

# Assessment of Performance and Emissions Characteristics of Diesel Engine using Water Diesel Emulsion: A Review

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## Abstract

Finding sustainable alternative fuel to substitute fossil fuel is a study area of interest for most organizations and societies. Such alternative energy should keep the balance between emissions improvement and diesel engine performance. Water-diesel (W/D) emulsion fuel is considered as an auspicious alternative fuel that can improve diesel engine performance and lower harmful exhaust emissions. This review critically discusses the effect of the obtained blend on diesel engine performance and emission characteristics based on the available experimental findings in the literature. The review also highlights the concept of water-diesel emulsion fuel, surfactant, and hydrophilic-lipophilic balance value (HLB). The types of emulsion and micro-explosion phenomena were also discussed. According to the literature review, most of the researchers suggested a significant improvement of the environmental footprint when W/D is used to reduce particulate matter (PM) and nitrogen oxides (NO<sub>x</sub>). However, other studies criticize the increase in carbon monoxide (CO) and hydrocarbon (HC) emissions.

**Keywords:** Emissions characteristics; Engine performance; Micro-explosion phenomenon; Water-diesel emulsion.

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## 1. Introduction

The diesel engine is one of the most efficient and reliable energy transformation devices available to date. It is used in various applications, For example, power generation, transportation, agriculture, offshore drilling, military, marine and telecommunication generator sets. However, because the use of diesel is increasing, the stock of diesel is diminishing very rapidly, with a continuous increase in harmful pollution. These include nitrogen oxides (NO<sub>x</sub>), carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>), Oxides of sulfur (SO<sub>x</sub>), hydrocarbon (HC), smoke, etc. (Debnath *et al.*, 2015). The large quantities of these toxic gases contribute too many

environmental problems. The reduction of NO<sub>x</sub> and particulate matter (PM) emissions is of specific interest nowadays for diesel engines. They are primarily generated because of the ready availability of oxygen and high combustion temperature, and there is a critical need to diminish them for NO<sub>x</sub> control. The possible techniques for controlling NO<sub>x</sub> include exhaust gas recirculation, delaying the injection time, selective catalytic reduction, and doping some oxygenated compounds with fuel. One recently proposed method to reduce these emissions is using water-diesel (W/D) emulsion fuel in a diesel engine instead of pure diesel (Kumar *et al.*, 2018).

Combustion of W/D emulsion fuel produces a superior result for both emissions characteristics and engine performance. The ability to reduce NO<sub>x</sub> and PM, thus meeting internal combustion engine emission regulations, is probably the most appealing reason for using this emulsion instead of conventional pure diesel. Furthermore, improved brake power and thermal brake efficiency have also contributed to considering this recent approach. It is worth mentioning that using W/D emulsion fuel does not require any modification of the currently used compression ignition, which approves the flexibility of using the proposed emulsion fuel (Kapadia *et al.*, 2019).

Water fuel emulsion is prepared by dissolving water in diesel and mixing it. Since the two phases are immiscible, surfactants are added to create a thermodynamically stable mixture. Surfactants are commonly classified into hydrophilic and lipophilic. Hydrophilic surfactant tends to attack polar materials like water. On the other hand, lipophilic surfactant shows stability in non-polar liquids (Hasannuddin *et al.*, 2014). Hydrophilic-lipophilic balance value (HLB) measures the hydrophilic or lipophilic nature of the surfactant. The HLB values range from 0 to 20, where 0 indicates a total lipophilic, while the value of 20 indicates an entirely hydrophilic. Diesel does not dissolve in water permanently due to its non-polarity. However, water in oil emulsion can be obtained with mixing, whether with a surfactant or without. In both cases, mixing plays an essential role in reducing the water diameter so it can disperse and link to the fuel molecule (Ithnin *et al.*, 2018).

Hence, this study reports and analyzes the impact of water-diesel emulsion on diesel engine performance characteristics and emissions based on the available literature.

## 2. Types of Emulsion

Emulsions are made to produce a stable mixture of two immiscible components like oil and water. The percentage of water to oil, the type of surfactant, and the mixing mechanism are the main factors that determine the stability of emulsion during its use (Gopidesi and Rajaram, 2019).

The Emulsion can be categorized based on phase and droplet size as discussed below:

### 2.1. Based on Phase

To produce the emulsion building blocks, two or more inactive immiscible fluids are typically dispersed in different ways inside each other. Based on phase, emulsions can be divided broadly into two classifications. These are primary and secondary emulsions.

#### 2.1.1. Primary Emulsions

This type is also called a two-phase emulsion. It is built by incorporating two naturally immiscible phases called dispersing and continuous phase. When water becomes the dispersing phase and oil becomes the continuous phase, the emulsion is called water in oil and vice versa. In both emulsion types, surfactants are used in a percentage of 0.5 – 5% by volume to create a stable mixture (Alahmer *et al.*, 2010).

#### 2.1.2. Secondary Emulsion

This type is also called multiple emulsions. In this emulsion, the outer and inner phases are detached by a dispersed phase called the intermediate phase. The main two kinds of secondary emulsions are water in oil in water (W/O/W) and oil in water in oil (O/W/O) emulsions. The former is recommended for pharmaceutical application, while the latter is suggested for fuel preparation (Alahmer *et al.*, 2010).

### 2.2. Based on Size of Particles

The dispersed phase particle size is one of the criteria that can sharply determine the type of emulsion. Emulsions can be classified into macro-emulsions, micro-emulsions, and nano-emulsions.

#### 2.2.1. Macro-emulsions

This type has a particle size of more than 400 nm where it is visual under the microscope. This type of emulsion is thermodynamically unstable; once formed,

it tends to revert to its original and immiscible state. It has low interfacial tension due to the high dispersed phase particle size, thus, the low surface of interfacial per unit volume. Macro-emulsions are the most used kind of emulsions industrially; this is because of their ease of preparation and their low cost because they contain a low amount of surfactant (Rosen and Kunjappu, 2012).

### 2.2.2. Micro-emulsion

Unlike macro-emulsion, the micro-emulsion is a thermodynamically stable mixture. The particle size of this type is ranged from 100 to 400 nm. The free energy of micro-emulsion formation depends on how surfactant reduces the system's oil-water interface surface tension and change in entropy. The time needed to prepare micro-emulsion is relatively long. The prepared emulsions find several applications in the sectors of the pharmaceutical industry and cosmetics (Rieger, 2017).

### 2.2.3. Nano-emulsion

Unlike micro-emulsions, Nano-emulsions are prepared using fewer surfactant amounts. This emulsion type has a particle size of less than 100 nm. These emulsions can be prepared by exposing the mixture to high-power ultrasounds or using a high-pressure homogenizer. Because of their high kinetic energy and tiny particle size, they find many applications, particularly in the food, cosmetics, and personal care market (Holmberg and Österberg, 1986).

## 3. Surfactant and HLB

Surfactant (Also called the surface active agent) is a molecule that contains a hydrophilic (water-soluble, its head) group and lipophilic groups (oil-soluble, its tail). HLB measures the hydrophilic or lipophilic nature of the surfactant. The HLB values range from 0 to 20, where 0 indicates a total lipophilic, while the value of 20 indicates an entirely hydrophilic. The same concept applies to water/diesel emulsion; the surfactant with low HLB is used to lower the interfacial tension between the dispersing phase (water droplet)

and the continuous phase (diesel). Griffin was the first who proposed a formula to calculate the value of HLB as equation (1).

$$HLB = 20 M_h / (M_h + M_l) \dots\dots\dots\text{Equation (1)}$$

where  $M_h$  and  $M_l$  are the molecular weight of the hydrophilic and lipophilic portion of the molecule (Debnath *et al.*, 2015).

Despite the many available and commercial surfactants with different HLB values, TWEEN80 and SPAN80 were the most used surfactants reported in the literature.

## 4. Micro-explosion Phenomena

In W/D emulsion fuel, water remains embedded within diesel droplets with the assistance of the surfactant. Once the kind of emulsion is sprayed on a hot combustion chamber, heat is convected on the fuel droplet's surface. As water and diesel have different boiling temperatures, the evaporation rates of these two liquids will be different. For this reason, the water molecule can reach its superheated stage faster than diesel causing vapor expansion breakup. It is at this stage, the two phenomena; micro-explosion and puffing prevail. In puffing, water leaves the droplet in a tiny size. Micro-explosion is a quick breakdown of droplets. There will be secondary atomization of droplets in the micro-explosion phenomena in which droplets disintegrate further into smaller sizes increasing the surface volume. This successively improves the blending of air and fuel. As a direct consequence, the combustion efficiency will increase, as shown in Figure 1 (Hagos *et al.*, 2011).

## 5. Impact of Water-diesel Emulsions on Performance Characteristics and Emissions

Abu-Zaid (2004) studied the impact of water-diesel emulsion fuels on engine performance characteristics. He showed that the addition of water with pure diesel fuel improved combustion efficiency. He also showed that the engine power, torque, and brake thermal efficiency increased as the water percentage in the emulsion increases.

Nadeem *et al.* (2006) used two types of surfactant to prepare water-diesel emulsion fuel. The first is conventional surfactant mixed with 5%, 10%, and 15% of water by volume. The second is Gemini surfactant mixed with 5%, 10%, and 15% of water by volume. The comparative study included engine performance and emissions. They suggested that the highest reduction in emissions was accomplished by the emulsion stabilized by Gemini surfactant containing 15% water content. Murali *et al.* (2006) used four emulsions of 5%, 10%, 15%, and 20% by volume of water in diesel fuel to study their effect on engine behavior compared with neat diesel fuel. The test results exposed that the addition of water in the form of emulsion improved combustion efficiency.

The optimum percentage of water in emulsion based on emission parameters and specific fuel consumption compared with diesel fuel operation was 15%. Kannan and Udayakumar (2009) performed an experimental study on the influence of using water-diesel emulsion fuels on performance and emission for a single-cylinder-direct-injected (DI) diesel engine. They concluded that the diesel-water emulsion fuel could improve the brake thermal efficiency and brake-specific fuel consumption. They also concluded that increasing water percentage in diesel fuel caused a decrease in NO<sub>x</sub> and HC concentrations. Figure 2 shows the impact of diesel-water emulsion fuels on brake thermal efficiency concerning engine brake power change.

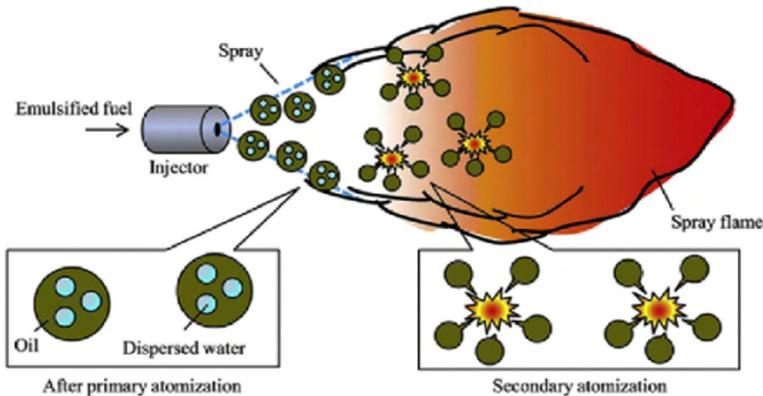


Figure 1. Primary and secondary atomization in spray flame of emulsified fuel (Hagos *et al.*, 2011).

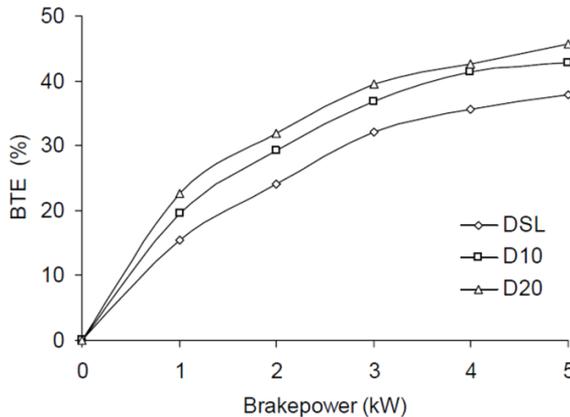


Figure 2. The impact of diesel-water emulsions on brake thermal efficiency for change in break power (Kannan and Udayakumar, 2009).

Selim and Ghannam (2009) investigated the engine performance parameters using water-diesel emulsions containing water of 10%, 20%, and 30% of water by volume compared with neat diesel. They reported that mixing water with pure diesel fuel caused the brake-specific fuel consumption to increase marginally and the brake power output to drop marginally. Sudrajad *et al.* (2011) compared pure diesel fuel and emulsified fuel containing 10% water, 89% diesel oil, and 1% surfactant in a cylinder diesel engine at a constant speed with different engine loads. Measurement of engine emissions characteristics has generally demonstrated a decrease in engine emissions like NO<sub>x</sub>, CO, and SO<sub>2</sub> emission compared with pure diesel fuel.

They also concluded that the nitric oxide concentration is decreased for the emulsion fuels compared with neat diesel. On the other hand, an increase in CO and CO<sub>2</sub> emissions was noticed. Saravanan *et al.* (2013) studied

the blending of water with diesel fuel. A single-cylinder diesel engine was used in this study. The test results showed that the blending of water with diesel fuel reduced emissions like NO<sub>x</sub> and HC. Figure 3 shows the variation of HC emission versus engine load using water-diesel emulsion.

Kumar *et al.* (2013) studied the diesel engine's performance and emission characteristics using 10% water-diesel emulsion compared with base diesel at different injection angles. The results showed that the use of emulsion fuel improved the brake thermal efficiency compared with neat diesel. Besides, there was a considerable reduction in CO, HC, NO<sub>x</sub>, and smoke with the addition of water to diesel fuel due to better combustion efficiency and decrement in the peak flame temperature inside the combustion chamber. Figure 4 explains the variation of NO<sub>x</sub> emission for engine brake mean effective pressure (BMEP) using pure diesel fuel and water-diesel emulsion fuel.

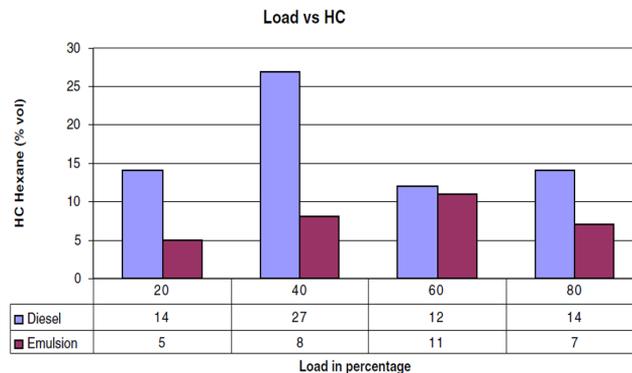


Figure 3. The variation of HC emission versus engine load using water diesel emulsion (Saravanan *et al.*, 2013)

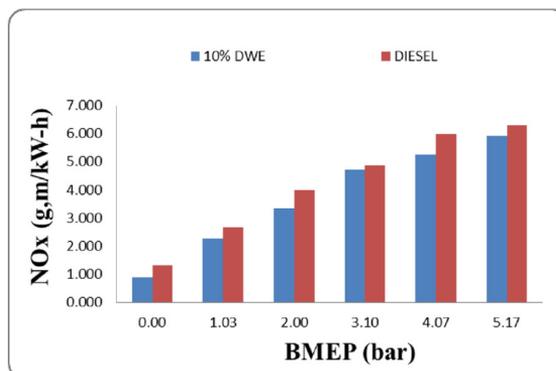


Figure 4. The variation of NOX emission versus engine BMEP using water diesel emulsion in comparison with pure diesel (Kumar *et al.*, 2013)

Sharma *et al.* (2013) studied the behavior of a single-cylinder diesel engine fueled with a water-diesel emulsion containing 5%, 10%, 15%, 20%, and 25% water compared with pure diesel fuel. As a result, the increase in water content in the emulsion BTE shows a little improvement at all load conditions. Further, a decrease in CO emission was noticed by increasing the water content in the fuel samples at all load conditions because of the micro-explosion phenomena resulting in the complete combustion of fuel inside the engine. Gonguntla *et al.* (2014) compared base diesel and water-diesel emulsion fuel containing 6% of water content on a single-cylinder, DI, water-cooled diesel engine coupled to an eddy current dynamometer. They found a 24% reduction in NO<sub>x</sub> and a 42% reduction in CO emissions than base diesel. In addition, the brake-specific fuel consumption increased by 6.6% using emulsified fuel. Syu *et al.* (2014) analyzed the impact of water-diesel emulsion fuels on the performance and emissions of a diesel engine generator set. The test results showed that the thermal efficiency increased by about 1.2% to 19.9%. Further, water-diesel emulsion leads to a significant decrement of NO<sub>x</sub> emission about 18.3% to 45.4% compared with neat diesel fuel. Ithnin *et al.* (2015) performed an experimental study on DI diesel engines using four types of water-diesel emulsion ranged from 5% to 20% by volume and base diesel fuel. They reported that NO<sub>x</sub> and PM emissions decreased for all types of water-diesel emulsion fuels than base diesel fuel, but CO and CO<sub>2</sub> emissions increased at low and high loads compared with base diesel fuel. Seifi *et al.* (2016) used four emulsions (2%, 5%, 8% and, 10% water by volume) and neat diesel fuel to study the engine performance and noise emissions. The test results showed that mixing little water, 2%, to pure diesel fuel increased the engine power and demonstrated equivalent torque and noise emission values. Vigneswaran *et al.* (2014 - 2015) focused on water-diesel emulsion fuel containing 10% water, 89.8% diesel, and 0.2% surfactant compared with pure diesel fuel.

Triton X-100 was the type of surfactant used. They observed that the engine's mechanical efficiency using emulsified fuel increased by 14% compared to pure diesel fuel. They also observed an improvement in exhaust emissions like HC, CO, and NO<sub>x</sub>. Azimi *et al.* (2016) tested the engine performance and emissions using water-diesel emulsion fuels ranged from 0% – 10% by volume. They observed that the water-diesel emulsion containing 2% water improved engine performance and decreased exhaust emissions. Abdurahman *et al.* (2016) studied the engine performance and emissions using five types of water-diesel emulsion fuels ranged from 0% – 40% by volume and neat diesel fuel. They found that the mixing of water with fuel improved combustion efficiency. They also found a reduction in NO<sub>x</sub> and CO emissions. Hasannuddin *et al.* (2016) studied the effect of adding water to pure diesel fuel on combustion efficiency and emission characteristics. The results proved that the NO<sub>x</sub> and PM were reduced with increasing water content in the blend.

Kanti *et al.* (2017) employed 10% of water emulsified diesel fuel to examine the engine performance compared with neat diesel. They reported that the engine power, brake thermal efficiency, and brake-specific fuel consumption using water-diesel emulsion was equivalent to pure diesel and even better at higher engine load. Syafiq *et al.* (2017) used water-diesel emulsion fuels mixed by surfactant Span 80 and Tween 80. The comparisons were made in different water content (5%, 10%, and 15%) of emulsion on engine performance. They reported that the addition of water up to 15% in emulsion improves the diesel engine's combustion efficiency. In addition, the ignition delay and peak pressure increased, but the power curve decreased with increasing the water content. Basha and Balushi (2019) have examined the influence of water-diesel emulsion fuel on engine performance and emissions using pure diesel fuel and W/D emulsion fuels (2% and 4% by volume). The obtained results showed that blending water to pure diesel improved the brake thermal efficiency and the brake-specific fuel consumption.

In addition, harmful emissions like NO<sub>x</sub>, CO, HC, and smoke were reduced compared with pure diesel. El-Din *et al.* (2019) experimented the engine performance and emissions with water-diesel emulsion fuels. They found that specific fuel consumption of the engine using water-diesel emulsions decreased by 8% compared with neat diesel with 4 wt % surfactant concentration and 7 wt % water content and at engine load of 1 kW. They also found that the lowest HC, CO, and NO<sub>x</sub> emissions values of 66%, 48%, and 32% were achieved using 6 wt% of surfactant concentration and 7% water content at an engine load of 1 kW. El Shenawy *et al.* (2019) experimentally measured and analyzed the engine performance characteristics and emissions for a single-cylinder, four-stroke, diesel engine using three concentrations of water such as the water-diesel emulsions (3% WD, 6% WD, and 9%WD) compared with pure diesel. The obtained results showed that the use of water-diesel emulsions improved the brake-specific fuel consumption and brake thermal efficiency. Further, it decreased the NO<sub>x</sub>, CO, and UHC emissions as well as smoke opacity. Hoseini and Sobati (2019) studied the effect of water-diesel emulsion fuels on a diesel engine. Experimental tests were performed on a single-cylinder diesel engine using pure diesel fuel, water-diesel emulsion fuels (in the range of 5% – 10% by volume), surfactant content (in the range of 0.5%–2% by volume), and HLB (in the range of 5–8). They found that the optimum emulsion fuel was 5% water, 2% surfactant, and an HLB of 6.8. Jhalani *et al.* (2019) tested the impact of diesel engines using various water-diesel emulsion fuels containing 5%, 10%, 15%, and 20% water by volume. The test results proved that emulsion containing 15% water-in-diesel is optimal based on performance and emissions.

Kumar *et al.* (2019); in their experiment studied a diesel engine coupled with an AC generator used to evaluate the performance parameters, combustion, and emissions characteristics of the engine when fueled with neat diesel and water-diesel emulsion.

The obtained results showed better performance and emissions using water-diesel emulsion fuel. Arohman *et al.* (2019) tested the engine using water-diesel emulsion with water percentages of 30% and 35% by volume and diesel fuel compared with pure diesel. The test result showed significant improvement in thermal efficiency using emulsified fuels. While CO and HC emissions increased with increasing water ratio in the blend. Okumuş *et al.* (2020) studied the performance and NO<sub>x</sub> emissions of an engine using pure diesel, 5%, 10%, and 15% water content. They found that up to 5.22% and 5.46% power reduction were observed at maximum torque and power speed with the use of emulsified fuel. They also found that water-diesel emulsified fuels provided a reduction of NO<sub>x</sub> emissions compared with neat diesel. Hassan *et al.*, (2021) studied the impact of water mixing with different percentages from 2% to 8% with neat diesel fuel on performance and emissions of diesel engines. The test results showed that water-diesel emulsion fuels can notably decrease NO<sub>x</sub> emissions and smoke. However, it has a negative influence on the performance parameters and CO, HC, and noise emissions.

Senthur *et al.* (2021) used five samples of fuel, pure diesel, eucalyptus biodiesel 20% (E20) by volume with diesel, DWM 1 (94% diesel, 5% water and 1% surfactants), DWM 2 (89% diesel, 10% water and 1% surfactants) and DWM 3 (84% diesel, 15% water and 1% surfactants). They found that DWM 3 fuel has produced the best overall results among the other tested fuels by achieving the least pollutant emissions and the highest brake thermal efficiency of the engine. The study of Khatri *et al.* (2021), the performance parameters of the engine showed a minor difference between water-diesel emulsion fuels and pure diesel. The CO, HC, NO<sub>x</sub>, and smoke emissions were decreased extremely in comparison to pure diesel.

Different studies that used W/D emulsion have been presented and summarized in Table 1. The increase or decrease of different engine performance characteristics and emission parameters as given in the table are for pure diesel.

**Table 1:** Comparison of different studies that used water-diesel blends in CI engines.

Diesel engine type	Test condition	Water content	Effect on emissions	Effect on performance	Optimum blend	Ref.
PETTER PHIW, 1 cylinder, 659 cc	at 1200–3300 rpm	0, 5, 10, 15 and 20% by volume	N/A	B.S.F.C ↑, P ↑, T ↑, $\eta_{th}$ ↑ and EGT ↓	20%	(Abu-Zaid, 2004)
FORD, XLD 418,4 cylinders, water-cooled, 1753 cc	Different engine speeds	0,5,10,15 % by volume	CO ↓, NOx ↓, PM ↓, and SOx ↓	B.S.F.C ↑, P ↓, T ↓, and BMEP ↓	15%	(Nadeem et al., 2006)
6 cylinders, water-cooled, naturally aspirated, 5759 cc	at a constant speed of 2400 rpm	0, 5, 10, 15 and 20% by volume	CO ↓, HC ↓, NOx ↓, smoke ↓ and PM ↓	B.S.F.C ↑ and $\eta_{th}$ ↑	15%	(Murali et al., 2006)
Kirloskar, 1cylinder, 4 stroke,	constant speed with a fuel injection pressure of 200 bars	0, 10, 20 % by volume	CO ↓ and NOx ↓	B.S.F.C ↓ and $\eta_{th}$ ↑	20%	(Kannan and Udayakumar, 2009)
Ricardo E6,1 cylinder, IDI,4 stoke	variable injection timing, engine speed, load, and compression ratio	0, 10, 20,30 % by volume	N/A	B.S.F.C ↑, P ↓	20%	(Selim and Ghannam, 2009)
TF120 YANMAR, 1 cylinder, water-cooled, 0.638 L	at 2000 rpm with a variable of engine load.	0, 10% by volume	CO ↓ NOx ↓ and SO <sub>2</sub> ↓	FC ↓	10%	(Sudrajad et al., 2011).
1 cylinder, 4 strokes, water-cooled	Different loads	0,15% by volume	PM ↓, NOx ↓ CO ↑, HC ↓, and CO <sub>2</sub> ↓	B.S.F.C ↑, $\eta_{th}$ ↑ and $\eta_{mech}$ ↑	15%	(Saravanan et al., 2013)
1 cylinder, 4 strokes, 611cc	Different loads and various injection angles	0, 10% by volume	CO ↓, NOx ↓, HC ↓, and smoke ↓	B.S.F.C ↑ and $\eta_{th}$ ↑	10%	(Kumar et al., 2013)
Kirloskar, water-cooled, 4 strokes, diesel variable compression ratio (VCR), 661 cc	Different loads ad different CRs.	0, 5, 10, 15, 20, 25% by volume	CO ↓, NOx ↓, HC ↓, and smoke ↓	$\eta_{th}$ ↑ B.S.F.C ↓ and EGT ↓	10% for lower CRs. And 25% for higher CRs.	(Sharma et al., 2013)
1 cylinder, direct-injection, water-cooled	Different loads and different speeds	0, 6% by volume	CO ↓ and NOx ↓	B.S.F.C ↑, EGT ↓ $\eta_{th}$ ↑ at higher load	6%	(Gonguntla et al., 2014)
4 stroke, air-cooled, 1-cylinder, 418 cc	Different loads	0% to 15% with an increment of 5% by volume	CO ↑, NOx ↓, and HC ↑	$\eta_{th}$ ↑	10%	(Syu et al., 2014)
4-Stroke, single cylinder, air-cooled, 0.406 L	Different loads	0, 5, 10, 15, and 20% by volume	PM ↓, NOx ↓ CO ↑, CO <sub>2</sub> ↓ at higher loads	B.S.F.C ↓	20%	(Ithnin et al., 2015)
Perkins,6 cylinders, 5.8 L	Different loads	0, 2, 5, 8 and 10% water by volume	N/A	P ↑, T ↑ W/D 2%	2%	(Seifi et al., 2016)
Kirloskar, 1 cylinder, 661 cc	Different loads	0, 10% by volume	CO ↓, NOx ↓, HC ↓	$\eta_{mech}$ ↑	10%	(Vigneswaran et al., 2014-2015)
4 cylinders-water-cooled, four-stroke, four cylinders	1600 to 1900 rpm	0, 2, 5, 8 and 10% water by volume	CO ↑, NOx ↓ and HC ↓ for W/D 2%	P ↑, T ↑ W/D 2%	2%	(Azimi et al., 2016)

**Table 1:** Comparison of different studies that used water-diesel blends in CI engines. (Cont.)

Diesel engine type	Test condition	Water content	Effect on emissions	Effect on performance	Optimum blend	Ref.
Yanmar TF120M	1200 to 2500 rpm	0,5, 10, 20,30,40 % by volume	NOx ↓ and CO <sub>2</sub> ↓	T ↑ W/D 15% and P ↑ W/D 15% at no load	15%	(Abdurahman <i>et al.</i> , 2016)
1 cylinder, air-cooled, 400 cc	Different loads	0, 10, and 20% by volume	NOx ↓ and PM ↓ CO <sub>2</sub> ↓ CO ↑ and soot ↓	FC ↑ and EGT ↓	20%	(Hasannuddin <i>et al.</i> , 2016)
Kirloskar, 1 cylinder, Water cooled, VCR	Different loads	0,10% by volume	N/A	$\eta_{th}$ ↑ at higher load and B.S.F.C ↑	10%	(Mondal and Mondal, 2017)
YANMAR TF120M, 1 cylinder, 0.638L	Different loads	5, 10, and 15% by volume	N/A	P ↓ with increasing water content except for higher load	15%	(Syafiq <i>et al.</i> , 2017)
light-duty diesel engine generator	Different loads	0,2,4%by volume	CO ↓, NOx ↓, CO <sub>2</sub> ↓, and HC ↓	$\eta_{th}$ ↑ and B.S.F.C ↓	4%	(Basha and Al Balushi, 2019)
DEUTZ FIL511,air-cooled single-cylinder the diesel engine of the type	Different loads	0, 5, 6, and 7% water	CO ↓, NOx ↓, HC ↓, and smoke opacity ↓	$\eta_{th}$ ↑ and B.S.F.C ↓	7%	(El-Din <i>et al.</i> , 2019)
DEUTZ FL 511/W (PPCCI), 1 cylinder, 825 cm <sup>3</sup>	Different loads	0,3,6,9% by volume	CO ↓, NOx ↓, HC ↓ and smoke opacity ↓	$\eta_{th}$ ↑ and B.S.F.C ↓	9%	(El Shenawy <i>et al.</i> , 2019)
Lombardini-Diesel 3LD510, 1-cylinder 4-stroke, 510 cc	1800 r/min, at full load	in the range of 5%–10% by volume),	NOx ↓ CO ↑, HC ↑ and CO <sub>2</sub> ↑	P ↓, T ↓, $\eta_{th}$ ↑ and B.S.F.C ↑	5%	(Hoseini and Sobati, 2019)
Kirloskar TV1, Single cylinder, 4 stroke, 661 cc	Different loads and CRS	0, 5, 10, 15, and 20% by volume	NOx ↓ and smoke opacity ↓	$\eta_{th}$ ↑	15%	(Jhalani <i>et al.</i> , 2019)
GF3BMG (TV1), single cylinder 4-stroke, 5.5 k,W	Different loads	0,20% water to diesel ratio	CO ↓, NOx ↓, HC ↓ and CO <sub>2</sub> ↑	$\eta_{th}$ ↑, B.S.F.C ↑ and EGT ↓	20%	(Kumar <i>et al.</i> , 2019)
Diesel Diamond DI 800, single cylinder, 4-stroke, 411 cc	Different loads	30% and 35% by volume	CO ↑, HC ↑ and smoke opacity ↓	$\eta_{th}$ ↑ and B.S.F.C ↑	35%	(Arohman <i>et al.</i> , 2019)
Antor 3LD510, Single cylinder, 510 cc	Variable speed and full load conditions	0, 5, 10, and 15% by volume	NOx ↓	P ↓, T ↓ and B.S.F.C ↑	10%	(Okumuş <i>et al.</i> , 2020)
Perkins/AD 3.152	Different loads	0% to 10% with an increment of 2% by volume	CO ↑, NOx ↓ HC ↑ and smoke opacity ↓	$\eta_{th}$ ↓ and B.S.F.C ↑	10%	(Hassan <i>et al.</i> , 2021)
single cylinder, 4 stroke Kirloskar diesel engin, 661 cc	Different loads	0, 5, 10, and 15% by volume	CO ↓, NOx ↓, HC ↓ and smoke opacity ↓	$\eta_{th}$ ↑, S.E.C ↑ and EGT ↑ except 15% of water blend	15%	(Senthur <i>et al.</i> , 2021)
3.5 kW power, single cylinder with 4 strokes, variable C.R	1500 rpm and fixed C.R	0, 5% by volume	CO ↓, NOx ↓, HC ↓ and smoke opacity ↓	$\eta_{th}$ ↓ and B.S.F.C ↑	5%	(Khatri <i>et al.</i> , 2021)

↓ = decrease, ↑ = increase, B.S.F.C = brake specific consumption, S.E.C = specific energy consumption, FC = fuel consumption, P = brake power, T = torque,  $\eta_{th}$  = brake thermal efficiency,  $\eta_{mech}$  = mechanical efficiency,  $\eta_v$  = volumetric efficiency, EGT = exhaust gas temperature

## 5. Discussion

### 5.1 Discussion on engine performance characteristics

Most of the researchers reported that blending water to diesel fuel increased brake-specific fuel consumption. As the water content in the emulsified fuel increases, a larger content of diesel is replaced by the same water content. This implies less diesel fuel is contained inside each volume of the emulsion. Besides, the presence of water droplets inside the emulsion fuel results in rapid vaporization of the emulsified fuel and combustion with a longer premixed, which in turn results in a more ignition delay and subsequent more fuel consumption (Abu-Zaid, 2004; Alahmer *et al.*, 2010; Arohman *et al.*, 2019; Khatri *et al.*, 2021; Kumar *et al.*, 2019; Murali *et al.*, 2006; Nadeem *et al.*, 2006; Okumuş *et al.*, 2020; Selim and Ghannam, 2009; Sudrajad *et al.*, 2011). On the other hand, other researchers reported that blending water to diesel fuel decreased brake-specific fuel consumption due to several factors. First, the formation of finer droplets due to micro-explosion improves the atomization and, therefore, the combustion. Second, the combustion to diffusion combustion ratio of fuel burned is more because of the longer ignition delay. The presence of water inside the fuel increases local excess air. In addition, more air goes into the spray due to increased momentum and penetrating force. Cooling loss is reduced because of the lower flame temperature in the vicinity of water within the fuel (Basha and Al Balushi, 2019; El-Din *et al.*, 2019; Ithnin *et al.*, 2015; Kannan and Udayakumar, 2009; Sharma *et al.*, 2013).

The addition of water to neat diesel improved the brake thermal efficiency due to the micro-explosion phenomenon, in which small water droplet vaporize and results in better atomization of diesel inside the cylinder. In this way, emulsified fuel proved demonstrated out to better fuel when BTE is considered (Abu-Zaid, 2004; Alahmer *et al.*, 2010; Arohman *et al.*, 2019; Kumar *et al.*, 2019; Kumar *et al.*, 2013; Murali *et al.*, 2006; Saravanan *et al.*, 2013; Senthur *et al.*, 2021; Sharma *et al.*, 2013; Syu *et al.*, 2014).

The decrease of engine power and torque using emulsified fuels was observed by some researchers and attributed this due to the lower heating value of water emulsion diesel (Hoseini and Sobati, 2019; Nadeem *et al.*, 2006; Okumuş *et al.*, 2020; Selim and Ghannam, 2009). In contrast, other researchers found an increase in power and torque. According to their clarification, the rise in torque due to the additional force on top of the piston was given by the steam's pressure. When the charge is fired in the cylinder, the water would turn to high-pressure steam. In addition, the higher viscosity of the emulsified fuel than that of the base fuel and the presence of water promotes finer, cloud-like atomization of the emulsified mixture during the injection. Thus, it improves combustion efficiency significantly.

The increase of power attributed to the addition of water in diesel fuel extends the ignition delay period. The ignition delay period occurs when the injected fuel inside the cylinder undergoes chemical and physical preparation for combustion. Consequently, the emulsified fuel requires less compression (negative) work than the pure diesel fuel because of the longer ignition delay during the compression stroke. This helps reach a higher peak pressure after the top dead center to generate additional power output during the expansion stroke. In addition, when the ignition delay prolongs, more diesel fuel would be physically prepared (evaporation, mixing) for chemical reaction, which increases the content of diesel burned and the rate of heat release in the premixed burning. This leads to improvement of combustion and combustion efficiency (Abu-Zaid, 2004; Azimi *et al.*, 2016; Seifi *et al.*, 2016).

Increasing water percentage in emulsified fuel decreased the EGT. The heat absorbed by the extra water can clarify the reduction in the exhaust gas temperature. The latent heat of the water will cool the charge because the evaporation of water and the average cylinder temperature following injection and before ignition decreases as the water content increases in the emulsion fuel (Abu-Zaid, 2004; Gonguntla *et al.*, 2014; Hasannuddin *et al.*, 2016; Kumar *et al.*, 2019; Sharma *et al.*, 2013).

## 5.2 Discussion on Engine Emissions

The majority of the studies found a significant reduction in nitric oxides emissions with the increase of water content in emulsified fuel. This is because of the finely dispersed water droplets of the emulsion, causing a phenomenon known as a heat sink, which decreases the local adiabatic flame temperature. The lower combustion temperature in emulsified fuel directly impacts NO<sub>x</sub> formation because the mechanism of NO<sub>x</sub> generation is highly temperature subordinate (Alahmer *et al.*, 2010; Jhalani *et al.*, 2019; Kannan and Udayakumar, 2009; Khatri *et al.*, 2021; Kumar *et al.*, 2019; Murali *et al.*, 2006; Nadeem *et al.*, 2006; Okumuş *et al.*, 2020; Sudrajad *et al.*, 2011).

Increasing the water content level in the emulsion fuel increases the CO and HC emissions value in some studies. They attributed that due to the lower exhaust temperature of the engine. Hence, CO and HC emissions values were higher. In addition, the results show that the high viscosity of the fuel with increasing water content in the emulsified fuel may cause poor fuel spray in the injection. During the compression process, a part of the emulsified diesel droplets might not be occurring as micro-explosions, therefore leading to CO and HC formation (Arohman *et al.*, 2019; Hassan *et al.*, 2021; Hoseini and Sobati, 2019; Ithnin *et al.*, 2015; Syu *et al.*, 2014). On the other hand, other studies showed that the combustion of emulsified fuels generated lower CO and HC emissions than pure diesel fuel due to the burning of emulsified fuel produces a large extent of micro-explosions and secondary atomization, resulting in a higher degree of mixing of the unburned mixture. This indicates improved combustion due to proper dispersion and homogenization of water into diesel fuels (Kannan and Udayakumar, 2009; Khatri *et al.*, 2021; Kumar *et al.*, 2019; Murali *et al.*, 2006; Nadeem *et al.*, 2006; Senthur *et al.*, 2021; Sharma *et al.*, 2013; Vigneswaran *et al.*, 2014 - 2015).

Increasing the water content level in the emulsion fuel increases CO<sub>2</sub> compared with pure diesel fuel. They attributed that due to the increasing amount of oxygen atoms in

emulsified fuel. In other words, the emulsified fuel becomes lean (Hoseini and Sobati, 2019; Kumar *et al.*, 2019). In contrast, some researchers found a decrease in CO<sub>2</sub> levels due to the burning of the emulsified fuels generates a large number of micro explosions, leading to a more excellent mixing of the reactant mixture (Abdurahman *et al.*, 2016; Basha and Al Balushi, 2019; Ithnin *et al.*, 2015; Saravanan *et al.*, 2013).

The decrease of PM when using water-diesel emulsion fuel is maybe because of the better blending and improved atomization caused by the micro-explosion phenomena. In addition, the blending of water in the emulsion increases the OH radicals concentration, which promotes the oxidation of soot precursors (Hasannuddin *et al.*, 2016; Ithnin *et al.*, 2015; Murali *et al.*, 2006; Nadeem *et al.*, 2006; Saravanan *et al.*, 2013).

The smoke opacity of water-diesel emulsion fuels is lower than neat diesel fuel because of the uniform fuel mixture; thus the combustion rate would increase, and the gas phase oxidation and thermal cracking will decrease. Besides, the water absorbs heat, which would lower the cylinder temperature. Hence, the formation of smoke could reduce (Arohman *et al.*, 2019; Hassan *et al.*, 2021; Khatri *et al.*, 2021; Kumar *et al.*, 2013; Murali *et al.*, 2006; Senthur *et al.*, 2021; Sharma *et al.*, 2013).

## 6. Conclusion

According to the available literature about using W/D emulsion fuel as an alternative to diesel, many aspects can be concluded. There is a debate in the literature concerning the negative impact of using W/D emulsion fuel on the environment because of emissions characteristics. Some studies reported an increase in CO and HC emissions, maybe due to using different types of engines and various emulsion preparations techniques. However, after surveying many publications, it can be concluded that most of the potential studies showed that using W/D emulsion fuel improved both CI engine performance and emissions characteristics, particularly PM and NO<sub>x</sub>. Performance parameters improvement is confirmed by enhancing the power, torque,

specific fuel consumption, and brake thermal efficiency of the engine due to the power of micro-explosion. This phenomenon served to create better atomization, therefore better W/D emulsion combustion compared with conventional diesel fuel. It can be concluded that the depletion of fossil energy resources, as well as the positive environmental benefits of using W/D emulsion fuel, can place the proposed blend among the top candidates to replace conventional fuel.

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