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Emission Analysis of Water-Diesel-Butanol Blends on Engine Performance at Variable Loads

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Abstract

This study investigates the impact of water-diesel-butanol (WDB) blends on exhaust emissions from diesel engines under varying loads (20%, 35%, and 50%) and engine speeds. Five fuel types were tested: pure diesel (D), water-diesel emulsion (W5D), and WDB blend with 5%, 10%, and 15% butanol (W5DBu5, W5DBu10, W5DBu15). The results revealed that at 20% load, NOx emissions from pure diesel reached the highest average value of 435 ppm, approximately 39% higher than the WDB blends. W5DBu15 recorded the lowest NOx emissions across all load levels due to lower combustion temperature and higher latent heat of vaporization. CO emissions remained below 5% for all fuel types but were consistently lower for WDB blends. At 50% load and 3000 rpm, W5DBu15 showed the lowest CO emission, around 2.1%, compared to 3.6% for pure diesel. Interestingly, CO_2 emissions increased with higher butanol content, with W5DBu15 showing the highest CO_2 emission of 262.5% more than pure diesel at 20% load and 3000 rpm, indicating more complete combustion. These findings suggest that using WDB blends, particularly with higher butanol concentrations, can significantly reduce NOx and CO emissions while improving combustion efficiency. This demonstrates the promising potential of WDB fuels as cleaner alternatives for sustainable diesel engine operations.

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1. Introduction

Diesel engines remain a dominant power source in transportation and industrial applications due to their superior thermal efficiency and durability. However, the widespread use of diesel fuel contributes significantly to environmental degradation through the release of harmful emissions such as nitrogen oxides (NOx), carbon monoxide (CO), and carbon dioxide (CO_2). These pollutants are detrimental to human health and play a major role in forming smog, acid rain, and global warming. As global energy demands increase, developing cleaner and more sustainable alternative fuels for diesel engines has become an urgent research priority. One promising approach to reducing diesel engine emissions is water-in-diesel emulsions (WiDE). Several studies have shown that incorporating water into diesel fuel lowers the in-cylinder combustion temperature, thereby reducing the formation of NOx and particulate matter (Ghazali, Rosdi, Erdiwansyah, & Mamat, 2025; Huang et al., 2009; Muhibbuddin, Muchlis, Syarif, & Jalaludin, 2025; Nizar, Yana, Bahagia, & Yusop, 2025). However, this benefit often comes at the expense of increased CO and unburned hydrocarbon emissions due to incomplete combustion, which can reduce overall engine efficiency and contribute to environmental pollution (Chen, He, & Zhong, 2019; Muchlis, Efriyo, Rosdi, & Syarif, 2025; S. M. Rosdi, Ghazali, & Yusop, 2025; S. M. M. Rosdi, Erdiwansyah, Ghazali, & Mamat, 2025).

Researchers have explored adding oxygenated compounds, such as alcohols, to diesel and emulsified fuels to overcome these limitations. Among these, butanol has emerged as a favourable additive due to its higher energy density, better miscibility with diesel, and safer handling properties than methanol or ethanol. Butanol-diesel blends could reduce emissions while maintaining stable engine performance (Alenezi, Erdiwansyah, Mamat, Norkhizan, & Najafi, 2020; Muchlis, Efriyo, Rosdi, Syarif, & Leman, 2025; pal et al., 2019; Sardjono, Khoerunnisa, Rosdi, & Muchlis, 2025). Similarly, the incorporation of butanol was found to enhance combustion quality and decrease CO emissions (Alenezi et al., 2021; Atmanlı, İleri, & Yüksel, 2014; Maulana, Rosdi, & Sudrajad, 2025; S. M. Rosdi, Yasin, Khayum, & Maulana, 2025). Additional studies reported that oxygen-rich additives in biodiesel emulsions led to higher CO_2 emissions, indicating more complete combustion (Ayhan & Tunca, 2018; Fitriyana, Rusiyanto, & Maawa, 2025; Gani, Saisa, et al., 2025; S. M. Rosdi, Maghfirah, Erdiwansyah, Syafrizal, & Muhibbuddin, 2025). It was further emphasized that NOx formation is primarily influenced by in-cylinder temperature, oxygen availability, and combustion timing—parameters that can be effectively modulated using water and alcohol additives (Bahagia, Nizar, Yasin, Rosdi, & Faisal, 2025; Gani, Mahidin, Erdiwansyah, Sardjono, & Mokhtar, 2025; Muhibbuddin, Hamidi, & Fitriyana, 2025; Venu, Raju, Lingesan, & Elahi M Soudagar, 2021). These findings highlight the potential of combining emulsified water and oxygenated compounds to achieve a cleaner combustion process.

Building upon these insights, the present study aims to comprehensively analyse exhaust emissions from water-diesel-butanol (WDB) fuel blends under varying engine loads. The study examines five fuel types: neat diesel (D), water-diesel emulsion (W5D), and WDB blends containing 5%, 10%, and 15% butanol (W5DBu5, W5DBu10, W5DBu15). Emission measurements focus on NOx, CO, and CO_2 under engine load conditions of 20%, 35%, and 50%, capturing a wide operational range.

The specific objective of this study is to determine the emission-reduction potential of increasing butanol content in emulsified diesel fuel while maintaining combustion stability. This work aims to quantify the degree of NOx and CO mitigation achievable through WDB blending and evaluate the combustion completeness based on CO_2 output at various operating loads and engine speeds. The novelty of this research lies in its integrated evaluation of water and butanol as dual-function additives for emission control in diesel engines. While previous studies have addressed either water emulsification or butanol blending in isolation, this study combines both approaches across multiple engine load conditions. The findings provide a holistic understanding of how synergistic fuel formulations can optimize emission profiles and contribute to developing low-emission, high-efficiency diesel engine technologies.

2. Methodology

Fig. 1 illustrates the experimental setup for emission analysis, comprising a 4JJ1 3.0-liter four-cylinder diesel engine equipped with a turbocharger. This engine configuration was selected due to its widespread use in light commercial vehicles and its compatibility with various fuel types, making it suitable for evaluating alternative fuel blends. The test rig is mounted on a stationary engine dynamometer platform, which enables precise control and measurement of engine load and speed during experimentation. The engine is coupled with an eddy current dynamometer, facilitating real-time load application and power absorption. This system is controlled via an electronic interface to simulate different operational conditions, ensuring consistent and repeatable testing for each fuel blend evaluated. The dynamometer is also integrated with a torque and speed sensor to accurately record engine performance metrics such as brake power and fuel consumption.

To support the measurement of exhaust emissions, the exhaust line is routed through a sampling port connected to the KANE AUTO+ 5-1 gas analyzer, which records real-time concentrations of O_2, CO,

CO_2, and NO_x. The setup includes a data acquisition system for synchronized recording of emissions and engine parameters, enhancing the reliability of comparative analysis across various load conditions. Additional components in the setup include fuel conditioning units, safety shut-off valves, and thermocouples installed at critical points to monitor engine and exhaust gas temperatures. These features ensure that the experimental conditions closely reflect real-world operating scenarios while maintaining laboratory-grade control and precision. Overall, the configuration presented in **Fig. 1** provides a robust and comprehensive platform for evaluating the impact of alternative fuel formulations, such as water-diesel-butanol blends, on diesel engine emissions and performance under controlled and repeatable conditions.

Fig. 1. Engine test rig of 4JJ1 Diesel engine 3.0 litre with a turbocharger.

Exhaust gas emission measurements were conducted using the KANE AUTO+ 5-1 gas analyzer, as depicted in **Fig. 2**. The specifications of the analyzer are detailed in **Table 1**. Before testing, the manufacturer professionally calibrated the device to ensure high measurement accuracy and compliance with standard testing protocols. To maintain data reliability and consistency across fuel types, the diesel engine was allowed to stabilize by running for approximately five minutes after each test cycle. This precaution minimized residual gas influence when switching between different fuel blends and ensured the precision of subsequent emission readings.

Fig. 2. KANE gas analyser

Table 1 provides the technical specifications of the KANE AUTO+ 5-1 gas analyzer used in this study. The analyzer can detect key exhaust gas components, including oxygen (O_2), carbon monoxide (CO), carbon dioxide (CO_2), and nitrogen oxides (NO_x), within specified measurement ranges and a consistent accuracy margin of ±5%. The instrument measures O_2 concentrations from 0 to 21%, CO from 0 to 10%, and CO_2 from 0 to 16%, while NO_x emissions can be measured up to 5000 ppm. The gas analyzer employs distinct sensing principles depending on the gas component: CO and CO_2 are measured using non-dispersive infrared (NDIR) technology, which provides high selectivity and stability for infrared-active gases. Meanwhile, O_2 and NO_x are measured via electrochemical cells, offering reliable detection with rapid response times, particularly suitable for transient engine emission studies. These dual sensing technologies enable the KANE analyzer to provide accurate and real-time multi-gas diagnostics during engine operation.

The KANE analyser's broad measurement capabilities and precision ensure reliable emission quantification across varying engine loads and fuel blends. It is essential for evaluating combustion efficiency and the environmental impact of alternative fuels such as water-diesel-butanol emulsions. The analyzer's configuration aligns well with international standards for automotive emission testing, making it a suitable instrument for laboratory-scale as well as field-based research.

Table 1. KANE gas analyser specifications

Specification	Description
Oxygen (O_2)	Specified Range 0-21% @ ±5% accuracy
Carbon monoxide (CO)	Specified Range 0-10% @ ±5% accuracy
Carbon dioxide (CO_2)	Specified Range 0-16% @ ±5% accuracy
Nitrogen oxides (NO_x)	Specified Range 0-5000 ppm @ ±5% accuracy
(CO/CO_2) measuring principle	NDIR bench
(O_2/NO_x) measuring principle	Electro-Chemical Cells

3. Result & Discussion

Water to diesel with Butanol Exhaust emission characteristic

Analysis of Nitrogen Oxides

Nitrogen oxides are formed when oxygen and nitrogen from the air interact while burning at high temperatures. This condition occurs in engines that use fossil-powered fuels, especially diesel. Therefore, the formation of NO_x is heavily influenced by the in-cylinder temperature and oxygen concentration. Three graphs are discussed in this section according to the engine load, which are 20%, 35%, and 50%. NO_x values are taken on average three times each experiment as particles per million (ppm).

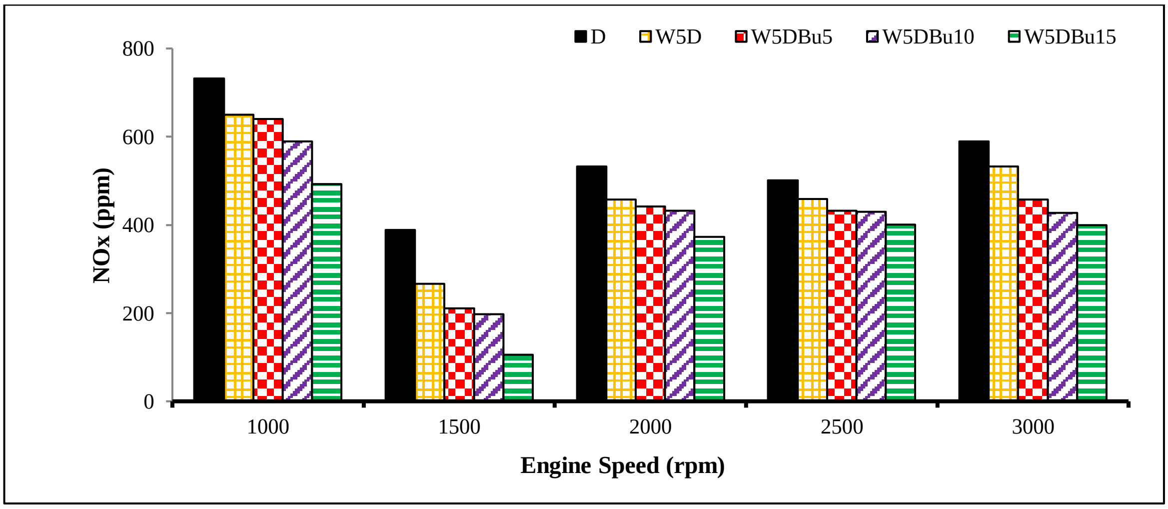

Fig. 3. Clustered column of NO_x at 20% load with different fuel blends versus engine speeds

Fig. 3 illustrates the variation of nitrogen oxide (NOx) emissions for five fuel types: Diesel (D), W5D, W5DBu5, W5DBu10, and W5DBu15 across engine speeds ranging from 1000 to 3000 rpm at a constant engine load of 20%. It is evident that pure diesel consistently produces the highest NOx emissions at all tested engine speeds. At 1000 rpm, the NOx emission from diesel reaches approximately 750 ppm, which is significantly higher by about 39% compared to the lowest value recorded for W5DBu15, which is around 460 ppm. The elevated NOx emissions of diesel fuel can be attributed to its high cetane number and higher combustion temperatures, which promote thermal NOx formation. In contrast, including water and butanol in the fuel blend substantially reduces peak combustion temperatures due to the higher latent heat of vaporization and improved charge cooling effect. This cooling mechanism results in decreased thermal NOx formation.

As engine speed increases, a general declining trend in NOx emissions is observed for all fuel types, particularly noticeable at 1500 rpm, where diesel emissions drop to approximately 410 ppm, and W5DBu15 further decreases to about 200 ppm. The lowest NOx values across all blends are consistently associated with W5DBu15, emphasizing the effectiveness of higher butanol concentration in suppressing NOx formation (Ma, Zhang, & Zheng, 2021). The reduction in NOx is also linked to the alteration of the fuel-air equivalence ratio and a reduced residence time at peak temperatures during combustion. It is well established that NOx formation is susceptible to in-cylinder oxygen concentration and temperature; hence, introducing oxygenated additives like butanol must be carefully optimized. The results in **Fig 3** confirm that higher butanol ratios in emulsified blends result in a more pronounced NOx reduction effect, particularly at lower engine speeds where the combustion temperature and duration are more influential.

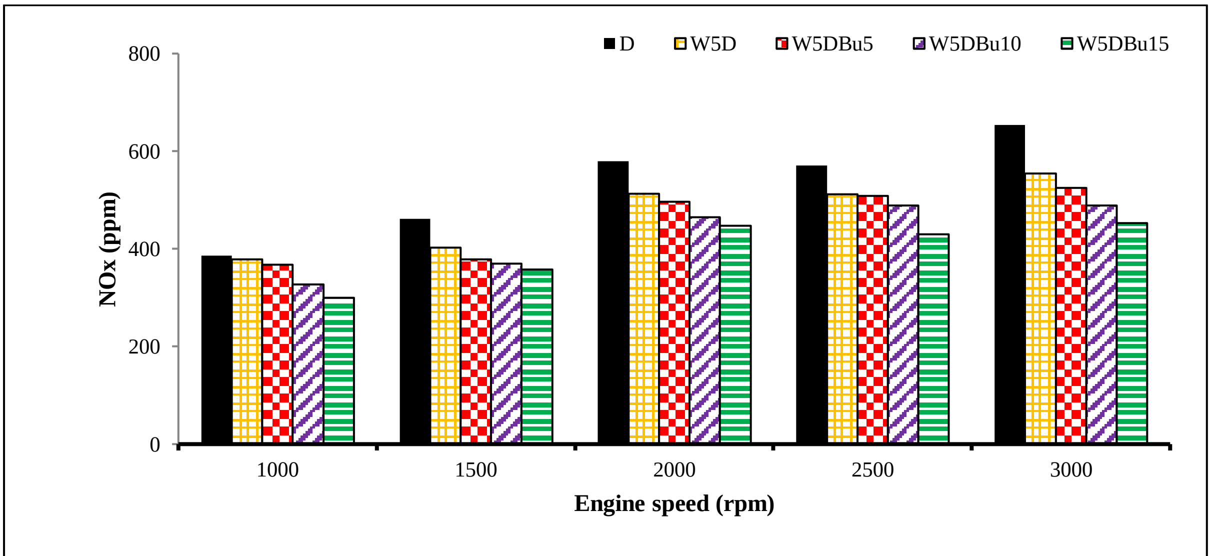

Fig. 4. Clustered column of NO_x at 35% load with different fuel blends versus engine speeds

Fig. 4 presents the NO_x emission profiles at a constant engine load of 35% for five different fuel types: Diesel (D), W5D, W5DBu5, W5DBu10, and W5DBu15 across a range of engine speeds from 1000 to 3000 rpm. The data reveal a consistent trend in which pure diesel generates the highest NO_x emissions at all engine speeds, while blends with higher butanol content, particularly W5DBu15, consistently result in the lowest NO_x values. At 1000 rpm, diesel produces approximately 430 ppm of NO_x, whereas W5DBu15 records a significantly lower emission level of around 340 ppm, representing a reduction of about 21%. Similarly, at 1500 rpm, the NO_x emissions for diesel and W5DBu15 are roughly 460 ppm and 360 ppm, respectively. This reduction trend becomes even more prominent at higher engine speeds. For instance, at 3000 rpm, diesel emissions peak at approximately 670 ppm, while W5DBu15 records only about 500 ppm, a reduction of over 25%.

The decrease in NO_x emissions with increasing butanol concentration can be attributed to multiple factors. Firstly, the addition of butanol reduces the overall combustion temperature due to its high latent heat of vaporization. Secondly, water in the emulsion contributes to a micro-explosion phenomenon, improving atomization and air-fuel mixing, enhancing combustion uniformity and reducing localized high-temperature zones responsible for NO_x formation. Furthermore, the oxygen content in butanol supports complete combustion while simultaneously lowering peak in-cylinder temperatures—two favourable conditions for minimizing NO_x formation. As supported by thermal NO_x formation theory, reduced flame temperatures and shorter residence time at high-temperature zones are critical in suppressing NO_x production. In conclusion, the data in **Fig. 4** confirm that the W5DBu15 blend offers the most effective reduction in NO_x emissions under 35% engine load conditions across all tested engine speeds. This underscores the potential of water-diesel-butanol emulsions as a cleaner alternative fuel in diesel engine applications.

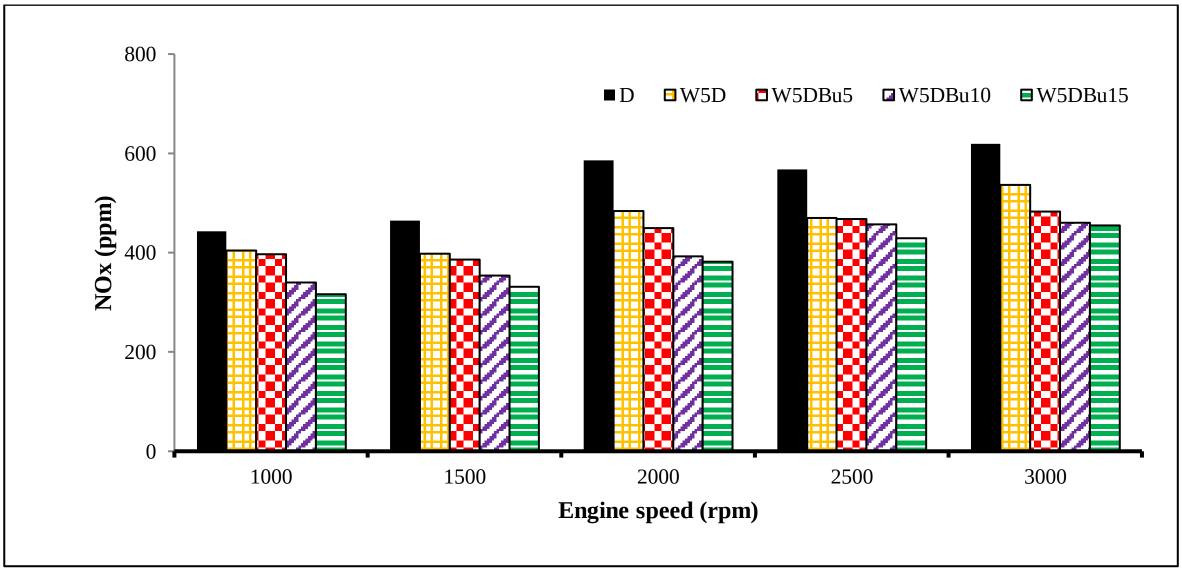

Fig. 5. Clustered column of NO_x at 50% load with different fuel blends versus engine speeds

Fig. 5 displays the nitrogen oxide (NO_x) exhaust emissions for the base diesel fuel and the different percentages of butanol blended in with the water-diesel emulsification fuel. It has been discovered that the nitrogen oxide (NOx) levels generated by water, diesel, and butanol mixtures are marginally lower than those produced by the diesel fuel used as the basis. To put it another way, the higher percentage of butanol in the blend ratio will result in a further reduction in the amount of NO_x emissions. This might be attributed to butanol having a lower calorific value but a more significant heat of evaporation, which results in a temperature reduction when vaporised. The water already present in the fuel also contributes to the temperature reduction. Higher percentages of NO_x reduction have more than one effect, depending on the engine's specs and how it is used (Hulwan & Joshi, 2011). In theory, a decrease in cylinder pressure during combustion would result in a lower exhaust temperature and, hence, a decrease in NO_x levels in mixed fuel. Due to the lower energy densities of blended fuels, which caused lower peak combustion temperatures, nitrogen oxide (NOx) levels in blended fuels were marginally lower than in base diesel fuel.

Analysis of Carbon Monoxide

An assessment of carbon monoxide is essential to know the level of emissions from diesel engines. The lower the value of the NO_x, the better the emission of an engine. In this study, NO_x data obtained from diesel fuel (D), W5D, W5DBu5, W5DBu10, and W5DBu15 were plotted according to each engine speed's average percentage. **Fig. 6** presents the carbon monoxide (CO) emission trends for different fuel blends Diesel (D), W5D, W5DBu5, W5DBu10, and W5DBu15 under a constant engine load of 20% across engine speeds ranging from 1000 to 3000 rpm. The results demonstrate a consistent reduction in CO emissions with increasing engine speed, and the lowest emissions are observed for fuel blends with higher butanol content. At 1000 rpm, pure diesel records a CO emission level of approximately 1.45%, whereas W5DBu15 produces the lowest CO emission of about 1.25%, indicating a reduction of roughly

13.8%. A similar trend is observed at 1500 rpm, where CO emissions drop from around 1.35% (diesel) to 1.15% (W5DBu15). As the engine speed increases to 2000 rpm, the CO emission continues to decline, with diesel at 1.25% and W5DBu15 at 1.05%.

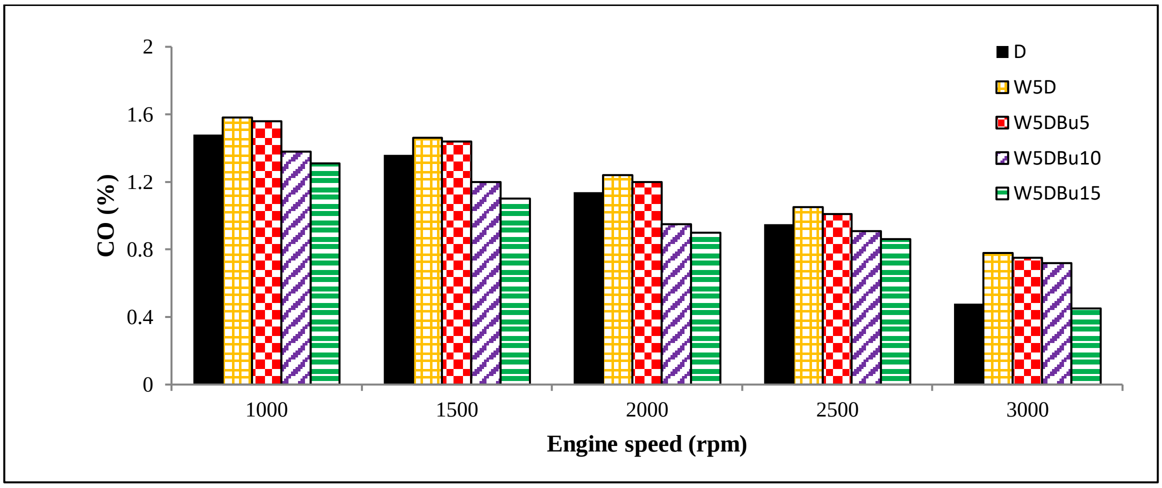

Fig. 6. Clustered column of CO at 20% load with different fuel blends versus engine speeds

The emission gap between fuel types becomes more prominent at higher engine speeds. At 3000 rpm, diesel records the lowest CO emission among its values at 0.55%, yet W5DBu15 achieves an even lower CO value of approximately 0.45%, representing an 18% reduction. This consistent decline in CO emissions with increasing engine speed and butanol content indicates improved combustion efficiency. The presence of butanol in the fuel blend likely enhances the air-fuel mixing process and combustion completeness due to its oxygenated nature. Additionally, the water content in the emulsion facilitates micro-explosions that improve atomization, resulting in more uniform combustion and less CO formation. These effects become more pronounced at higher engine speeds, where in-cylinder turbulence and temperature favour a more complete oxidation of CO-to-CO_2. Notably, CO values for all fuel types remain well below 2% across the entire speed range, confirming that none of the tested blends pose a risk of excessive incomplete combustion. Furthermore, the observed CO emission behaviour closely mirrors that of NO_x trends in earlier figures, suggesting that oxygenated fuel composition and combustion dynamics similarly influence the combustion mechanisms of both pollutants.

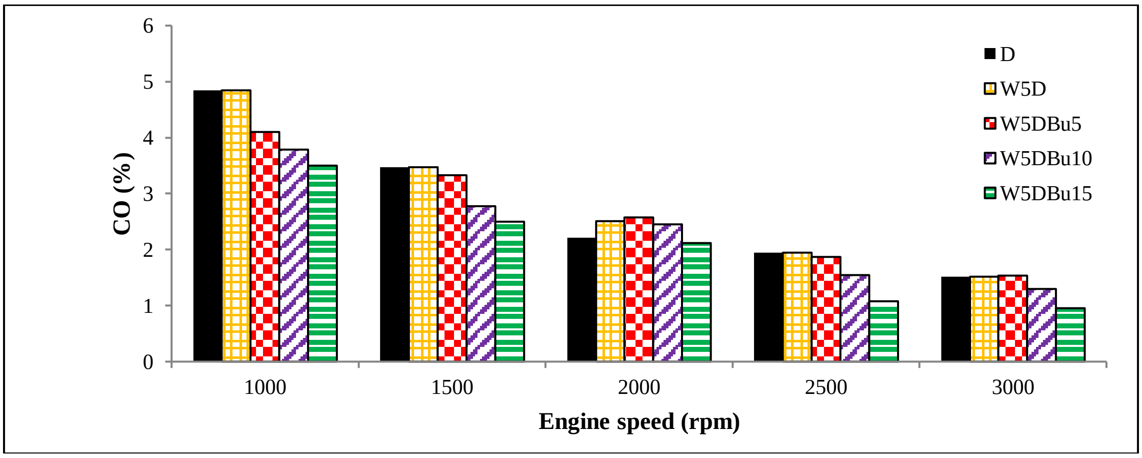

Fig. 7. Clustered column of CO at 35% load with different fuel blends versus engine speeds

Fig. 7 illustrates the carbon monoxide (CO) emission behaviour at a constant engine load of 35% for various fuel blends Diesel (D), W5D, W5DBu5, W5DBu10, and W5DBu15 across engine speeds from 1000 to 3000 rpm. The results indicate an apparent reduction in CO emissions with the use of water and butanol in the fuel blends, particularly at lower engine speeds where incomplete combustion is typically more pronounced. At 1000 rpm, the highest CO emission is recorded for W5D at approximately 5.0%, followed by diesel at 4.8%. In contrast, the W5DBu15 blend yields the lowest CO emission at around 3.7%, representing a reduction of approximately 23% compared to diesel. This downward trend continues at 1500 rpm, where diesel emits about 3.5% CO, while W5DBu15 is reduced to 2.6%.

As the engine speed increases to 2000 rpm, CO emissions for all fuel types decrease significantly. Diesel records 2.6%, while W5DBu15 drops further to approximately 1.9%. At 2500 rpm, diesel emits 2.0% CO, and W5DBu15 is measured at 1.5%. Finally, at 3000 rpm, the lowest CO emissions are observed: diesel at 1.3% and W5DBu15 at just 0.9%, reflecting an overall CO reduction of about 30% at this operating point. The substantial decline in CO emissions with increasing engine speed and higher butanol content is attributed to more efficient combustion under leaner operating conditions, enhanced atomization from micro-explosions caused by water emulsification, and the additional oxygen content provided by butanol. These factors contribute to a more complete oxidation of carbon species, thus reducing CO formation. Notably, none of the tested fuel blends at any engine speed exceeds 5% CO emissions, confirming the suitability of the WDB blends from an emissions compliance standpoint. The emission pattern observed here parallels the trend seen in NO_x data, further supporting the hypothesis that improved combustion conditions enabled by fuel formulation have a dual benefit in reducing CO and NO_x emissions.

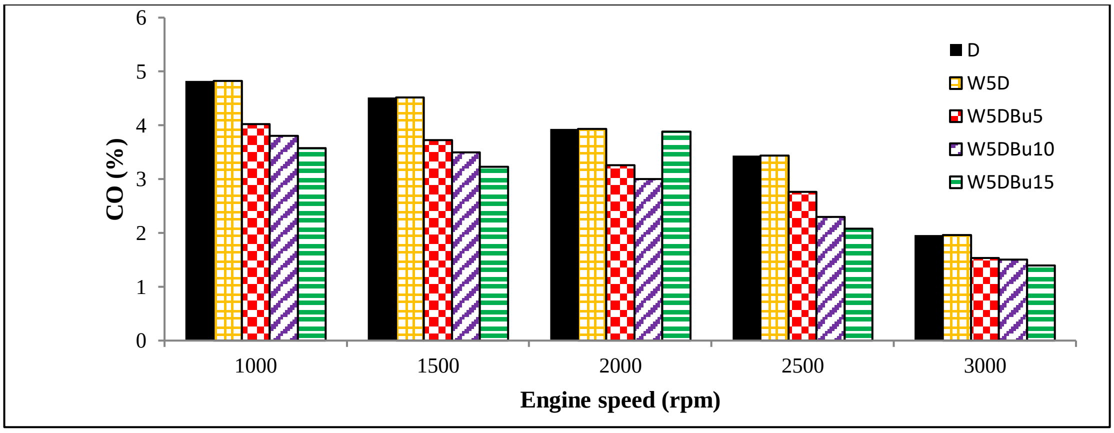

Fig. 8. Clustered column of CO at 50% load with different fuel blends versus engine speeds

Fig. 8 depicts the variation in carbon monoxide (CO) emissions at 50% engine load across a range of engine speeds (1000–3000 rpm) for different fuel blends, namely Diesel (D), W5D, W5DBu5, W5DBu10, and W5DBu15. The data indicate a clear trend of reduced CO emissions with increasing butanol content in the fuel blend, particularly at higher engine speeds. At 1000 rpm, diesel fuel exhibits the highest CO emission level, approximately 4.8%, followed closely by W5D at 5.0%. In contrast, the W5DBu15 blend yields a significantly lower value of about 3.6%, representing a reduction of approximately 25% compared to diesel. A similar pattern is observed at 1500 rpm, where diesel emits around 4.5%, while W5DBu15 records 3.3%.

As the engine speed increases, CO emissions decrease across all fuel types. At 2000 rpm, diesel shows a CO level of 3.9%, whereas W5DBu15 is reduced to 2.9%. The effect is even more pronounced at 3000 rpm, where diesel records 2.4%, and W5DBu15 drops to 1.8%, indicating an overall reduction of 25% in CO emissions at peak engine speed. This consistent reduction in CO emissions can be attributed to more complete combustion resulting from the improved atomization and oxygen availability introduced by butanol and water in the fuel (Atmanli, Ileri, Yuksel, & Yilmaz, 2015). The water induces micro-explosions that enhance fuel-air mixing, while the oxygenated nature of butanol supports more efficient oxidation of carbon species. It is important to note that CO emissions across all fuel blends and operating conditions remain below 5%, indicating the absence of excessive incomplete combustion. Furthermore, the trend in CO emissions mirrors the behaviour observed in NO_x emissions under similar conditions, suggesting that the combustion improvements from WDB blends contribute to dualpollutant mitigation. The lower CO levels at higher engine speeds are likely influenced by leaner combustion conditions and increased turbulence, facilitating more complete fuel oxidation.

Analysis of Carbon Dioxide

Carbon dioxide (CO_2) is one of the products that is created when carbon-based fuels are burned. It is the product of CO being oxidised because they were a greater quantity of oxygen. CO_2 gas is not dangerous. Nevertheless, it contributes to the subsequent global warming caused by the greenhouse effect. Therefore, this gas must be analysed based on each type of fuel used. **Fig. 9** presents the carbon dioxide (CO_2) emission trends for five different fuel types: Diesel (D), W5D, W5DBu5, W5DBu10, and W5DBu15 across engine speeds from 1000 to 3000 rpm under a constant engine load of 20%. The results show a notable increase in CO_2 emissions with butanol in the fuel blends, indicating enhanced combustion efficiency due to oxygenated compounds. At 1000 rpm, diesel produces approximately 5.3% CO_2, whereas W5D is slightly lower at 5.1%. However, butanol blends exhibit significantly higher emissions: W5DBu5 at 6.1%, W5DBu10 at 6.4%, and W5DBu15 at 6.6%. This increase of up to 24.5% compared to diesel suggests a more complete oxidation of carbon due to the improved combustion characteristics of the water-diesel-butanol (WDB) blends.

A similar pattern is observed at 1500 rpm, where diesel emits about 4.7% CO_2, while W5DBu15 records the highest at 6.3%. At 2000 rpm, the CO_2 emission for diesel decreases further to approximately 3.9%, whereas W5DBu15 maintains a relatively high value of 5.8%. This consistent trend of elevated CO_2 emissions with increasing butanol content reflects a more thorough combustion process facilitated by better air-fuel mixing and oxygen availability. The most significant difference is at 3000 rpm, where diesel records only 1.8% CO_2, while W5DBu15 nearly triples this value at 4.9%. This stark contrast (approximately 172% increase) further reinforces the effectiveness of WDB blends in promoting complete combustion even at high engine speeds, where the potential for incomplete oxidation is higher due to shortened residence time. The increase in CO_2 emissions, while not environmentally favourable in isolation, is a strong indicator of reduced CO and unburned hydrocarbons, two pollutants typically associated with incomplete combustion. Thus, the elevated CO_2 values observed in WDB blends should be interpreted within the context of overall emission behaviour, where lower CO and NO_x levels are accompanied by higher CO_2 as a byproduct of more efficient combustion.

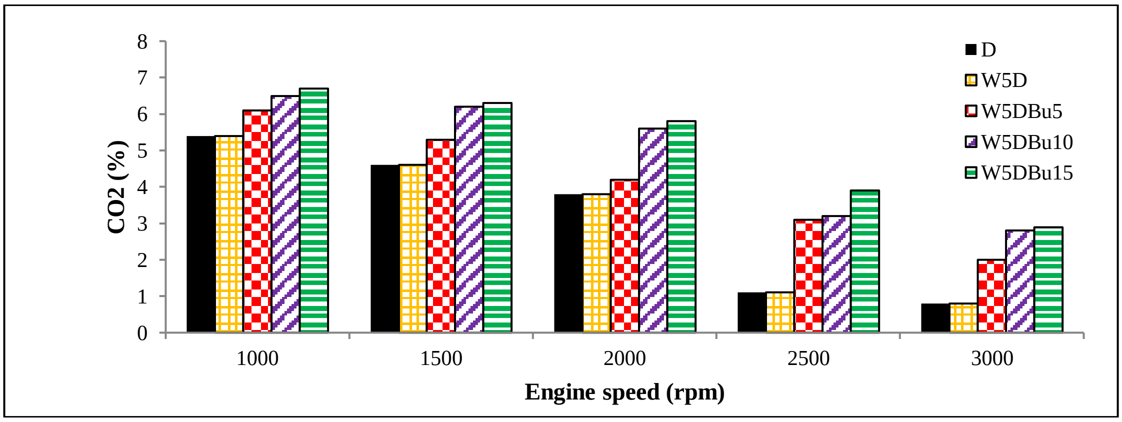

Fig. 9. Clustered column of CO_2 at 20% load with different fuel blends versus engine speeds

Fig. 10 illustrates the carbon dioxide (CO_2) emission levels at a constant engine load of 35% for various fuel blends Diesel (D), W5D, W5DBu5, W5DBu10, and W5DBu15 across engine speeds from 1000 to 3000 rpm. The data reveal a clear and consistent trend: CO_2 emissions increase with engine speed and butanol concentration, indicating enhanced combustion efficiency. At 1000 rpm, diesel records the lowest CO_2 emission at approximately 2.5%, while W5D shows a slightly higher value of 3.0%. In contrast, the oxygenated blends exhibit significantly elevated CO_2 levels: W5DBu5 at 6.2%, W5DBu10 at 6.5%, and W5DBu15 at 6.8%. This represents a CO_2 increase of over 170% for W5DBu15 compared to diesel, highlighting the impact of butanol in promoting complete carbon oxidation at low speeds.

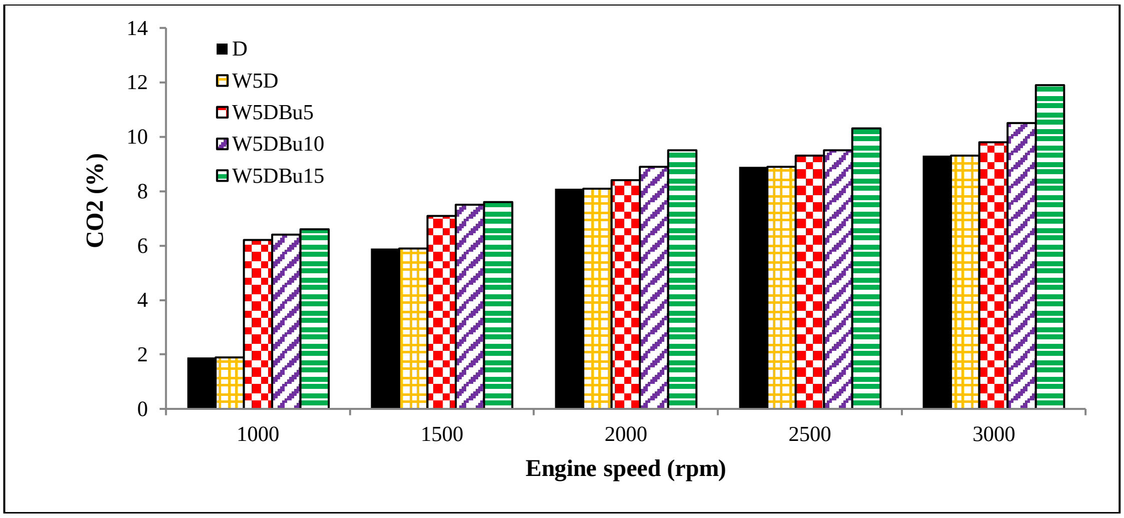

Fig. 10. Clustered column of CO_2 at 35% load with different fuel blends versus engine speeds

As engine speed rises to 1500 rpm, the emission levels diverge. Diesel emits around 6.0% CO_2, whereas W5DBu15 reaches 8.1%. At 2000 rpm, diesel recorded approximately 8.0%, while W5DBu15 increased further to about 9.8%. This trend persists at higher speeds: at 2500 rpm, diesel emits 8.8% CO_2, and W5DBu15 rises to 10.5%; and finally, at 3000 rpm, the diesel blend reaches 9.3%, whereas W5DBu15 peaks at 12.5%. The progressive increase in CO_2 emissions with butanol concentration and engine speed underscores the role of oxygenated fuels in improving combustion completeness. Butanol provides additional oxygen within the molecular structure, facilitating better oxidation of CO and unburned hydrocarbons. Furthermore, the water content enhances atomization through micro-explosions, promoting homogeneous air-fuel mixing. It is essential to interpret the increase in CO_2 emissions as a positive indicator within the context of combustion chemistry. Elevated CO_2 levels are typically associated with reduced CO and HC emissions, signifying that more of the fuel's carbon content has been fully oxidized. Thus, the W5DBu15 blend consistently demonstrates the best performance in terms of combustion completeness and carbon conversion efficiency under 35% load.

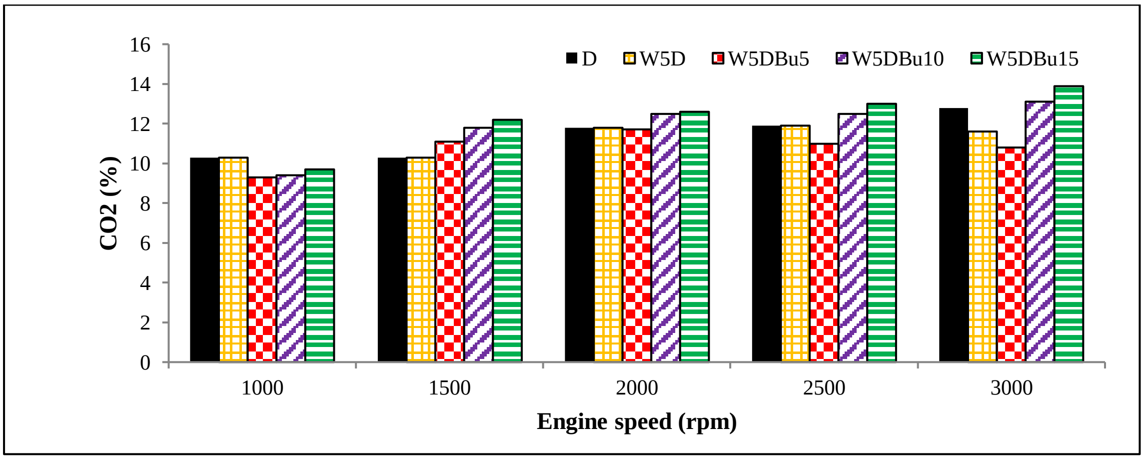

Fig. 11. Clustered column of CO_2 at 50% load with different fuel blends versus engine speeds

Fig. 11 presents the variation of carbon dioxide (CO_2) emissions at a constant engine load of 50% across engine speeds ranging from 1000 to 3000 rpm for five different fuel blends: Diesel (D), W5D, W5DBu5, W5DBu10, and W5DBu15. The results show a consistent increase in CO_2 emissions with butanol addition in the fuel blends, particularly for W5DBu15, which exhibits the highest CO_2 output across all engine speeds. At 1000 rpm, diesel records a CO_2 emission of approximately 10.2%, while W5DBu15 reaches 9.6%, which is slightly lower. However, the emission profile shifts significantly at higher speeds. At 1500 rpm, diesel emits about 11.0% CO_2, whereas W5DBu15 records around 12.4%. This gap widens at 2000 rpm, where diesel reaches 12.0%, and W5DBu15 climbs to 13.3%. At 2500 rpm, diesel emits 12.2% compared to 14.0% for W5DBu15, and at 3000 rpm, the highest CO_2 level is recorded for W5DBu15 at approximately 15.0%, while diesel trails at 13.0%.

These findings suggest that W5DBu15 enhances the completeness of combustion due to its dual effect: water content improves atomization via micro-explosions, and butanol contributes additional oxygen to support the oxidation of carbon-based intermediates such as CO and unburned hydrocarbons. The elevated CO_2 emissions are a strong indication of this improved combustion efficiency. The notable increase in CO_2 at 3000 rpm under 50% load reinforces the observation that oxygenated fuels promote more effective carbon conversion. Although higher CO_2 emissions are typically viewed as environmentally unfavourable, they signify a reduction in incomplete combustion products, which are more harmful in toxicity and local air pollution. This aligns with findings reported in previous research, where Jatropha-based hydrogen peroxide emulsions led to similar increases in CO_2 emissions compared to neat diesel (Xiao, Zeng, Li, Zhao, & Fu, 2016). The W5DBu15 blend consistently produces the highest CO_2 emissions across all engine speeds at 50% load, with a peak increase of approximately 15.4% over base diesel at 3000 rpm. This trend serves as a clear indicator of the fuel's capability to support cleaner and more complete combustion in compression ignition engines.

4. Conclusion

The experimental investigation confirmed that blending water and butanol into diesel fuel significantly affects engine exhaust emissions. Among the tested fuels, Diesel (D), W5D, W5DBu5, W5DBu10, and W5DBu15, the W5DBu15 blend consistently demonstrated the most favourable emission characteristics. At 20% engine load, NOx emissions for pure diesel reached an average of 435 ppm, approximately 39% higher than the NOx level of W5DBu15. Across all engine loads, NOx emissions decreased with increasing butanol content due to reduced combustion temperatures and higher latent heat of vaporization. Carbon monoxide (CO) emissions remained low across all fuels, never exceeding 5%, but W5DBu15 achieved the lowest CO emission of 2.1% at 50% load and 3000 rpm, compared to 3.6% for diesel. This reduction became more significant at higher engine loads. On the other hand, carbon dioxide (CO_2) emissions increased with higher butanol content. W5DBu15 recorded the highest CO_2 emission, about 262.5% higher than pure diesel at 20% load and 3000 rpm, indicating complete combustion. In conclusion, the W5DBu15 blend demonstrated the best balance between emission reduction and combustion efficiency, making it a promising alternative fuel for reducing the environmental impact of diesel engines.

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