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Emission and Performance in a Diesel Engine Operating on Diesel-Biodiesel-Butanol Blends Derived from Waste Cooking Oil

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ABSTRACT

In this investigation, the performance and emission profiles of a diesel engine, fueled by biodiesel derived from waste cooking oil (WCO), were evaluated. The biodiesel was incorporated into diesel fuel in various concentrations, and the potential enhancement of these mixtures with butanol was also explored. Experimental trials were conducted at a consistent engine speed of 2250 rpm across five distinct engine loads (4, 5.5, 7, 8.5, and 10 kW) to scrutinize engine performance and quantify exhaust emissions. An air-cooled, single-cylinder diesel engine served as the experimental apparatus. Pure Iraqi diesel (D) was used as a baseline, prior to the assessment of several fuel blends, including D80B20 (20% biodiesel, 80% diesel), D80B10BU10 (10% biodiesel, 10% butanol, 80% diesel), and D70B15BU15 (15% biodiesel, 15% butanol, 70% diesel). The results indicated a decline in engine performance across all fuel types, with the most pronounced deterioration observed at lower loads. The brake specific fuel consumption escalated by 13.37%, 16.98%, and 3.92% for the tested blends, relative to diesel. Concurrently, exhaust gas temperatures decreased by 12.5%, 23.5%, and 2.9%, respectively. Furthermore, CO emissions diminished by 22.00%, 46.0%, and 14.4%, while CO2 emissions rose by 16.67%, 41.36%, and 11.73%, respectively, when compared to diesel. HC concentrations were curtailed by 42.55%, 69.11%, and 10.64%, respectively. NOx emissions exhibited a reduction of 3.8% and 24.9% for D80B10BU10 and D70B15BU15, while a 3.5% increase was observed with D80B20. The findings suggest that ternary mixtures were associated with less favorable outcomes compared to their binary counterparts.

1. INTRODUCTION

The escalating deterioration of air quality in urban environments has emerged as a crucial concern in the context of the rapid expansion of the vehicle industry and associated exhaust emissions [1]. This issue is predominantly driven by the utilization of petrol and diesel engines, which pose substantial implications for human health. Diesel engines, in particular, have been widely adopted across sectors including agriculture, transportation, and power generation, due to their inherent stability and high thermal efficiency [2, 3]. Consequently, the use of diesel fuel has been prevalent in these sectors [4]. However, as natural resources deplete and production costs escalate, the necessity for alternative sources becomes increasingly urgent [5, 6].

The pressing need to replace fossil fuels and conserve the environment has led researchers to concentrate their efforts on discovering cost-effective alternative fuel sources, thereby reducing the reliance on fossil fuels [7]. This line of inquiry has yielded environmentally friendly and economically viable fuel alternatives. Among these, biodiesel and alcohol have emerged as promising candidates to serve as alternatives in diesel engines [8]. These fuels, being renewable, domestically produced, non-toxic, readily available, and eco-friendly, offer significant benefits [9].

Biodiesel, a renewable fuel alternative, can be directly utilized in diesel engines. The integration of biodiesel into diesel can result in a decrease in CO, hydrocarbon (HC), and PM emissions [10, 11]. In the context of the high cost of edible vegetable oils, biodiesel, derived from non-edible vegetable oil, has surfaced as an environmentally sustainable fuel choice [12, 13]. However, the high viscosity and low volatility of vegetable oils initially resulted in operational challenges in biodiesel engines. A viable solution to this issue was found in the process of transesterification, which efficiently reduces the viscosity of vegetable oils, thus mitigating the aforementioned problems [14].

Furthermore, bio-alcohols, sourced from renewable materials, have been identified as potent alternative fuels for engines. The category of low alcohols encompasses methanol, ethanol, propanol, and butanol, each containing fewer than four carbon atoms. These alcohols can be produced from agricultural waste and biomass. However, due to their low density, these alcohols are unstable when mixed with diesel. Some, like methanol, are even toxic and hence not recommended for use [15].

Conversely, hexanol, butanol, octanol, and pentanol are classified as higher alcohols, as they contain four or more carbon atoms [16]. Current research has shifted its focus towards these higher alcohols as potential next-generation alternative fuels. Higher alcohols offer the advantage of dissolving diesel without phase separation, negating the need for co-solvents or emulsifying agents to enhance stability [17]. However, due to their high water content, high latent heat of vaporization, and high latent heat of combustion, bioalcohols cannot be directly used in diesel engines [10].

Despite these challenges, biodiesel and bioalcohols, when blended with diesel, present promising prospects as alternative and renewable fuels. While edible oils may be employed for biodiesel production, their potential adverse impact on human consumption must be taken into consideration. Consequently, this study prioritizes the use of vegetable oils and non-edible oils for the preparation of biodiesel, given that these substances are not suitable for human consumption. This approach also enables the repurposing, renewal, and conversion of unwanted waste into useful materials.

A mixture incorporating butanol has been utilized with encouraging results to improve fuel properties and address the deficiencies of biodiesel [18]. Senthur Prabu et al. [19] conducted an experiment on a direct-injection diesel engine to compare the performance of diesel, biodiesel, and a blend of biodiesel and n-butanol at different volume percentages. It was observed that butanol markedly reduced NO_x, CO, and smoke opacity emissions, although it negatively affected certain combustion parameters. In a similar vein, Yilmaz and Davis [20] investigated the emissions from a diesel engine generator when powered with blends of used fry oil biodiesel (waste oil methyl ester) and varying volumes of n-butanol. The study reported an increase in HC emission, a decrease in NO_x emission, and an insignificant influence on CO emission compared to pure biodiesel under different engine loads. Marri et al. [21] suggested that incorporating butanol into biodiesel at concentrations as high as 29% by volume could enhance combustion efficiency without necessitating engine modifications. This led to an increase in productivity and a decrease in emissions of particulate matter (PM), nitrogen oxides (NO_x), carbon monoxide (CO), and hydrocarbons (HC). Further, Zhang and Balasubramanian [22] evaluated the impact of diesel, biodiesel, and butanol mixtures on engine performance using a single-cylinder diesel engine with direct injection. The study found that the inclusion of up to 15% butanol in the biodiesel blend (B20) resulted in increased fuel consumption and thermal efficiency.

In addressing the urgent need for sustainable energy alternatives, a substantial body of research has been devoted to the investigation of biofuel blends and their effects on diesel engine performance and emissions. Notably, Tüccar et al. [23] established that augmenting the composition of a diesel-microalgae biodiesel blend (B20) with butanol results in a sizeable reduction in carbon monoxide, nitrogen oxides, and smoke emissions. Despite a concurrent decrease in engine torque and braking power, an overall enhancement in fuel efficiency was observed. Complementing these findings, an examination by Rakopoulos et al. [24] of diesel fuel mixed with butanol, bio-cottonseed oil, and ethanol illustrated that this particular blend led to an increased ignition delay time and a decreased maximum in-cylinder pressure. Alongside these changes, a rise in hydrocarbon emissions, nitrogen oxides, carbon dioxide, and smoke opacity was reported, indicating a potential trade-off between engine performance and environmental impact.

Providing further insight into the potential of butanol as a biofuel additive, Imtenan et al. [25] conducted tests on a diesel-biodiesel blend augmented with a volume of 5-10% n-butanol and diethyl ether. Applied to a 4-cylinder turbocharged indirect injection diesel engine, significant improvements in combustion and emission characteristics were noted at 10% butanol and diethyl ether, further underscoring the promise of butanol as a viable higher alcohol for biofuel blends.

These advancements in biofuel technology bear particular relevance to regions such as Iraq, where diesel engines power a substantial proportion of vehicles, machinery, and electricity generators [26, 27]. The resultant pollutant emissions from these engines contribute significantly to air quality degradation, yielding profound implications for environmental and public health.

In view of these challenges, the present study seeks to evaluate the performance and emissions of a diesel engine utilising butanol-augmented biodiesel fuel blends. The experimental design involved the formulation of mixtures including DB D80B20, D80B10 BU10, and D70B15 BU15, each encompassing varying proportions of diesel, biodiesel, and butanol. Employing a single-cylinder diesel engine operating at a constant speed across diverse load conditions, it was found that the results yielded by these biofuel blends were promising, particularly in comparison to pure diesel fuel.

This study, therefore, aims to contribute to the development of a biofuel alternative suitable for widespread implementation in Iraq, potentially circumventing the need for costly engine modifications. By doing so, this research aspires to alleviate the environmental and health implications of diesel engine emissions, thereby fostering a more sustainable energy future.

2. EXPERIMENTAL SETUP

2.1 Experimental procedure and specifications

The tests were conducted using TD202 Diesel engine. Figure 1 displays an outline of the experimental device. Information regarding the engine's primary characteristics can be found in Table 1. The TD202 compression-ignition type engine is a small air-cooled diesel engine designed for testing small single-cylinder engines. For example, lawnmowers, cultivators, pumps, and generators, as Figure 2A demonstrates. The engine load test package is equipped with a user-friendly potent hydraulic dynamometer. Running water through the dynamometer effectively dissipates the motor's power, making large electrical supplies or load resistors unnecessary for its operation. To gauge exhaust gas temperature, a K-type thermocouple came in handy. Efficient as it may be, the dynamometer's unique feature is its way of utilizing water. EGMA-CG-450, a multi-gas emissions analyzer was used to measure the concentrations of CO_2, CO, NO_x, and HC. To test engine performance and exhaust emissions, the engine was run at a fixed speed of 2250 rpm and five different loads (4, 5.5, 7, 8.5, 10 kW). Figure 2B shows the measurement system used in the experiments. Before switching to the biodiesel blend, the engine was warmed up by running it on diesel fuel for a few minutes. The engine was also run with diesel fuel before shutting it down. To ensure consistency and accuracy, the tests were conducted three times. The Engineering Technical College of Najaf / Al-Furat Al-Awsat University was the location for all experimental work.

Table 1. Technical details of test engine

Items	Specification
Dimensions	Width 400 mm Height 450 mm Depth 350 mm
Net weight	35 kg
Fuel type	Diesel
Fuel tank	Caramel/light brown-painted steel with vent and filter cap
Absolute maximum power	3.5 kW (4.8 hp) at 3600 rev.min^{-1}
Continuous rated power	3.1 kW at 3000 rev.min^{-1}
Bore	69 mm
Stroke/crank radius	62 mm/31 min
Connected rod length	104 mm
Engine capacity	232 cm^3
Compression ratio	22:1
Oil type	Multigrade SAE 5 W-40
Oil capacity	2.6 Liter

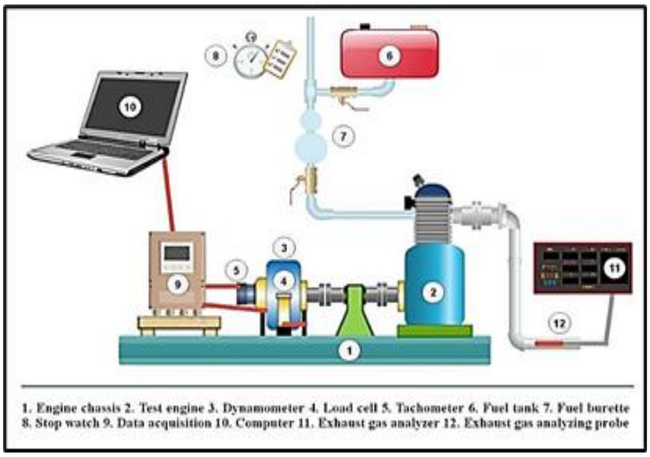

Figure 1. The schematic diagram of the test equipment

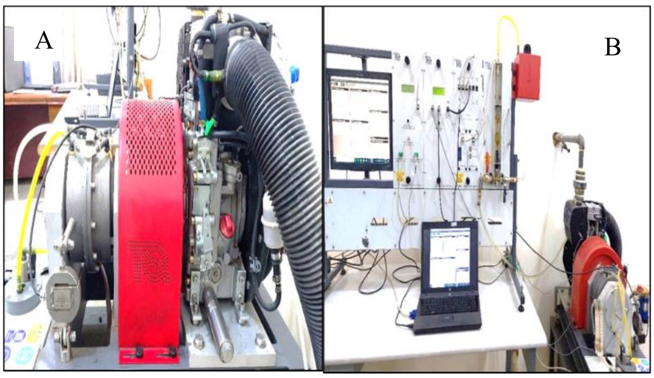

Figure 2. (A) A photo for the experimental engine rig, and (B) The engine rig with measuring system

2.2 Used fuels

Iraqi Diesel was used as a reference in the experimental work. There were two types of biofuel blends used in the tests: binary blends (D80B20) of diesel and biodiesel (waste cooking oil) and triple blends (D80B20) consisted of diesel and biodiesel with 10% and 15% butanol (C_4H_{10}). The characteristics of the used fuels are detailed in Table 2.

Table 2. Physical properties of the fuel

Blending Symbol	Density (kg/m^3) at 20℃	Flash Point ℃	API	Cetane Number (CN)	LHV (kJ/kg)
Diesel	840	64	25	52	42500
Biodiesel	892.2	>120	27.1	56.5	37500
D80B20	845	89.2	35.3	54	41450
D80B10BU10	827.5	56.8	39.5	51	41000
D70B15BU15	827.9	57	39.4	50.8	40250

2.3 Biodiesel preparation

Waste cooking oil was purchased from local stores. Heavy pollutants were first taken out of the oil using a medium-permeability sieve, and then any leftover impurities were taken out using filter paper. The waste cooking oil is mixed with methanol alcohol and potassium hydroxide (KOH) to prepare blended biodiesel. Methanol (6:1 mole ratio) and (1% oil/volume) of (KOH) are required to produce one litre of (WCO). Throughout 90-minute mixing process, the admixture is kept at (50 to 65℃), near the boiling point of the alcohol, but not exceeding it.

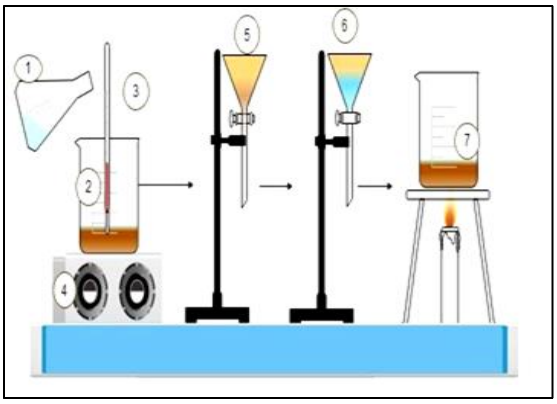

Figure 3. Transesterification process 1- methoxide 2-wco oil 3-thermometer 4-magnetic stirrer 5-separation process 6-washing process 7-drying process

The mixture was then allowed to settle in a separating funnel and left for (8-12) hours to allow the components to separate into two liquid layers. The top layer consists of biodiesel or (FAME), while the bottom layer comprises glycerol. The glycerol is then kept out of the separating funnel to separate the reaction mixture from (FAME and glycerine). After the glycerol is extracted, the FAME mixture is left with impurities like alcohol and spent catalyst. To meet the prescribed quality criteria for biodiesel, the resulting mixture of fatty acids methyl esters (FAME) from the transesterification reaction must be refined. This means that FAME need to be washed with distilled water and then drying. Water-soluble pollutants, including methanol, catalyst, and glycerine, can be washed away with multiple rinses in hot water at (70°C). To clean biodiesel, combine it with distilled water and shake vigorously for a minute. This procedure eliminates any remaining impurities in the methanol (KOH) and glycerine. After that, it has to be heated to 120°C to eliminate any remaining moisture. Once this is done, the biodiesel may be used in a vehicle's fuel system. The process flow for making biodiesel is depicted in Figure 3. Step-by-step instructions for making biodiesel are depicted in Figure 4.

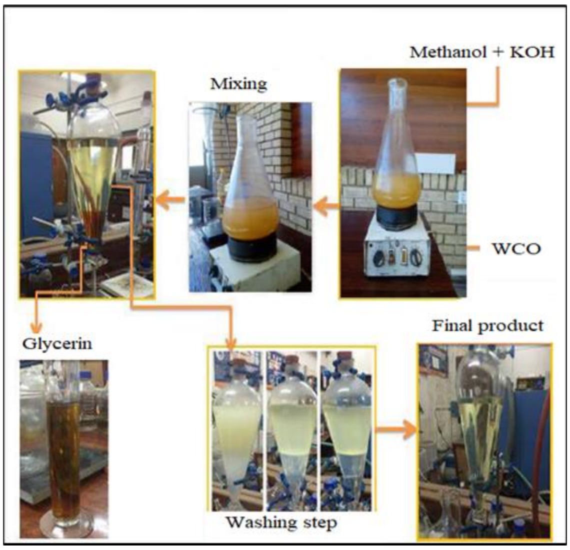

Figure 4. Biodiesel preparation steps

2.4 Performance evaluation parameters

2.4.1 Mass flow rate of fuel (kg/h)

By measuring how long (t) it takes the engine to burn through a given volume of diesel, the fuel consumption can be evaluated using the following formula:

$$\dot{m}_f = \frac{\rho f \times v \times 10^{-6}}{t} \times 3600[\frac{kg}{h}] \quad (1)$$

2.4.2 Brake-specific fuel consumption (kg/kW.hr)

The efficiency with which an engine converts fuel into useful work is indicated by another essential metric generated from the same data: brake specific fuel consumption (BSFC).

The following formula is used to determine this:

$$BSFC = \frac{\dot{m}_f}{b.p} \quad (2)$$

2.4.3 Brake power (kW)

The braking power is determined using equation follow.

$$b.p = \frac{2\pi NT}{60} \times 10^{-3}\,[kW] \quad (3)$$

2.4.4 Brake thermal efficiency (%)

The thermal efficiency may be estimated by calculating the fuel consumption and power output.

$$\eta_{bth} = \frac{b.p}{\dot{m}_f \times Q_{HV}} \times 100\% \quad (4)$$

3. RESULTS AND DISCUSSIONS

3.1 Brake thermal efficiency (BTE)

In internal combustion engines, the brake thermal efficiency (η_{bth}) signifies the ratio of the output work to the input energy [28]. While examining, it was discovered that (η_{bth}) and engine load directly correlated with all fuel blends. Additionally, the BTE stands in a reversed relation to BSFC, which implies that when BSFC is higher, BTE is lower [29]. According to Figure 5, D80B10BU10, D70B15BU15, and D80B20 fuel blends at 2250 rpm experienced a reduction of on average 8.50%, 9.75%, and 1.39%, respectively, in the brake thermal efficiency (η_{bth}), as compared to diesel fuels. The best performance in terms of BTE was found in pure diesel, while for all blends, it was found to be lower. The lower thermal efficiency in biodiesel blends is due to the lower calorific value of biodiesel (derived from cooking oil) compared to diesel fuel. This high-viscosity fuel reduces the engine's engine efficiency. Furthermore, the experimental results identified that (η_{bth}) rates for triple alcohol blends were consistently below those for diesel in all the tested fuels. It can be explained by the cooling effect of alcohol caused by its high heat of vaporization, which absorb it from the combustion chamber causing this decrease in (η_{bth}) rates. As a result of these findings, the study by Goga et al.'s [7] position on this issue is justified.

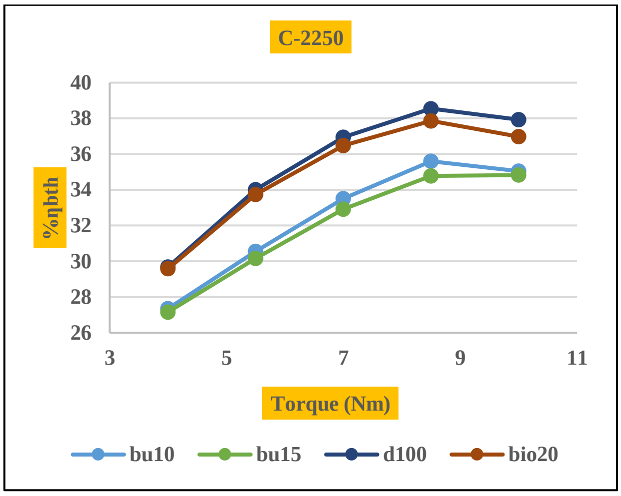

Figure 5. Variation of brake thermal efficiency (Ƞbth) depending on engine loads

3.2 Brake specific fuel consumption (BSFC)

The gradual decline of BSFC as engine speed was fixed and its load was increased is due to the mixture become more homogeneous and efficient, leading to better thermal efficiency [30]. Analysing BSFC allows evaluating fuel conversion efficiency to useful energy and is a crucial parameter. At 2250 rpm, D80B10BU10, D70B15BU15, and D80B20 fuel blends experienced an average increase in BSFC compared to diesel fuel, as shown in Figure 6. The average increase for each blend was 13.37%, 16.98%, and 3.92%, respectively.

Interestingly, the study also found that as engine load increased, BSFC decreased. As the engine load grew, the engine's efficiency and combustion quality were enhanced. Despite lower calorific values, lower heating value, and higher viscosity, biodiesel and alcohol blends consistently yielded higher BSFC compared to conventional diesel fuel. Achieving the same power output as diesel fuel required additional fuel pumped from the fuel pump, worsening BSFC. This conclusion coincides with the findings of studies [7, 31].

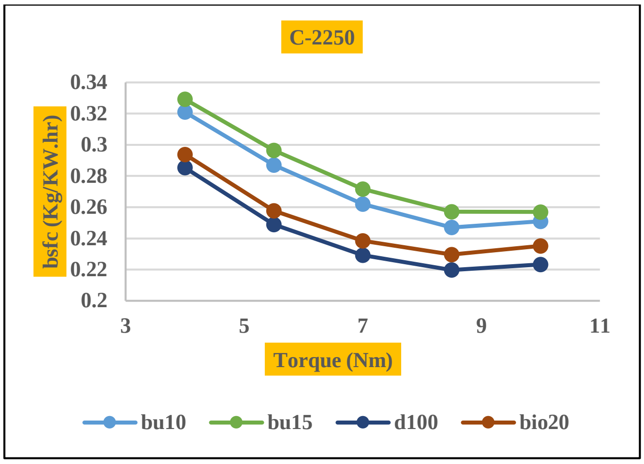

Figure 6. Variation of brake specific fuel consumption (BSFC) depending on engine loads

3.3 Exhaust gas temperature (EGT)

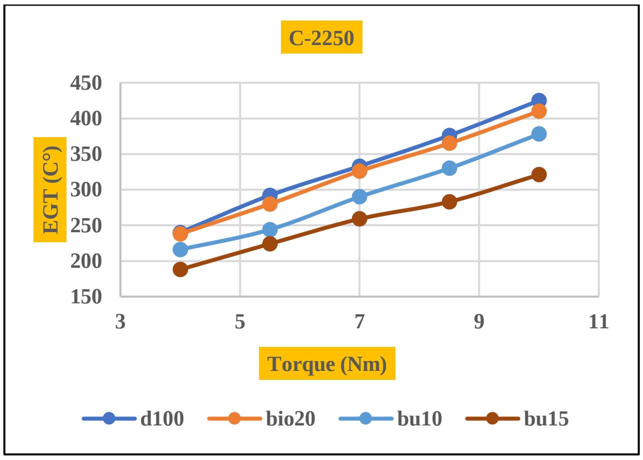

Figure 7. Variation of exhaust gas temperature (EGT) depending on engine loads

The combustion process's effectiveness is mirrored by a CI engine's exhaust gas temperature (EGT). Information about this temperature indicates how well the combustion process is going [32]. EGT rose linearly as engine load increased. Injected fuel quantity increased with engine load increase, which elevated the combustion temperatures inside the chamber with all fuels tested. This is also was reported by reference [33]. At 2250 rpm, Figure 7 displays the EGT for different fuel blends (D80B10BU10, D70B15BU15, and D80B20). On average, for variable engine loads there was a decrease in EGT by 12.5%, 23.5%, and 2.9%, respectively, compared to diesel. The combustion of diesel fuel generates more heat than other fuels due to its high EGT. As fuel combustion continues, more heat is released until the process is complete. In comparison, incorporating alcohol into diesel fuel decreases EGT, likely due to the lower fuel blend energy content and the cooling effect caused by the higher latent heat of evaporation of the alcohol blends. This finding is consistent with the results reported in study [34].

4. EXHAUST EMISSIONS

4.1 Carbon monoxide (CO)

Surprising as it may be, carbon monoxide lacks any discernible physical properties. The toxic nature of CO is notorious, and its effects on human health are overwhelmingly negative [35]. Even a small quantity of CO can contribute to feelings of breathlessness and headaches [36]. The expression of lost chemical energy, carbon monoxide (CO), plays a major role in exhaust gases. An exhaust's carbon monoxide (CO) composition highlights incomplete combustion resulting from insufficient oxygen. Successful prevention of carbon monoxide (CO) production depends on maintaining optimal levels of oxygen in the environment [37].

At 2250 rpm, the CO emission differences for fuels D80B10BU10, D70B15BU15, and D80B20 were displayed in Figure 8. The amounts varied according to the engine load. On average, CO dropped by 22.00%, 46.0%, and 14.4% compared to diesel fuels at various engine loads. In the figure, a noticeable trend is the rise of CO emissions with an increase in load due to a decrease in air/fuel ratio with increasing fuel injected in the combustion chamber quantity. Additionally, incorporating blends containing biodiesel and alcohol exhibits inversely proportional to CO emissions. More oxygen content in the biodiesel and alcohol composition makes these fuels have better emission characteristics than regular diesel [38]. Biodiesel has less carbon and more oxygen, so combustion products get the right amount of air for neutral burning. The injection starts earlier and a longer combustion duration is caused by the decreased compressibility and increased cetane number of biodiesels. This, in turn, effectively reduces CO. Additionally, the short ignition delay due to the higher cetane number contributes to shorter combustion duration and wider complete combustion reaction regions. Corresponding with studies [39-41], this outcome is achieved.

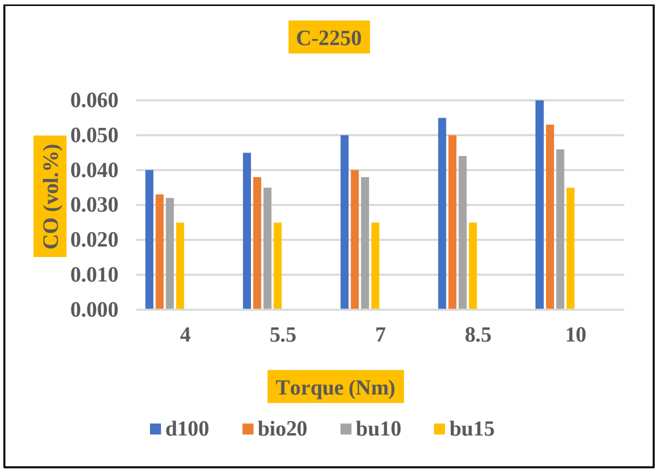

Figure 8. Carbon monoxide graphic according to engine load

4.2 Carbon dioxide (CO_2)

Greenhouse effects caused by CO_2 emissions make it the foremost cause of global warming worldwide. This leads to significant public health issues and even ozone creation [42]. A vital factor that can help determine the completeness of combustion in a diesel engine cylinder is observing the CO_2 emissions. Generally, more oxygen molecules in the cylinder can increase the possibility of complete combustion generation. At 2250 rpm, Figure 9 details the varied levels of CO_2 levels exemplified in D80B10BU10, D70B15BU15, and D80B20 fuel blends. Compared to diesel fuels, carbon dioxide emissions increased by approximately 16.67%, 41.36%, and 11.73% on average, based solely on differing engine loads.

Additionally, every fuel blend experienced a concurrent increase in CO_2 emissions when engine loads increased. Complete combustion led to binary and ternary blends surpassing diesel fuel in CO_2 emissions resulting from their structures containing excess oxygen. The evaporation of fuel would be improved with the lower density and kinematic viscosity of the ternary blends, leading to a consistent increase in CO_2 emissions. This is consistent with study [43], as per study [14].

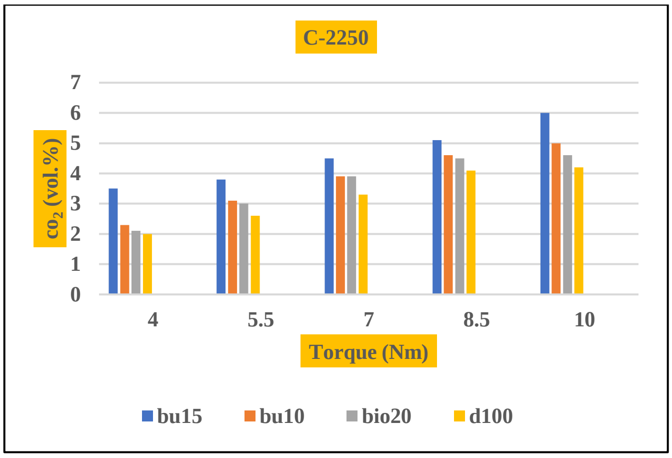

Figure 9. Carbon dioxide (CO_2) graphic according to engine load

4.3 Unburned hydrocarbon (UHC)

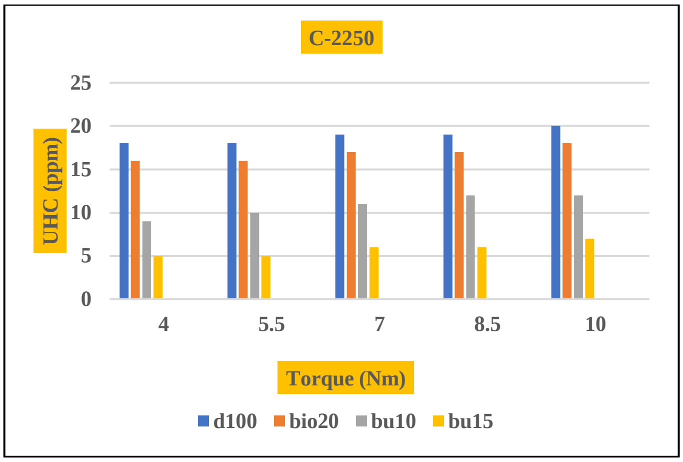

Figure 10. Variation of Unburned hydrocarbons (UHC) depending on engine loads

Incomplete combustion within the combustion chamber from a blend of air and fuel is what generates hydrocarbon emissions. The major cause for this is the sluggish speed of combustion, which leads to an insufficient burn. In diesel engines, lower-quality combustion results in more unburnt HC emissions [44]. Figure 10 contains an intriguing display of emission results for various biodiesel and alcohol blends in diesel fuel, with varying loads and stable engine speeds. While running at 2250 rpm, D80B10BU10, D70B15BU15, and D80B20 noticeably reduced Unburned hydrocarbons (UHC), with averagely decreased values of 42.55%, 69.11%, and 10.64%, respectively, in comparison to diesel fuel, in accordance to engine loads.

Interestingly, when incorporating biodiesel and alcohol mixtures into diesel fuel blends, there were corresponding decreases in exhaust UHC levels as the amount of biodiesel and alcohol mixtures increased, compared to diesel fuel. Complete combustion was possible due to the higher oxygen content of biodiesel and alcohol mixtures in the combustion region, resulting in lower UHC emissions compared to diesel fuel. Increased unburned hydrocarbon (UHC) emissions were caused by diesel fuel's lack of oxygen in the combustion zone. Concerning the fuel mixture, the cetane number and oxygen content are elevated due to the inclusion of biodiesel. Such elevation entails a decrease in UHC emission and an increase in combustion efficiency. Moreover, complete fuel conversion is facilitated by the shorter combustion duration. This conclusion is in concordance with studies [45, 46].

4.4 Nitrogen oxide (NO_x)

The environment and people's respiratory systems are negatively affected by NO_x emissions, making it an issue that must be addressed. Reduction and minimization practices are necessary. Several variables impact NO_x emissions, including the engine cylinder temperature, fuel viscosity, density, CN, oxygen content, and heat of evaporation, as detailed by the source [47]. In Figure 11, we can observe the NO_x emission variation in diesel fuel blends with alcohol and biodiesel in various load and constant speed scenarios, including D80B10BU10 and D70B15BU15, as well as D80B20 at 2250rpm. Unlike diesel fuels, NO_x emissions witnessed a notable decrease of 3.8% and 24.9% on average, except D80B20.

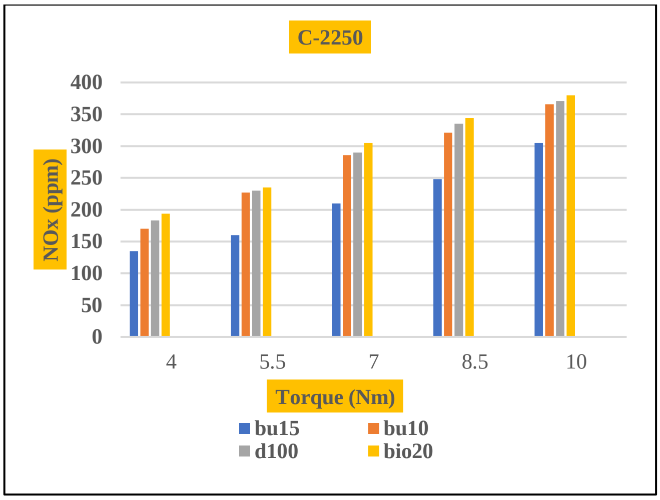

Figure 11. Variation of Nitrogen of Oxides (NO_x) depending on engine loads

Interestingly, when engine loads were considered, the NO_x increased by 3.5% on D80B20. For all fuel types tested, it was noted that NO_x emissions rise as engine load increases. This is because more fuel gets burned, resulting in a slightly higher temperature. Additionally, NO_x emissions from biodiesel fuel are higher than diesel fuel emissions. This is due to biodiesel's higher cetane number, viscosity, and oxygen content. According to test outcomes, the addition of an alcoholic element to blends leads to a reduction in NO_x emissions as the proportion of alcohol in ternary blends increases. Since alcohols have a low cetane number and a high latent heat of vaporization, they have a cooling effect during burning by reducing the flame's temperature. This conclusion is supported by the studies [7, 14, 48, 49].

5. CONCLUSION

As part of this study, butanol will be incorporated into a blend of diesel and biodiesel that is derived from waste cooking oil. The operation and emissions of a single-cylinder, direct injection diesel engine was examined. Based on the data in this study, the following conclusions can be drawn:

1. The combination of WCO biodiesel with butanol can produce a fuel that does not separate into phases when it is blended with neat diesel. As a result, the fuel takes on different chemical and physical characteristics.

2. The combustion process is impacted by introducing biodiesel from waste cooking oil as well as butanol in traditional diesel, as can be inferred from the findings of these experiments.

3. The D80B20 blend boasts top-notch engine performance with the best engine power and engine brake thermal efficiency - making it the clear victor of blends.

4. When adding biodiesel to diesel fuel (D80B20), the NO_x emissions was increased by 3.5% compared to neat diesel. However, the ternary fuel blends (biodiesel-diesel-alcohols) NO_x levels were reduced by 3.8% and 24.9%. This is because of fuel density, ignition delay, and fuel aromatic content.

5. The HC concentrations were reduced by 42.55%, 69.11%, and 10.64%, compared to diesel. Butanol high oxygen content resulted in a significant reduction in HC emissions.

6. Biodiesel and diesel fuel blends, both binary and ternary, yield a noteworthy decrease in CO emissions by 22.00%, 46.0%, and 14.4% while CO_2 levels were increased by 16.67%, 41.36%, and 11.73% compared to diesel, respectively.

7. Break thermal efficiency (BTH) was shown to be lower for both binary (biodiesel-diesel) and ternary (biodiesel-diesel-alcohols) fuel mixes when compared to fossil diesel fuel D100.

Future experiments can be conducted to determine the effects of injecting different types of fuel at optimum injection timings for each blend on engine performance and pollution.

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