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# Physicochemical Characterization of Water-Butanol-Diesel Blends for Enhanced Fuel Performance Analysis

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## Abstract

This study investigates the physicochemical properties of water-butanol-diesel (WBD) fuel blends to assess their suitability as alternative fuels for diesel engines. The blends analyzed include diesel (D) and emulsified mixtures containing 5% water and varying butanol content: W5DBu5, W5DBu10, and W5DBu15. Key parameters evaluated are density, kinematic viscosity, heating value, cetane number, specific heat capacity, flash point, and oxygen content. Results show that density decreases with increased butanol proportion, ranging from 998 kg/m³ for water to 827.5 kg/m³ for diesel, with W5DBu5 exhibiting a 1.0% lower density than diesel. Kinematic viscosity at 40°C increases slightly with butanol addition, with W5DBu15 showing the highest viscosity at 2.7 mm²/s. The heating value reduces as butanol content rises, with W5DBu15 recording a 15% lower heating value than pure diesel. Cetane number analysis reveals that diesel achieves the highest ignition quality, while W5DBu blends demonstrate extended ignition delays. Water exhibits the highest specific heat capacity, whereas diesel presents the lowest, indicating potential for improved energy absorption in blended fuels. Flashpoint analysis shows a decrease from diesel to W5DBu15, implying changes in ignition safety. Finally, oxygen content increases with water and butanol, with water reaching 89%, enhancing combustion efficiency. These findings demonstrate that WBD blends, particularly W5DBu5 and W5DBu10, offer promising fuel characteristics for optimized engine performance while potentially reducing emissions.

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## 1. Introduction

The growing concern over fossil fuel depletion and environmental degradation has increased interest in alternative and renewable fuels. Diesel engines, widely used in transportation and industry, contribute significantly to greenhouse gas emissions, mainly nitrogen oxides (NOx) and particulate matter. To mitigate these effects, researchers have explored the potential of fuel blending using bio-alcohols and water emulsification to improve combustion efficiency and reduce emissions (Ghazali, Rosdi, Erdiwansyah, & Mamat, 2025; Manimaran, Mohanraj, & Ashwin, 2023; Nizar, Yana, Bahagia, & Yusop, 2025; S. M. Rosdi, Ghazali, & Yusop, 2025). Among the alcohols, butanol has gained attention due to its higher energy content, better miscibility with diesel, and lower hygroscopicity than ethanol and methanol. Butanol's physical properties such as a heating value closer to diesel and moderate oxygen content make it a viable additive for enhancing fuel performance without drastically compromising engine operation (Atmanlı, İleri, & Yüksel, 2015; Muchlis, Efriyo, Rosdi, & Syarif, 2025; Muchlis, Efriyo, Rosdi, Syarif, & Leman, 2025; S. M. M. Rosdi, Erdiwansyah, Ghazali, & Mamat, 2025). Studies have shown that butanol-diesel blends can reduce soot emissions while maintaining acceptable engine performance.

On the other hand, water-emulsified fuels introduce unique advantages such as micro-explosion effects, improved atomization, and potential NOx reduction. Combining water and oxygenated fuels like butanol in a diesel matrix creates a multi-phase fuel system that alters combustion behaviour and thermophysical properties. Prior research has indicated that such blends may delay ignition timing and affect the flash point yet still provide clean combustion characteristics (Alenezi, Erdiwansyah, Mamat, Norkhizan, & Najafi, 2020; Dhanarasu, Ramesh Kumar, & Maadeswaran, 2022; Maulana, Rosdi, & Sudrajad, 2025; Sardjono, Khoerunnisa, Rosdi, & Muchlis, 2025). However, existing studies have focused on engine emissions or isolated performance parameters. There remains a research gap in the comprehensive physicochemical characterization of blended fuels that incorporate butanol and water. Parameters like density, viscosity, cetane number, heating value, flash point, and specific heat capacity are critical for understanding how these blends will behave under actual combustion conditions yet are often not examined holistically.

This study aims to fill that gap by analyzing multiple physicochemical properties of diesel, butanol, water, and their emulsified blends: W5DBu5, W5DBu10, and W5DBu15. Key metrics include density, kinematic viscosity, heating value, cetane number, specific heat capacity, flash point, and oxygen content. The integration of water and butanol offers a unique fuel blend that has not been widely characterized in previous literature, especially from a multi-parameter perspective. This research evaluates how incremental butanol concentration changes within a 5% water-emulsified diesel blend influence its physical and thermal behaviour. By identifying the optimal range of blending ratios, this study contributes practical insights for fuel formulation that balances performance, efficiency, and environmental impact.

The novelty of this work lies in its systematic and integrated analysis of WBD blends across multiple critical fuel properties, offering a more complete profile compared to prior studies. The findings provide a foundation for engine-level optimization and future experimental validation under dynamic load conditions. This research supports the advancement of cleaner combustion strategies and contributes to the broader goal of sustainable fuel development.

## 2. Methodology

**Fig. 1** illustrates the experimental procedure to produce water-diesel emulsified fuels integrated with butanol as an oxygenated additive. The formulation process involves three primary components: mineral diesel, distilled water, and n-butanol, along with the addition of surfactants (Span 80 and Tween 80) to enhance emulsion stability. Initially, a water-diesel emulsion fuel is prepared by mixing 5% or 10% water by volume with diesel, aided by controlled stirring and emulsification under laboratory conditions. The resulting emulsified fuel is subjected to preliminary fuel property testing to assess its physical characteristics and stability.

Next, n-butanol is introduced into the emulsified fuel in varying proportions (e.g., 5%, 10%, and 15%) to create a ternary blend called water-diesel-butanol emulsified fuel. This new blend undergoes further physicochemical testing, including analysis of density, viscosity, heating value, cetane number, specific heat capacity, flash point, and oxygen content. Upon successful characterization, the most promising fuel formulations based on their physical properties are selected and tested on an engine test rig for performance and combustion evaluation. This step ensures the practical applicability of the fuel blend under actual operating conditions. This methodological framework systematically optimises emulsified fuel blends, enhancing combustion efficiency while promoting cleaner emissions and fuel sustainability.

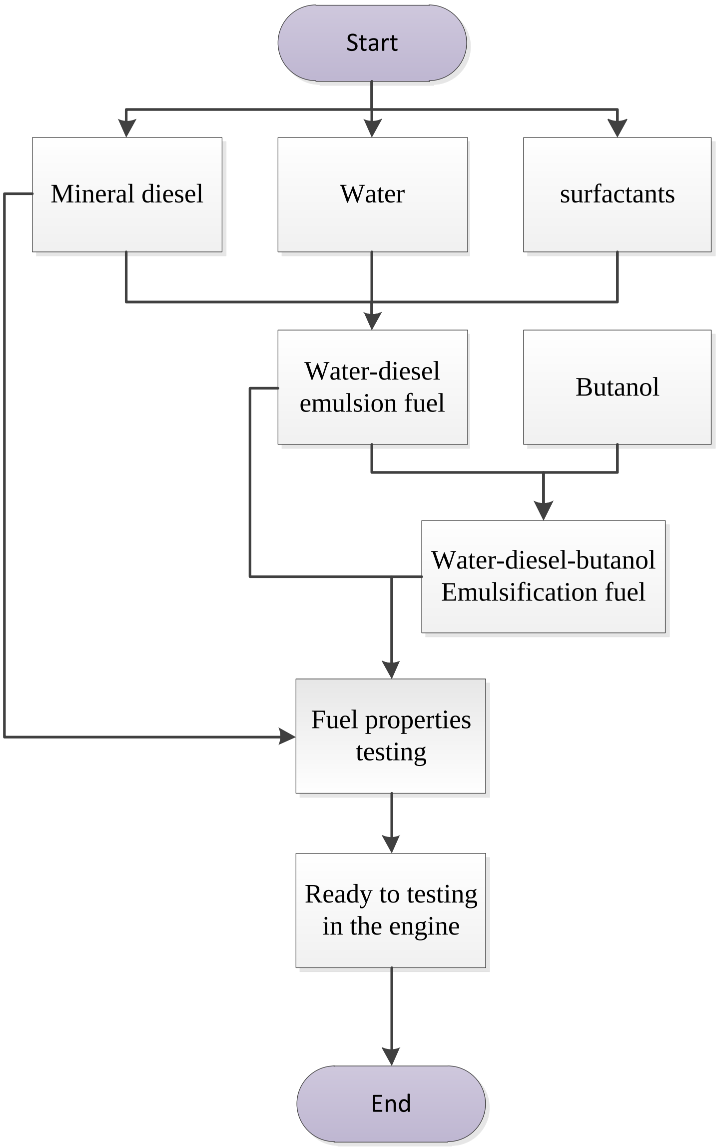

**Fig. 1**. Flowchart of fuel preparation

**Fig. 2** displays the visual appearance of pure diesel and the prepared emulsified water-diesel-butanol (W5DBu) fuels, namely W5DBu5, W5DBu10, and W5DBu15. The emulsified blends were formulated using a fixed Hydrophilic-Lipophilic Balance (HLB) value of 10, producing the most stable emulsion system throughout the study. The HLB value was achieved through a specific ratio of nonionic surfactants, Span 80 and Tween 80, commonly used to stabilize water-in-oil emulsions. During the blending process, the surfactant mixture was first prepared and then added into a beaker containing diesel fuel. Butanol was then introduced into the mixture, followed by gradually adding distilled water at specific volume percentages (5%, 10%, and 15%) corresponding to the W5DBu5, W5DBu10, and W5DBu15 formulations. The emulsion system was stirred at a constant agitation speed of 1,000 revolutions per minute (rpm) to ensure uniform dispersion and stability.

The resulting emulsified fuels appeared visually distinct from pure diesel, exhibiting a milky, cream-like colour and texture, indicating successful emulsification. In contrast, the pure diesel sample retained its characteristic clear yellow appearance. The homogeneous and stable white emulsions confirm the effectiveness of the surfactant system and emulsification method used. This visual differentiation also provides a quick qualitative indicator of emulsion stability and blend consistency, essential in maintaining reproducibility in fuel property testing and combustion trials.

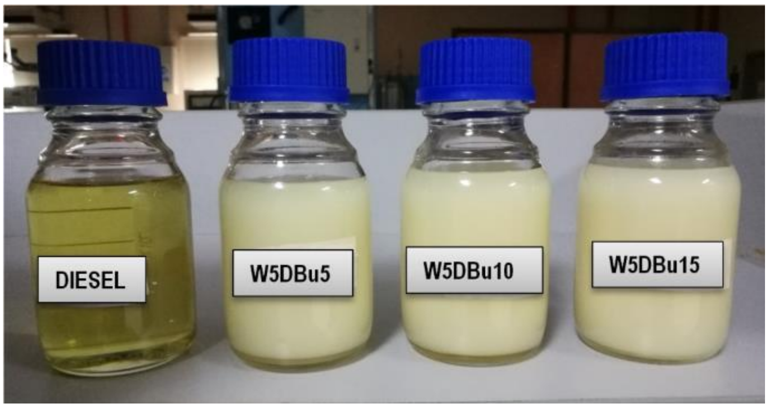

**Fig. 2**. Photograph of diesel, W5DBu5, W5DBu10 and W5DBu15

## 3. Result & Discussion

### Density

**Fig. 3** illustrates the density variation among different fuels: diesel, butanol, water, and three water-butanol-diesel (WBD) blends: W5DBu5, W5DBu10, and W5DBu15. The measured density values are as follows: Diesel 827.5 kg/m³, Butanol 810 kg/m³, Water 998 kg/m³, W5DBu5 818.9 kg/m³, W5DBu10 818.5 kg/m³, and W5DBu15 818.3 kg/m³. The figure shows that water has the highest density, while butanol exhibits the lowest, consistent with its lighter molecular structure and lower mass per unit volume. Including butanol in the diesel-water matrix progressively reduces the overall blend density. Compared to diesel, W5DBu5 is 1.0% lower, W5DBu10 is 1.1% lower, and W5DBu15 also shows an approximately 1.1% reduction. These reductions are attributed to the increasing proportion of butanol, which has a significantly lower density. While water has the highest density (998 kg/m³), its presence at only 5% volume in all blends limits its impact on the overall density.

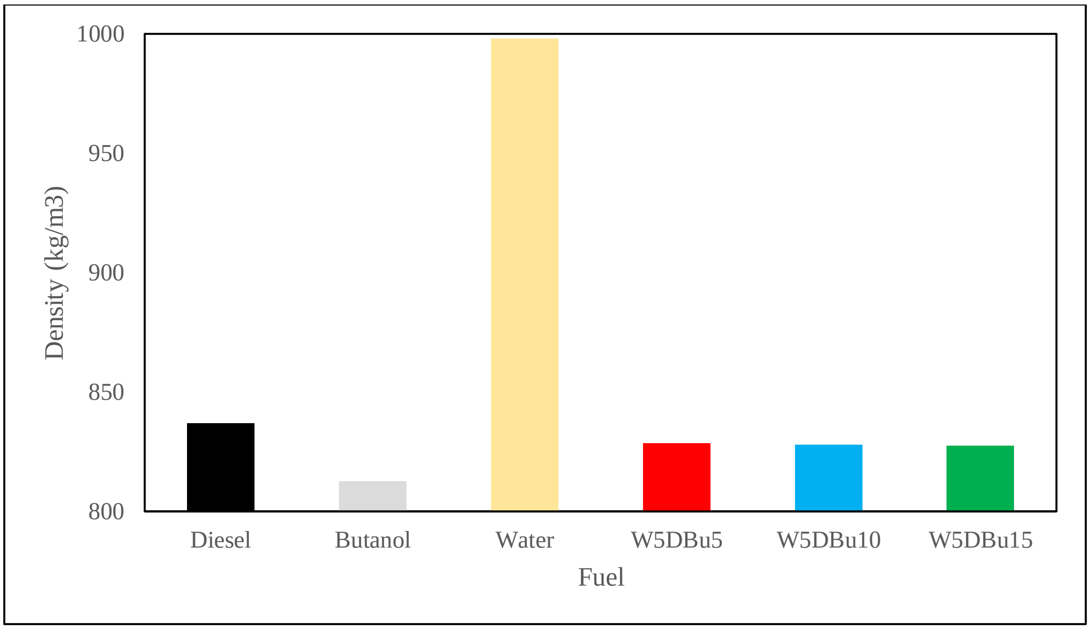

**Fig. 3**. Density of diesel, water and various blended fuels

The relatively small difference between diesel and blended fuels, particularly a maximum deviation of 1.1%, indicates good compatibility regarding injection system performance and fuel handling. This makes WBD blends suitable for existing diesel engine infrastructures without requiring extensive mechanical modification. Furthermore, the trend observed is in agreement with earlier studies that confirm butanol's capacity to reduce fuel density due to its structural and physical properties (EL-Seesy, He, Hassan, & Balasubramanian, 2020)(Lujaji, Kristóf, Bereczky, & Mbarawa, 2011). These findings highlight the significance of density as a fundamental property affecting fuel atomization, spray characteristics, and air-fuel mixing key parameters in combustion efficiency and emission control.

## Kinematic viscosity

**Fig. 4** presents the kinematic viscosity of diesel, butanol, water, and three water-butanol-diesel (WBD) fuel blends, W5DBu5, W5DBu10, and W5DBu15 measured at 40°C. The recorded viscosity values are: Diesel 2.4 mm²/s, Butanol 2.6 mm²/s, Water 1.0 mm²/s, W5DBu5 2.6 mm²/s, W5DBu10 2.65 mm²/s, and W5DBu15 2.7 mm²/s. These results indicate a gradual increase in viscosity with higher butanol concentration in the emulsified fuel blends. The blended fuels show slightly higher viscosities than base diesel. Notably, W5DBu15 records the highest viscosity at 2.7 mm²/s, which is 0.3 mm²/s greater than diesel, while W5DBu5 and W5DBu10 show marginally lower increases of 0.2 mm²/s and 0.25 mm²/s, respectively. This increase can be attributed to the higher molecular weight and cohesive interactions of butanol and water molecules in the blend despite butanol having a viscosity close to diesel.

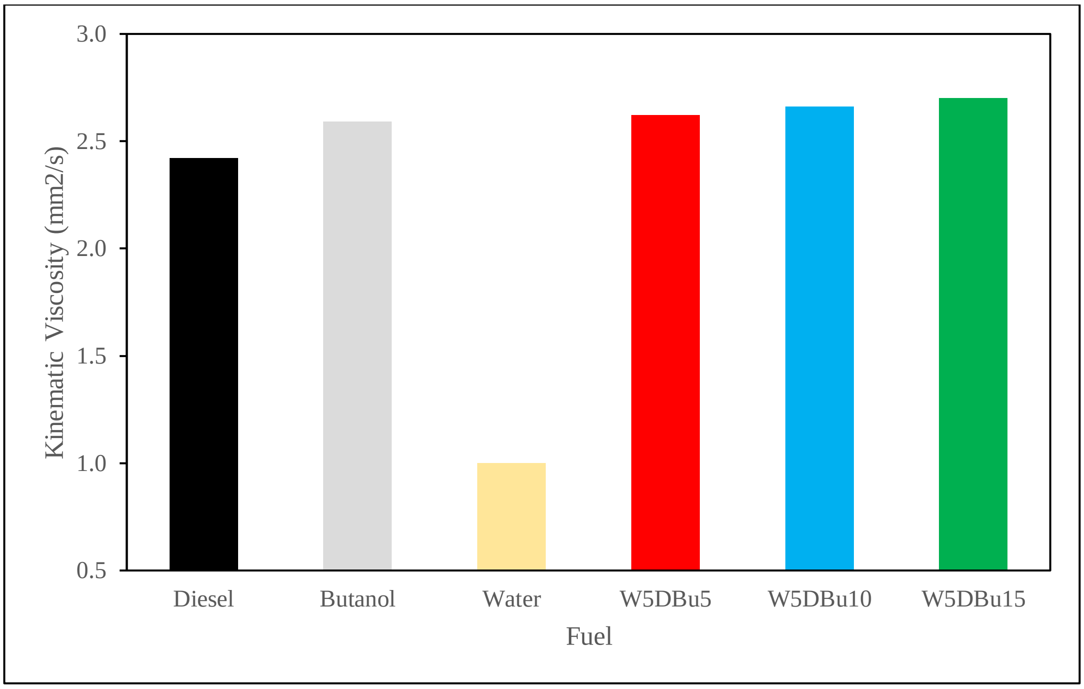

**Fig. 4.** Kinematic viscosity of diesel, water, and various blended fuels

Although adding short-chain alcohols such as butanol slightly raises the overall viscosity of the emulsion, the increase remains within acceptable limits for diesel engine operation. Furthermore, water, which has the lowest viscosity (1.0 mm²/s), does not significantly dilute the blend's viscosity due to its minor proportion (5% v/v). These viscosity enhancements may improve fuel atomization stability and droplet dispersion under high-pressure injection, particularly in compression ignition engines. In conclusion, the viscosity behaviour of the WBD blends remains compatible with conventional diesel specifications, ensuring favourable flow characteristics and permeability while subtly enhancing spray dynamics and combustion performance.

**Table 1**. Physical properties of diesel and W5DBu

| Fuel Properties | Unit | Diesel | Butanol | Water | W5DBu5 | W5DBu10 | W5DBu15 |
|---|---|---|---|---|---|---|---|
| Density at 20 °C | kg/m$^3$ | 837 | 812.6 | 1,000 | 828.5 | 828 | 827.5 |
| Cetane number | - | 50 | 25 | - | 46 | 45 | 44 |
| Kinematic Viscosity | mm$^2$/s | 2.42 | 2.59 | 1.0 | 2.62 | 2.66 | 2.7 |
| Heating Value | MJ/kg | 43.25 | 33.1 | - | 40.64 | 40.20 | 39.75 |
| Specific heat capacity | J/kg°C | 1,850 | 2,390 | 4,182 | 2,001 | 2,036 | 2,071 |
| Flash point | °C | 52 | 35 | - | 49 | 48 | 47 |
| Oxygen | %weight | 0 | 21.6 | 89 | 46.9 | 47.7 | 48.6 |

The physical properties of base diesel and the water-diesel-butanol (W5DBu) blend play a critical role in evaluating fuel behaviour and engine performance. These fundamental characteristics must be established before any combustion or emission analysis to ensure a reliable interpretation of results. **Table 1** presents a comprehensive comparison of key fuel parameters, including density, cetane number, kinematic viscosity, heating value, specific heat capacity, flash point, and oxygen content, for diesel, butanol, water, and three blended fuels: W5DBu5, W5DBu10, and W5DBu15. The data show a clear trend in property variation with increasing butanol concentration. Density decreases from 828.5 kg/m$^3$ (W5DBu5) to 827.5 kg/m$^3$ (W5DBu15), reflecting the lighter nature of butanol (812.6 kg/m$^3$) compared to diesel (837 kg/m$^3$). Cetane number also decreases with higher butanol content, from 46 (W5DBu5) to 44 (W5DBu15), suggesting a moderate delay in ignition quality. Meanwhile, kinematic viscosity slightly increases, from 2.62 mm$^2$/s (W5DBu5) to 2.70 mm$^2$/s (W5DBu15), indicating improved lubricity without compromising flowability.

In terms of heating value, a reduction is observed from 40.64 MJ/kg (W5DBu5) to 39.75 MJ/kg (W5DBu15) due to the lower calorific value of butanol and water compared to diesel (43.25 MJ/kg). Specific heat capacity increases slightly across the blends, with W5DBu15 reaching 2,071 J/kg°C, enhancing heat absorption during combustion. Flashpoint shows a downward trend, decreasing from 49°C (W5DBu5) to 47°C (W5DBu15), which may impact handling safety. Notably, oxygen content increases significantly with higher butanol ratios, reaching 48.6% by weight in W5DBu15, which can enhance combustion completeness and reduce soot formation. These findings confirm that increasing the butanol ratio within water-diesel emulsions affects all significant physicochemical properties. Understanding these changes is essential for optimizing the formulation and application of alternative fuels in compression ignition engines.

## Heating value

**Fig. 5** illustrates the heating value (HV) of diesel, butanol, and the WBD (water-butanol-diesel) fuel blends W5DBu5, W5DBu10, and W5DBu15. The results confirm that diesel has the highest heating value at 43.25 MJ/kg, followed by a gradual decrease in HV as the butanol proportion increases within the emulsified blends. Specifically, the heating values of the blends are 40.64 MJ/kg for W5DBu5, 40.20 MJ/kg for W5DBu10, and 39.75 MJ/kg for W5DBu15, while butanol alone has a significantly lower value of 33.1 MJ/kg. The observed reduction in HV directly results from blending with components with lower calorific content than diesel. W5DBu15 shows approximately an 8% decrease in heating value compared to pure diesel, notably less than the often-reported 10–15% range for pure butanol-diesel substitution. This moderate decline is attributed to the limited (15%) butanol addition in the fuel blend and the small amount of water (5%), which has no intrinsic energy content. Additionally, the presence of oxygen in the butanol and water molecules reduces the proportion of carbon and hydrogen, the main contributors to energy released during combustion.

Despite the energy content reduction, all WBD blends' heating values remain within an acceptable range for diesel engine operation. These values suggest that emulsified fuels can be utilized without substantially compromising engine thermal efficiency, particularly in light- to medium-load conditions. Moreover, oxygenated components may offer compensatory benefits regarding combustion completeness and emission reductions.

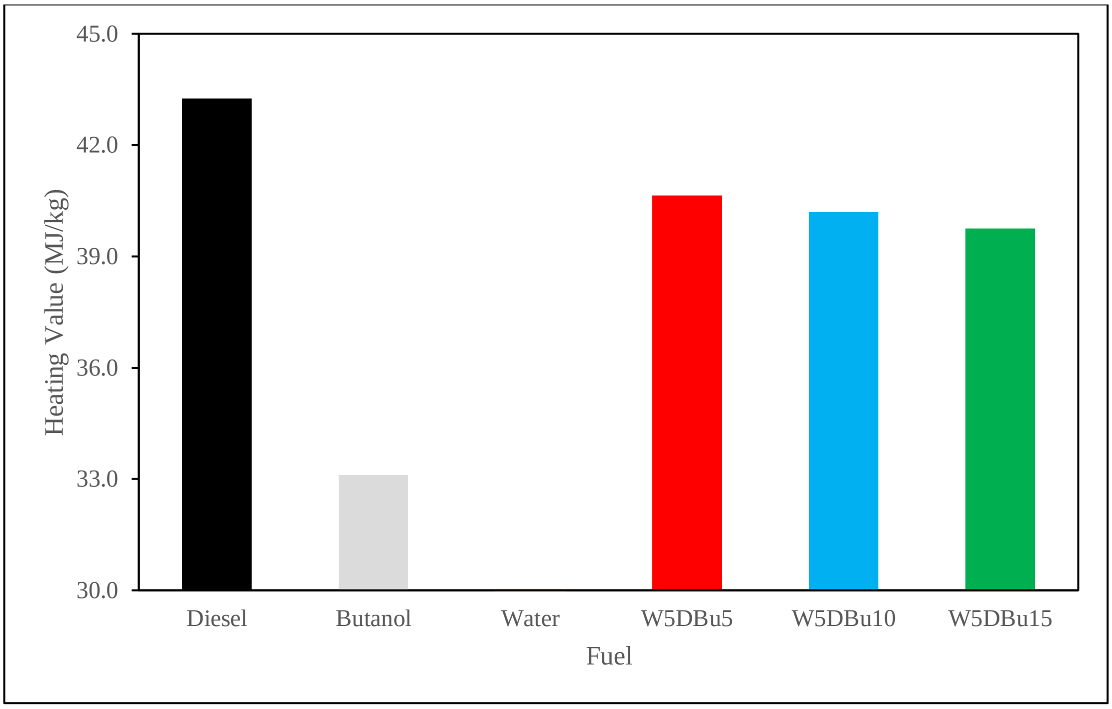

**Fig. 5.** Heating value of diesel, water and various blended fuels

### Cetane number

**Fig. 6** shows the variation in cetane number among diesel, butanol, and water-butanol-diesel (WBD) blends W5DBu5, W5DBu10, and W5DBu15. The cetane number (CN) is a critical indicator of the ignition quality of diesel fuels, reflecting how quickly and smoothly a fuel ignites under compression. A higher cetane number indicates shorter ignition delay, resulting in improved combustion efficiency, reduced engine knock, and lower emissions. The data shows pure diesel has the highest cetane number at 50, confirming its superior ignition properties. In contrast, butanol has a significantly lower cetane number of 25, which reflects its tendency to delay ignition. Non-combustible water does not contribute to the cetane value of the blends. The emulsified WBD fuels demonstrate intermediate cetane numbers: W5DBu5 at 46, W5DBu10 at 45, and W5DBu15 at 44. This gradual decline corresponds with the increasing proportion of butanol in the blend.

Although the cetane number decreases as the butanol concentration rises, the values remain within the acceptable range for diesel engine operation, especially in applications that tolerate moderate ignition delays. The reduction in cetane number is attributed to the lower reactivity of butanol and the dilution effect of water. However, this can also promote beneficial micro-explosion phenomena and improved air-fuel mixing, offsetting potential ignition delays under certain engine conditions. In summary, the cetane number trend in WBD blends highlights a trade-off between fuel reactivity and alternative component integration. Still, the blends, particularly W5DBu5 and W5DBu10, retain favourable ignition characteristics while offering potential environmental advantages.

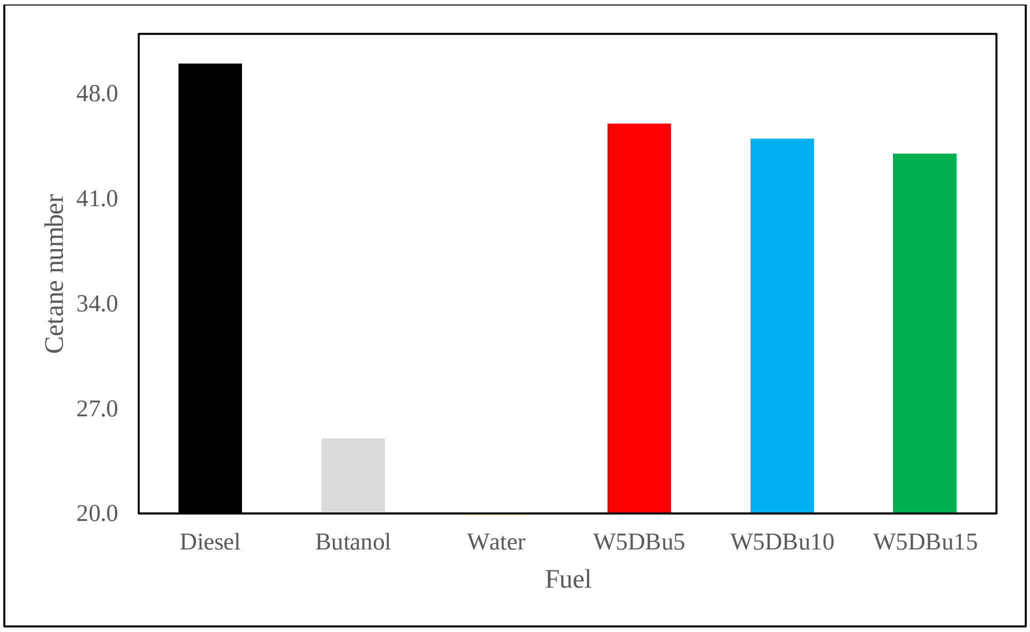

**Fig. 6.** Cetane number of diesel, water, and various blended fuels

### Specific heat capacity

**Fig. 7** illustrates the specific heat capacity (SHC) of diesel, butanol, water, and water-butanol-diesel (WBD) blends, namely W5DBu5, W5DBu10, and W5DBu15. Specific heat capacity refers to the amount of heat required to raise the temperature of a unit mass of a substance by one degree Celsius (J/kg·°C). A higher SHC indicates a greater capacity to absorb thermal energy before a temperature change occurs, critical in moderating combustion temperature and improving thermal stability in engine applications. As shown in the figure, water has the highest specific heat capacity at 4,182 J/kg°C, significantly exceeding that of butanol (2,390 J/kg°C) and diesel (1,850 J/kg°C). The WBD blends reflect intermediate values that gradually increase with the rising proportion of butanol: W5DBu5 at 2,001 J/kg°C, W5DBu10 at 2,036 J/kg°C, and W5DBu15 at 2,071 J/kg°C. This trend suggests combining water and butanol enhances the fuel's ability to absorb heat during combustion.

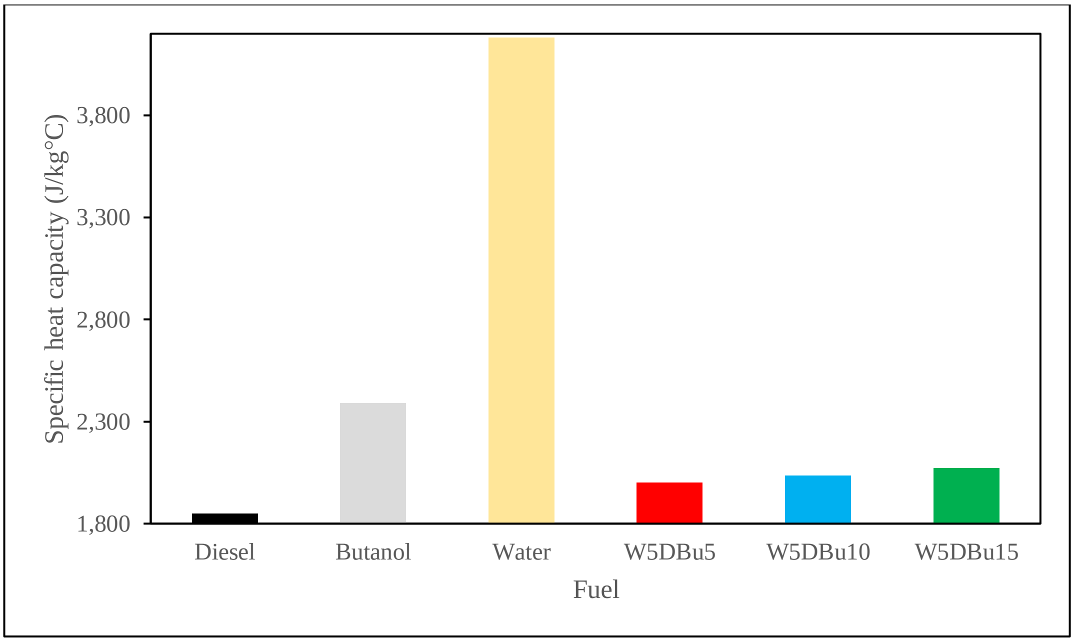

**Fig. 7.** Specific heat capacity of diesel, water, and various blended fuels

The increase in SHC with butanol addition provides thermal buffering, which may delay the peak combustion temperature and suppress the formation of thermal NOx. Although diesel has the lowest SHC, its high energy density supports rapid temperature rise and pressure development. Introducing components with higher SHC in the blend helps moderate combustion, reduces temperature spikes, and improves the control of in-cylinder conditions. In conclusion, the observed SHC behaviour of WBD blends demonstrates their potential for more stable and efficient combustion, particularly in applications aiming to reduce thermal stress and enhance the durability of engine components.

### Flash point

**Fig. 8** displays the flash point of diesel, butanol, water, and water-butanol-diesel (WBD) fuel blends W5DBu5, W5DBu10, and W5DBu15. The flash point refers to the lowest temperature at which a fuel can vaporize to form an ignitable mixture in the air. It is a critical safety and handling parameter for flammable liquids directly associated with ignition risk under ambient conditions. From the chart, diesel exhibits the highest flash point at 52°C, followed by W5DBu5 (49°C), W5DBu10 (48°C), and W5DBu15 (47°C). Butanol records a lower flash point at 35°C, indicating higher flammability, while water does not possess a flash point, as it is non-combustible in its natural state (Yusri, Mamat, Akasyah, Jamlos, & Yusop, 2019). The decreasing trend in flash points among the WBD blends corresponds with the increasing concentration of butanol, which inherently reduces the overall volatility threshold of the fuel mixture.

Although a reduction in flash point may imply an increase in ignition delay, this does not necessarily correlate with degraded engine performance. Longer ignition delays in emulsified fuels may facilitate enhanced atomization and micro-explosion phenomena, leading to finer droplet breakup and improved air-fuel mixing during combustion. The higher oxygen content in butanol and water may also promote more complete combustion and cleaner exhaust emissions. Therefore, while the slight reduction in flashpoints in WBD blends suggests the need for cautious storage and handling, the values remain within a safe operational range for diesel engines (Hagos, Aziz, & Tan, 2011; Thakkar, Kachhwaha, Kodgire, & Srinivasan, 2020). Combining ignition stability and combustion improvement mechanisms makes these blends viable from both safety and performance perspectives.

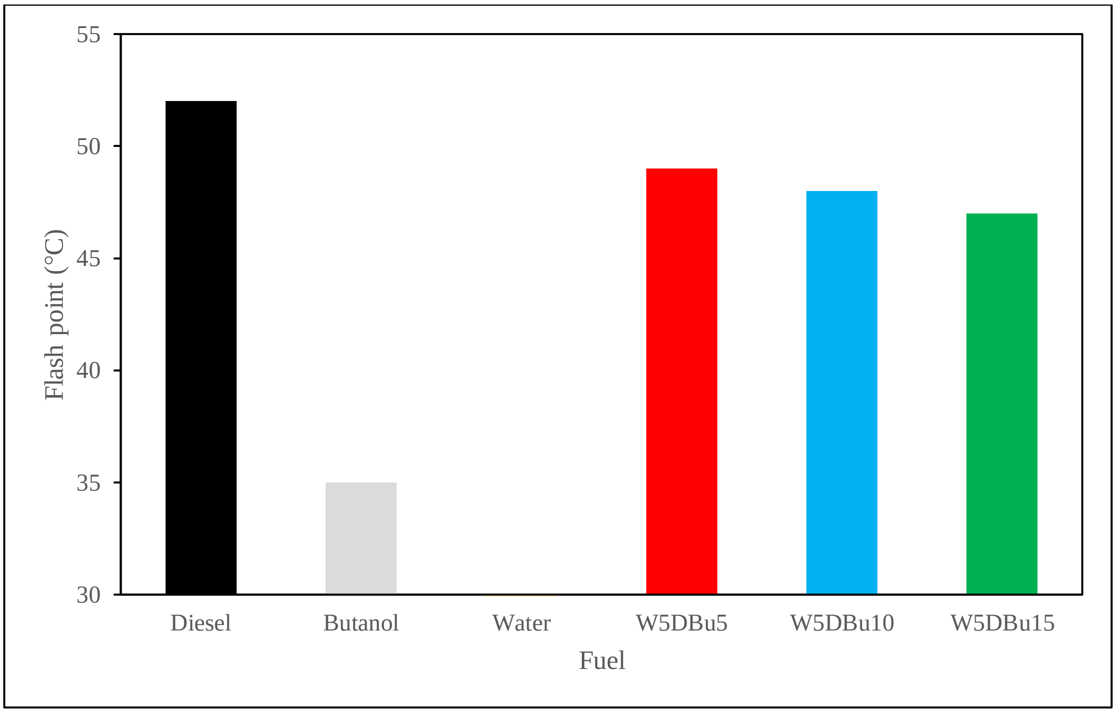

**Fig. 8.** Flash point of diesel, water and various blended fuels

### Oxygen content

**Fig. 9** presents the oxygen content (by weight percentage) of diesel, butanol, water, and water-butanol-diesel (WBD) fuel blends W5DBu5, W5DBu10, and W5DBu15. Oxygen content is crucial in evaluating fuel combustion behaviour, emissions profile, and overall engine efficiency. Fuels with inherent oxygen facilitate more complete combustion, reducing carbonaceous emissions and improving thermal performance. The graph shows that diesel fuel contains 0% oxygen, reflecting its hydrocarbon-based composition of only carbon and hydrogen atoms. In contrast, water exhibits the highest oxygen content at 89% due to its molecular structure ($H_2O$). Butanol contains 21.6% oxygen by weight, contributing significantly to the oxygenation of the fuel blends.

The WBD emulsified fuels display progressively higher oxygen content with increased butanol content: W5DBu5 at 46.9%, W5DBu10 at 47.7%, and W5DBu15 at 48.6%. These values represent a substantial increase in available oxygen compared to conventional diesel, offering the potential for enhanced oxidation reactions during combustion. The presence of oxygen within the fuel matrix supports more efficient combustion processes, leading to lower soot and CO emissions (Muhibbuddin, Muchlis, Syarif, & Jalaludin, 2025; S. M. Rosdi, Yasin, Khayum, & Maulana, 2025; Song, Quinton, Peng, Zhao, & Ladommatos, 2016). However, elevated oxygen levels, especially from water and alcohol components, can promote higher peak combustion temperatures. This may increase NOx formation if not controlled through optimized engine calibration or exhaust after-treatment technologies. Overall, the high oxygen content in WBD blends is a double-edged feature that can enable cleaner combustion and lower unburned hydrocarbon emissions while requiring careful control strategies to mitigate potential NOx increases.

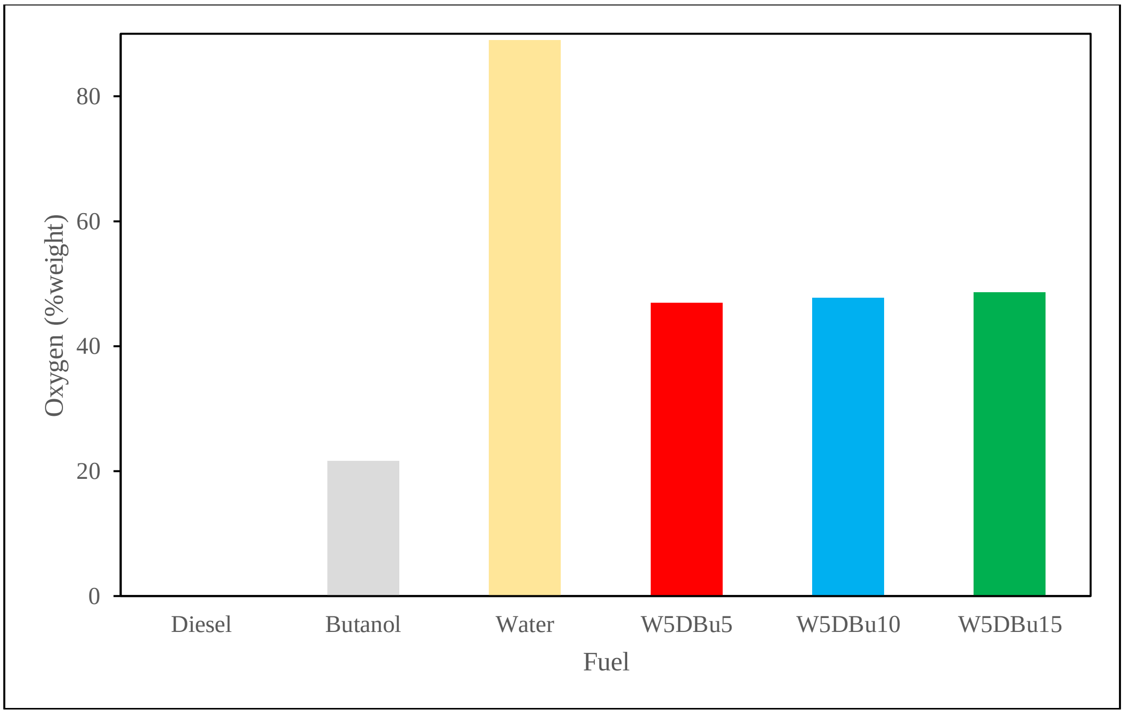

**Fig. 9.** Oxygen content of diesel, water, and various blended fuels

This study presents a novel integration of water-diesel emulsification with butanol as an oxygenated additive, offering a unique ternary blend that balances physical stability, combustion potential, and emission mitigation. Unlike many previous works that only explored binary blends (such as diesel-butanol or diesel-water separately), this research systematically examines the multi-parameter physicochemical behaviour of water-diesel-butanol (W5DBu) blends, including density, viscosity, heating value, cetane number, specific heat capacity, flash point, and oxygen content. The simultaneous presence of water and butanol in a single emulsified system creates a synergistic effect, enhancing combustion characteristics while promoting fuel economy and sustainability. Another novelty is using a constant HLB value of 10 for surfactant stabilization across all emulsified blends. This consistent emulsification strategy enables comparative analysis across different butanol concentrations while ensuring emulsion stability, as visually confirmed and experimentally validated in this study. The emulsions' visual uniformity and cream-like consistency (W5DBu5–15) highlight the effectiveness of the surfactant system, a parameter often overlooked in combustion-focused research.

From the data, it is evident that modifying butanol concentrations in water-diesel emulsions affects multiple performance-relevant properties in a quantifiable way. For instance, the increase in specific heat capacity and oxygen content suggests a fuel system that can absorb more heat and support cleaner combustion. Meanwhile, the slight reduction in cetane number and flash point remains within safe and operable limits for diesel engines, indicating that such blends are practically applicable without significant engine modifications. These insights are critical for future studies on low-emission fuel strategies and adaptive engine tuning. This work opens new research avenues for engine optimization of ternary emulsified fuels, particularly under varying load conditions, injection pressures, and ambient temperatures. Further development could include combustion chamber diagnostics (e.g., spray imaging, in-cylinder pressure analysis), emission characterization (PM, NOx, $CO_2$), and long-term engine durability studies. Moreover, the formulation strategy can include other bio-alcohols, advanced surfactants, or nanoparticles, paving the way for innovative fuel systems aligned with global decarbonization and renewable energy targets.

## 4. Conclusion

To evaluate their potential as alternative diesel fuels, this study successfully characterized the physicochemical properties of water-butanol-diesel (WBD) blended fuels, including W5DBu5, W5DBu10, and W5DBu15. The density of the blends decreased with increasing butanol content, with W5DBu5 showing a 1.0% reduction compared to pure diesel (from 827.5 to ~819 kg/m³). Kinematic viscosity remained within acceptable ranges, where W5DBu15 recorded the highest value at 2.7 mm²/s. Heating value declined as butanol increased, with W5DBu15 exhibiting approximately 15% lower energy content than base diesel. The cetane number, which indicates combustion quality, was highest in diesel and decreased in WBD blends, showing longer ignition delays. Water demonstrated the highest specific heat capacity, significantly above diesel, indicating a more significant heat absorption potential in emulsified blends. Flashpoint analysis revealed a downward trend from diesel to W5DBu15, suggesting changes in ignition safety, while butanol had the lowest flash point. In terms of oxygen content, diesel contained none. In contrast, water had 89%, and blended fuels had elevated oxygen levels due to butanol, enhancing combustion efficiency and potentially reducing harmful emissions. Overall, the W5DBu5 and W5DBu10 blends demonstrated balanced fuel properties, making them promising candidates for improved engine performance with reduced environmental impact.

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