Evaluation of Water-Diesel-Butanol Fuel Blends Under Varying Engine Conditions

Akasyah Mohd Khathri[1*], Che Haspu Robiah Daud[1], Muhammad Yusri Ismail[2], and Cristina Efremov[3]

[1]Department of Mechanical Engineering,
Politeknik Sultan Mizan Zainal Abidin,
KM 08, Jalan Paka, 23000 Kuala Dungun, Terengganu, Malaysia.

[2]Faculty of Mechanical and Automotive Engineering Technology,
Universiti Malaysia Pahang Al-Sultan Abdullah, 26600 Pekan, Pahang, Malaysia.

[3]Faculty of Mechanical Engineering and Transport,
Technical University of Moldova, 168 Stefan cel Mare Boulevard,
Chisinau, Republic of Moldova.

*Corresponding Author's Email: akasyah@psmza.edu.my

Article History: Received 12 April 2026; Revised 13 June 2026;
Accepted 14 June 2026; Published 30 June 2026

Abstract

Interest in alternative fuels for compression-ignition engines has grown as crude oil reserves decline and emission regulations become increasingly stringent. Water addition to diesel can reduce combustion temperature and induce microexplosion of fuel droplets, while n-butanol increases the oxygen content and further contributes chemical energy to the fuel blend. However, the effect of butanol concentration on the combustion behaviour of water-diesel emulsions under varying engine loads remains unclear. This study investigates the combustion characteristics of water-diesel-butanol blends across three engine loads, with a constant water fraction. Experiments were conducted using a four-cylinder, 3.0 L turbocharged Isuzu 4JJ1 common-rail diesel engine operated at 3000 rpm under 20%, 35% and 50% loads. Five fuels were tested including neat diesel (D), a water-diesel emulsion (W5D), and three ternary blends containing 5 vol.% water and 5, 10, and 15 vol.% n-butanol, denoted as W5DBu5, W5DBu10, and W5DBu15. The pressure traces were cycle-averaged, while the apparent heat release rate (HRR) and mass fraction burned (MFB) were calculated to evaluate combustion behaviour. Among the tested fuels, W5DBu15 exhibited the strongest combustion response with peak cylinder pressure and peak HRR reaching up to 7% and 21% higher than those of neat diesel, respectively. At low load, the MFB of the butanol-containing blends developed slightly later. However, this difference diminished as engine load increased. Overall, the findings of this study suggest that W5DBu10 provides a favourable balance between combustion intensity and stability, highlighting its potential for further evaluation as an alternative diesel fuel.

Keywords: Butanol, Combustion Analysis, Diesel Engine, Emulsion Fuel, Water Addition

1.0 Introduction

Road freight still depends heavily on diesel. This creates three main concerns. Petroleum reserves are limited, fuel prices change, and diesel exhaust damages the environment [2], [19]. Compression ignition (CI) engines remain common because of their efficiency, durability and high torque. Despite these advantages, their exhaust contains nitrogen oxides (NOx), carbon monoxide (CO) and particulate matter [3], [20]. Consequently, recent studies have examined alternative fuels that can be used in existing engines without hardware modification [1], [17]. Among these alternatives, alcohol-diesel blends have attracted because of their potential to reduce soot emissions. Ogunjide et al. [19] explained that lower soot formation in alcohol and diesel blends comes from the oxygen contained in alcohol molecules. Yilmaz et al. [3] reported similar results for higher alcohols. N-butanol is suitable for moderate blending without phase separation because of its heating value, diesel miscibility, cetane number and moisture resistance [2], [8], [20]. It has a heating value of about 33 MJ/kg and 21.6% oxygen by mass, making it more than a simple fuel diluent [1], [17]. Furthermore, its high latent heat of vaporisation delays ignition, leaving more fuel for premixed combustion and increasing peak cylinder pressure [1], [10], [18].

In contrast, water influences combustion differently through a predominantly cooling effect. Alahmer et al. [14] explained that dispersed water droplets absorb heat, reduce local flame temperature and consequently lower thermal Nox formation. Moreover, the droplets may cause microexplosion. Oliveira et al. [15] and El Nagy and Mohamed [16] explained that water inside a droplet becomes superheated before the surrounding diesel. Rapid vaporisation then breaks the original droplet into smaller droplets, providing more surface area for evaporation and mixing without modifying the injector. Nevertheless, when used alone, water would mainly dilute the fuel. When mixed with butanol, the added oxygen and fuel energy may balance the cooling effect, while microexplosion can enhance atomisation [5], [11].

Despite these reported mechanisms, previous studies have produced different results regarding combustion behaviour. Tipanluisa et al. [1] and Pullagura et al. [17] observed higher peak pressure with butanol addition. In contrast, Yu et al. [9] found lower pressure because of the alcohol's lower heating value and evaporative cooling. Likewise, different results have been reported for emulsified fuels. Oliveira and Brójo [13] and El Nagy and Mohamed [16] related higher pressure to microexplosion, while Mondal and Mandal [4] found that heat absorbed by water reduced peak pressure. These discrepancies may be attributed to differences in blend formulation and engine load. In particular, engine load affects the cylinder temperature and pressure history which can influence fuel evaporation, ignition and combustion behaviour [14], [19].

Although alcohol-diesel blends and emulsions of water in diesel have been widely studied, fewer studies have examined ternary blends containing a fixed water fraction with varying butanol content [11], [16], [20]. Published studies on ternary blends often incorporate biodiesel or another type of alcohol. For instance, Allasi et al. [7] combined n-butanol with algae biodiesel. Furthermore, many studies have been conducted using single-cylinder research engines at a single engine speed, making direct application to engines with several cylinders and common rail injection difficult [17], [18].

To address these gaps, this study investigated ternary diesel blends containing a fixed water fraction of 5 vol.% and varying n-butanol content from 5 to 15 vol.%. This formulation enabled the effect of increasing butanol content to be evaluated under a consistent water addition. Tests were conducted on a production four-cylinder, 3.0-litre turbocharged common-rail diesel engine, which is closer to a light commercial vehicle than a single-cylinder research engine. Cylinder pressure, heat release rate (HRR) and mass fraction burned (MFB) were compared at three engine loads to examine the effects of blend composition and operating condition. The novelty of this study lies in assessing fixed-water, variable-butanol ternary blends in a production multi-cylinder common-rail engine under varying load conditions. Accordingly, the objective of this study was to assess the combustion behaviour of these ternary blends under varying engine loads.

2.0 Methodology

Figure 1 illustrates the overall experimental workflow comprising two main stages which are fuel preparation and stability assessment, followed by engine testing and combustion-data analysis. Five fuels were prepared and evaluated for stability before being tested in the engine. The resulting combustion data were subsequently processed and compared to assess the effects of fuel composition and engine operating conditions.

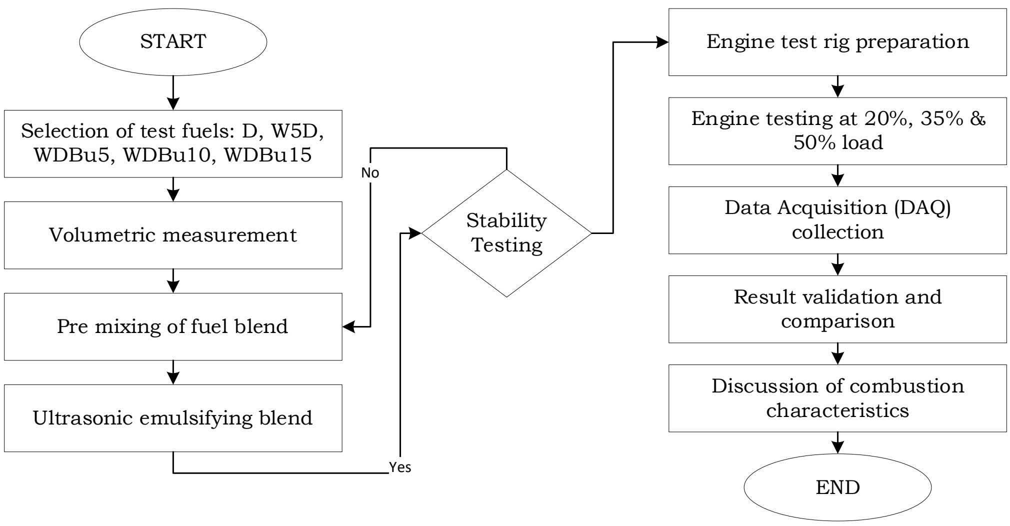


Figure 1: Experimental workflow for fuel preparation, stability assessment, engine testing and combustion-data analysis

2.1 Test Engine and Experimental Setup

The experiments were conducted using a four-cylinder, in-line, water-cooled Isuzu 4JJ1 diesel engine equipped with turbocharging, direct-injection and a common-rail fuel-injection system. The production engine was selected to provide combustion conditions representative of a modern multi-cylinder diesel powertrain, particularly in terms of turbocharged air intake and common-rail injection. This configuration also provides a practical comparison with previous alcohol-diesel studies that used single-cylinder research engines [1], [17]. The main specifications of the test engine are presented in Table 1.

Table 1: Specifications of the Isuzu 4JJ1 turbocharged test engine

Engine Parameter	Specification
Model	Isuzu 4JJ1 (turbocharged)
Type	4-cylinder, water-cooled, overhead valve, vertical in-line, direct injection
Bore	95.4 mm
Stroke	104.9 mm
Displacement	2.999 L
Number of cylinders	4, in-line
Compression ratio	17.5
Connecting rod length	150.0 mm
Piston pin offset	1.0 mm
Rated output	61.0 ± 3% kW at 2500 rpm
Maximum torque	280 ± 5% N·m at 1800 rpm
No-load maximum speed	2500 ± 10 rpm
Low idle speed	800 ± 10 rpm
Ignition system	Direct injection

The bore, stroke, connecting-rod length, piston-pin offset and compression ratio were used to determine the instantaneous cylinder volume required for the combustion analysis stage [1], [9]. The rated output and maximum torque were used as references for establishing the 20%, 35% and 50% engine-load conditions.

An eddy-current dynamometer was used to control the engine speed and load during testing. Figure 2 illustrates the test cell: engine and dynamometer, separate tanks for reference and test fuels, fuel flow meter, air-intake line, and a cooling-tower circuit. The adjacent control room carried the dynamometer panel, DEWECa and DEWESoft acquisition units and an exhaust-gas analyser. Crank-angle-referenced in-cylinder pressure came from a piezoelectric transducer [1], [6], [15].

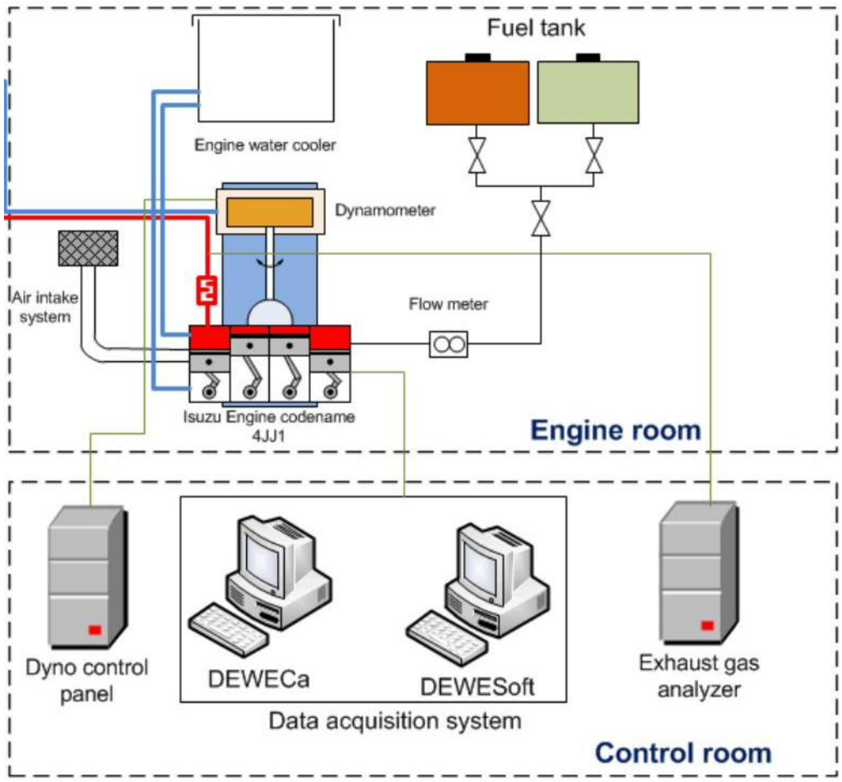


Figure 2: Schematic of the experimental test cell and measurement system

2.2 Fuel Blend Preparation

Five fuels were prepared and tested: neat diesel (D), a binary water-diesel emulsion (W5D), and three ternary water-diesel-n-butanol blends (W5DBu5, W5DBu10 and W5DBu15). The water content was fixed at 5 vol.% for all water-containing blends, while the numerical designation following "Bu" represents the n-butanol content of 5, 10 or 15 vol.%. The fuel compositions are presented in Table 2.

Table 2: Volumetric composition of the test fuels

Fuel	Diesel (vol.%)	Water (vol.%)	Butanol (vol.%)
D	100	0	0
W5D	95	5	0
W5DBu5	90	5	5
W5DBu10	85	5	10
W5DBu15	80	5	15

Two considerations determined these proportions. Mondal and Mandal [4] and Oliveira et al. [15] found that 5 vol.% water can trigger micro-explosion while limiting the heating-value penalty and separation risk; peak pressure and storage life deteriorate above about 10 vol.%. Butanol was capped at 15 vol.% to avoid injector or calibration changes. This limit also matches the blend ranges of Tipanluisa et al. [1], Fernández-Rodríguez et al. [2] and Pullagura et al. [17].

Blend preparation is shown in Figure 3. Diesel, water and butanol were measured in the Table 2 ratios into a sealed container and shaken by hand, then homogenised so that the water dispersed as fine droplets. Span 80/Tween 80 surfactant (HLB ≈ 6) was added at 2 vol.%, inside the 1-3 vol.% band reported as sufficient for a stable emulsion without excess residue [13], [15], [16]. Homogenisation turned the mixtures from clear to opaque milk-white, the appearance associated with a stable emulsion [16].

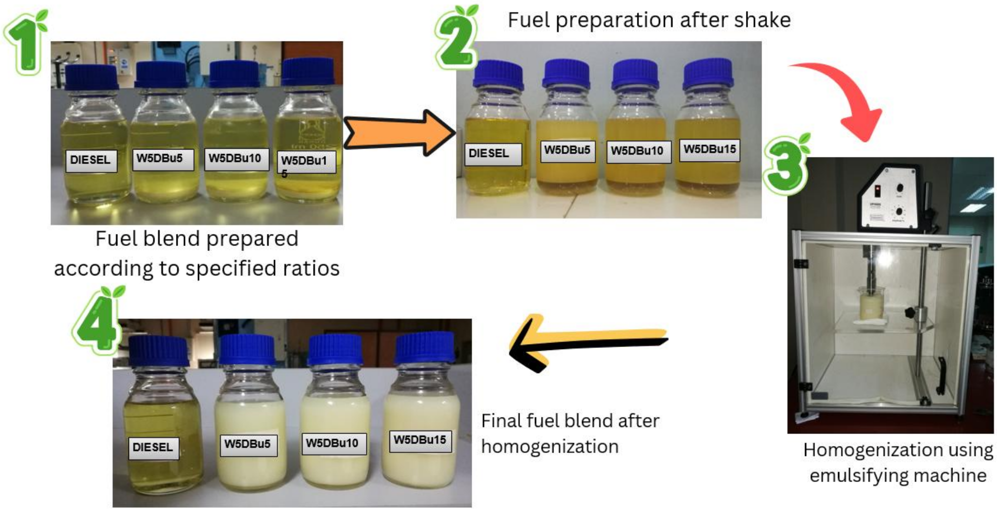


Figure 3: Fuel blend preparation process

2.3 Test Conditions and Combustion Analysis

Each fuel was run at 3000 rpm under 20%, 35% and 50% load, covering low, intermediate and medium-to-high operation. Part load was emphasised because the disagreement noted in Section 1 is sharpest there, where in-cylinder temperature is low enough for ignition delay and vaporisation penalties to dominate [14], [19]. Pressure was logged over consecutive cycles and cycle-averaged against cyclic variation [1], [6]. Apparent net heat release followed from the first-law, single-zone model of Equation (1) [1], [9].

$$dQ/d\theta = [\gamma/(\gamma - 1)]\, P\, (dV/d\theta) + [1/(\gamma - 1)]\, V\, (dP/d\theta) \quad (1)$$

Here $dQ/d\theta$ is net heat release rate per crank angle, P in-cylinder pressure, V instantaneous cylinder volume, θ crank angle and γ is the ratio of specific heats. The single-zone form requires only measured pressure and the geometry of Table 1, and is the formulation used by Tipanluisa et al. [1], Yu et al. [9] and Pullagura et al. [17]. Mass fraction burned (MFB) is obtained from Equation (2), normalising cumulative against total heat release.

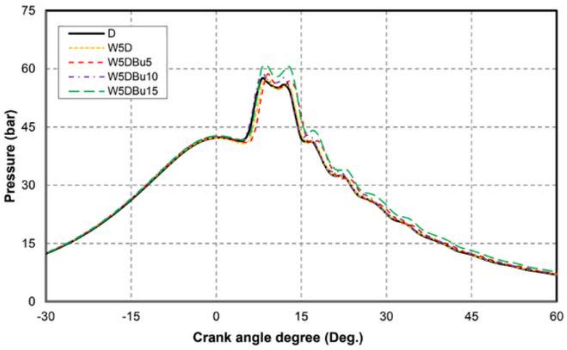
$$xb(\theta) = Q(\theta) \;/\; Qtotal \quad (2)$$

where $xb(\theta)$ is the mass fraction burned at a given crank angle, $Q(\theta)$ the cumulative heat released to that angle and Qtotal the total. Pressure, heat release rate and MFB describe combustion intensity, timing and completeness, respectively [6], [18].

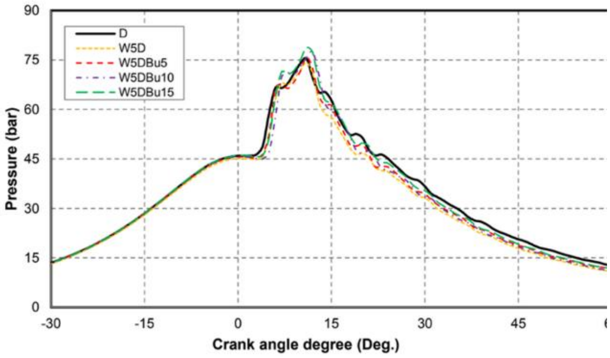
3.0 Results and Discussion

3.1 In-Cylinder Pressure

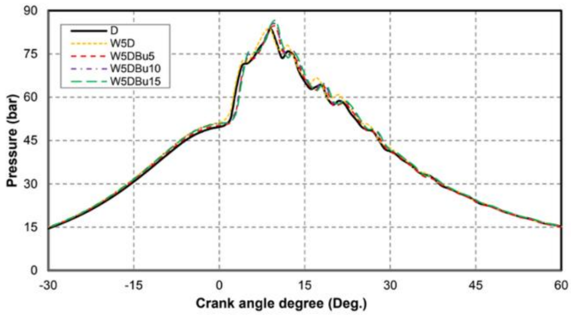
Figure 4 presents in-cylinder pressure against crank angle for the five fuels at each load. Peak pressure rose with load throughout, as more fuel and stiffer pre-ignition compression would suggest [1], [14]. The influence of fuel composition grew as butanol content increased.



(a)



(b)



(c)

Figure 4: In-cylinder pressure versus crank angle at (a) 20%, (b) 35%, and (c) 50% engine load

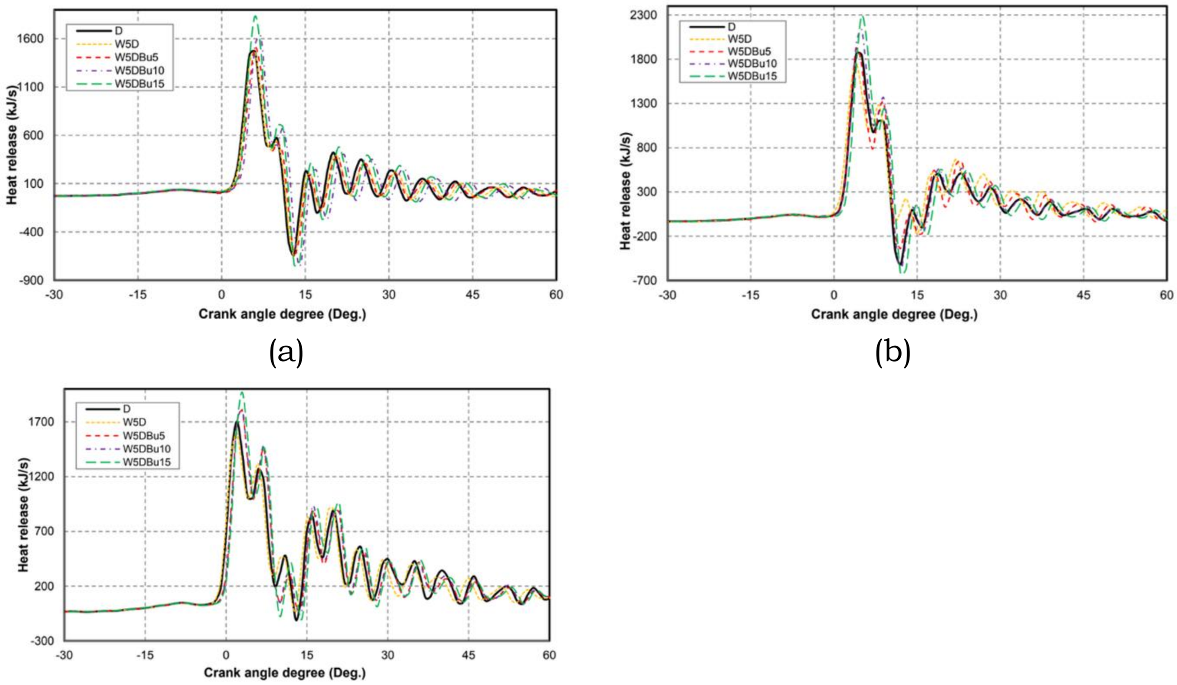
At 20% load, diesel peaked near 57 bar and W5DBu15 near 61 bar, about 4 bar or 7% higher (Figure 4(a)). Tipanluisa et al. [1] and Pullagura et al. [17] observed the same trend, relating it to fuel-bound oxygen and a longer ignition delay that increases premixed combustion near top dead centre. W5D instead peaked slightly below diesel, at about 56 bar, consistent with heat absorption by water [4], [14]. Oliveira and Brójo [13] and El Nagy and Mohamed [16] reported emulsion peaks above diesel. Droplet size and surfactant formulation may account for the difference because finer droplets undergo stronger micro-explosion [13], [16]. Here, water cooling and butanol enhancement appear to oppose one another, with the butanol effect clearer above about 10 vol.%.

At 35% load, W5DBu15 peaked near 78 bar and diesel near 74 bar, a 5% difference (Figure 4(b)). The smaller gap than at 20% load may reflect a warmer charge, shorter ignition delay and a smaller premixed fraction [1], [18]. The butanol-rich blends still burned later and for longer, as observed by Tipanluisa et al. [1] and Lapuerta et al. [10]. Yu et al. [9] and Shadidi and Allahyari [20] reported lower pressure with alcohol, but their blends contained at least 20 vol.%. At that level, the lower heating value may outweigh the premixed gain.

At 50% load, W5DBu15 reached roughly 87 bar and diesel about 83 bar (Figure 4(c)). The 4% difference was smaller, and the pressure curves were now more closely grouped. Once charge temperature is high enough, ignition delay is short for every fuel and phasing follows in-cylinder conditions rather than fuel chemistry [14], [19]. W5DBu10 and W5DBu15 nonetheless developed the strongest pressure, consistent with oxygenated and emulsified fuels burning more completely under fast-oxidation conditions [1], [4], [15].

3.2 Heat Release Rate

Figure 5 shows the apparent heat release rate (HRR) for each fuel and load. Because HRR follows the pace of energy conversion, it resolves the premixed and diffusion phases more finely than peak pressure does [6], [18].



(a) (b) (c)

Figure 5: Heat release rate versus crank angle at (a) 20%, (b) 35%, and (c) 50% engine load

At 20% load, Figure 5(a) puts the premixed HRR peak of W5DBu15 near 1,750 kJ/s against 1,500 kJ/s for diesel, a 17% jump against only 7% in peak pressure. Butanol therefore concentrates the release rather than enlarging it, consistent with the longer ignition delay described in Section 1 [1], [10], [17]. Late-burn oscillation is also visible. Yu et al. [9] and Ogunjide et al. [19] found similar behaviour at low load and high oxygenate content, suggesting a need for combustion control.

At 35% load, W5DBu15 reached about 2,290 kJ/s and diesel 1,900 kJ/s, a 21% increase (Figure 5(b)). W5DBu10 and W5DBu15 also exceeded W5D, showing that water alone did not cause the rise. Oliveira and Brójo [13] and El Nagy and Mohamed [16] mainly linked higher HRR to micro-explosion. In these tests, water seems to support mixing and later combustion, while the premixed peak grows with butanol content. The faster release would increase the pressure-rise rate, so injection timing may need adjustment for noise [6], [18].

At 50% load, W5DBu15 peaked near 1,880 kJ/s and diesel near 1,700 kJ/s, the smallest increase at 11% (Figure 5(c)). As with pressure, the benefit of a longer ignition delay diminished as load rose [14], [19]. Some late-phase oscillation remained but combustion still completed. Overall, more butanol produced a higher HRR peak at every load, consistent with reports for oxygenated CI-engine fuels [6], [12].

3.3 Mass Fraction Burned

Figure 6 plots MFB against crank angle, indicating the progress and completion of combustion [6], [18].

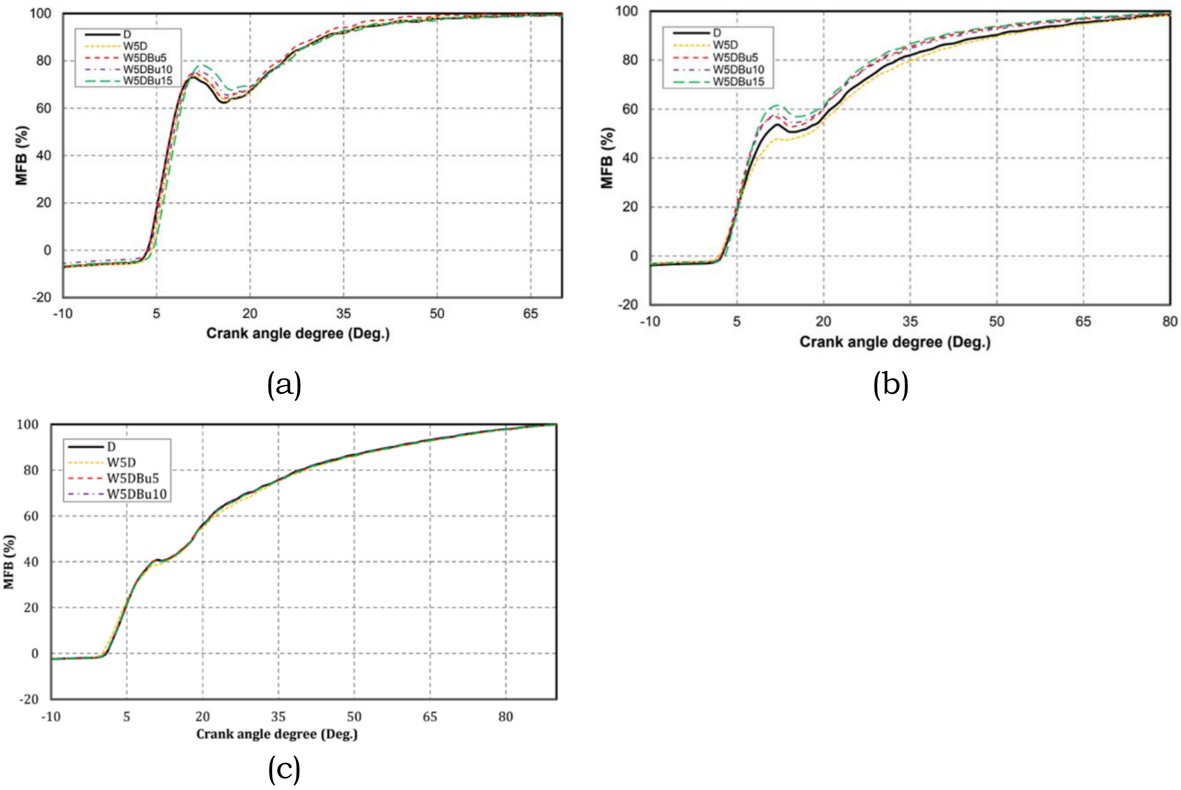


Figure 6: MFB development with crank angle at (a) 20%, (b) 35%, and (c) 50% engine load

At 20% load, diesel and W5D reached 50% MFB first, at about 6.5 crank angle degrees after top dead centre (Figure 6(a)); W5DBu10 and W5DBu15 required roughly 7.5 degrees. All fuels nevertheless completed combustion within about 60 degrees. The slower MFB rise of the butanol blends reflects the ignition delay described in Section 2.3 and produces a more gradual low-load burn [1], [10], [17].

At 35% load, the order became different. At 20 crank angle degrees, MFB was around 60% for W5DBu15, 55% for diesel and 50% for W5D (Figure 6(b)). The butanol blends reached 90% MFB about 5 to 7 degrees earlier than diesel. Previous studies linked shorter combustion with higher thermal efficiency and lower soot [3], [12]. Here, W5D extended the combustion period, while butanol shortened it. This shows that the additives did not work independently. Faster and hotter combustion may increase NOx [3], [12], but exhaust emission data are required.

At 50% load, the MFB curves nearly overlapped, with less than 2% difference at any crank angle (Figure 6(c)). At higher temperature and pressure, the cylinder condition was controlled combustion phasing and made the oxygenate effect less noticeable [14], [19]. The ternary blends therefore operated within this load range with only a small timing penalty, which is relevant to a light commercial engine [1]. All three diagnostics show the same pattern. Butanol sharpened combustion but delayed ignition by about one crank angle degree. With water fixed at 5 vol.%, cooling moderated pressure rise and micro-explosion aided mixing [4], [15], [16]. The fuel effect depended strongly on load: the maximum HRR gain was 21% at low-to-intermediate load and 11% at 50% load. W5DBu10 gave the best balance of pressure, heat release and stability, retaining most of the W5DBu15 gain without the same late-burn fluctuation. Several limits apply. Testing covered one speed and three loads, and neither brake thermal efficiency nor exhaust emissions were measured, both of which any environmental claim would require. Droplet size was also not measured, leaving its role in micro-explosion unresolved.

4.0 Conclusion

This study investigated the combustion characteristics of water-diesel-butanol blends at different engine loads while maintaining a constant water fraction. The results demonstrate that both engine load and n-butanol concentration influence combustion characteristics. Among the tested fuels, W5DBu15 produced the highest peak cylinder pressure and heat release rate with increases of up to 7% and 21%, respectively, compared with neat diesel. In contrast, W5DBu10 provided the most favourable balance between combustion intensity and stability across the tested operating conditions. Thus, these findings show that incorporating an appropriate proportion of water and n-butanol can modify the combustion behaviour of a common-rail diesel engine without hardware modification, highlighting the potential of these blends as alternative diesel fuels. Future studies should focus on brake thermal efficiency, exhaust emissions, fuel stability, long-term engine durability and injection-timing optimisation to establish their overall performance and operating limits. The results of this study provide a basis for further validation, scale-up and commercial evaluation of W5DBu10 as a potential alternative fuel for existing common-rail diesel applications.

Acknowledgements
The authors gratefully acknowledge Politeknik Sultan Mizan Zainal Abidin and Universiti Malaysia Pahang Al-Sultan Abdullah for their technical support and provision to access the engine test facilities. The authors also thank the colleagues and technical staff who assisted with the experimental work.

Author Contributions

Akasyah Mohd Khathri: Conceptualisation, Methodology, Investigation, Writing – Original Draft;
Che Haspu Robiah Daud: Data Curation, Validation, Writing – Review & Editing;
Muhammad Yusri Ismail: Supervision, Validation, Writing – Review & Editing;
Cristina Efremov: Formal Analysis, Writing – Review & Editing.

Conflicts of Interest

This manuscript has not been published elsewhere and is not under consideration by any other journal. All authors have read and approved the manuscript, consent to its submission, and confirm there are no conflicts of interest to declare.

References

[1] L. Tipanluisa, N. Fonseca, J. Casanova, and J. M. López, "Investigation of diesel/n-butanol blends as drop-in fuel for heavy-duty diesel engines: Combustion, performance, and emissions," *Energy Conversion and Management*, vol. 255, 115334, pp. 1–16, 2022, doi: 10.1016/j.enconman.2022.115334.

[2] D. Fernández-Rodríguez, M. Lapuerta, and L. German, "Progress in the use of biobutanol blends in diesel engines," *Energies*, vol. 14, no. 11, 3215, pp. 1–24, 2021, doi: 10.3390/en14113215.

[3] N. Yilmaz, F. M. Vigil, A. Atmanli, and B. Donaldson, "Detailed analysis of PAH formation, toxicity, and regulated pollutants in a diesel engine running on diesel blends with n-propanol, n-butanol, and n-pentanol," *Energies*, vol. 15, no. 17, 6487, pp. 1–17, 2022, doi: 10.3390/en15176487.

[4] P. Mondal and B. K. Mandal, "Effect of fuel injection pressure on the performances of a CI engine using water-emulsified diesel (WED) as a fuel," *Energy, Sustainability and Society*, vol. 14, no. 1, 15, pp. 1–14, 2024, doi: 10.1186/s13705-024-00442-7.

[5] A. I. EL-Seesy, M. S. Waly, A. Nasser, and R. M. El-Zoheiry, "Improvement of the combustion, emission, and stability features of diesel-methanol blends using n-decanol as cosolvent," *Scientific Reports*, vol. 12, 18963, pp. 1–20, 2022, doi: 10.1038/s41598-022-20326-0.

[6] J. Li, Z. Zhang, Y. Ye, W. Li, T. Yuan, H. Wang, Y. Li, D. Tan, and C. Zhang, "Effects of different injection timing on the performance, combustion and emission characteristics of diesel/ethanol/n-butanol blended diesel engine based on multi-objective optimization theory," *Energy*, vol. 260, 125056, pp. 1–15, 2022, doi: 10.1016/j.energy.2022.125056.

[7] H. L. Allasi, S. Murugan, H. K. Ananda, and D. Vairavel, "Enhancing diesel engine performance and emissions with n-butanol enhanced biodiesel derived from Scenedesmus obliquus algae," *Scientific Reports*, vol. 15, no. 1, 12924, pp. 1–18, 2025, doi: 10.1038/s41598-025-92369-y.

[8] A. S. Avcı and S. F. Yavaşoğlu, "Performance, combustion, emission and optimization characteristics of biodiesel–n-butanol blends enriched with Ni2O3 nanoparticles in a diesel engine," *Scientific Reports*, vol. 16, 2026, doi: 10.1038/s41598-026-36115-y.

[9] S. Yu, C. Cao, and W. Lv, "Combustion and emission characteristics investigation of a marine diesel engine powered by diesel/biodiesel/n-butanol blends," *Energy Science & Engineering*, vol. 10, no. 9, pp. 3317–3330, 2022, doi: 10.1002/ese3.1220.

[10] M. Lapuerta, Á. Ramos, J. Barba, and D. Fernández-Rodríguez, "Cold- and warm-temperature emissions assessment of n-butanol blends in a Euro 6 vehicle," *Applied Energy*, vol. 218, pp. 173–183, 2018, doi: 10.1016/j.apenergy.2018.02.178.

[11] L. Aguado-Deblas, F. J. López-Tenllado, D. Luna, F. M. Bautista, A. A. Romero, and R. Estévez, "Advanced biofuels from ABE (acetone/butanol/ethanol) and vegetable oils (castor or sunflower oil) for using in triple blends with diesel: Evaluation on a diesel engine," *Materials*, vol. 15, no. 18, 6493, pp. 1–19, 2022, doi: 10.3390/ma15186493.

[12] A. K. Azad, P. Halder, Q. Wu, M. G. Rasul, N. M. S. Hassan, and V. Karthickeyan, "Experimental investigation of ternary biodiesel blends combustion in a diesel engine to reduce emissions," *Energy Conversion and Management: X*, vol. 20, 100499, pp. 1–13, 2023, doi: 10.1016/j.ecmx.2023.100499.

[13] P. Oliveira and F. Brójo, "An experimental study on the performance and emissions of an 8% water-in-diesel emulsion stabilised by a hydrophilic surfactant blend," *Energies*, vol. 17, no. 6, 1328, pp. 1–20, 2024, doi: 10.3390/en17061328.

[14] H. Alahmer, A. Alahmer, M. I. Alamayreh, M. Alrbai, R. Al-Rbaihat, A. Al-Manea, and R. Alkhazaleh, "Optimal water addition in emulsion diesel fuel using machine learning and sea-horse optimizer to minimise exhaust pollutants from diesel engine," *Atmosphere*, vol. 14, no. 3, 449, pp. 1–21, 2023, doi: 10.3390/atmos14030449.

[15] P. Oliveira, F. Brójo, R. Serôdio, and J. Serôdio, "Investigation of water-in-diesel emulsion behavior formulated for performance conditions in a single-cylinder diesel engine," *Energies*, vol. 18, no. 4, 934, pp. 1–22, 2025, doi: 10.3390/en18040934.

[16] H. A. El Nagy and M. A. E. A. Mohamed, "Stable diesel microemulsion using diammonium ionic liquids and their effects on fuel properties, particle size characteristics and combustion calculations," *Scientific Reports*, vol. 14, 7728, pp. 1–18, 2024, doi: 10.1038/s41598-024-57955-6.

[17] G. Pullagura, J. R. Bikkavolu, S. Vadapalli, V. V. S. Prasad, K. R. R. Chebattina, D. Barik, and M. S. Dennison, "Performance, combustion and emission reduction characteristics of a diesel engine fuelled with n-butanol blended diesel fuel," *Heliyon*, vol. 10, no. 4, e26519, pp. 1–14, 2024, doi: 10.1016/j.heliyon.2024.e26519.

[18] A. Mylavarapu, R. Manikandan, M. Alwetaishi, and P. V. Elumalai, "Impact of butanol and hexanol on RCCI engine efficiency and emission characteristics using sapota oil methyl ester and response surface methodology," *Scientific Reports*, vol. 15, 2025, doi: 10.1038/s41598-025-11243-z.

[19] S. B. Ogunjide, W. J. Zhong, T. Pachiannan, Y. Z. Zhu, Z. He, and Q. Wang, "A review of combustion, performance and emissions characteristics of alcohol-diesel blends in compression ignition engines," *Results in Engineering*, vol. 25, 106768, pp. 1–25, 2025, doi: 10.1016/j.rineng.2025.106768.

[20] B. Shadidi and A. Allahyari, "A comprehensive review of C1–C6 alcohol-diesel blends: physicochemical properties, combustion characteristics, and advanced optimization techniques," *Green Chemistry Letters and Reviews*, vol. 19, no. 1, 2670811, pp. 1–30, 2026, doi: 10.1080/17518253.2026.2670811.