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

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## Abstract
Rising fuel demand, dwindling petroleum reserves and stricter emission limits have renewed interest in oxygenated and emulsified fuels for compression-ignition engines. Water-in-diesel emulsions moderate combustion temperature and drive secondary atomisation through micro-explosion, while butanol supplies fuel-bound oxygen and improves fuel-air mixing. The coupled behaviour of water and butanol in a single ternary blend, and its response to engine load, is still not fully resolved. This study aims to evaluate the combustion behaviour of water-diesel-butanol blends under varying engine loads in a four-cylinder, 3.0-litre turbocharged Isuzu 4JJ1 direct-injection diesel engine. Neat diesel, a water-diesel emulsion (W5D) and three ternary blends with a fixed 5% water fraction and 5%, 10% and 15% butanol (W5DBu5, W5DBu10 and W5DBu15) were tested at 3000 rpm under loads of 20%, 35% and 50%. In-cylinder pressure, apparent heat release rate and mass fraction burned were derived from the measured pressure trace. Butanol raised the peak pressure and sharpened the heat release through stronger premixed combustion, whereas the water fraction smoothed the pressure rise and lengthened the burn. At low load, the ternary blends ignited later but burned more completely, while at higher load the combustion phasing of all fuels converged. W5DBu10 gave the most balanced response, combining a strong pressure rise with stable, complete combustion at medium-to-high loads. These combustion outcomes indicate potential for improved efficiency and cleaner oxidation, but direct emission and brake-efficiency measurements are required before environmental benefits can be quantified. The findings confirm that carefully proportioned water-diesel-butanol blends can run in an unmodified diesel engine; future work should integrate performance and exhaust-emission measurements with injection-timing optimisation to exploit their efficiency potential.

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

## 1.0 Introduction
The continued reliance of the global transport sector on petroleum-derived diesel remains a pressing concern because of the finite nature of crude-oil reserves, the volatility of fuel prices and the environmental burden associated

with diesel combustion [2]. Compression-ignition (CI) engines are valued for their high thermal efficiency, durability and torque output, yet they are also significant emitters of nitrogen oxides (NOx), carbon monoxide (CO) and particulate matter [3]. These competing pressures have motivated extensive research into cleaner fuel alternatives that can be adopted without major engine modification, so that the existing vehicle fleet may benefit immediately [1].

Among the alternatives investigated, oxygenated fuels and fuel emulsions have attracted particular attention. Short-chain and higher alcohols supply oxygen within the fuel molecule, which promotes more complete oxidation and reduces soot formation [3], [7]. n-Butanol is an especially attractive candidate because, relative to ethanol and methanol, it offers a higher energy density, better blend stability with diesel, a higher cetane number and lower hygroscopicity, allowing it to be used at moderate fractions with minimal phase-separation problems [2], [8]. When added to diesel, butanol tends to extend the ignition delay and enlarge the premixed combustion phase, which alters the shape of the heat release and the peak in-cylinder pressure [1], [10]. Recent experimental studies on butanol-containing blends and comprehensive reviews of alcohol–diesel fuels further demonstrate that combustion behaviour, efficiency and emissions depend strongly on the alcohol fraction, engine load and combustion strategy [17], [18], [19], [20].

Water addition, usually in the form of a stabilised water-in-diesel emulsion, follows a different mechanism. The dispersed water droplets absorb heat and lower the local flame temperature, which suppresses thermal NOx formation, while the sudden vaporisation of the superheated water causes the surrounding fuel to disintegrate in a process known as micro-explosion. This secondary atomization improves fuel-air mixing and can enhance combustion completeness [4], [9]. Combining butanol and water in a single ternary blend is therefore appealing, as the oxygen enrichment from butanol and the thermal moderation and micro-explosion from water may act in a complementary manner [5], [11].

Nevertheless, the two additives influence the combustion process in opposing directions in several respects. Butanol can intensify the premixed burn, whereas water tempers the peak pressure and slows the reaction. The net outcome depends strongly on blend composition and the prevailing engine operating condition, particularly load, which governs the in-cylinder temperature and pressure history. Recent water-in-diesel studies continue to report a strong dependence of combustion and emissions on water fraction, surfactant formulation and load [13], [14], [15], while recent alcohol-diesel studies emphasise the importance of blend composition and injection strategy [7], [8], [16]. Few studies have systematically compared ternary water-diesel-butanol blends under varying loads using detailed combustion diagnostics. This constitutes the research gap addressed here.

The significance of this work lies in providing experimental evidence, from a modern common-rail turbocharged diesel engine, on how a fixed water fraction combined with increasing butanol content affects the combustion parameters that govern engine performance and emissions. Such information helps identify a practical blend that balances efficiency and combustion stability without hardware modification. Accordingly, the objective of this study is to evaluate the combustion behaviour of water-diesel-butanol blends under varying engine loads and speeds by analysing three key combustion parameters: the in-cylinder pressure, the heat release rate and the mass fraction burned.

## 2.0 Methodology

### 2.1 Test Engine and Experimental Setup

The experiments were carried out on a four-cylinder, in-line, water-cooled Isuzu 4JJ1 turbocharged diesel engine equipped with a direct-injection common-rail system. This engine is representative of light commercial vehicle powertrains and provides a stable platform for combustion analysis. The principal specifications of the engine are summarised in Table 1.

Table 1: Specifications of the Isuzu 4JJ1 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 engine was coupled to an eddy-current dynamometer that controlled the speed and load during each test. A schematic of the complete test cell is presented in Figure 1, comprising the engine, dynamometer, a fuel supply system with separate tanks for reference and test fuels, a fuel flow meter, an air-intake system and an engine water-cooling circuit served by a cooling tower. Instrumentation and data acquisition were housed in an adjoining control room, where the dynamometer control panel, the DEWECa and DEWESoft data-acquisition units and an exhaust-gas analyser recorded the operating and combustion data. The in-cylinder pressure was measured with a piezoelectric transducer referenced to the crank angle so that the combustion parameters could be computed.

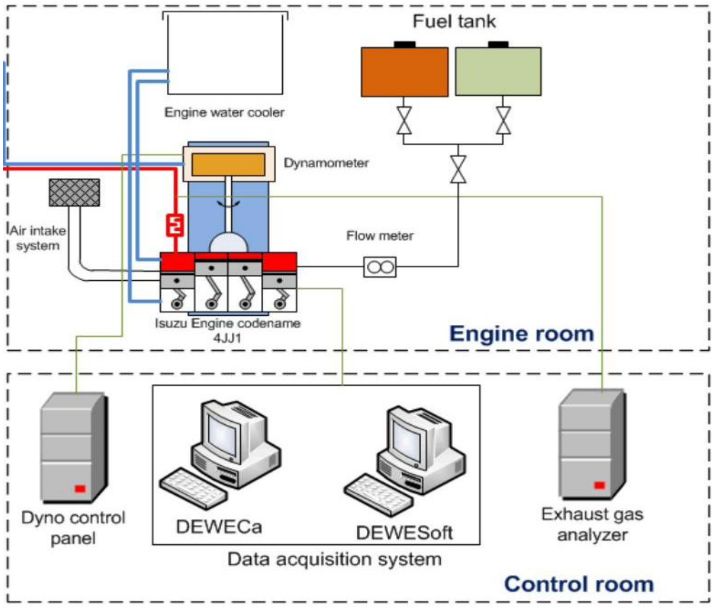



Figure 1: Schematic of the test cell for the experimental setup

## 2.2 Fuel Blend Preparation

Five fuels were prepared for comparison: neat diesel (D) as the baseline, a binary water-diesel emulsion (W5D), and three ternary water-diesel-butanol blends (W5DBu5, W5DBu10 and W5DBu15). In the adopted nomenclature, the leading term denotes the water content, fixed at 5% by volume, while the numeral following "Bu" denotes the butanol content of 5%, 10% and 15% by volume. The corresponding compositions are listed in Table 2. Holding the water fraction constant while increasing the butanol fraction isolates the influence of butanol on the combustion process.

Table 2: Composition of the tested fuel blends (by volume)

| 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 |

The blends were prepared following the sequence shown in Figure 2. Each fuel was first measured according to the specified volumetric ratio and combined in a sealed container. After manual shaking, the mixture was homogenised using an emulsifying machine to disperse the water phase finely within the diesel and to obtain a stable, milky emulsion. A surfactant blend of Span 80 and Tween 80 (HLB ~6) at 2% by volume was used to stabilise the emulsion. The photographs in Figure 2 illustrate the visual change from the clear initial mixtures to the uniform, opaque blends obtained after homogenization, confirming the formation of a stable emulsion suitable for engine testing.

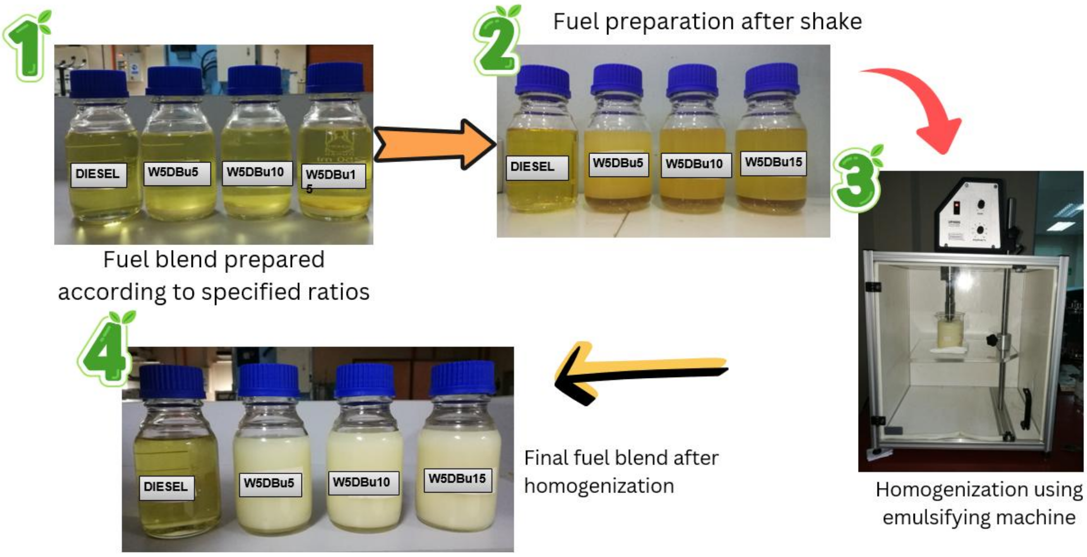



Figure 2: Stages of the fuel sample preparation process

### 2.3 Test Conditions and Combustion Analysis

All fuels were tested at a constant engine speed of 3000 rpm under three engine loads of 20%, 35% and 50%, which represent low, intermediate and medium-to-high operating conditions. For each test the in-cylinder pressure was recorded over successive engine cycles and averaged to reduce cyclic variation. The apparent net heat release rate was then obtained from the pressure data using the first law of thermodynamics for a single-zone combustion model [1], expressed in Equation (1).

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

where $dQ/d\theta$ is the net heat release rate per crank angle, P is the in-cylinder pressure, V is the instantaneous cylinder volume, θ is the crank angle and γ is the ratio of specific heats. The mass fraction burned (MFB) was subsequently determined by normalising the cumulative heat release against the total heat released during the combustion event, as given in Equation (2).

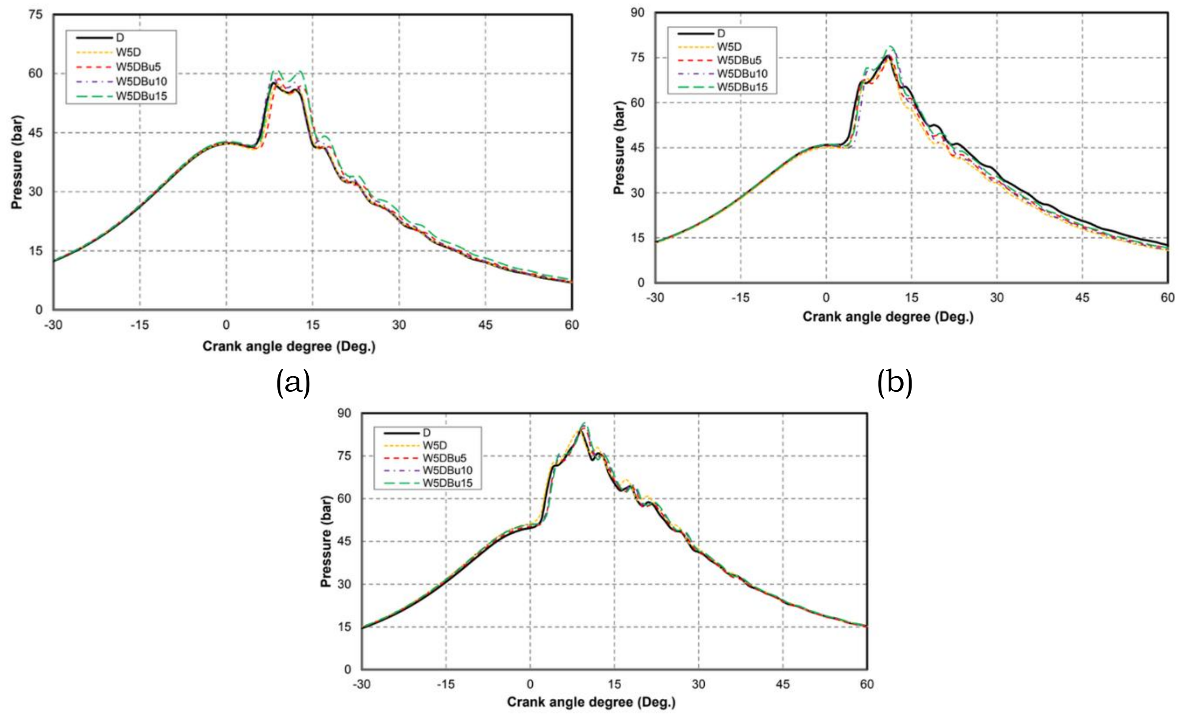
$$xb(\theta) = Q(\theta) \,/\, Qtotal \quad (2)$$

where xb(θ) is the mass fraction burned at a given crank angle, Q(θ) is the cumulative heat released up to that angle and Qtotal is the total heat released. Together, the in-cylinder pressure, heat release rate and mass fraction burned describe the intensity, timing and completeness of combustion and form the basis of the analysis that follows.

# 3.0 Results and Discussion

## 3.1 In-Cylinder Pressure

Figure 3 presents the in-cylinder pressure traces against the crank angle for all fuels at the three engine loads. As expected, the peak pressure increased with load for every fuel, since a higher load raises the quantity of fuel injected and the compression conditions before ignition. The influence of the fuel composition, however, became clearer as the butanol content increased.




(a) (b)

(c)

Figure 3: In-cylinder pressure versus crank angle at (a) 20%, (b) 35% and (c) 50% engine load

At the low load of 20%, the addition of butanol raised the peak in-cylinder pressure relative to neat diesel. From Figure 3(a), the peak for diesel is approximately 56 bar, whereas the highest-butanol blend, W5DBu15, reaches about 60 bar, an increase of roughly 4 bar (about 7%). The water fraction, in contrast, tended to soften the pressure rise and produced a smoother trace, consistent with its temperature-moderating role. The combined effect was a slightly delayed but more energetic combustion event, indicating that the ternary blends can sustain useful combustion even under the less favourable low-load condition.

At the intermediate load of 35%, butanol continued to intensify the premixed combustion and increase the peak pressure, while the water fraction moderated the peak and contributed to the micro-explosion behaviour that promotes finer atomisation. Figure 3(b) shows that W5DBu15 peaks near 78 bar compared with approximately 74 bar for diesel. The higher-butanol blends, W5DBu10 and W5DBu15, displayed a delayed but extended burn. This behaviour suggests that these blends are promising at intermediate load, although injection timing should be examined to accommodate the longer ignition delay.

At the medium-to-high load of 50%, the trends became most pronounced. Butanol raised the peak in-cylinder pressure and prolonged the burn, whereas water stabilised the combustion, smoothed the pressure rise and enhanced mixing through micro-explosion. In Figure 3(c), W5DBu15 reaches approximately 87 bar, compared with around 82 bar for diesel. The combined blends W5DBu10 and W5DBu15 therefore produced the strongest pressure development, with only a slight delay in the pressure rise. These observations are consistent with previous reports that oxygenated and emulsified fuels can improve combustion completeness at higher loads where the in-cylinder temperature favours rapid oxidation [1], [4], [15].

### 3.2 Heat Release Rate

The apparent heat release rate (HRR) profiles are shown in Figure 4. The HRR reflects the rate at which chemical energy is converted during combustion and is therefore a sensitive indicator of the influence of the fuel additives on the premixed and diffusion phases of the burn.

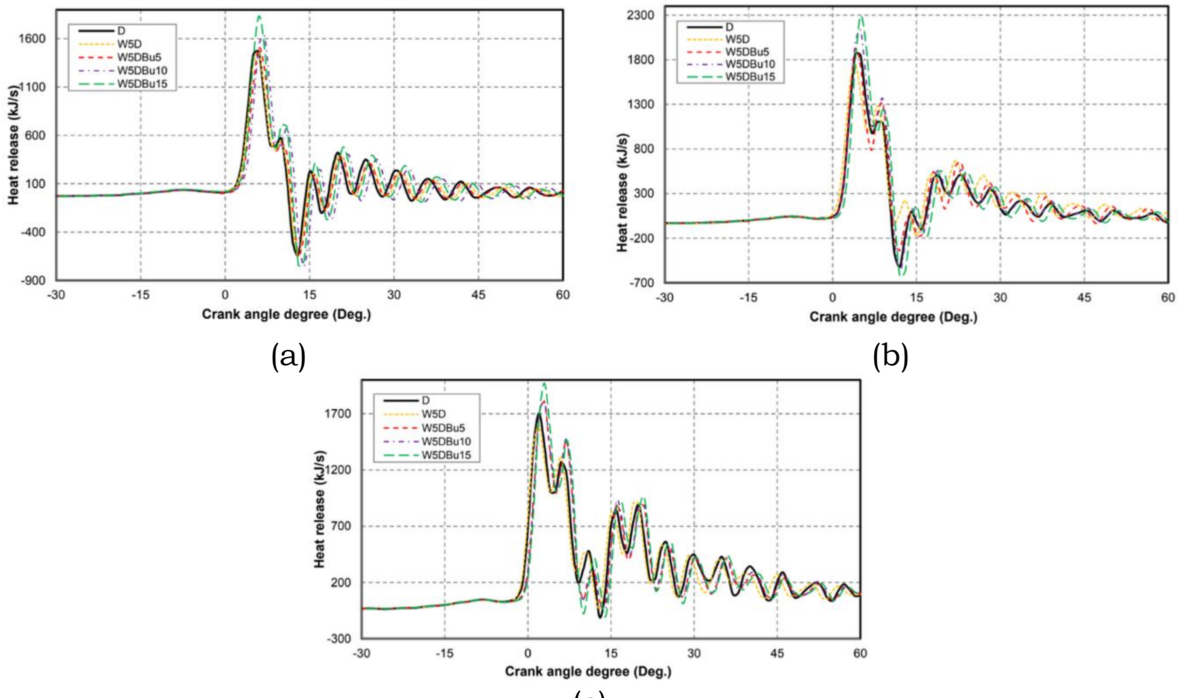



Figure 4: Heat release rate versus crank angle at (a) 20%, (b) 35% and (c) 50% engine load

At 20% load, water and butanol increased heat-release intensity, most clearly for W5DBu15. In Figure 4(a), its premixed HRR peak is approximately 1,800 kJ/s, compared with roughly 1,550 kJ/s for diesel. The combustion was sharper and more energetic, although a slight instability appeared during the late combustion phase. This indicates that low-load operation with high oxygenate content may require attention to the combustion-control strategy to maintain stable running.

At 35% load, the ternary blends, particularly W5DBu10 and W5DBu15, exhibited stronger premixed combustion and higher energy-release rates. The W5DBu15 peak in Figure 4(b) is approximately 2,250 kJ/s, compared with about 1,850 kJ/s for diesel. The extended ignition delay associated with butanol allows more fuel to be prepared before ignition, producing a more vigorous premixed burn. This points to efficiency potential, but also emphasises that injection timing must be managed carefully to control ignition delay and avoid excessive pressure-rise rates.

At 50% load, the W5DBu blends again showed higher and sharper heat release with improved premixed-combustion intensity, accompanied by a small and manageable reduction in late-phase stability. Figure 4(c) indicates a peak of approximately 1,950 kJ/s for W5DBu15, about 200 kJ/s above diesel. Overall, heat release became more intense as butanol content increased, confirming that butanol strengthens early combustion while water contributes to a smoother overall process. The trends agree with the general understanding that oxygenated additives enhance premixed heat release in CI engines [5], [8], [16].

## 3.3 Mass Fraction Burned

Figure 5 shows the mass fraction burned (MFB) curves, which describe the progress and completeness of combustion as a function of crank angle.

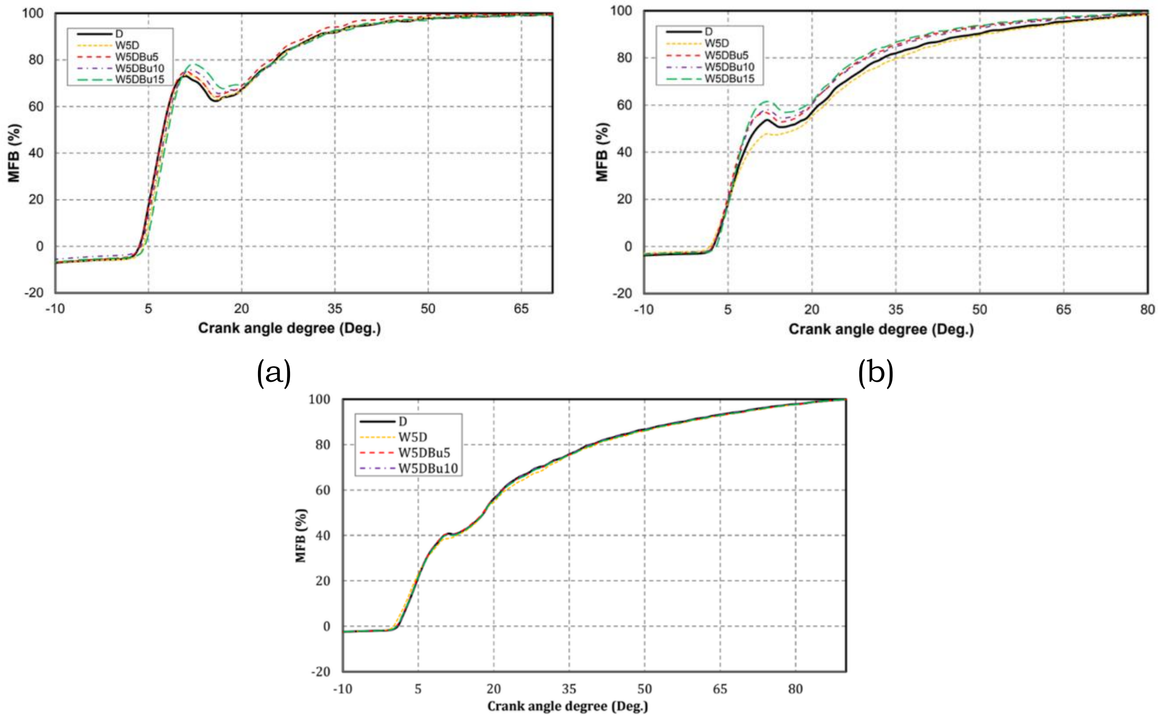



Figure 5: Mass fraction burned versus crank angle at (a) 20%, (b) 35% and (c) 50% engine load

At 20% load, neat diesel and the water-diesel emulsion began to burn earlier and reached completion more quickly, whereas the butanol-rich blends W5DBu10 and W5DBu15 ignited later but burned in a more complete and gradual manner. This gradual combustion is favourable for stability and cleaner burning at low load, though it reinforces the earlier observation that ignition timing may need adjustment to fully realize the efficiency benefit.

At 35% load, the MFB curves indicated that diesel and the water-diesel emulsion progressed steadily but relatively slowly, while the ternary blends, especially W5DBu10 and W5DBu15, achieved faster and more complete combustion owing to the extended ignition delay and improved premixing. The resulting reduction in burn duration is beneficial for thermal efficiency and for lowering soot formation, although the faster combustion may increase the tendency for NOx formation and therefore requires balanced control [3], [12].

At 50% load, all fuels, including the water-butanol blends, exhibited stable combustion with only negligible differences in burn duration and with complete combustion achieved within the normal crank-angle window. This convergence indicates that at medium-to-high load the in-cylinder pressure and temperature dominate the combustion phasing, so that the effect of the oxygenate content becomes less influential than at low load. The ternary blends are therefore fully viable in this operating regime with minimal penalty to combustion phasing or efficiency.

Taken together, the three combustion parameters give a consistent picture. Increasing the butanol content strengthens and sharpens combustion but slightly delays ignition, while the fixed water fraction moderate's temperature, smooths the pressure development and improves mixing through micro-explosion. The load exerts a strong overriding influence, the fuel effect being most pronounced at low and intermediate load and diminishing at higher load. Across the range examined, W5DBu10 offered the most favourable compromise between pressure development, heat release and combustion stability, and is identified as the most balanced blend for medium-to-high load operation.

## 4.0 Conclusion

The combustion characteristics of water–diesel–butanol blends were successfully evaluated based on in-cylinder pressure, heat release rate (HRR) and mass fraction burned (MFB). The results demonstrate that engine load was the dominant factor governing combustion behaviour, with higher loads producing higher peak cylinder pressure, faster heat release and more complete combustion. The incorporation of butanol enhanced premixed combustion and combustion intensity, although it slightly prolonged the ignition delay. Meanwhile, the addition of water moderated the combustion process through the micro-explosion effect, promoting improved fuel–air mixing and more stable combustion. Among the tested fuels, the W5DBu10 blend exhibited the most favourable combustion characteristics, providing the best balance between combustion pressure, heat release and stability, particularly under medium-to-high engine loads. Overall, the findings indicate that appropriately formulated water–diesel–butanol blends can be utilised in an unmodified diesel engine while maintaining favourable combustion performance. Future studies should investigate engine performance, exhaust emissions and injection timing optimisation to further improve the efficiency and environmental benefits of these fuel blends.

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## Author Contributions

**Akasyah M. K.**: Conceptualisation, Methodology, Investigation, Writing – Original Draft Preparation; **Che Haspu Robiah Daud**: Data Curation, Validation, Writing – Review & Editing; **Muhammad Yusri Ismail**: Supervision, Validation, Writing – Review & Editing.

## Conflicts of Interest

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

## Declaration of Generative AI Usage

During the preparation of this manuscript, the authors used Claude AI (Anthropic) to assist with language refinement, paraphrasing and formatting of the text. After using this tool, the authors reviewed and edited the content as required and take full responsibility for the content of the published article. No data, results or references were generated by the tool.

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