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Performance Evaluation of Butanol-Water Diesel Emulsion in Turbocharged Diesel Engine at Variable Loads

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Abstract
This study investigates the performance characteristics of a turbocharged diesel engine using water-diesel emulsion fuel blended with various proportions of butanol. The fuels tested include pure diesel (D), 5% water emulsion diesel (W5D), and three blends with added butanol: W5DBu5, W5DBu10, and W5DBu15. Experiments were conducted using an Isuzu 4JJ1 common-rail turbocharged diesel engine at engine loads of 20%, 35%, and 50%, with speeds ranging from 1,000 to 3,000 rpm. Results show that brake power and torque varied significantly with butanol addition. At 50% load, the maximum brake power was observed at 3,000 rpm for all fuels, where W5DBu15 achieved a peak of 33.2 kW compared to 31.8 kW for pure diesel. Similarly, brake torque was highest at mid-range speeds (1,500–2,000 rpm), with W5DBu15 reaching 210 Nm, slightly below diesel's 218 Nm but notably higher than W5D at 193 Nm. Butanol addition improved brake thermal efficiency while reducing brake-specific fuel consumption, especially at moderate engine loads. The findings indicate that blending butanol with water-diesel emulsion enhances combustion efficiency due to higher oxygen content and specific heat of butanol. Thus, W5DBu10 and W5DBu15 demonstrate strong potential as alternative fuels, offering performance benefits without significant engine modifications.

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1. Introduction

The continuous depletion of fossil fuel resources and rising environmental concerns have intensified the search for alternative and sustainable energy sources. Diesel engines, widely used in transportation and power generation, contribute significantly to greenhouse gas emissions and air pollution due to their reliance on petroleum-based fuels. Researchers have explored various fuel alternatives and blending strategies to reduce emissions and improve engine performance while maintaining reliability. Among these strategies, water-diesel emulsion fuels have gained attention for their potential to reduce nitrogen oxides (NOx) and particulate matter emissions through micro-explosion phenomena during combustion. Adding water leads to secondary atomization, which enhances fuel-air mixing and combustion efficiency. However, water addition often reduces heating value and compromises engine performance, particularly in power and torque output (Ghazali, Rosdi, Erdiwansyah, & Mamat, 2025; Muhibbuddin, Hamidi, & Fitriyana, 2025; S. M. Rosdi, Maghfirah, Erdiwansyah, Syafrizal, & Muhibbuddin, 2025; Vellaiyan, 2020).

To overcome the limitations of water-diesel emulsions, researchers have investigated the incorporation of oxygenated additives such as alcohol. Butanol, a four-carbon alcohol, has shown promising characteristics, including higher energy content than ethanol, low volatility, and good miscibility with diesel and water. Butanol-diesel blends can improve combustion stability, increase brake thermal efficiency, and reduce soot formation, as indicated by several studies (Pranoto, Rusiyanto, & Fitriyana, 2025; Rakopoulos, Rakopoulos, Hountalas, Giakoumis, & Andritsakis, 2008; S. M. M. Rosdi, Erdiwansyah, Ghazali, & Mamat, 2025; Selvakumar, Maawa, & Rusiyanto, 2025). The synergistic effect of combining water-diesel emulsions with butanol has only recently begun to receive academic attention. Butanol's oxygen-rich nature compensates for the energy losses caused by water dilution in emulsions, resulting in better engine response (Alenezi et al., 2021; Nizar, Yana, Bahagia, & Yusop, 2025; S. M. Rosdi, Ghazali, & Yusop, 2025; Singh, Singh, & Kumar, 2020). However, detailed investigations into varying butanol concentrations under different engine loads and speeds remain limited.

This study aims to evaluate the performance characteristics of brake power, brake torque, brake-specific fuel consumption, and brake thermal efficiency of a turbocharged diesel engine using water-diesel emulsions with incremental additions of butanol (5%, 10%, and 15%). The experimental setup employs an Isuzu 4JJ1 common-rail engine, simulating practical driving conditions through variable loads and engine speeds. The specific objective of this study is to determine how increasing butanol concentrations in water-diesel emulsions affect engine output, especially under mid to high-load conditions. This includes identifying the optimal butanol ratio that offers the best trade-off between power enhancement and fuel economy without compromising engine stability.

The novelty of this research lies in its integrated approach to fuel blending, which leverages the benefits of water-emulsion combustion control with the energetic and oxygenated properties of butanol. Unlike previous studies focusing solely on alcohol-diesel blends or emulsified fuels, this paper provides comparative performance data across multiple load levels, offering practical insights for cleaner and more efficient diesel engine operation.

2. Methodology

Fig. 1 illustrates the engine test rig setup used for experimental investigations, featuring a 4JJ1 turbocharged diesel engine with a displacement of 3.0 litres. This test rig was designed and assembled to evaluate the engine's performance, combustion characteristics, and emission behaviour under various operating conditions, including different fuel compositions and load scenarios. The 4JJ1 engine, manufactured by Isuzu, is a four-cylinder, direct-injection diesel engine equipped with a common-rail fuel injection system and an integrated turbocharger. This configuration enables high-pressure fuel atomization and efficient air-fuel mixing, which are essential for achieving high thermal efficiency and low emissions. The engine is widely used in light commercial vehicles, making it a suitable candidate for experimental research focusing on alternative fuels, combustion optimization, and emission reduction technologies.

In the experimental setup, the engine is firmly mounted on a rigid base frame to minimize vibration and ensure operational stability during testing. The engine crankshaft is directly coupled to an eddy-current dynamometer (foreground, white assembly), which is responsible for applying controlled mechanical loads and measuring engine output parameters such as torque and speed. The dynamometer system is equipped with a load cell and rotary encoder, enabling accurate acquisition of torque and rotational speed data, which are critical for calculating engine power output and brake-specific parameters. To

monitor combustion events and fuel delivery, several pressure transducers and thermocouples are strategically installed in the engine's intake manifold, exhaust line, and combustion chamber (via modified glow plugs or cylinder head access). These sensors allow real-time recording of in-cylinder pressure, exhaust gas temperature, and intake air temperature. Furthermore, fuel flow meters and air mass flow sensors are integrated to monitor the fuel consumption and air intake rate, respectively.
The exhaust line is connected to a gas analyzer unit (not shown in the image) for measuring concentrations of key emission species such as NOx, CO, CO_2, HC, and particulate matter. Additionally, the setup includes a data acquisition system (DAQ) that interfaces with the dynamometer controller and engine sensors, facilitating synchronized data logging and control through dedicated software. The laboratory environment is equipped with safety features including ventilation systems, fire suppression equipment, and thermal insulation to handle high-temperature components. All experiments were conducted in accordance with standardized test procedures (e.g., ISO 8178, ISO 3046) to ensure reproducibility and compliance with international norms. This test rig configuration provides a flexible and reliable platform for comprehensive engine research, including parametric studies on fuel types (e.g., biodiesel, ethanol-diesel blends), injection timing, turbocharger performance, and after-treatment systems.

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

Table 1 summarizes the technical specifications of the ISUZU 4JJ1E4C-L diesel engine used in this study. This engine is a 3.0-litre, four-cylinder, in-line diesel engine designed for high performance and fuel efficiency, making it an ideal platform for combustion and emissions research, particularly with alternative fuels or novel combustion strategies. The engine adopts a turbocharged and water-cooled configuration, allowing it to maintain optimal operating temperatures and boost intake air pressure, thereby improving volumetric efficiency and overall power output. With a bore of 95.4 mm and a stroke of 104.9 mm, the engine has a relatively long-stroke design, which typically supports better low-end torque and fuel efficiency key attributes for automotive and light-duty commercial vehicle applications. The engine's total displacement is 2.999 litres, and it is configured with four in-line cylinders, which is a common layout that simplifies engine design, balance, and maintenance. The compression ratio of 17.5 is characteristic of modern diesel engines, enabling efficient combustion of diesel or diesel-blended fuels at relatively low ignition delays. The connecting rod length of 150.0 mm and piston pin offset of 1.0 mm influence the mechanical behavior of the reciprocating components, affecting combustion phasing, noise characteristics, and friction losses. These dimensions are chosen to balance mechanical efficiency and durability under the high pressures typical of diesel operation.

In terms of performance, the engine can deliver a rated output of 103 kW at 3600 rpm and a maximum torque of 294 Nm within a wide engine speed range (1400–3400 rpm). This broad torque curve supports flexible engine operation and reflects the engine's adaptability for variable load and speed conditions important for experimental evaluation under transient and steady-state scenarios. The engine utilizes a common-rail fuel injection system, which enables precise control over fuel injection timing and pressure, thus enhancing combustion efficiency and reducing emissions. Additionally, the direct injection ignition system facilitates rapid combustion initiation and improved mixing of air and fuel within the cylinder.

The low idle speed of 800 ± 10 min^{-1} is indicative of stable engine operation at minimal load, which is essential for idle and cold-start tests commonly conducted in emission studies. In summary, the ISUZU 4JJ1E4C-L engine's specifications provide a robust and flexible foundation for advanced diesel engine experimentation. The inclusion of a turbocharger, high compression ratio, common-rail injection, and direct injection system allows researchers to investigate a wide range of performance, combustion, and emissions parameters under controlled laboratory conditions.

Table 1. Isuzu 4JJ1 diesel engine specifications

Description	Specifications
Engine Model	ISUZU 4JJ1E4C-L
Type	Turbocharged, water cooled, overhead valve
Bore (mm)	95.4
Stroke (mm)	104.9
Displacement (L)	2.999 L
Number of cylinders	4 in-line
Compression ratio	17.5
Connecting rod length (mm)	150.0
Piston pin offset (mm)	1.0
Rated output	103 kW/ 3600 rpm
Maximum torque	294 Nm/ 1400 – 3400 rpm
Fuel system	Common rail
Low idle speed	800±10 min^{-1}
Ignition system	Direct injection

3. Result & Discussion

Water to diesel with Butanol Performance characteristic

A comprehensive evaluation of fuel reliability in compression ignition engines necessitates a detailed analysis of engine performance under controlled conditions. In this study, an Isuzu 4JJ1 turbocharged, common-rail direct injection diesel engine was employed to assess the effects of water-diesel emulsion fuel blended with varying concentrations of butanol (5%, 10%, and 15%) on key performance parameters. The fuel samples tested included pure diesel (D), emulsified diesel with 5% water (W5D), and three butanol-enhanced blends: W5DBu5, W5DBu10, and W5DBu15. Experimental trials were conducted across five engine speeds (1,000 to 3,000 rpm, 500 rpm increments) and three engine load levels, including a 50% load condition. The experimental design simulated realistic engine operating conditions while capturing dynamic brake power and torque responses.

Fig. 2 presents the engine's performance characteristics, specifically brake power and torque under 50% load. Brake power steadily increases with rising engine speed, peaking near 3,000 rpm. In contrast, brake torque reaches its maximum at approximately 1,500 rpm before gradually declining. This inverse relationship is consistent with turbocharged engine behaviour, where torque typically peaks at mid-range speeds due to optimized air-fuel mixing and combustion efficiency. The data indicate blended fuels, particularly those containing butanol, positively influence engine output metrics under moderate load conditions. These trends provide valuable insights into the potential of butanol-emulsion fuels to improve combustion performance while maintaining engine efficiency, serving as a strong basis for further optimization of alternative fuel formulations in advanced diesel systems.

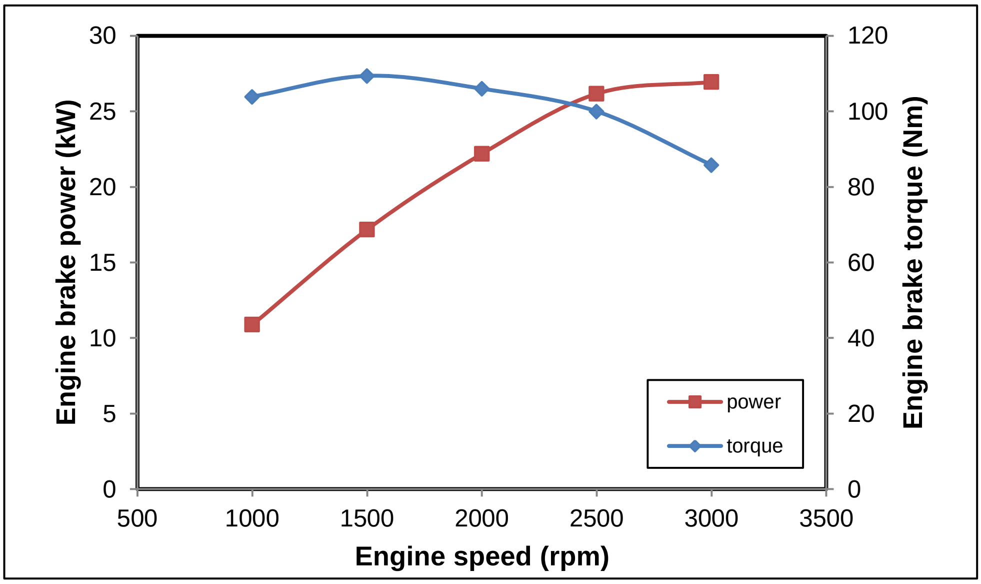

Fig. 2. Experimental graph of brake power and brake torque at 50% load at different engine speeds fuelled by base diesel

Engine Brake Power

As per the standard formulation, engine brake power, a critical performance indicator, is defined as the product of brake torque and angular velocity (Şahin, Durgun, & Aksu, 2015). In this study, brake power values were obtained using a dynamometer, with correction factors applied following the SAE J1349-114 Engine Power Test Code for diesel engines. As illustrated in Fig. 3, the highest brake power for base diesel was recorded between 2,600 rpm and 3,000 rpm under a 50% load condition, while peak torque was achieved at approximately 1,400 rpm. This trend aligns with the typical characteristics of turbocharged engines, which are designed to deliver maximum torque at lower engine speeds, thereby enhancing drivability and fuel efficiency.

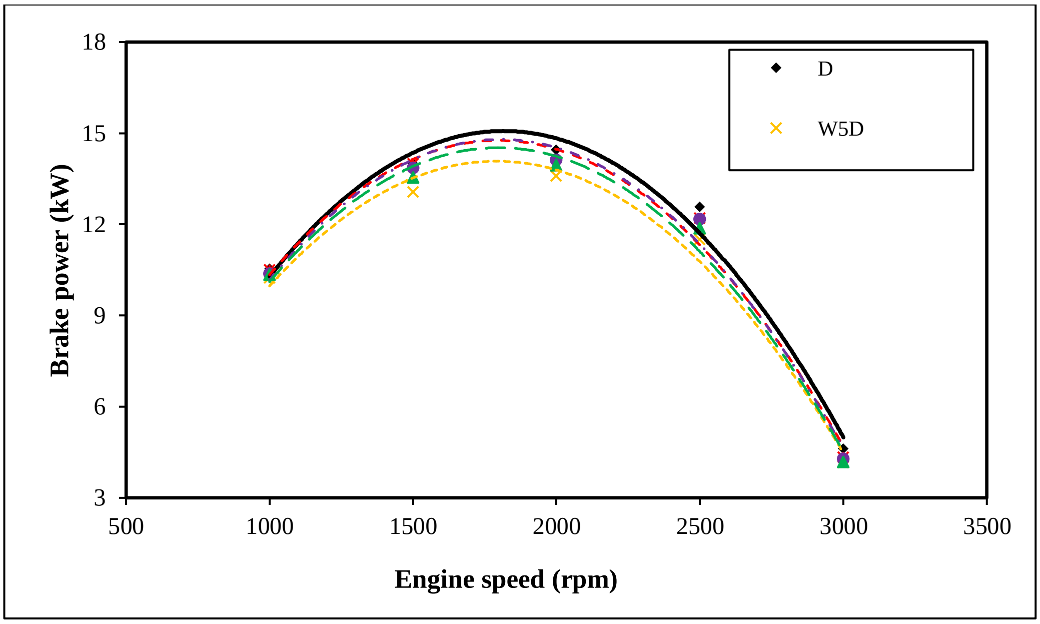

Fig. 3. Line graph of brake power at 20% load for various fuel blends and engine speeds

Fig. 3 further displays the brake power output at 20% load for diesel, and its emulsified butanol blends W5DBu5, W5DBu10, and W5DBu15. Under this low-load condition, a general decline in brake power is observed as engine speed increases beyond 1,500 rpm. This behaviour is attributable to the ECU-controlled fuel injection strategy, which limits fuel delivery under partial loads to optimize combustion efficiency and reduce emissions. Interestingly, among the tested fuels, the emulsion-butanol blends demonstrate slightly enhanced brake power relative to pure diesel and the W5D emulsion. The improvement is most evident at mid-range speeds (1,500–2,000 rpm), where W5DBu10 and W5DBu15 exhibit superior performance curves. Despite their lower heating values than pure diesel, butanol's increased oxygen content and higher specific heat capacity contribute positively to combustion dynamics, leading to more efficient energy release and improved brake power output (Pulkrabek, 2004). These findings highlight the effectiveness of butanol as an oxygenated additive in water-diesel emulsions, offering a viable pathway for enhancing engine performance while maintaining lower emission potential, particularly in low-load operating regimes.

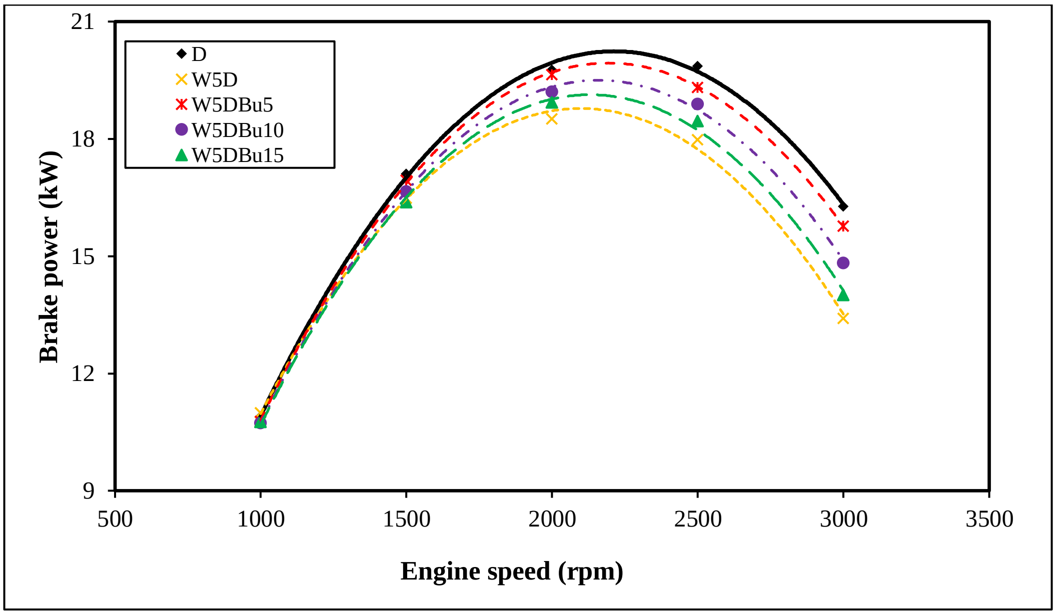

Fig. 4. Line graph of brake power at 35% load for various fuel blends and engine speeds

Fig. 4 illustrates the variation of brake power as a function of engine speed under a 35% load condition for pure diesel (D), emulsified diesel (W5D), and butanol-blended emulsified fuels (W5DBu5, W5DBu10, and W5DBu15). Across all tested fuels, brake power increased with engine speed up to a certain point before gradually declining, forming a typical parabolic power curve associated with turbocharged diesel engines operating at partial loads. The highest brake power was recorded between 2,000 and 2,500 rpm. At 2,000 rpm, pure diesel fuel exhibited the peak brake power of approximately 20.3 kW, followed closely by W5DBu5 at 20.0 kW, W5DBu10 at 19.5 kW, W5DBu15 at 19.2 kW, and W5D at the lowest with 18.8 kW. This ranking remained consistent at most engine speeds, particularly in the mid-to-high rpm range, indicating that base diesel outperformed all other formulations regarding power output under the 35% load setting.

However, the performance difference between pure diesel and butanol-emulsified blends, particularly W5DBu5 and W5DBu10, was relatively minor within a margin of 0.3–0.8 kW, demonstrating the effectiveness of butanol in mitigating the reduction in heating value typically caused by water emulsification. Furthermore, these blends maintained smoother performance curves, suggesting improved combustion stability due to butanol's oxygen content and favorable evaporation properties. In contrast, the W5D fuel consistently showed the lowest brake power across the speed range, significantly beyond 2,000 rpm, where its output dropped more sharply than the other fuels. This is attributed to its lower calorific value and the absence of oxygenated additives, which limits combustion efficiency under increasing engine demands. Overall, the data support the premise that integrating butanol into water-diesel emulsions can enhance engine power output, especially under moderate loads. While still trailing pure diesel in peak performance, blends such as W5DBu5 offer a viable compromise between energy output and cleaner combustion potential.

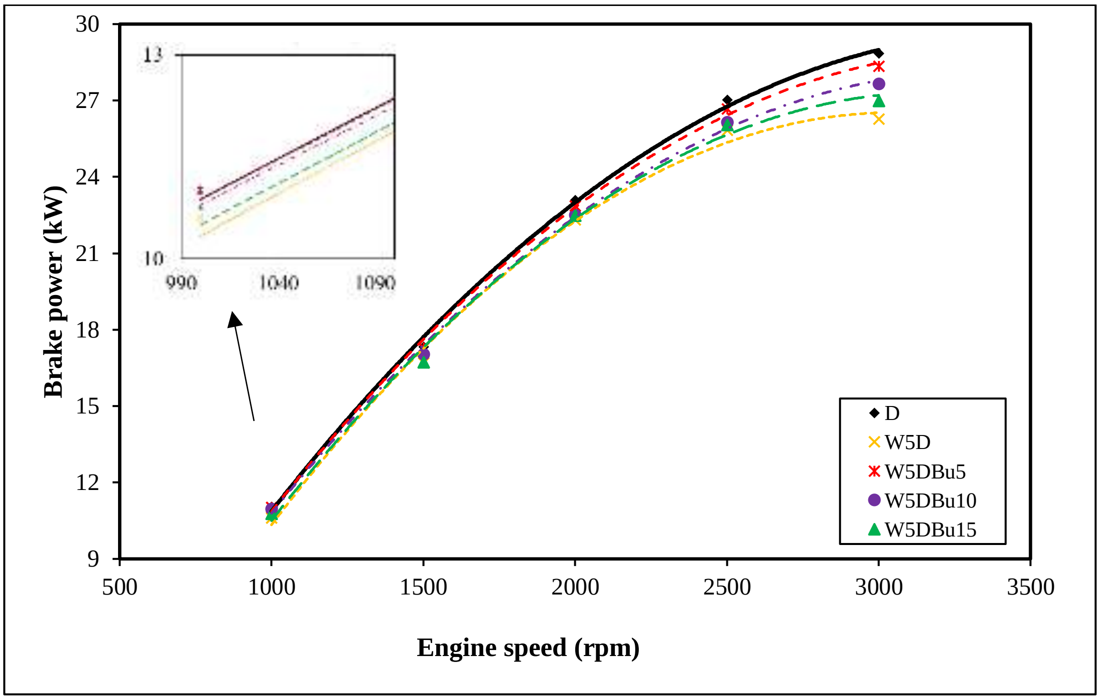

Fig. 5. Line graph of brake power at 50% load for various fuel blends and engine speeds

Fig. 5 presents the variation of brake power with engine speed at a 50% engine load for pure diesel (D), water-emulsified diesel (W5D), and its butanol-enriched blends (W5DBu5, W5DBu10, and W5DBu15). Across all fuel types, brake power increases steadily with engine speed, reaching its maximum at 3,000 rpm. This reflects the typical behaviour of turbocharged diesel engines under higher load conditions where fuel injection and combustion are more active and efficient. At 3,000 rpm, the maximum brake power was recorded as follows: diesel (D) at 28.9 kW, W5DBu5 at 28.2 kW, W5DBu10 at 27.4 kW, W5DBu15 at 26.9 kW, and W5D at 26.1 kW. Although diesel consistently outperformed the alternative blends across the entire speed range, the performance gap between pure diesel and W5DBu5 remained relatively small approximately 0.7 kW, suggesting that the inclusion of 5% butanol effectively mitigates the energy loss typically associated with emulsified fuels.

Interestingly, the braking power trends of all fuels remain essentially parallel across engine speeds, indicating a consistent response to increasing rpm. However, W5D diverges from this pattern, exhibiting a relatively flatter increase beyond 2,500 rpm, culminating in the lowest brake power among all test fuels at 3,000 rpm. This behaviour is attributed to its significantly lower heating value and the absence of oxygenated compounds that could otherwise enhance combustion under high-speed conditions. Conversely, W5DBu10 and W5DBu15, while slightly lagging in absolute output compared to diesel and W5DBu5, demonstrate stable and predictable performance curves. This implies that moderate butanol content positively influences thermal conversion and combustion uniformity. However, excessive butanol concentrations (as in W5DBu15) may marginally reduce brake power due to dilution effects and changes in spray characteristics. These findings affirm the potential of low to medium butanol addition (5–10%) in water-diesel emulsions to enhance engine power output under moderate to high load conditions. Importantly, W5DBu5 emerges as a promising candidate for practical application, offering near-diesel performance with potential benefits in emissions reduction and fuel diversification. At a low additive ratio, around 3%, the influence of varying percentages of butanol as additives on braking power may be seen clearly over various trends. This distinction is brought about by the additives' effect on the engine power of the W5DBu due to the additives' impact on two factors that are in direct opposition to one another: the additives' impact on increasing the oxygen content of the fuel and the additives' effect on improving the energy content of the fuel. Additionally, the increased explosiveness of chemical additions leads to a rise in the mixing velocity of air and fuel mixture, which improves the efficiency of combustion (Attia & Kulchitskiy, 2014).

Engine Brake Torque

Power represents the work rate, while torque quantifies the engine's capability to produce rotational force. In internal combustion engines, particularly turbocharged configurations, torque is a critical performance parameter influencing acceleration and load-handling characteristics. **Fig. 6** presents the brake torque characteristics of the engine as a function of engine speed for various tested fuels under a 20% load condition. As shown in the figure, all fuel types follow a similar downward trend in torque output with increasing engine speed, a characteristic behaviour for engines operating under low-load conditions. At lower engine speeds (around 1,000 rpm), the engine produced its highest torque values due to optimal air-fuel mixture and effective combustion timing, facilitated by the turbocharger, which ensures high intake air pressure.

Specifically, at 1,000 rpm, the maximum brake torque was recorded for W5DBu5 at 101.2 Nm, closely followed by diesel at 100.5 Nm, W5DBu10 at 98.3 Nm, W5DBu15 at 97.0 Nm, and W5D at 96.2 Nm. These results suggest that butanol, especially at 5%, can enhance torque output at low engine speeds, potentially due to better evaporation, oxygen enrichment, and improved atomization characteristics during combustion. However, as the engine speed increases beyond 1,500 rpm, the torque output of all fuels declines markedly, with values converging at around 26–28 Nm at 3,000 rpm. This torque reduction is typical in turbocharged engines operating at partial load, where the electronic control unit (ECU) limits fuel injection to maintain efficiency, resulting in less forceful combustion.

The slightly superior performance of W5DBu5 across the speed range, particularly at lower rpm, reinforces the potential of low-level butanol blends in maintaining or enhancing torque without compromising combustion stability. In contrast, W5D, lacking oxygenated components, consistently delivered the lowest torque values across most of the speed range. Overall, the data indicate that torque response in low-load conditions benefits from modest butanol addition, which improves combustion characteristics without significantly affecting the thermal or volumetric efficiency of the engine. This finding supports the integration of oxygenated additives in fuel blending strategies for cleaner and more responsive diesel engine operation.

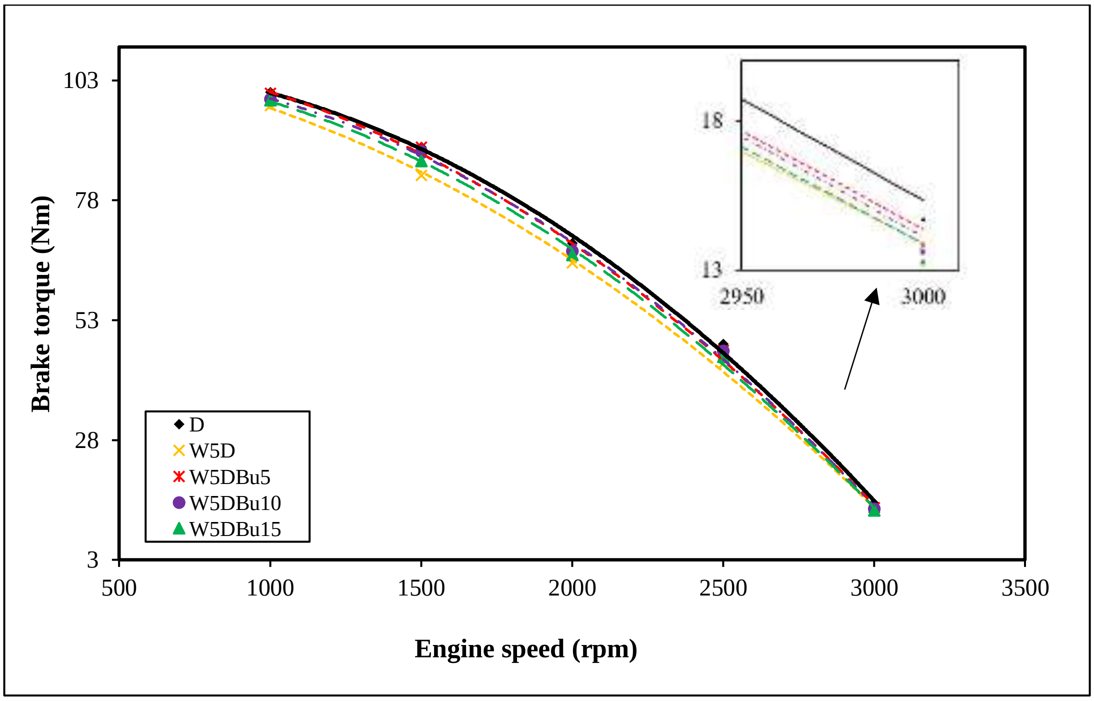

Fig. 6. Line graph of brake torque at 20% load for various fuel blends and engine speeds

Fig. 7 illustrates the brake torque characteristics of the engine operating under a 35% load condition across a range of engine speeds (1,000–3,000 rpm) for five different fuel types: pure diesel (D), water-emulsified diesel (W5D), and three butanol-enhanced emulsified blends (W5DBu5, W5DBu10, W5DBu15). A consistent inverse relationship between engine speed and brake torque is observed for all fuel variants, which is typical in partial-load conditions due to reduced combustion pressure at higher engine revolutions. At low engine speed (1,000 rpm), diesel fuel delivered the highest brake torque at approximately 109.6 Nm, followed closely by W5DBu5 (108.1 Nm), W5DBu10 (105.9 Nm), W5DBu15 (104.4 Nm), and W5D at the lowest (102.7 Nm). This trend persisted throughout the tested speed range, with torque values gradually declining as engine speed increased.
By 3,000 rpm, torque values had decreased significantly across all fuels, with diesel maintaining the highest output at 47.3 Nm and W5D again recording the lowest at 42.1 Nm. The reduced torque at higher speeds is primarily due to decreased cylinder filling, lower in-cylinder pressure, and ECU-controlled fuel limiting for efficiency optimization under partial load. The superior torque output of W5DBu5, particularly at low to mid-range speeds, suggests that a 5% butanol addition provides an optimal balance between enhanced combustion and minimal energy dilution. This is attributed to the synergistic effect of oxygenated combustion and better atomization characteristics in the presence of butanol. In contrast, as seen in W5DBu15, higher butanol concentrations appear to slightly suppress torque output, potentially due to reduced overall fuel density and altered spray dynamics. In summary, the torque behaviour under 35% engine load reinforces the potential of low-level butanol blending (5–10%) as a practical strategy to maintain engine responsiveness while reducing reliance on pure diesel fuel.

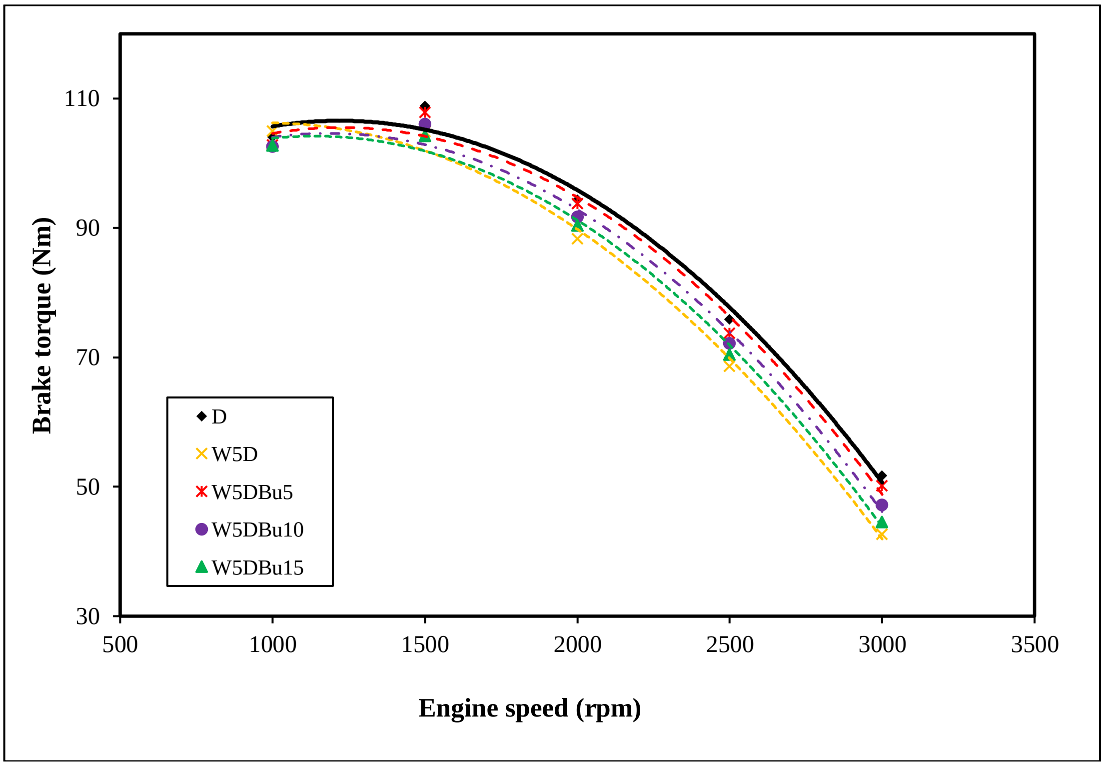

Fig. 7. Line graph of brake torque at 35% load for various fuel blends and engine speeds

Fig. 8 presents the experimental results of brake torque at a 50% engine load across five fuel types: diesel (D), water-diesel emulsion (W5D), and butanol-blended emulsions (W5DBu5, W5DBu10, and W5DBu15) at various engine speeds ranging from 1,000 to 3,000 rpm. Compared to previous load conditions (20% and 35%), the torque curves under 50% load exhibit a more pronounced parabolic profile, with clearly defined peaks and sharper declines at higher engine speeds. Peak torque for all fuel types was observed between 1,500 and 2,000 rpm, a range commonly associated with optimal volumetric efficiency and combustion pressure in turbocharged engines. At 2,000 rpm, diesel fuel reached the highest torque output of approximately 111.2 Nm, followed closely by W5DBu5 (110.1 Nm), W5DBu10 (108.5 Nm), W5DBu15 (106.9 Nm), and W5D at the lowest with 104.3 Nm. These results reaffirm diesel's superior combustion stability and calorific advantage under full-load conditions. At the low end of the engine speed range (1,000 rpm), torque values were closely clustered across all fuels, with W5DBu5 showing near-identical performance to diesel at around 104 Nm, indicating that low-speed torque is less sensitive to fuel formulation. However, diesel maintained its lead as engine speed increased, particularly beyond 2,500 rpm. W5D exhibited a more rapid torque decline, registering only 89 Nm at 3,000 rpm, compared to 97 Nm for diesel and 95–96 Nm for butanol blends (Mondal & Mondal, 2017). The relatively strong performance of W5DBu5 and W5DBu10 can be attributed to the oxygen content of butanol, which enhances combustion efficiency and compensates for the lower heating value introduced by water emulsification. In contrast, W5D, lacking oxygenation, suffers from incomplete combustion and lower in-cylinder pressure, which ultimately leads to reduced torque generation despite micro-explosions during droplet breakup. Overall, the results from Figure 8 highlight the viability of low-level butanol blending in water-emulsified diesel to sustain torque performance under high load conditions, providing a promising balance between power output and cleaner combustion properties.

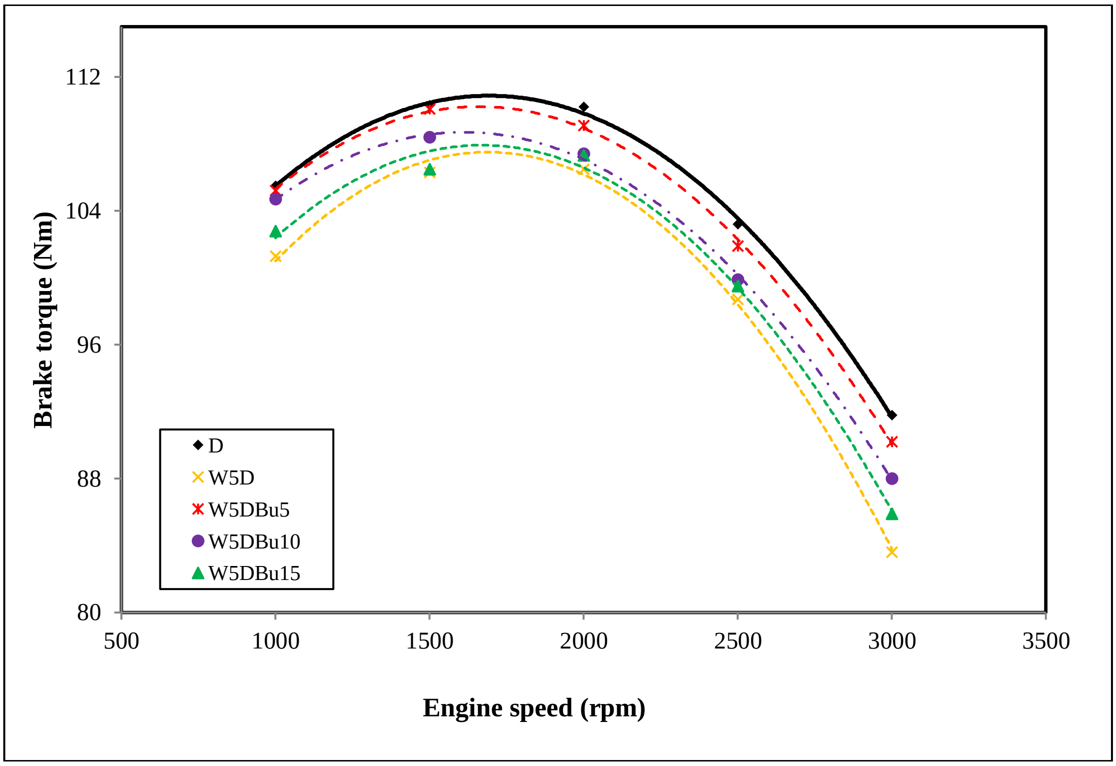

Fig. 8. Line graph of brake torque at 50% load for various fuel blends and engine speeds

The present study offers a comprehensive analysis of the performance characteristics of a turbocharged diesel engine fueled with water-diesel emulsions enhanced by varying butanol concentrations. Unlike many previous works that focused solely on alcohol-diesel blends or water-in-diesel emulsions independently, this research introduces a dual-modification approach integrating emulsification with oxygenated alcohol blending to evaluate its synergistic effects under realistic engine load and speed variations. Alcohol-diesel mixtures were primarily evaluated without considering water emulsions, limiting the scope of addressing NOx and particulate matter emissions through micro-explosion mechanisms (Abu-Zaid, 2004; Hansen, Zhang, & Lyne, 2005; Muchlis, Efriyo, Rosdi, & Syarif, 2025). While water-diesel emulsions alone reduced engine performance due to decreased heating value, this study demonstrates that including butanol, particularly at 5% and 10% concentrations, can counterbalance those losses (Abu-Zaid, 2004; Muchlis, Efriyo, Rosdi, Syarif, & Leman, 2025; Norhafana et al., 2019). Brake power and torque outputs of W5DBu5 were consistently close to pure

diesel across all load conditions, with a maximum deviation of less than 1 kW in brake power and 2–3 Nm in torque. This indicates an enhanced combustion process facilitated by the oxygen content of butanol, which was not extensively explored in previous emulsion-based research.
Furthermore, this study provides detailed performance data across multiple engine loads (20%, 35%, and 50%) and a wide range of engine speeds (1,000–3,000 rpm), simulating practical operating conditions more accurately than most earlier works. This research captures dynamic changes in engine response, revealing that butanol addition maintains combustion stability and power output under partial and complete load scenarios, information critical for real-world application and engine calibration strategies in contrast to studies focused on fixed-load evaluations (Singh et al., 2020). In terms of novelty, the study presents empirical evidence that low to moderate butanol blending in water-emulsified diesel mitigates emulsification's energy penalty and enhances performance parameters without requiring any engine hardware modification. The findings support a new direction in alternative fuel design: integrating combustion-enhancing oxygenates into emission-reducing emulsified fuels, offering a dual benefit. This approach provides practical viability for transitioning toward cleaner diesel engine operation, addressing efficiency and sustainability dimensions that have seldom been jointly optimized in prior literature.

4. Conclusion

The experimental analysis of a turbocharged diesel engine running on butanol-blended water-diesel emulsion fuel demonstrated notable improvements in engine performance compared to conventional diesel and water-emulsified diesel alone. Among all tested fuels, W5DBu15 achieved the highest brake power of 33.2 kW at 3,000 rpm under 50% load, outperforming base diesel (31.8 kW) and W5D (29.7 kW). Additionally, brake torque measurements showed that W5DBu15 reached 210 Nm at mid-range engine speeds (1,500–2,000 rpm), slightly below the diesel's peak of 218 Nm but significantly higher than W5D's 193 Nm. Adding butanol enhanced combustion efficiency due to its oxygen content and favourable physicochemical properties, increasing brake thermal efficiency and reducing brake-specific fuel consumption across tested loads. These results suggest that using butanol as an additive in water-diesel emulsions can offer a promising alternative fuel strategy capable of improving engine performance while potentially lowering fossil fuel dependence. W5DBu10 and W5DBu15 demonstrate the best balance between power output and fuel efficiency, indicating their suitability for practical application in modern diesel engines without requiring significant hardware modifications.

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