/D) 7% showed an increase of approximately 8%, while (W/D) 17% showed an increase of 24% compared with pure diesel. This increase may be attributed to the higher fuel consumption associated with the emulsified fuels, together with the micro-explosion phenomenon, which enhances fuel atomization and promotes carbon oxidation, leading to increased CO<sub>2</sub> formation. These results are consistent with Mahmood et al. [14]. Regarding engine load, CO<sub>2</sub> emissions increased with increasing load due to higher fuel consumption and elevated combustion temperatures, which promoted carbon oxidation and increased CO<sub>2</sub> concentration in the exhaust gases, consistent with Oliveira et al. [12]. Figure 5 illustrates the effect of fuel type and engine load on CO<sub>2</sub> emissions.

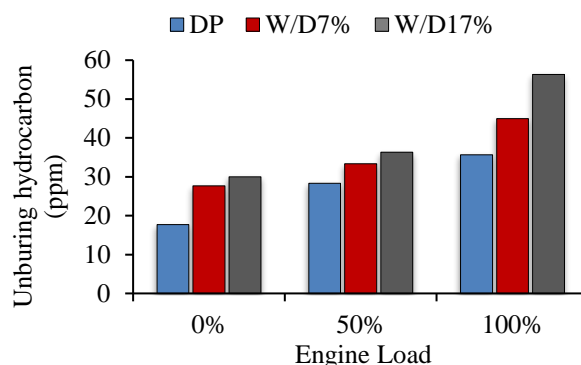


**Fig 5** Content of CO<sub>2</sub> in exhaust gas at various engine load.

### 3.4. Unburned hydrocarbons (HC)

A (W/D)7% emulsion recorded a 30% increase compared to pure diesel, while a (W/D)17% emulsion recorded a 50% increase. This increase may be attributed to the lower in-cylinder temperature caused by water evaporation, which suppresses hydrocarbon oxidation. In addition, changes in fuel spray characteristics and viscosity, together with the presence of surfactants, may contribute to incomplete combustion and consequently

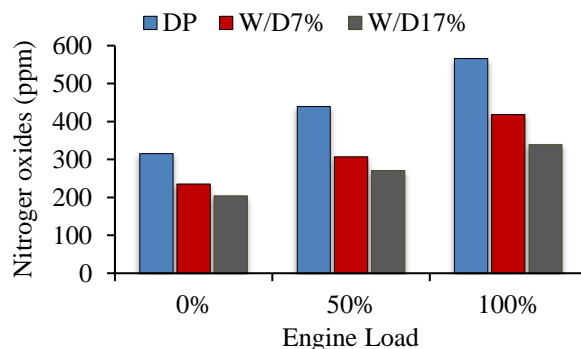
higher HC emissions. This relates to the emulsified fuel's viscosity compared to pure diesel and different injection spray characteristics. These results are consistent with those reported by Oliveira et al. [22]. Figure 6 illustrates the effect of fuel type and engine load on unburned hydrocarbon emissions. Overall, increasing the water content in the emulsion results in higher HC emissions.



**Fig 6** Content of HC in exhaust gas at various engine load.

### 3.5. Nitrogen oxides (NO<sub>x</sub>)

Figure 7. Illustrates the effect of fuel type and load on nitrogen oxide (NO<sub>x</sub>) emissions. The results show that NO<sub>x</sub> emissions were consistently lower in emulsified fuels compared to pure diesel. Specifically, the W/D)7% showed a relative decrease of 27% compared to pure diesel, and the W/D)17% showed a decrease of 38%. This is due to the lower combustion temperature from slower chemical reaction rates, leading to reduced NO<sub>x</sub> emissions. These findings align with Alahmer et al [10]. Regarding load, NO<sub>x</sub> emissions increased with all fuel types due to higher cylinder temperature under engine load. These results are consistent with Mahmood et al [14].

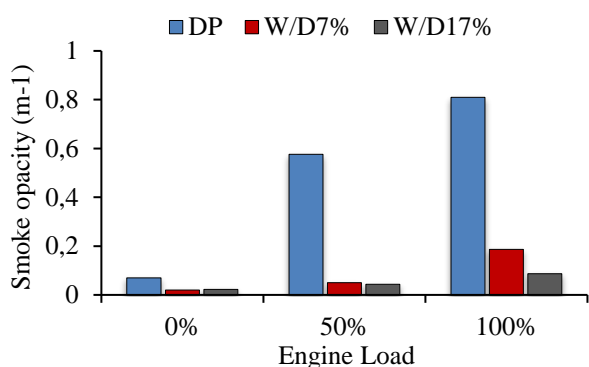


**Fig 7** Content of NO<sub>x</sub> in exhaust gas at various engine load.

### 3.6. Smoke opacity

Figure 8 illustrates the effect of fuel type and load on exhaust smoke opacity. The results show a significant reduction in exhaust smoke opacity when using water-diesel emulsions. The exhaust smoke opacity of the

(W/D) 7% and (W/D)17% showed a relative decrease of 82% and 89%, respectively, compared with pure diesel fuel.



**Fig 8** Content of Smoke opacity in exhaust gas at various engine load.

Regarding load, exhaust smoke opacity increased with all tested fuel types as engine load increased due to higher fuel consumption and increase combustion chamber temperature [23].

## Conclusions

This study evaluated the effect of water–diesel emulsions on diesel engine emissions under the investigated operating conditions. The results showed that both emulsions reduced NO<sub>x</sub> and particulate matter emissions compared with pure diesel, while CO, CO<sub>2</sub>, HC emissions and fuel consumption increased. The 7% W/D emulsion showed a better overall emission performance than the 17% W/D emulsion, with lower increases in fuel consumption and incomplete combustion products. Therefore, under the investigated operating conditions, the 7% W/D emulsion can be considered the most suitable fuel among the tested emulsions

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