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Towards Smart Green Blue Infrastructure

EXPERIMENTAL ASSESSMENT TO REDUCE EMISSION OF COMPRESSION IGNITION ENGINE VIA DIESEL/BIODIESEL/WATER BLENDS

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1. **ABSTRACT:** *Environmental concerns are a driving factor in alternative fuel development. Diesel and biodiesel are commonly utilized for engines; however, their emission causes significant pollution. Fuel additives are a promising method to reduce emissions. This research is emulsified water into diesel and biodiesel fuels per volume of 1%, 3%, and 5% to form W1, W3, and W5 for the diesel/water mixture and B30W1, B30W3, and B30W5 for B30/water mixture to evaluate their affection on performance and emissions. All blends exposed to an ultrasonication blender are to be homogeneous. A single-cylinder engine is utilized for experiments at 2000 rpm with different loads (0%-80%) of full load. The results revealed that in 80% of the full load, the diesel/water blends achieved the highest NO_x reduction. It considered the produced ACPA biodiesel to be an eco-friendly and clean fuel. It also gained better complete combustion at 80% load by lesser percent of CO emission of 23% relates to local-fossil diesel, and B30 recorded approximate brake specific fuel consumption at 80% of full load; therefore, the water surrogates with biodiesel through these percentages aren't reliable for performance and emission.*

INTRODUCTION

Massive emissions, an increase in global temperature, and a surge in the pace of ozone depletion are caused by fossil fuels. Compression ignition engines (CI) emit a huge amount of carbon dioxides with an expectation to peak by 2030 at approximately 37.1 billion tons [1]. Greenhouse gases (GHG_s) are now the top priority for the whole civilized world. The Kyoto Protocol specified six essential GHG_s under the UNFCCC [2]. Urban development is responsible for approximately 80% of the world's carbon emissions [3]. Aliphatic hydrocarbons in fossil diesel fuel range in boiling point from 130 to 370 °C and are found in the C8 to 28 range. Diesel engines generally emit mono-carbon dioxide (CO), oxides of nitrogen (NO_x), hydrocarbon content (HC), particulate matter (PM), and sulfur oxides (SO_x) [4]. The PM and NO_x emissions have a crucial impact on health [5]. Annual marine fuel usage ranged from around 250-325 million tons. in contrast, the average emissions yearly of SO_x, NO_x, and CO_2 were 11.3, 20.9, and 1016 million tons [6]. The maritime industrial sector is regarded as the world's major emitter of NOx due to greater engine combustion temperatures and pressures. In 2007, around 25 MMT (million metric tons) of emissions were produced by merchant vessels [7]. Due to this, the International Maritime Organization (IMO), The UN organization in charge of marine emission reductions has established a target for global shipping of achieving a 50% decrease in emissions from 2008 to 2050 [8]. The emission mitigation potential of alternative maritime fuels, such as natural gas, methanol, biofuels, hydrogen, and ammonia, Alternative marine fuels, such as natural gas, methanol, biofuels, hydrogen, and ammonia, have their potential to reduce emissions. The various decarbonization pathways are recommended in recent studies that have been reviewed [9]. Biofuels have a variety of sources of fuel produced by converting raw biomass or biomass waste into liquid or gaseous fuels. The three most promising biofuels for ships are hydro-treated vegetable oil (HVO), fatty acid methyl esters (FAMEs), and liquid biogas (LBG) [10]. The composition and quality of the feedstock, particularly the free fatty acids portion, and alcohol employed in the methanol or ethanol manufacturing process, are key factors in the quality of the biodiesel [11].

The water blending to diesel and biodiesel is a motivating point for acquiring the Low Combustion Chamber (LCT) concept for better engine emission. Still, it should be employed without compromising the engine performance. As summarized in the next paragraph, many researchers contributed to the same research scope for optimizing the engine's characteristics.

The authors [12] participated in the LCT concept evaluation by using straight-run naphtha as a low-cost addition to diesel and diesel/biodiesel fuels. The results suggest that the diesel/straight-run naphtha blends reduce NOx by 47-23% while consuming 7.5% less fuel than the fossil diesel experiment, however, the biodiesel/diesel/naphtha experiment remains disputable due to increased brake specific fuel consumption (bsfc) and kicking-off synchro motor at high loads. Jeevahan *et al.* [13] have asserted that binary and ternary blends are an advantageous solution for reducing emissions due to their lower cost compared to other methods of exhaust gas after treatment, which require more modifications to the exhaust chimney and higher initial cost for the assets. Jiaqiang *et al.* [14] used water as an emission reduction utilizing a variety of strategies such as water fumigation, direct water injection, and water-diesel emulsion. According to Peng et al. [15], the most effective technique is the water-diesel emulsion (WDE) strategy, which can decrease NO_x emissions from diesel engines without altering the engine's design. Amirnordin *et al.* [16], found that water in biodiesel blends enhances fuel atomization because water has a lower boiling temperature than biodiesel molecules. Hence, water molecules evaporate first, causing a burst of finer fuel droplets that create a microexplosion phenomenon. This phenomenon causes a shorter fuel evaporation time, an enhanced air-fuel mixing process, and an enhancer for combustion according to Khond and Kriplani [17]. Gowrishankar and Krishnasamy [18] conducted an experimental comparison between biodiesel-water emulsion within water percentages of 3%, 6%, and 9% by mass, and biodiesel water injection via port fuel injector (PFI) at various loads. The results of biodiesel-water emulsion had a faster burning rate, less reduction of cylinder pressure, and a higher amount of NO_x reduction of 40% at 9% water emulsion, while PFI reduced around 20% of NO_x emissions. Khanjani and Sobati [19] characterized the effect of water content ranging from 3-7%, waste fish oil (WFO) biodiesel content ranging from 3-7%, and surfactant concentration ranging from 1-2% on emission reduction. The combination of (3% WFO biodiesel- 6% water- 1% surfactant) was the most efficient emulsion blend compared to neat diesel, resulting in a 42% diminishing in CO emissions, a 34% reduction in unburned hydrocarbon emissions, and a 25% drop in NO_x. Abdollahi *et al.* [20] investigated diesel engine emissions using a nano-emulsion fuel containing 5% waste cooking oil biodiesel and 5%

distilled water. The findings revealed that the nano-emulsion blend reduced CO, HC, and NO_x emissions while increasing CO_2.

This study focuses on the affections of low percentages of water on diesel and diesel/biodiesel fuels with an experimental series without adding surfactant to the blends. An ultrasonication blender was used to acquire homogeneous blends for characterizing the performance and emission of CI engines under various loads. The influence of changes in physicochemical parameters for the employed blends was emphasized to relate them with the observed findings. The ideal blend is identified in the findings.

MATERIAL AND METHOD

1.1 Test Fuels

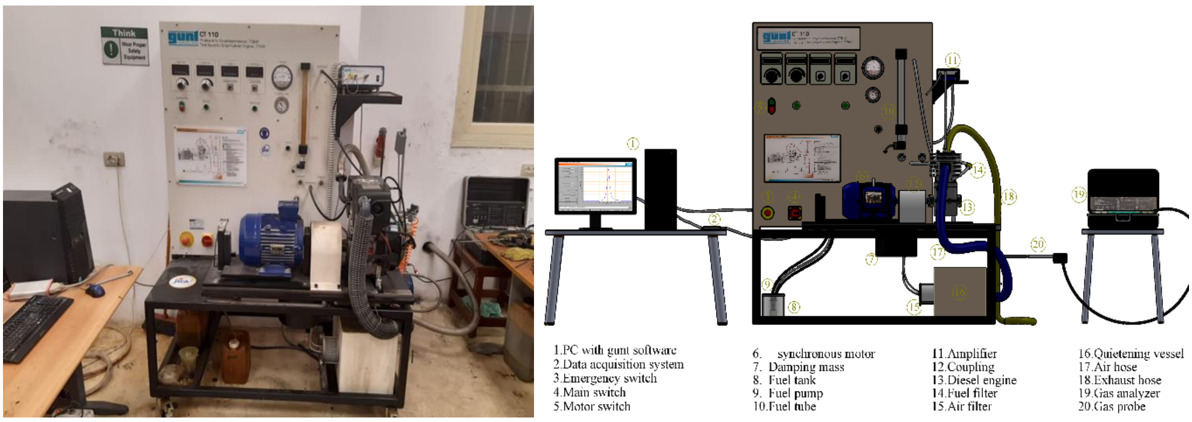
Water was employed as a binary and ternary additive in the current study together with two different fuel types: fossil diesel and diesel/biodiesel blend with a 30% by volume for biodiesel. The local station that provides the diesel, where the biodiesel was produced from WCO, Alexandria Company for Petroleum Additives (ACPA) manufactures, a reputable petrochemical company. The water was obtained from the laboratory tap. Table (1) shows the characteristics of the base fuels.

Table 1. Diesel and biodiesel Physicochemical Properties [21-23].

Properties	*Bio-diesel*	*Diesel*	*Method*
Density at 23 °C, Kg/m³	882	839	(ASTM-D-1298)
Auto-ignition Temperature, °C	225	246	(ASTM-E-659)
Net-heat Value, MJ/Kg	37.1	43.1	(ASTM-D-240)
Kinematic Viscosity at 40 °C, CSt	4.6	3.8	(ASTM-D-445)
Free Methanol	0.5	-	%wt.
Ester Content	93	-	%wt.

1.2 Experimental test rig

A single-cylinder (HATZ-1B30-2), a 4-stroke engine with direct injection, is used for performing the experiments. The facility is set up at the energy resources laboratory (E-JUST), and its specification is mentioned [24]. Experiments were performed in a constant engine revolution at 2000 rpm and with different engine loads of 0, 3, 6, 9, and 12 Nm. The Synchronous motor simulated the experimental loads on the CI engine. The emission analyzer was used in the Bacharach ECA 450 experiment model to measure NO_x and CO emissions. The data acquisition captured the engine's parameters during each experiment and record it separately. The engine photo and diagram are shown in Fig. (1).



1.3 Uncertainty analysis

Equation (1) illustrates uncertainty analysis using the root sum square (RSS) formula. This is used to calculate the proportion of inaccuracy in experimental parameters:

$$U_R = \pm\sqrt{\sum_{i=1}^{n}\left(\frac{\partial R}{\partial x_i}U_{tx_i}\right)^2}, \quad (1)$$

where U_R identifies the uncertainty of the dependent parameter R's, which is influenced by n independent variables of x. The U_{tx_i} determine the total quantity of uncertainty for each independent variable. Pressure, engine speed and torque, crank angle, and fuel flow rate are the independent variables investigated in this study. The dependent variables are brake power and brake-specific fuel consumption. According to Table (2), The manufacturer-specified range and precision of measuring tools were utilized to calculate the uncertainty of independent parameters. (Ur) The experimental random uncertainty calculated by Eq.(2) occurs in conjunction with systematic uncertainty Us, which may be used to calculate instrument accuracy [25].

$$U_r(\%) = \pm\frac{(t \times SD/\sqrt{N})}{X_m} \times 100 \quad (2)$$

The scholars computed the statistic t, in contrast. At a 95% confidence level, the standard deviation (SD) of N different measurements is equal to 1.96 by using Eq.(3) [25]. Calculating the overall uncertainty of the independent variables involving the systematic Us and random Ur uncertainties. It was found that, respectively, 1.36% and 3.47% of the brake power and brake-specific fuel consumption.

$$U_t = \sqrt{U_s^2 + U_r^2} \quad (3)$$

Table 2. The measured parameters' extent, precision, accuracy, and total uncertainty.

Exhaust gas analyzer parameters	*Extent*	*Precision*	*Instrument uncertainty (Us)*	*Random Uncertainty (U_R)*	*Total Uncertainty (U_t)*
CO (ppm)	0 - 4000 ppm	1 ppm	(± 10 ppm) or ± 5% of Value	± 1.16 %	± 5.13%
NO_x (ppm)	0 - 4000 ppm	1 ppm	(± 5 ppm) or ± 5 % of Value	± 0.43 %	± 5.02%
Pressure transducer (bar)	0-250	–	± 1% of Value	± 1%	± 1.41%
Crank angle encoder (degree)	0-720	0.5	± 0.5°	± 0.3%	± 0.58%
Torque indicator (Nm)	0-50	0.1	±1% of Value	± 0.38%	± 1.07%
Fuel burette (cm3)	153	–	± 0.2 cm^3	± 4%	± 4.06%
Speed sensor (rpm)	0-10000	1 rpm	± 5 rpm	± 0.1%	± 0.27%

RESULTS AND DISCUSSION

1.4 Fuel blend properties

The (6) blends were blended with an ultrasonication blender at a medium amplitude of 60% for 15 minutes to acquire a stabilized emulsion. The calorific value of WDE is diminished for the water surrogates values 1%,3%, and 5%; within diminishing values are 1.2%, 3.7%, and 6.2%, respectively. In contrast, WBE blends (B30W1, B30W3, B30W5) diminished their heating values by adding water's value within the range of 1.2%, 3.6%, and 5.8%; consequently. The WDE blends' kinematic viscosity values are slightly increased by adding water for the three blends (W1), (W3), and (W5) raised by 1%, 3.2%, and 5.3%, respectively. While the biodiesel optimum blend (B30) viscosity is spiked by 7.4%, 18.1%, and 44.4% for their blends B30W1, B30W3, and B30W5; consequently. That could be ascribed to due to the fuel/water emulsion's static electrical attraction and friction, which leads to smaller and dispersed particles [14,26].

1.5 Engine Performance

The bsfc was measured for each experiment as shown in Fig. (2a). The bsfc change of WDE blends is illustrated in Fig. (2b). At 3 and 6 Nm, the higher bsfc resulted in the higher water percentage W5 blend within increments of 26% and 15%, respectively, related to D100 bsfc. This could be caused by lower combustion chamber temperature and less effect of the microexplosion phenomenon. At 9 Nm, the bsfc of W1 and W3 showed the same bsfc as D100, while the higher water blend W5 showed a modest increment of 3% related to D100. Consequently, at a 12Nm load with a higher combustion temperature, the lesser WDE blend W1 recorded a significant declination of bsfc of 9%, and W3 equal to bsfc of D100 reinforced by better air-fuel mixing by microexplosion phenomenon, and the higher WDE blend W5 spiked an increment for bsfc of 10%. These results reveal that the higher emulsified blends lead to more fuel consumption related to base fuels, which could indicate a higher demand to generate more energy for water evaporation, Which agrees with[14,27] In Fig. (2c), the WBE blends showed a negative effect on bsfc with an increasing range of up to 55% in the various loads that caused by the higher viscosity of blends which does not acquire better mixing among fuel and air [19,28].

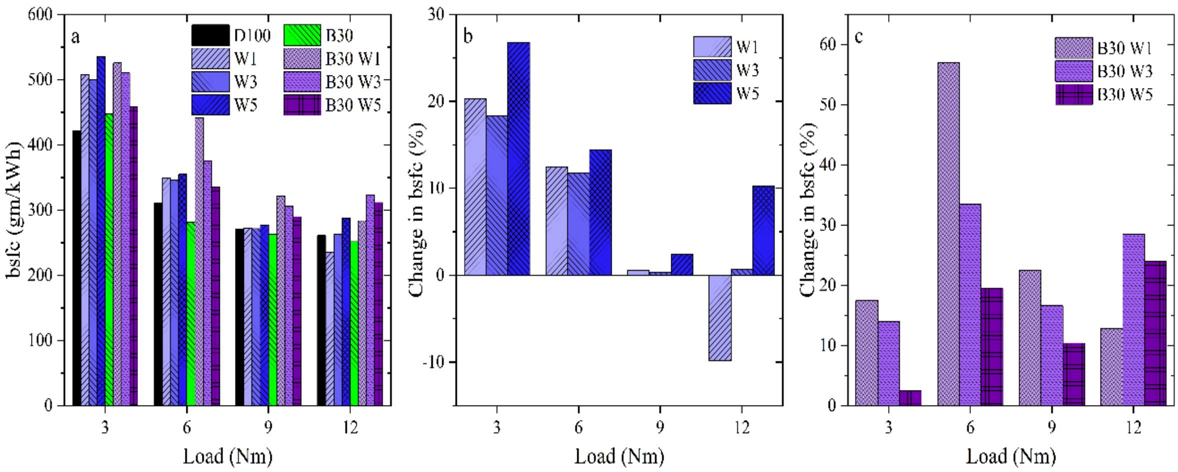


Figure 2: (a) bsfc variance for blends at experiment loads at 2000 rpm, (b) bsfc change percent for W1, W3, W5 relative to D100, (c) bsfc change percentage for B30W1, B30W3, B30W5 relative to B30

1.6 Combustion Characteristics

Fig. (3a)

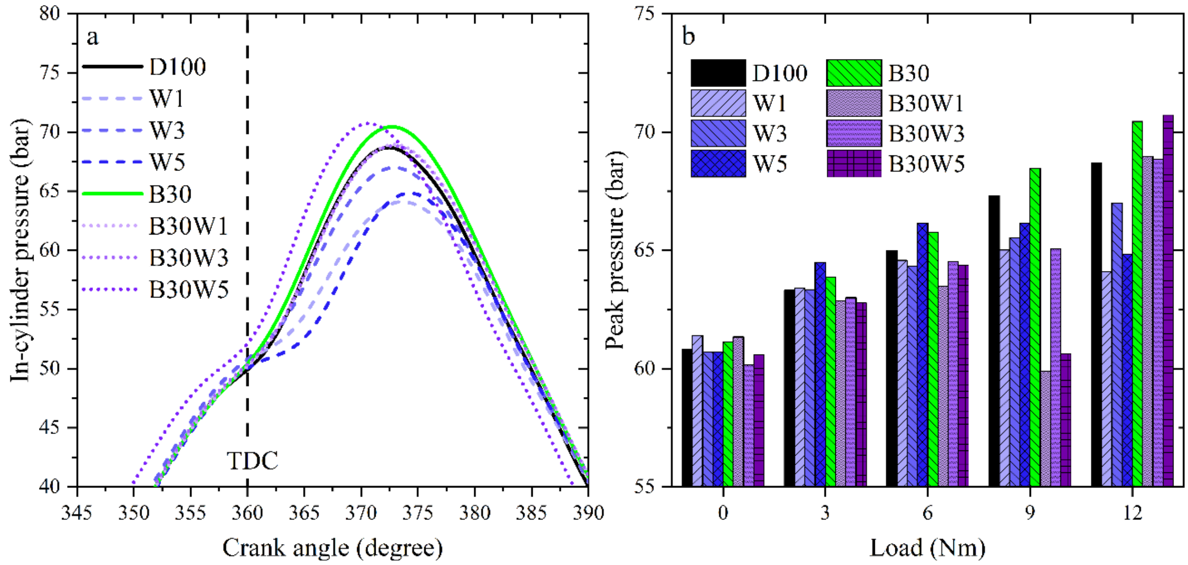


Figure 3: (a) In-cylinder Pressure vs. °CA for the Test blends at load 12Nm and 2000 rpm, and (b) Peak Pressure for Fuel Blends at various loads

demonstrates a relation between in-cylinder pressures (bar) versus the crank angle (degree). The biodiesel/water blends reflected a better pressure comparison to the diesel/water blends; specifically, the B30W5 blend showed a higher and earlier in-cylinder pressure related to other blends. The starting pressure raising is being of 2.5°CA earlier than the other blends, with the recorded peak pressure being 70.5 bar as shown in Fig. (3b). It would be associated with the affection of the phenomenon of micro-explosion, which resulted in improved oxygen exposure for the atomized fuel; additionally, The inclusion of oxygen in biodiesel promotes early ignition of combustion (SOC) [28]. The pressure of the other biodiesel/water blends (B30W1) and (B30W3) is slightly dropped related to B30 pressure and becomes approximately equal to D100 pressure with a value of around 68.5 bar as referred to in Fig. (3b). Otherwise, diesel/water blends show fluctuating In-cylinder pressure values reinforcing the Coefficient of Variation (COV) results. The drop of In-cylinder pressure for diesel/water blends is the dominant trend specifically at the higher load; additionally, the pressure risen is a bit delayed to be after the TDC with retarding of the start of combustion (SOC) that coincides with the results in research [26], and contradicts the biodiesel/water blends its pressures rise at TDC, and that could be interpreted as the combination of oxygen presence in biodiesel and micro-explosion phenomenon, which acquires a better oxygen exposure and consequently the optimum start of combustion (SOC) timing and hitting better pressure values.

The heat release versus the crank angle degree is illustrated in Fig. (4a), while Fig. (4b) clarifies the CA50 (the 50% heat release at CA) with delayed or earlid angles for each blend. The higher percentage of water of diesel/water in the W5 blend spiked the maximum heat released value of 31 J more than B30 and D100 but with a delaying angle of around 1.5°CA related to D100. Hence these results asserted that the microexplosion phenomenon bursts the fuel droplets into finer ones, which increases the extracted heat from blends combined with delay and lowering of peak pressure related to D100; as mentioned before in Fig. (3b). Additionally, the other diesel/water blends W1 and W3 both recorded approximate heat release values of 29 J.; but within varied delay angles of 2°CA and 1°CA respectively; related to D100. On the other side, the biodiesel/water blends B30W1 and B30W3 show approximate HRR related to B30 with a marginal drop of 0.5 J of Heat value. Otherwise, the higher value of water percent in biodiesel for B30W5 reflects a remarkable drop of HR value within 3-5 J related to B30 and delayed raise angle (SOC) before TDC within 3°CA with non-gradual rate and early drop as illustrated in Fig (4a). The CA50 of HR for B30W5 is earlid at load 12Nm as shown in Fig. (4b). This drop of heat release for B30W5 could be interpreted as the higher resistant effect of water to the ignition process which dominated in the higher biodiesel/water B30W5, further the less heating value of the biodiesel/water blends, and lesser fuel-air mixture [28]. Overall, the microexplosion process gained a higher heat release and better combustion process in the higher water percentage value for diesel/water blends with delaying of the 50% of heat release angle because of its higher heating values and its higher viscosity of blends; whilst the better biodiesel/water blends were B30W3 to keep optimum HRR.

Emission Characteristic

The Results of NO_x emission reflected the higher values caused by the neat-diesel experiment at the various engine loads. The NO_x further increase is shown in Fig. (5), resulting from raising the engine load for all blends as the combustion chamber temperature is increased. The higher water presence in diesel-emulsified surrogate W5 decreased the NO_x emission nevertheless the engine load.

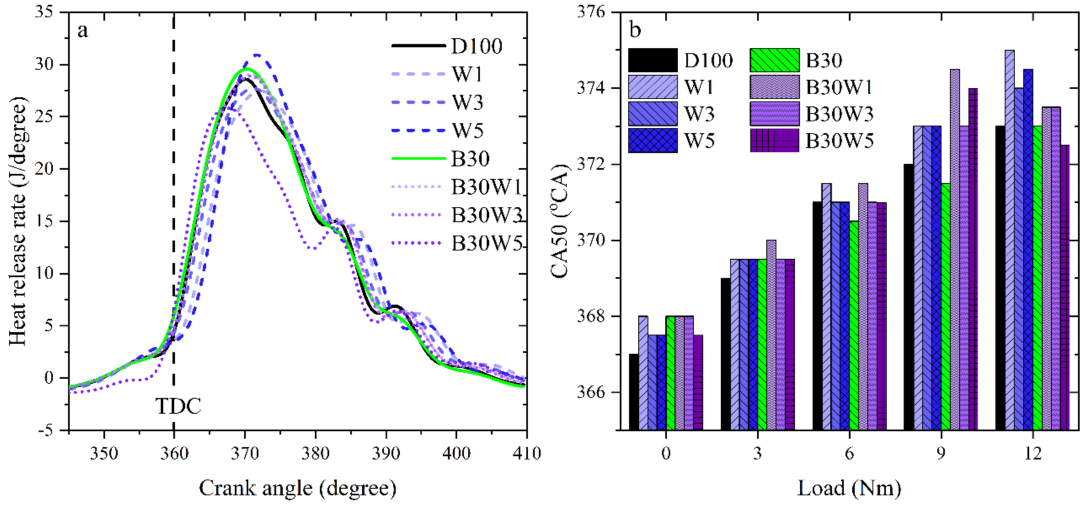


Figure 4: (a) Net heat release rate vs. crank angle for fuel blends at 12 Nm and 2000 rpm, and (b) CA50 angles vs. load for tested fuel blends at various loads.

However, there is a significant reduction for all diesel/water blends. The remarkable reduction percentage is (W5) 41% related to D100 emission at load 12Nm, while the other blends (W1) and (W3) their NO_x emission reduced by around 36% at the same load. Approximately similar results have been reported by many researchers [26,28] that using emulsion fuel reduces NO_x because of the lower firing temperature during ignition due to water's high latent heat evaporation (phase transition of a liquid to vapor) which is considered an endothermic reaction that consuming the heat in ignition phase [29]. The optimum blend of biodiesel/diesel was B30, which is lesser in NO_x emission than D100 of 29% at a 12Nm load. That might be ascribed to its production process in ACPA's improved manufacturing and filtering method, as well as it is chemical composition and lower free methanol and ester concentration [30], as shown in Table (1). The additive water values to biodiesel/water blends acquired a marginal diminishing for NO_x emission in most engine loads. The NO_x reduction percent for B30W1 and B30W3 was reported at 1.2% and 3.8% relative to B30 at 12Nm load; however, the B30W5 recorded an increase of 2.5% at the same load. The higher viscosity of the biodiesel/water blend could be an increasing reason for NO_x emission for B30W5; increasing water percent is raising the blend kinematic viscosity, which causes injection pressure increment and advancing in injection timing; which consequently raises the NO_x emission. [31,32].

The formation of CO usually indicates incomplete combustion inside the combustion chamber and that is mainly because of the slow-burning rate of heterogenous soot in the last phase of the combustion [33]. Fig. (6) shows the PPM of carbon monoxide amount for various blends at the experimental loads; which illustrates the marginal reduction of CO emission by increasing engine load. Remarkably, the D100 appears to release the most CO of any blend, particularly at low load, due to an inadequate combustion chamber temperature to convert CO to CO_2 [34]; and the absence of water affections through the microexplosion phenomenon [26]. At all loads, the diesel/water blends expressed a better air-fuel mixing and complete combustion related to D100, therefore it is interpreted that the microexplosion phenomenon produces a finer fuel droplet with a better air mixing process which reduces the emitted CO emission. On the other side, biodiesel/water blends B30W3 and B30W5 showed an obvious increment in CO emission related to B30 values at several loads. The B30W1 fluctuates among the engine loads; at idling and 3Nm loads are lesser than B30 while at 6,9, and 12Nm is higher CO emission than B30. The physicochemical blend properties are shown lesser calorific values of biodiesel/water blends rather than diesel/water blends, in addition, the biodiesel/water blends have higher viscosity relative to diesel/water blends. That could be interpreted as a reduction of inside-cylinder temperature because of less released heat as shown in Fig. (4a) which is expected lowered beyond 1400 K, which could cause a slowing in the CO oxidation process [34]. This is because the emulsion contains water, and it could additionally be having less effectiveness of microexplosion phenomenon occurring by the higher kinematic viscosity of biodiesel/water blends.

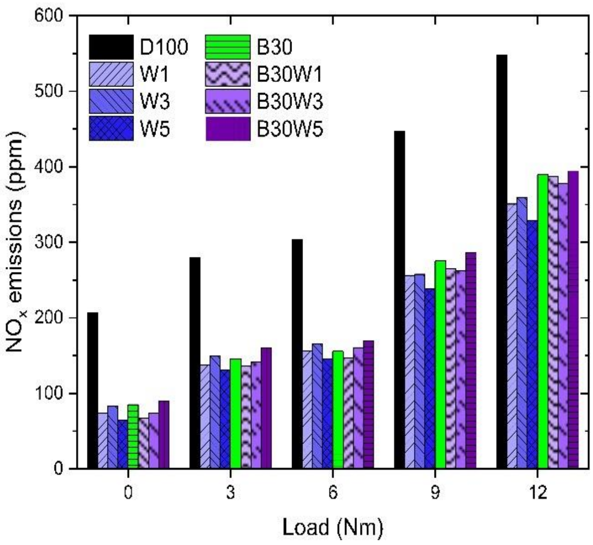


Figure 5. NOx emissions varied among all tested fuels at (0-12) Nm at 2000 rpm.

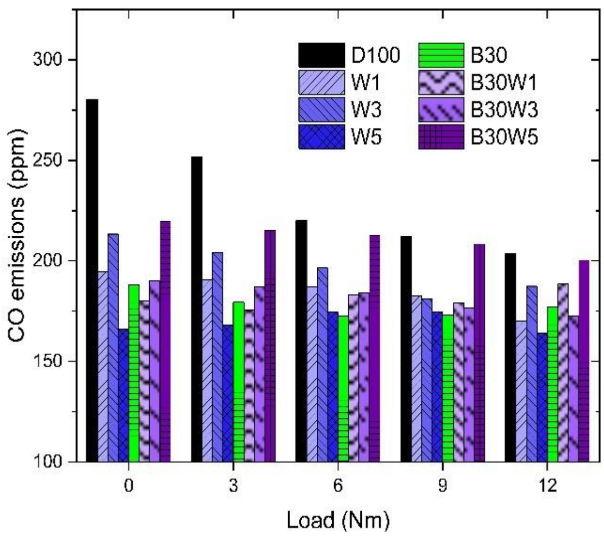


Figure 6. CO emissions varied among all tested fuels at (0-12) Nm at 2000 rpm

CONCLUSIONS

One could conclude from the aforementioned findings, that the increasing water percentage for diesel fuel and biodiesel is shown a higher bsfc at all loads for all blends. An exception is recorded with a bsfc reduction of 9% for the W1 blend at 80% of the full load relative to D100. Furthermore, the approximate bsfc value of W1 and W3 at 60% of the engine's full load relates to D100. Whilst the biodiesel/water blends reflect a higher bsfc at all engine loads. The water absorbs the amount of combustion chamber heat for vaporization in the homogeneous combustion phase which reduces the NO_x emission and that could cause incomplete combustion for unsuitable water amount. The diesel/water blends hit a better NO_x reduction at 80% of full load, specifically, W1 declined 36% of NO_x emission with the best compromising of CO emission with a diminishing value of 17.5% related to D100. The B30 is considered an optimum blend in comparison to biodiesel/water blends and fossil diesel which acquired NO_x emission reduction of 30% to 50% at a load range of 20% to 80% of the engine's full load. It can consider the produced ACPA biodiesel to be an eco-friendly and clean fuel and it also gained better complete combustion at 80% load by lesser percent of CO emission of 23% relates to local-fossil diesel. Furthermore, B30 recorded approximate bsfc at 80% of the engine's full load and with stable engine performance. Biodiesel/water blends reflect a negligible effect for NO_x reduction with a slight increase in CO emission at 80% of the full load relative to the B30 blend. Overall, it could not be considered the water surrogate with biodiesel through these percentages is an effective blend.

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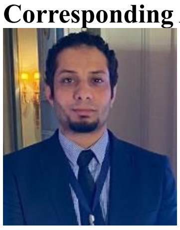

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