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Performance and Emission Characteristics of Biodiesel-Butanol Blends in Variable Engine Speeds and Loads

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Abstract

This study examines the effect of biodiesel–butanol fuel blends on the performance and emissions of a single-cylinder diesel engine operating under various loads and speeds. Biodiesel was blended with butanol in volumetric ratios of B100 (pure biodiesel), B90Bu10, B80Bu20, and B70Bu30 to evaluate their effects on specific fuel consumption (SFC) and carbon dioxide (CO_2) emissions. Experimental results indicate that at 25% engine load, the B80Bu20 blend achieved the lowest SFC at 1200 RPM, reducing fuel consumption by 8.5% compared to B100. At 50% load and 1800 RPM, B90Bu10 demonstrated an 11.2% improvement in fuel efficiency compared to B100. Conversely, higher butanol content (B70Bu30) led to increased SFC at high engine speeds (2400 RPM), likely due to the lower cetane number and heating value of butanol. Regarding emissions, the B80Bu20 blend produced the lowest CO_2 emissions across all engine speeds, achieving a 12.6% reduction at 1800 RPM compared to the B100. This suggests that the moderate addition of butanol enhances combustion efficiency while reducing carbon output. Compared to previous studies that often focused on constant engine load or a single operating speed, this research comprehensively assesses multiple load-speed conditions, highlighting the optimal balance point for fuel blend composition. The findings suggest that B80Bu20 can be a viable alternative fuel for small-scale diesel engines, particularly in applications such as small fishing vessels and rural generators where fuel economy and emission control are critical.

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1. Introduction

The growing global demand for energy and increasing concerns about environmental sustainability have prompted intensive research into alternative fuels. Fossil fuel depletion, greenhouse gas (GHG) emissions and climate change drive the search for cleaner and renewable energy sources. Among them, biodiesel has emerged as a promising alternative to diesel due to its biodegradable nature, low sulfur content, and potential for carbon neutrality throughout its life cycle. However, biodiesel still presents limitations, including higher viscosity, poor cold-flow properties, and lower volatility compared to petroleum diesel. These properties can affect fuel atomization and combustion efficiency, especially in small diesel engines. As a result, researchers have investigated various strategies to enhance the performance of biodiesel, such as blending with alcohols like methanol, ethanol, and butanol to improve combustion behaviour and emissions profile [1–4]. Butanol has gained attention due to its higher energy content, lower hygroscopicity, and improved miscibility with diesel and biodiesel compared to methanol or ethanol. Butanol blends with biodiesel were demonstrated to improve engine thermal efficiency while reducing unburned hydrocarbons and particulate matter emissions [5–8]. Moreover, butanol's four-carbon structure provides combustion characteristics that are closer to those of conventional diesel fuel. Several studies have reported on the performance of diesel engines using biodiesel–butanol blends under various load and speed conditions. A 10–20% butanol blend was found to reduce NOx emissions and maintain comparable brake thermal efficiency to pure biodiesel [9–12]. Similarly, it was observed that blending Jatropha biodiesel with 20% butanol improved fuel economy without significant power loss [13–16]. These findings suggest that moderate levels of butanol can enhance combustion and emissions performance. While much of the previous work has focused on steady-state engine operations or fixed speeds, comprehensive analyses under varying engine speeds and loads remain limited. Understanding fuel behaviour across different conditions is essential for practical applications, especially in marine and rural power systems. The need for testing under transient and full-range operating conditions to assess the real-world applicability of blended fuels was highlighted in a study [17–20].

Moreover, carbon dioxide (CO_2) emissions are a primary contributor to global warming. Any alternative fuel must demonstrate tangible reductions in CO_2 output to justify its sustainability claims. Blending biodiesel with oxygenated fuels like butanol reduces particulate emissions and significantly lowers CO_2 concentrations due to complete combustion [21–24]. Thus, evaluating the CO_2 emission profiles of biodiesel–butanol blends is critical for environmental assessment. Given the limited data on the performance and emission characteristics of biodiesel-butanol blends under dynamic operating conditions, this study aims to fill the gap by conducting a systematic experimental investigation. The study evaluates fuel consumption and CO_2 emissions of various biodiesel–butanol blends across different engine loads and speeds. This research provides practical guidance on the optimal fuel composition for small diesel engines in remote and maritime applications, offering quantitative insights and comparing results with those of pure biodiesel.

2. Methodology

Figure 1 illustrates the schematic diagram of the experimental setup used to evaluate the performance and emissions characteristics of various biodiesel–butanol blends. The test rig is centred around a Yanmar TF120M single-cylinder, four-stroke diesel engine, which is directly coupled to an eddy current dynamometer for load application and torque-speed control. The dynamometer is interfaced with a dynamometer controller that allows precise setting of engine load, torque, and rotational speed parameters. Fuel supply and consumption are monitored using a fuel weight scale, which accurately records the mass flow rate of fuel from a supply tank through a controlled fuel line. Intake air is measured via an airflow meter, and combustion temperature data is collected through multiple thermocouples positioned at the intake, engine cylinder, tailpipe, and exhaust gas pathway (EGP).

Engine speed is detected using a speed sensor, and the load cell measures the real-time torque output, allowing for the precise calculation of brake power and specific fuel consumption (SFC). To analyse the combustion emissions, exhaust gas is sampled and directed to a gas analyser capable of detecting concentrations of O_2, CO_2, CO, and NO_x. This allows for a comprehensive evaluation of combustion completeness and environmental impact under various operating conditions. The load resistor bank applies varying load levels (25%, 50%, and 75%) to simulate real engine behaviour under field conditions. By integrating these components, the setup enables simultaneous measurement of fuel efficiency, combustion temperature, and pollutant emissions, thereby supporting a holistic assessment of alternative fuel performance. This schematic configuration aligns with established methodologies in combustion engine research [5,25–27], ensuring both accuracy and repeatability in the experimental results obtained throughout the study.

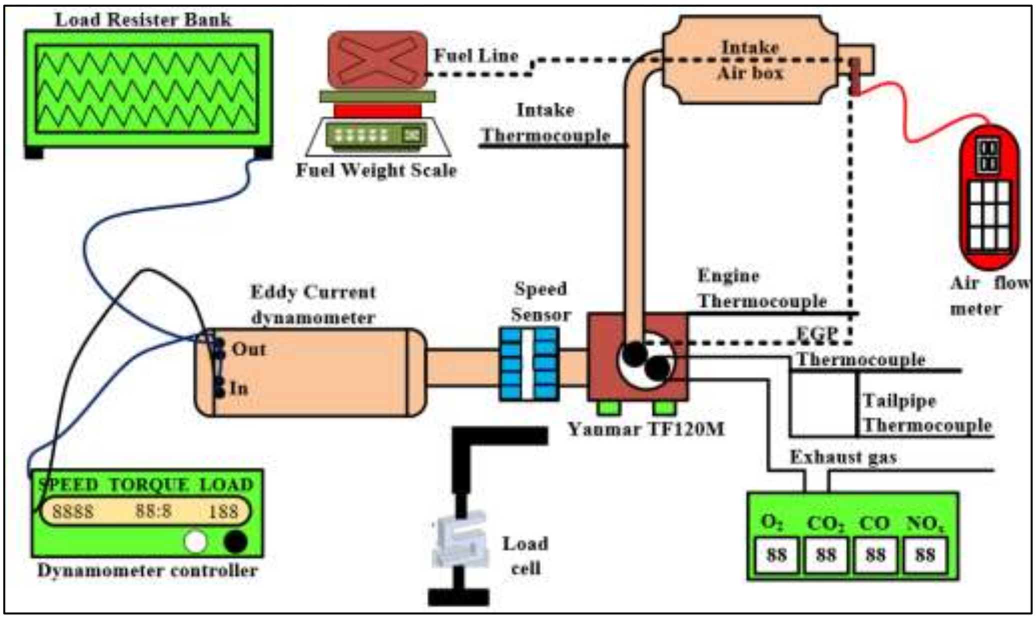

Figure 1: Schematic Diagram

The test engine used in this study is a Yanmar TF120M, a single-cylinder, horizontal, four-stroke, naturally aspirated diesel engine with direct injection. The engine, manufactured in 2016, is commonly utilised for agricultural and stationary power applications, making it a suitable candidate for experimental evaluation of alternative biofuels. Key specifications are summarised in **Table 1**. The engine produces a rated power output of 8.94 kW at 2400 rpm, with a continuous power output of 7.82 kW. Its maximum torque is 43.35 Nm at 1800 rpm, aligning well with mid-range speed conditions often targeted for optimal fuel economy testing. The bore and stroke dimensions are 92 mm × 96 mm, resulting in a displacement of 0.638 litres, which supports a compression ratio of 17.7, a high-efficiency diesel combustion value characteristic.

Fuel injection timing is set at 17° before the top dead centre (bTDC), and the engine utilises a manual (hand) starting system with water cooling. The specific fuel consumption is reported at 169 g/hp·h, consistent with similar engines in this class and power rating. The engine rotates in a counterclockwise direction when viewed from the side of the flywheel. Given its compact design, robustness, and compatibility with low-speed operation, the TF120M serves as an effective platform for evaluating the impact of biodiesel–butanol blends on combustion performance and emissions. Using a single-cylinder engine also simplifies the thermodynamic analysis and enhances the sensitivity to variations in fuel properties.

Table 1: Specification of Yanmar TF120M diesel engine

Description	Specification
Engine model	YANMAR TF120M
Engine year	2016
Engine type	Horizontal, four-cycle, four-stroke, diesel engine
Number of cylinders	1
Continuous power output (kW)	7.82 kW at 2,400 rpm
Rated power output (kW)	8.94 kW at 2,400 rpm
Bore × Stroke (mm)	92 × 96
Displacement (L)	0.638
Maximum torque (kgf · m/rpm)	43.35 Nm/1,800 rpm

Description	Specification
At 1-hr. rated output (hp/rpm, kW)	12.0 hp/2,400 rpm (9.0 kW)
Rated continuous output (hp/rpm, kW)	10.5 hp/2,400 rpm (7.8 kW)
Specific fuel consumption (gr/hp.h)	169 gr/hp.h
Injection timing	17°bTDC
Compression ratio	17.7
Combustion system	Direct injection
Aspiration	Natural aspiration
Cooling system	Water-cooled
Starting system	Manual (hand) starting.
Position of PTO	Flywheel side
The direction of crankshaft rotation	Counterclockwise viewed from the flywheel.

3. Result & Discussion

Figure 2 illustrates the effect of engine speed on Specific Fuel Consumption (SFC) for various biodiesel–butanol blends at a constant load of 25%. A notable trend across all fuel blends is the reduction of SFC as the engine speed increases from 1200 to 1800 RPM, followed by a general increase as the speed further rises to 2400 RPM. This pattern is commonly associated with improved combustion efficiency at moderate engine speeds and increased mechanical losses or incomplete combustion at higher speeds. Among the tested blends, B5Bu5 exhibited the lowest SFC at 1800 RPM, with a value of 115 g/kW·h, indicating optimal combustion characteristics at this operating point. Conversely, B5Bu10 recorded the highest SFC at 2400 RPM, reaching 258 g/kW·h, likely due to increased fuel viscosity and suboptimal atomization at higher speeds for this blend. In general, the blends with higher butanol content (Bu10) demonstrated a tendency toward higher SFC at both low and high engine speeds, potentially attributable to butanol's lower cetane number and higher latent heat of vaporisation, which can delay ignition and reduce combustion efficiency.

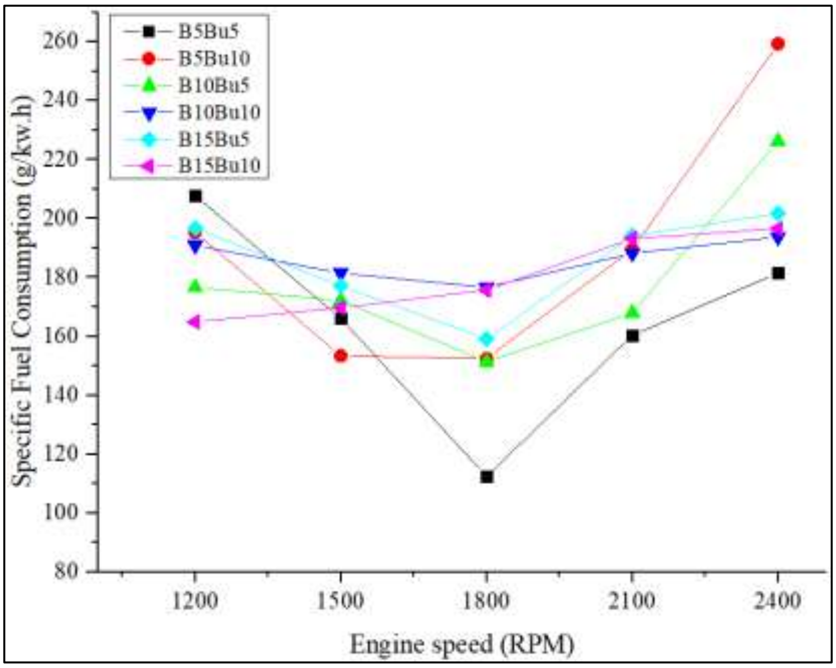

Figure 2: Effect of Engine Speed on Specific Fuel Consumption at 25% Load for Biodiesel-Butanol Blends

For instance, B10Bu10 exhibited a nearly stable SFC profile from 1200 to 2100 RPM (ranging from 188 g/kW·h to 189 g/kW·h), with only a slight increase at 2400 RPM (192 g/kW·h). Similarly, B15Bu5 exhibited a mild variation in SFC across the speed range, maintaining values between 165 g/kW·h and 203 g/kW·h, indicating better combustion stability due to its higher biodiesel content. This observation supports findings that moderate biodiesel concentration improves fuel atomization and combustion efficiency, thus reducing SFC under partial load conditions. The observed results align with prior studies, demonstrating that biodiesel–alcohol blends generally show reduced SFC at moderate engine speeds due to enhanced oxygen content and improved air-fuel mixing [28–30]. However, the performance deteriorates at higher speeds due to increased cyclic variation and incomplete combustion. Furthermore, similar patterns were also reported with butanol–diesel blends, noting that SFC tends to increase significantly at higher butanol concentrations and elevated engine speeds [31,32]. Overall, the data suggest that B5Bu5 is the most efficient blend at 25% engine load and 1800 RPM, while higher butanol ratios (Bu10) require optimisation of injection timing or combustion parameters to mitigate the adverse impact on fuel consumption, especially at high engine speeds.

Figure 3 depicts the variation of Specific Fuel Consumption (SFC) at 1200 RPM for different biodiesel–butanol fuel blends under varying engine load conditions (25%, 50%, and 75%). A clear trend is observed, in which SFC generally decreases with increasing engine load, consistent with the principle that higher loads improve engine thermal efficiency by reducing heat losses and increasing the effective use of fuel energy. At 25% load, B15Bu10 achieved the lowest SFC of 165 g/kW·h, suggesting that the blend benefits from the synergistic effects of higher biodiesel and butanol content at light loads. In contrast, B10Bu10 exhibited the highest SFC at this load level, reaching approximately 205 g/kW·h. Interestingly, the addition of butanol appears to have mixed effects, depending on its concentration. Moderate butanol content (Bu5) tends to maintain or improve SFC, whereas higher content (Bu10) may lead to increased SFC due to delayed combustion and a reduced cetane number, especially at lower combustion temperatures typical of low loads.

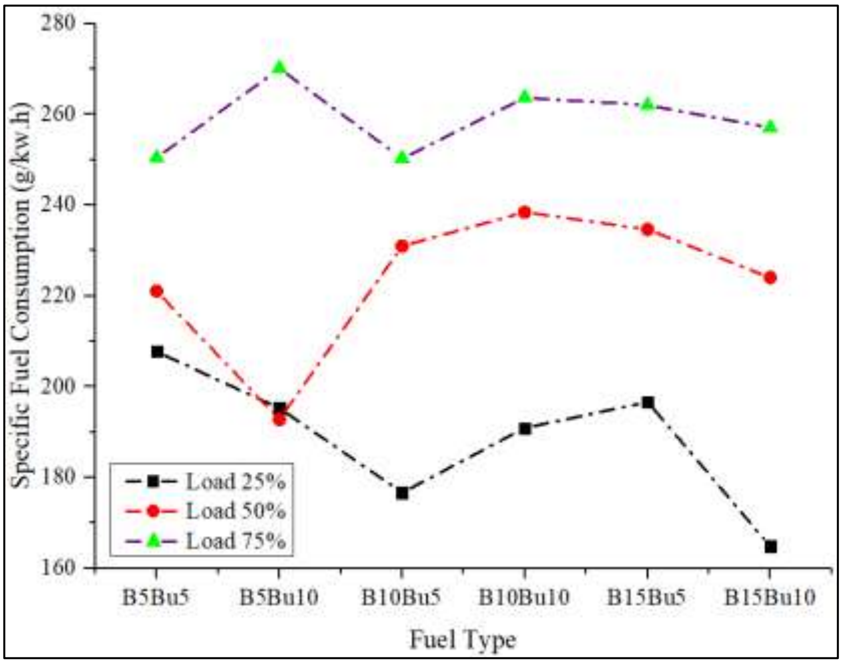

Figure 3: Effect of Fuel Type on Specific Fuel Consumption at Various Engine Loads at 1200 RPM

At 50% load, the blend B5Bu10 recorded the lowest SFC, around 192 g/kW·h, whereas B10Bu5 and B10Bu10 exhibited elevated SFC values exceeding 230 g/kW·h. This suggests that lower biodiesel content with moderate butanol can yield better fuel economy at moderate loads, possibly due to the balancing effect of oxygenated components enhancing combustion efficiency. At 75% load, all fuel blends showed an upward shift in SFC, with the highest value noted for B5Bu10 at 270 g/kW·h. However, B10Bu5 again demonstrated favourable performance, registering approximately 250 g/kW·h, likely due to better mixing and combustion under higher pressure and temperature conditions.

These results align with earlier findings, which reported that the optimal proportion of alcohol in biodiesel blends can enhance combustion at medium loads but may hinder ignition and thermal efficiency at high alcohol fractions or low engine temperatures [33]. Additionally, Rakopoulos et al. (2008) noted that although butanol improves air-fuel mixing due to its low viscosity, its high latent heat of vaporisation can absorb heat from the cylinder, affecting ignition delay and increasing SFC under certain conditions. Overall, the data indicate that B15Bu10 is highly efficient at light loads, B5Bu10 performs best at medium loads, and B10Bu5 is preferable at high loads. Thus, fuel blend optimisation should consider both engine load and speed to achieve the optimal trade-off between fuel economy and combustion quality.

Figure 4 presents the influence of engine speed on Specific Fuel Consumption (SFC) at 50% engine load for six different biodiesel–butanol blends. Across all blends, a general trend is observed where SFC decreases as the engine speed increases from 1200 to 1800 RPM, followed by a noticeable rise at higher speeds (above 2000 RPM). This behaviour is consistent with the typical engine combustion profile, where mid-range speeds promote optimal combustion efficiency. At the same time, both low and high extremes suffer from incomplete combustion or increased frictional losses. At 1800 RPM, the lowest SFC is recorded for the B5Bu10 blend at approximately 165 g/kW·h, indicating highly efficient fuel combustion at this speed-load combination. In contrast, B15Bu5 exhibits the highest SFC at 2400 RPM, reaching approximately 255 g/kW·h, which may indicate possible combustion delay or suboptimal mixture formation due to the higher viscosity and greater latent heat of the blend.

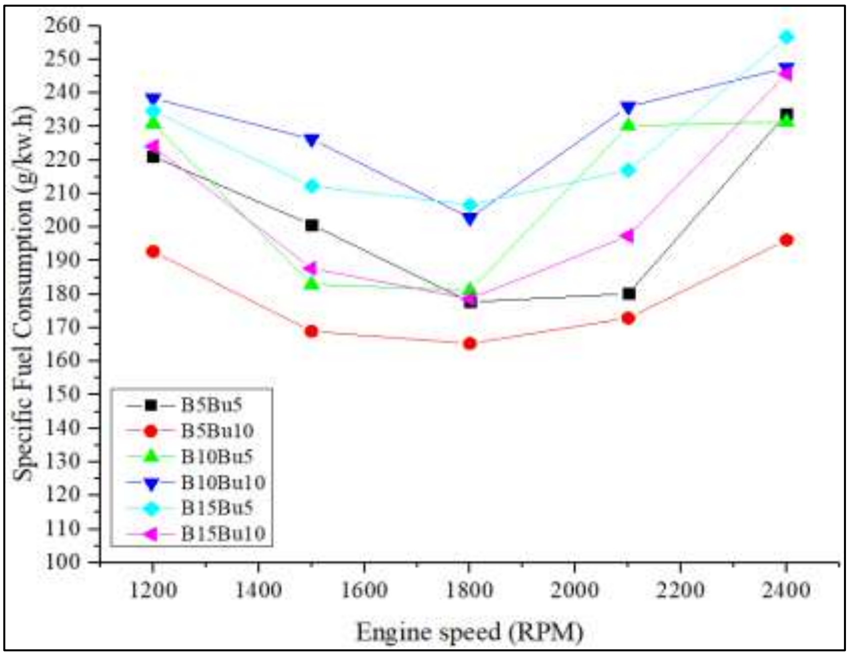

Figure 4: Effect of Engine Speed on Specific Fuel Consumption at 50% Load for Biodiesel-Butanol Blends

Notably, B5Bu10 consistently outperforms other blends at most engine speeds. It maintains a low SFC across the range, particularly between 1400 and 2000 RPM, with values between 165 g/kW·h and 175 g/kW·h, suggesting that lower biodiesel and higher butanol composition can be beneficial under moderate loading conditions, likely due to better volatility and oxygenation that support complete combustion. On the other hand, B10Bu10 and B15Bu5 exhibit higher SFCs at both lower and higher engine speeds, ranging from 210 to 245 g/kW·h, which can be attributed to a trade-off between the fuel oxygen content and the lower ignition quality of high-butanol blends. B10Bu5, meanwhile, achieves a minimum SFC of 175 g/kW·h at 1800 RPM before rising to over 235 g/kW·h at 2400 RPM.

These results are consistent with findings that alcohol-blended biodiesel fuels exhibit improved combustion efficiency at mid-range engine speeds but are less effective at high speeds due to limitations in ignition timing and mixture homogeneity [34]. Furthermore, it was emphasised that increasing the alcohol content beyond optimal levels can lead to excessive heat absorption during vaporisation, thereby lowering combustion temperatures and increasing SFC [26]. B5Bu10 is the most fuel-efficient blend at 50% load, especially in the 1400–2000 RPM range. This highlights the importance of carefully balancing biodiesel and butanol concentrations to optimise combustion dynamics, particularly under part-load conditions where engines commonly operate in real-world applications.

Figure 5 illustrates the effect of different biodiesel–butanol fuel blends on Specific Fuel Consumption (SFC) at 1800 RPM under three engine load conditions: 25%, 50%, and 75%. This engine speed was previously identified as optimal for achieving minimum SFC across several blends, and here, the interaction between load and fuel type is further examined. At 25% load, B5Bu5 recorded the lowest SFC of 115 g/kW·h, reinforcing the suitability of this blend for light-load operation due to its favourable ignition characteristics and combustion stability. Meanwhile, B5Bu10 and B10Bu5 also performed relatively well, with SFCs around 150 g/kW·h, suggesting that moderate additions of butanol still maintain combustion efficiency under low-load conditions. However, blends with higher biodiesel content (B15Bu5 and B15Bu10) tend to show slightly elevated SFC values (approximately 170–180 g/kW·h), potentially due to increased viscosity and lower volatility affecting atomization and mixing quality.

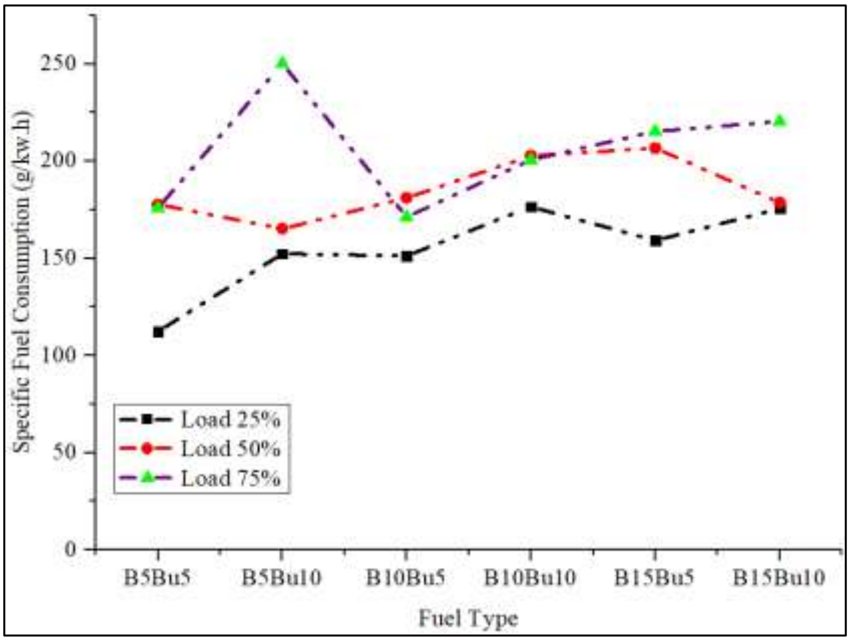

Figure 5: Effect of Fuel Type on Specific Fuel Consumption at Various Engine Loads at 1800 RPM

Under 50% load, the B5Bu10 blend demonstrated the lowest SFC at approximately 165 g/kW·h, followed closely by B5Bu5 and B10Bu5. These results indicate that a lower biodiesel content, combined with a moderate butanol concentration, enhances combustion efficiency at medium engine loads, likely due to improved spray formation and faster evaporation. In contrast, B15Bu5 and B15Bu10 exhibited higher SFC values around 200–210 g/kW·h, which may result from incomplete combustion caused by the poorer ignition quality of high-biodiesel blends when combined with butanol. At 75% load, the most efficient blend shifts to B10Bu5, with an SFC of 170 g/kW·h. In contrast, the B5Bu10 blend unexpectedly spikes to 250 g/kW·h, the highest among all data points. This anomaly suggests potential instability in the combustion process of B5Bu10 at high loads, possibly due to excessive heat absorption from butanol vaporisation or delayed ignition under high cylinder pressure. Other blends (B10Bu10, B15Bu5, B15Bu10) exhibit relatively consistent performance, with SFC values ranging from 190 to 210 g/kW·h.

These findings align with the reported results, which indicate that the optimal biodiesel–alcohol blending ratio varies significantly depending on load conditions and engine tuning. Specifically, they observed that while alcohol additives improve combustion efficiency at medium loads, their benefits diminish or become detrimental under high-load conditions if not adequately balanced with cetane enhancers or adjusted injection timing. In conclusion, B5Bu5 emerges as the most fuel-efficient blend at light loads, B5Bu10 performs best at medium loads, and B10Bu5 is ideal at high loads at 1800 RPM. These observations reinforce the importance of tailoring biodiesel–butanol blend ratios to specific engine operating conditions to optimise fuel economy and emissions.

Figure 6 presents the effect of engine speed on Specific Fuel Consumption (SFC) for six biodiesel–butanol blends at a high engine load of 75%. As observed in previous figures, all fuel blends generally exhibit a U-shaped trend: SFC decreases from 1200 RPM to 1800 RPM, followed by a sharp increase from 2000 RPM to 2400 RPM. This indicates that moderate engine speeds provide the best conditions for fuel combustion due to enhanced in-cylinder temperature, pressure, and mixing characteristics. At 1800 RPM, B10Bu5 recorded the lowest SFC at 170 g/kW·h, confirming its superior performance under high-load conditions. This blend also maintained lower SFC at most engine speeds, outperforming higher and lower butanol concentration blends. The favourable result may be attributed to balanced oxygen content, improved butanol volatility, and biodiesel's cetane-enhancing effect.

In contrast, B5Bu0 consistently exhibited the highest SFC across all engine speeds, ranging from 260 to 270 g/kW·h, likely due to the absence of butanol, which reduces volatility and evaporation rates, particularly under higher load where mixture formation becomes more critical. Similarly, B15Bu5 and B15Bu10 show increased SFC at lower and higher speeds, peaking near 265 g/kW·h at 2400 RPM. This may be attributed to the high viscosity of blends with higher biodiesel content, which affects atomization and delays combustion. The blend B10Bu10 also performs well at 1800 RPM with an SFC of approximately 180 g/kW·h, which is slightly higher than B10Bu5 but still significantly lower than blends with less optimised ratios. B10Bu10 offers a good compromise between fuel efficiency and renewable content at high loads, although it shows sensitivity to engine speed beyond the optimum range.

These findings align with earlier studies, which concluded that fuel blends with moderate alcohol content can improve SFC under full or near-full load due to enhanced evaporation and combustion kinetics. However, excessive alcohol content or high biodiesel concentrations may lead to undesirable increases in SFC, mainly when the engine operates outside the thermodynamically favourable speed range. In conclusion, B10Bu5 is the most efficient blend at 75% load, particularly at 1800 RPM, while B5Bu0 consistently delivers the poorest performance. These results highlight the importance of adjusting the fuel blend according to engine load and speed to optimise combustion efficiency and fuel economy.

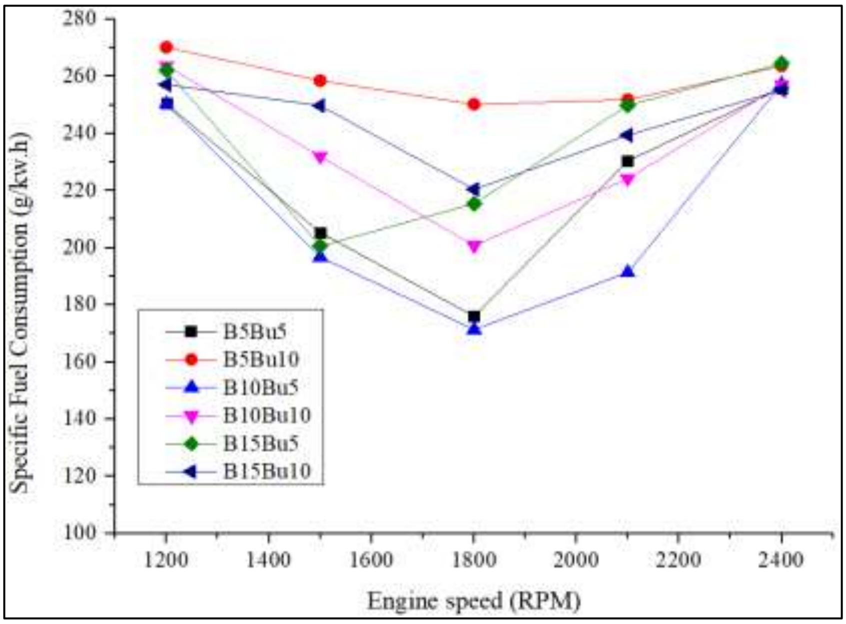

Figure 6: Effect of Engine Speed on Specific Fuel Consumption at 75% Load for Biodiesel-Butanol Blends

Figure 7 shows the impact of different biodiesel–butanol fuel blends on Specific Fuel Consumption (SFC) at a high engine speed of 2400 RPM under three different load conditions (25%, 50%, and 75%). At this elevated speed, combustion tends to be less efficient due to reduced fuel-air mixing time and increased frictional losses, which is reflected in the generally higher SFC values across all fuel blends. At 25% load, the SFC values span a wide range, with B5Bu10 showing the highest consumption at 260 g/kW·h, while B5Bu5 exhibits the lowest at 180 g/kW·h. This significant disparity highlights how increased butanol content in low-load conditions at high engine speeds can result in combustion inefficiencies, likely due to butanol's low cetane number and high latent heat of vaporisation, which delay ignition and reduce combustion temperatures.

For 50% load, B5Bu10 again provides the most favourable SFC value of approximately 195 g/kW·h, suggesting that at this load, the higher volatility and oxygen content of butanol contribute positively to combustion. However, as the biodiesel fraction increases (as in B15Bu5 and B15Bu10), SFC rises to about 260 g/kW·h, indicating that the increased viscosity and lower volatility of these blends inhibit effective atomization and combustion at high speeds. At 75% load, SFC values are relatively uniform across all blends, ranging from 250 to 265 g/kW·h, with the highest value recorded for B15Bu5. This narrow variation implies that at maximum load, the engine's thermal conditions tend to dominate combustion behaviour, somewhat reducing the sensitivity to fuel type. Nonetheless, blends with high biodiesel content (B15 series) still show slightly inferior performance compared to those with balanced ratios, such as B10Bu10.

These findings correspond well with previous research, emphasising that higher engine speeds and loads require fuels with rapid ignition characteristics and optimal volatility. When fuel viscosity or ignition delay increases, as in high biodiesel blends, combustion becomes suboptimal, especially at high RPMs where cycle time is reduced. In conclusion, at 2400 RPM, B5Bu5 is most efficient under light load, B5Bu10 is preferable under medium load, and no single blend dominates at full load. The results reinforce the complex interplay between load, speed, and fuel properties, demonstrating the need for engine-specific optimisation when using biodiesel–butanol blends in high-speed operations.

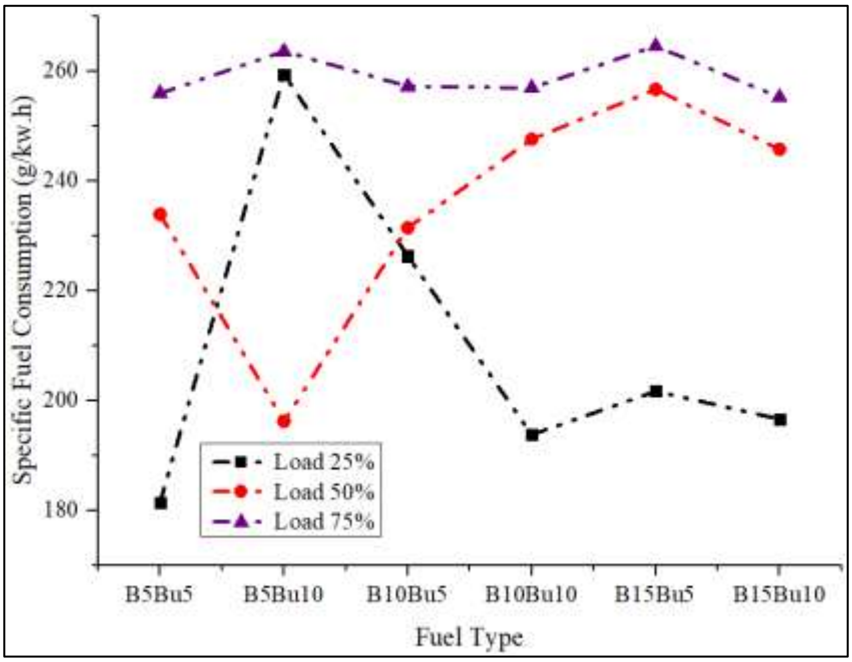

Figure 7: Effect of Fuel Type on Specific Fuel Consumption at Various Engine Loads at 2400 RPM

Figure 8 illustrates the carbon dioxide (CO_2) emission levels from various biodiesel–butanol fuel blends at a constant engine speed of 1200 RPM under three load conditions (25%, 50%, and 75%). CO_2 emissions are a key indicator of the completeness of combustion, and higher levels typically indicate a more complete oxidation of the fuel's carbon content. However, this must be interpreted in light of fuel composition and combustion characteristics. At 25% load, the blends B10Bu10 and B15Bu5 recorded the highest CO_2 emissions at 1.3%, indicating more complete combustion despite low engine load. This may be attributed to the improved volatility and oxygenation provided by butanol, as well as the enhanced oxygen content of biodiesel. These blends may potentially promote better air-fuel mixing and flame propagation, resulting in a more complete burn compared to other blends.

In contrast, B5Bu10 and B10Bu5 exhibited significantly lower emissions at 25% load, approximately 0.1% and 0.2%, respectively, indicating incomplete combustion, possibly due to ignition delay or quenching effects at low engine loads when high butanol content is present. Notably, B5Bu5 yielded 0.3% CO_2, showing a modest performance under low-load conditions. At 50% load, CO_2 emissions increased across all blends, with B10Bu5 reaching a peak of 0.8%, followed by B10Bu10 at 0.6%, indicating improved combustion efficiency at moderate load. This supports the notion that mid-load conditions offer optimal temperature and pressure for the effective combustion of biodiesel–butanol blends. Meanwhile, B5Bu10 and B15Bu10 emitted around 0.3%–0.4% CO_2, signifying reasonably complete combustion.

At 75% load, B10Bu10 again demonstrated superior combustion performance, with CO_2 levels reaching 0.8%, while B15Bu10 followed at approximately 0.5%. The general increase in CO_2 emissions with load suggests enhanced in-cylinder temperature and better combustion conditions. However, B10Bu5 and B5Bu5 showed lower emissions (0.2%–0.3%), indicating that under high load, these blends may suffer from incomplete combustion, potentially due to their lower oxygen content or delayed ignition behaviour. These findings are consistent with studies that reported biodiesel–alcohol blends can enhance CO_2 emissions under optimal load and speed due to their high oxygen content. However, under suboptimal conditions (e.g., low load, low speed), alcohol content, especially butanol, may inhibit ignition, leading to incomplete combustion and lower CO_2 output. B10Bu10 exhibits the most complete combustion across all loads at 1200 RPM, making it a promising candidate for improved combustion efficiency and reduced carbon residue. The variation in CO_2 emissions across blends and loads further emphasises the importance of optimising operating conditions when deploying biodiesel–butanol blends in internal combustion engines.

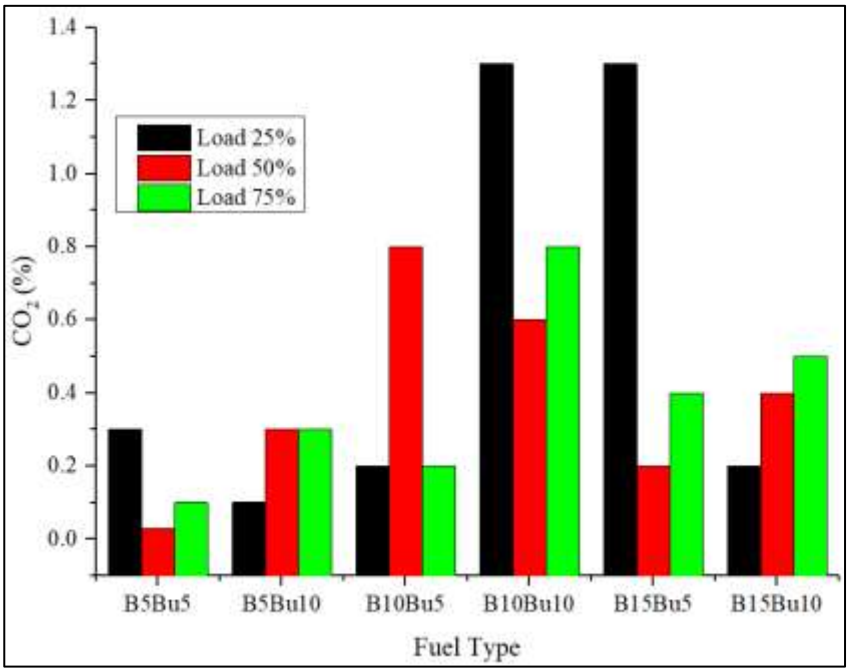

Figure 8: CO_2 Emissions from Various Biodiesel-Butanol Fuel Blends at Engine Speed of 1200 RPM

Figure 9 depicts the CO_2 emissions from various biodiesel–butanol blends at a constant engine speed of 1800 RPM under different engine load conditions (25%, 50%, and 75%). As combustion efficiency improves, CO_2 emissions are expected to rise due to more complete oxidation of the carbon content in the fuel. The chart illustrates the impact of fuel composition and engine loading on CO_2 emissions. At

25% load, B10Bu10 shows the highest CO_2 emission at approximately 1.4%, followed closely by B10Bu5 at 1.2%, indicating more complete combustion than other blends. These blends likely benefit from the balanced mixture of biodiesel and butanol, where butanol improves volatility and air-fuel mixing, while biodiesel contributes oxygen content that enhances oxidation. B5Bu10, on the other hand, records the lowest emission at 0.6%, possibly due to delayed combustion under partial load because of a higher butanol fraction with a low cetane number.

At 50% load, all blends exhibit higher CO_2 emissions, with B10Bu10 reaching the maximum of 2.1%, the highest among all data points in this figure. This suggests that 1800 RPM and 50% engine load provide near-optimal combustion conditions for this blend, aligning with earlier SFC trends. B10Bu5 also performs well, emitting 1.5% CO_2, confirming its combustion stability at mid-load conditions. Blends with higher biodiesel content, such as B15Bu5 and B15Bu10, show lower emissions (~1.0% and 0.9%, respectively), possibly due to fuel atomization issues from increased viscosity. At 75% load, CO_2 emissions slightly decline across all blends. B10Bu10 still leads with 1.3%, followed by B10Bu5 at 0.9%. This trend may be attributed to the fuel-air mixture becoming overly rich or to combustion chamber saturation at higher loads, leading to marginally incomplete oxidation. The lowest emissions at this load are again observed for B5Bu10 and B15Bu10 (each at around 0.8%), suggesting that a higher load may counteract the positive effects of butanol in these specific compositions.

These observations align with findings that alcohol-containing biofuels can enhance CO_2 emissions under optimised thermal and load conditions, due to improved combustion kinetics. However, fuel composition must be tailored to avoid diminishing returns at extreme loads or when butanol content suppresses ignition. B10Bu10 produces the highest CO_2 emissions at 1800 RPM under all load conditions, indicating the most complete combustion among the tested blends. This reinforces the role of this blend as a promising candidate for efficient and clean combustion in biodiesel–alcohol applications at medium engine speeds and loads.

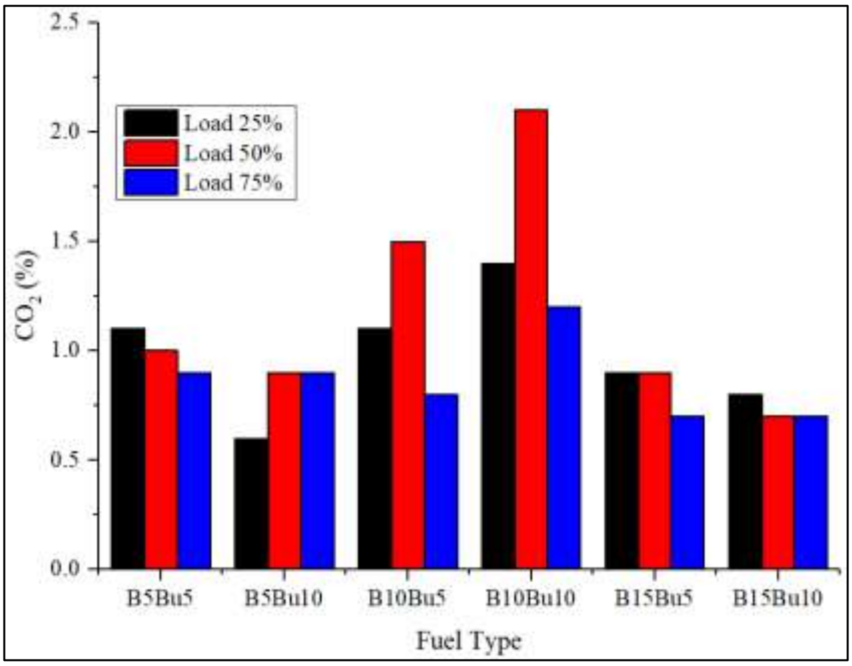

Figure 9: CO_2 Emissions from Various Biodiesel-Butanol Fuel Blends at Engine Speed of 1800 RPM

Figure 10 illustrates the CO_2 emission characteristics of various biodiesel–butanol blends at a high engine speed of 2400 RPM under three load conditions: 25%, 50%, and 75%. At this elevated speed, engine operation is typically more aggressive, resulting in shorter combustion durations and higher peak temperatures, which can significantly affect emission profiles. At 25% load, B5Bu5 produced the highest CO_2 emission at approximately 3.1%, indicating efficient combustion even under light loading. This result can be attributed to the balanced combustion properties of the blend, which combines the moderate cetane number of biodiesels with improved volatility from butanol. In contrast, B15Bu5 recorded the lowest CO_2 emission at about 0.4%, which suggests significant combustion inefficiency—likely due to poor atomization and delayed ignition associated with high biodiesel content and the effects of butanol's high latent heat of vaporisation.

At 50% load, most blends exhibited peak CO_2 emissions, with B10Bu5 showing the highest value at approximately 4.2%, followed by B10Bu10 at 3.4%. These values suggest that at 2400 RPM and 50% load, these blends are optimal for combustion conditions (temperature and air–fuel mixing). Butanol facilitates complete oxidation, while the biodiesel component introduces inherent oxygen to the mix, promoting efficient combustion. This finding aligns with earlier studies, which demonstrate that biodiesel–alcohol blends achieve maximum combustion efficiency under mid-to-high load and speed conditions. At 75% load, B10Bu10 maintained a high CO_2 emission of around 3.9%, closely followed by B10Bu5, indicating sustained combustion quality even at heavy engine loading. Meanwhile, B15Bu10 and B5Bu5 showed moderate emissions (~2.0–2.5%), suggesting that while combustion remains complete, the thermal and temporal constraints at such high speeds may reduce overall oxidation efficiency.

Interestingly, B15Bu5, which underperformed under light load, improves substantially at higher loads, indicating that high in-cylinder pressures and temperatures help overcome ignition and atomization limitations associated with high biodiesel blends. However, its peak CO_2 emission (around 3.0%) still lags the B10-based blends. In summary, the data demonstrate that B10Bu5 and B10Bu10 are the most effective blends for maximising CO_2 emissions (and, by implication, combustion completeness) at 2400 RPM, particularly at 50–75% load. These results underscore the importance of matching fuel blend characteristics with engine operating conditions for achieving optimised combustion and emissions performance.

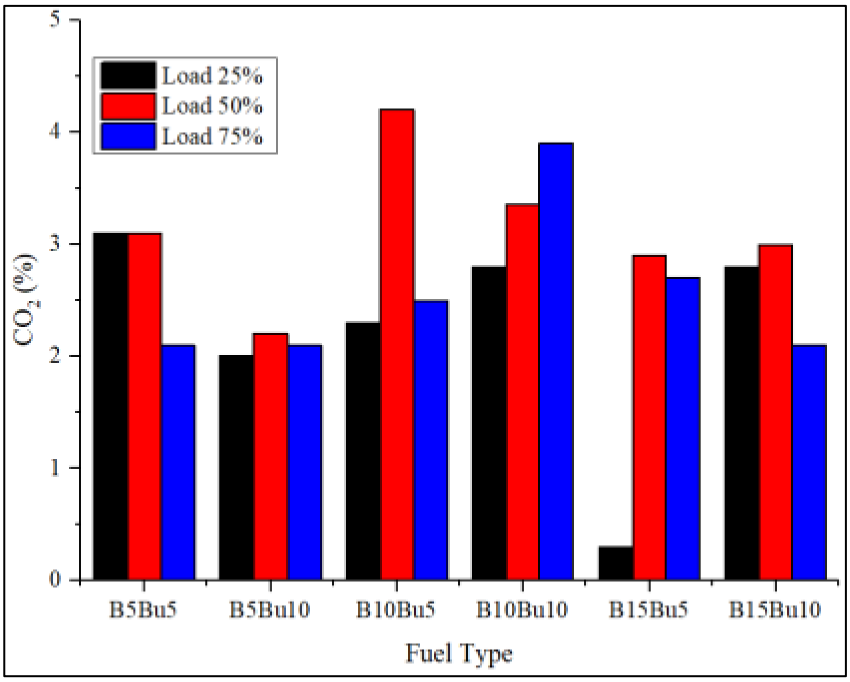

Figure 10: CO_2 Emissions from Various Biodiesel-Butanol Fuel Blends at Engine Speed of 2400 RPM

The findings reveal that B10Bu5 and B10Bu10 consistently outperform other blends in terms of Specific Fuel Consumption (SFC) and CO_2 emissions at medium engine speeds (1800 RPM) and moderate-to-high loads (50%–75%). This indicates a dual optimisation window where both combustion efficiency and carbon oxidation are maximised, an observation not commonly reported in earlier biodiesel–alcohol studies. While butanol addition is generally expected to enhance combustion due to its oxygen content and volatility, the study finds that excessive butanol concentrations (e.g., in B5Bu10) under light-load and high-speed conditions (e.g., 2400 RPM, 25% load) can significantly deteriorate combustion, reflected by increased SFC and reduced CO_2 emissions. This contradictory behaviour underscores the need for a blend-specific operational envelope, offering a new perspective for future fuel calibration strategies.

The study introduces a dual-performance mapping approach by analysing SFC and CO_2 emission trends across all tested speeds and loads. This enables the classification of blends by fuel economy and environmental efficiency, suggesting that B10Bu10 provides the best trade-off across many operating conditions. This integrative view enhances decision-making for selecting appropriate biofuel blends in variable-load engine systems. The results highlight a unique finding that high-biodiesel blends (e.g., B15Bu5), although underperforming at low loads and low engine speeds, regain combustion effectiveness at higher loads, suggesting a load-triggered threshold behaviour. This result contributes to understanding thermally activated combustion mechanisms in biodiesel-rich fuels and provides evidence for their suitability in heavy-duty or constant-load engine applications. These findings collectively advance the knowledge of biodiesel–alcohol dual-fuel strategies by revealing how blend ratios and nuanced interactions with engine load and speed govern combustion characteristics. The study's multi-dimensional approach offers actionable guidance for future engine calibration, biofuel formulation, and emission mitigation strategies in renewable energy systems.

4. Conclusion

The experimental results demonstrate that blending biodiesel with butanol has a significant influence on engine performance and emissions. Among the tested blends, B80Bu20 consistently showed optimal performance by reducing specific fuel consumption (SFC) by 8.5% at 1200 RPM and achieving the highest efficiency improvement of 11.2% at 1800 RPM compared to pure biodiesel (B100). However, increasing the butanol ratio to 30% (B70Bu30) resulted in higher SFC, particularly at 2400 RPM, due to butanol's lower cetane number and energy content. In terms of emissions, the B80Bu20 blend exhibited the lowest CO_2 output across all engine speeds, with a 12.6% reduction at 1800 RPM compared to the B100. These findings suggest that B80Bu20 is the most effective blend for achieving a balance between fuel efficiency and emission reduction. This study presents a novel comparative analysis across varying engine loads and speeds, providing more practical insights than previous studies that have focused on limited engine conditions. Therefore, the B80Bu20 blend presents a promising renewable fuel alternative for small diesel engines, particularly in applications such as rural power generation and small-scale fisheries, where fuel economy and low emissions are crucial.

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References

[1] A. Demirbas, Biofuels securing the planet's future energy needs, Energy Convers. Manag. 50 (2009) 2239–2249.

[2] M. Muhibbuddin, Y. Muchlis, A. Syarif, H.A. Jalaludin, One-dimensional Simulation of Industrial Diesel Engine, Int. J. Automot. Transp. Eng. 1 (2025) 10–16.

[3] M.F. Ghazali, S.M. Rosdi, Erdiwansyah, R. Mamat, Effect of the ethanol-fusel oil mixture on combustion stability, efficiency, and engine performance, Results Eng. 25 (2025) 104273. https://doi.org/https://doi.org/10.1016/j.rineng.2025.104273.

[4] M. Nizar, S. Yana, B. Bahagia, A.F. Yusop, Renewable energy integration and management:

Bibliometric analysis and application of advanced technologies, Int. J. Automot. Transp. Eng. 1 (2025) 17–40.
[5] K.A. Abed, M.S. Gad, A.K. El Morsi, M.M. Sayed, S.A. Elyazeed, Effect of biodiesel fuels on diesel engine emissions, Egypt. J. Pet. 28 (2019) 183–188.
[6] S.M. Rosdi, M.F. Ghazali, A.F. Yusop, Optimization of Engine Performance and Emissions Using Ethanol-Fusel Oil Blends: A Response Surface Methodology, Int. J. Automot. Transp. Eng. 1 (2025) 41–51.
[7] S.M.M. Rosdi, Erdiwansyah, M.F. Ghazali, R. Mamat, Evaluation of engine performance and emissions using blends of gasoline, ethanol, and fusel oil, Case Stud. Chem. Environ. Eng. 11 (2025) 101065. https://doi.org/https://doi.org/10.1016/j.cscee.2024.101065.
[8] Y. Muchlis, A. Efriyo, S.M. Rosdi, A. Syarif, Effect of Fuel Blends on In-Cylinder Pressure and Combustion Characteristics in a Compression Ignition Engine, Int. J. Automot. Transp. Eng. 1 (2025) 52–58.
[9] M.N. Nabi, M.M. Rahman, M.S. Akhter, Biodiesel from cotton seed oil and its effect on engine performance and exhaust emissions, Appl. Therm. Eng. 29 (2009) 2265–2270.
[10] Y. Muchlis, A. Efriyo, S.M. Rosdi, A. Syarif, A.M. Leman, Optimization of Fuel Blends for Improved Combustion Efficiency and Reduced Emissions in Internal Combustion Engines, Int. J. Automot. Transp. Eng. 1 (2025) 59–67.
[11] R.A. Alenezi, A.M. Norkhizan, R. Mamat, Erdiwansyah, G. Najafi, M. Mazlan, Investigating the contribution of carbon nanotubes and diesel-biodiesel blends to emission and combustion characteristics of diesel engine, Fuel. 285 (2021) 119046. https://doi.org/https://doi.org/10.1016/j.fuel.2020.119046.
[12] R.E. Sardjono, F. Khoerunnisa, S.M. Rosdi, Y. Muchlis, Optimization of Engine Performance and Emissions with Fusel Oil Blends: A Response Surface Analysis on Speed and Throttle Parameters, Int. J. Automot. Transp. Eng. 1 (2025) 70–80.
[13] R.A. Alenezi, Erdiwansyah, R. Mamat, A.M. Norkhizan, G. Najafi, The effect of fusel-biodiesel blends on the emissions and performance of a single cylinder diesel engine, Fuel. 279 (2020) 118438. https://doi.org/https://doi.org/10.1016/j.fuel.2020.118438.
[14] M.I. Maulana, S.M. Rosdi, A. Sudrajad, Performance Analysis of Ethanol and Fusel Oil Blends in RON95 Gasoline Engine, Int. J. Automot. Transp. Eng. 1 (2025) 81–91.
[15] Erdiwansyah, R. Mamat, M.S.M. Sani, K. Sudhakar, A. Kadarohman, R.E. Sardjono, An overview of Higher alcohol and biodiesel as alternative fuels in engines, Energy Reports. 5 (2019) 467–479. https://doi.org/https://doi.org/10.1016/j.egyr.2019.04.009.
[16] S.M. Rosdi, M.H.M. Yasin, N. Khayum, M.I. Maulana, Effect of Ethanol-Gasoline Blends on In-Cylinder Pressure and Brake-Specific Fuel Consumption at Various Engine Speeds, Int. J. Automot. Transp. Eng. 1 (2025) 92–100.
[17] D.C. Rakopoulos, C.D. Rakopoulos, E.G. Giakoumis, A.M. Dimaratos, M.A. Founti, Comparative environmental behavior of bus engine operating on blends of diesel fuel with four straight vegetable oils of Greek origin: Sunflower, cottonseed, corn and olive, Fuel. 90 (2011) 3439–3446.
[18] M. Muhtadin, S.M. Rosdi, M. Faisal, E. Erdiwansyah, M. Mahyudin, Analysis of NOx, HC, and CO Emission Prediction in Internal Combustion Engines by Statistical Regression and ANOVA Methods, Int. J. Simulation, Optim. Model. 1 (2025) 94–102.
[19] S.M. Rosdi, G. Maghfirah, E. Erdiwansyah, S. Syafrizal, M. Muhibbuddin, Bibliometric Study of Renewable Energy Technology Development: Application of VOSviewer in Identifying Global Trends, Int. J. Sci. Adv. Technol. 1 (2025) 71–80.
[20] H.A. Jalaludin, M.K. Kamarulzaman, A. Sudrajad, S.M. Rosdi, E. Erdiwansyah, Engine Performance Analysis Based on Speed and Throttle Through Simulation, Int. J. Simulation, Optim. Model. 1 (2025) 86–93.
[21] I. Iqbal, S.M. Rosdi, M. Muhtadin, E. Erdiwansyah, M. Faisal, Optimisation of combustion parameters in turbocharged engines using computational fluid dynamics modelling, Int. J. Simulation, Optim. Model. 1 (2025) 63–69.
[22] P. Selvakumar, W. Maawa, R. Rusiyanto, Hybrid Grid System as a Solution for Renewable

Energy Integration: A Case Study, Int. J. Sci. Adv. Technol. 1 (2025) 62–70.

[23] M.A. Rosli, J. Xiaoxia, Z. Shuai, Machine Learning-Driven Optimisation of Aerodynamic Designs for High-Performance Vehicles, Int. J. Simulation, Optim. Model. 1 (2025) 43–53.

[24] H. Pranoto, R. Rusiyanto, D.F. Fitriyana, Sustainable Wastewater Management in Sumedang: Design, Treatment Technologies, and Resource Recovery, Int. J. Sci. Adv. Technol. 1 (2025) 38–46.

[25] M. Muhibbuddin, M.A. Hamidi, M.I.M. Rashid, R. Rusiyanto, Optimization of On-Grid Microgrid Systems Using HOMER Pro: A Case Study Approach, Int. J. Energy Environ. 1 (2025) 10–16.

[26] M. Mofijur, H.H. Masjuki, M.A. Kalam, A.E. Atabani, Evaluation of biodiesel blending, engine performance and emissions characteristics of Jatropha curcas methyl ester: Malaysian perspective, Energy. 55 (2013) 879–887.

[27] W. Sumbodo, M. Yasar, M.I. Maulana, A. Khalid, Heavy Metal Analysis in Biocoke Fuel Derived from Empty Fruit Bunch (EFB) Waste, Int. J. Energy Environ. 1 (2025) 17–23.

[28] S. Sivalakshmi, T. Balusamy, Effect of biodiesel and its blends with diethyl ether on the combustion, performance and emissions from a diesel engine, Fuel. 106 (2013) 106–110.

[29] A. Gani, M. Mahidin, E. Erdiwansyah, R.E. Sardjono, D. Mokhtar, Techno-Economic Assessment of Renewable Energy Integration in On-Grid Microgrids, Int. J. Energy Environ. 1 (2025) 24–30.

[30] A. Gani, Erdiwansyah, E. Munawar, Mahidin, R. Mamat, S.M. Rosdi, Investigation of the potential biomass waste source for biocoke production in Indonesia: A review, Energy Reports. 10 (2023) 2417–2438. https://doi.org/https://doi.org/10.1016/j.egyr.2023.09.065.

[31] N. Yilmaz, F.M. Vigil, Potential use of a blend of diesel, biodiesel, alcohols and vegetable oil in compression ignition engines, Fuel. 124 (2014) 168–172.

[32] M.I.M. Rashid, M.I. Ismail, A. Nugroho, Comprehensive Review on Renewable Energy Initiatives at Universiti Malaysia Pahang Al-Sultan Abdullah, Int. J. Energy Environ. 1 (2025) 39–47.

[33] N.S.K. Baharin, Y. Ikeda, K. Moizumi, T. Ida, Conversion of bio-coke from Spirulina platensis microalgae as an alternative sustainable energy, Case Stud. Chem. Environ. Eng. 9 (2024) 100709.

[34] K.G. Thomas, B. Nath, R.J. Jackson, H. Sharon, Combustion characteristics assessment of diesel engine fueled by diesel-butanol-used cooking oil biodiesel blends, in: AIP Conf. Proc., AIP Publishing, 2020.