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Optimizing Biodiesel-Butanol Blends for Low CO_2 Emissions and Fuel Efficiency in Diesel Engines

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Abstract
This study investigates the impact of various biodiesel–butanol fuel blends on CO_2 emissions and brake-specific fuel consumption (BSFC) under different engine speeds and load conditions. Experiments were conducted using blends of biodiesel (B5, B10, B15) combined with butanol concentrations of 5% and 10% (Bu5, Bu10) at engine speeds of 1200, 1800, and 2400 rpm, across load levels of 25%, 50%, and 75%. The results indicate that both CO_2 emissions and BSFC are significantly influenced by fuel composition, engine load, and speed. Notably, blends such as B5Bu5 and B10Bu5 showed the lowest CO_2 emissions at high engine loads, reaching values as low as 0.2% at 75% load and 1200 rpm, suggesting enhanced combustion efficiency. At higher engine speeds, CO_2 emissions increased, especially at mid-load conditions, with B10Bu10 recording a peak emission of 4.2% at 2400 rpm and 50% load. Regarding BSFC, the B15Bu10 blend consistently demonstrated superior fuel efficiency, especially under full-load conditions, with the lowest recorded BSFC of 165 g/kWh at 25% load and 1200 rpm. Conversely, blends with excessive butanol content exhibited higher BSFC at low loads, indicating incomplete combustion. These findings highlight the importance of optimizing biodiesel–butanol ratios based on specific engine operating conditions. The study contributes valuable insights into cleaner alternative fuels, supporting efforts to reduce carbon emissions and improve energy efficiency in diesel engine systems.

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1. Introduction

The growing concern over fossil fuel depletion and the urgent need to mitigate greenhouse gas emissions have intensified global interest in alternative and renewable fuels for internal combustion engines. Among the various options, biodiesel derived from vegetable oils and waste fats has emerged as a viable substitute for conventional diesel fuel due to its biodegradable nature, low sulfur content, and renewable origin. However, biodiesel's relatively high viscosity and poor cold flow properties can limit its direct application in unmodified engines. To overcome these limitations, researchers have explored blending biodiesel with alcohols, particularly butanol, which offers favourable combustion characteristics, including better miscibility with diesel, higher energy content than ethanol, and improved volatility. Butanol's longer carbon chain enhances its cetane number and combustion stability, making it a suitable additive to biodiesel blends to enhance performance and emissions profile.

Previous studies have shown that biodiesel–butanol blends can reduce particulate matter and improve combustion efficiency under specific engine loads and speeds. For instance, it was reported that oxygenated fuels such as butanol could improve atomization and promote more complete combustion [1–4]. Similarly, it was demonstrated that alcohol blends with biodiesel could significantly affect CO_2 and NOx emissions depending on load and speed conditions [5–8]. Despite these advantages, the performance of such blends varies considerably based on their composition and engine operating parameters. The influence of engine load and rotational speed on emissions and fuel consumption has also been a significant topic in combustion research. Studies suggest that higher engine loads typically lead to improved thermal efficiency and reduced CO emissions but may also increase fuel demand [9–11]. These interactions underline the importance of optimizing blend ratios and operational conditions to achieve environmental and performance benefits.

Although several investigations have evaluated biodiesel–butanol blends, there remains a gap in comprehensive analysis across various engine loads and speeds using a systematic blend variation [12–14]. Most prior studies focus on either emission profiles or performance metrics separately, often under a limited range of conditions. Furthermore, inconsistencies in reported results highlight the need for more controlled and comparative evaluations using standardized fuel blend ratios [15–17]. In this study, a series of biodiesel–butanol blends, namely B5Bu5, B5Bu10, B10Bu5, B10Bu10, B15Bu5, and B15Bu10, were tested on a diesel engine across three different engine speeds (1200, 1800, and 2400 rpm) and three load levels (25%, 50%, and 75%). The primary objective was to investigate the effect of these blends on CO_2 emissions and brake-specific fuel consumption (BSFC) to determine optimal formulations for efficient and low-emission performance.

This research aims to identify biodiesel–butanol ratios that provide the best compromise between reducing CO_2 emissions and improving BSFC across varying engine operating conditions. This study provides quantitative comparisons that could guide fuel selection for future biodiesel applications in the transportation and power generation sectors. The novelty of this work lies in its integrated evaluation of performance and emissions across a full operational matrix (speed–load combinations) using carefully structured fuel blends. By mapping the combustion characteristics of each blend in diverse conditions, this research offers actionable insights for deploying low-emission biodiesel–butanol fuels in real-world diesel engines.

2. Methodology

Figure 1 illustrates the schematic of an experimental setup designed to evaluate the performance of a Yanmar TF120M diesel engine. This system integrates various sensors and measuring instruments to analyze thermal performance, fuel efficiency, and exhaust gas emissions during engine operation. Air enters the engine through an air flow meter and intake air box, while fuel is supplied via a fuel line that passes over a fuel weight scale, allowing accurate real-time measurement of fuel consumption. The combustion process inside the engine generates mechanical power and exhaust gases, which are then assessed for research purposes. Temperatures at different points of the system are monitored using multiple thermocouples: the intake thermocouple measures the temperature of incoming air; the engine thermocouple monitors engine body temperature during operation; the exhaust gas thermocouple (EGT) captures the temperature of exhaust gases before exiting the system; and the tailpipe thermocouple measures the temperature at the final exhaust outlet. The mechanical power generated by the engine is transferred to an eddy current dynamometer, which applies a controlled load to the engine. The energy

output is dissipated through a load resistor bank. Torque transmitted from the engine is measured using a load cell, while a speed sensor monitors the engine's rotational speed (RPM). All operational parameters, including speed, torque, and load, are displayed and managed using a dynamometer controller.
The exhaust gas is further analyzed using an emissions analyzer to determine the concentration of O_2, CO_2, CO, and NO_x gases. These parameters are critical in evaluating combustion efficiency and the environmental impact of the engine's emissions. This experimental configuration allows for a comprehensive assessment of diesel engine performance, making it particularly useful for studying the effects of alternative fuels, optimizing combustion, and developing environmentally friendly engine technologies.

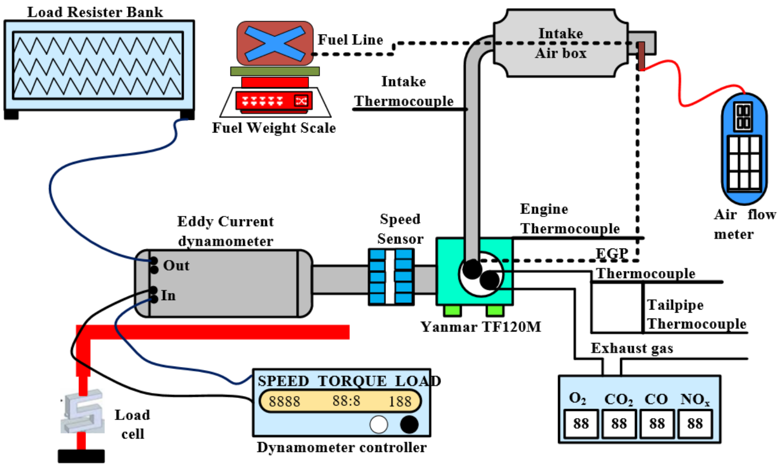

Figure 1: Schematic of Engine Experimental

Table 1 provides detailed technical specifications of the YANMAR TF120M engine, which is the experimental setup's primary power unit. This engine is categorized as a diesel 4-stroke, single-cylinder engine. It completes a power cycle in four strokes of the piston (intake, compression, power, and exhaust) and uses diesel fuel for combustion. Its single-cylinder design simplifies the engine structure, making it suitable for research and experimental purposes where ease of control and analysis are essential. The bore and stroke dimensions of the engine are 92 mm and 96 mm, respectively. The bore is the diameter of the cylinder, while the stroke is the distance the piston travels within the cylinder. These dimensions suggest that the engine is relatively undersquare (stroke > bore), which is typical for engines that prioritize torque over speed, ideal for applications requiring steady power output.

Table 1. Specifications of Engine

Description	Specification
Engine model	YANMAR TF120M
Engine type	diesel 4-stroke, one-cylinder engine
Bore x Stroke (mm)	92 × 96
Displacement (L)	0.638
Injection timing	17° BTDC
Compression ratio	17.7
Continuous output (HP)	7.82 kW at 2400 rpm
Rated output (HP)	8.94 kW at 2400 rpm

The engine has a displacement of 0.638 litres (or 638 cc), the total volume displaced by the piston in one complete cycle. This moderate displacement size supports the engine's role in small-scale or controlled experimental studies. The injection timing is set at 17° Before Top Dead Center (BTDC), which means fuel is injected into the combustion chamber 17 degrees before the piston reaches its topmost position during the compression stroke. This parameter is crucial as it directly influences

combustion efficiency, engine performance, and emission characteristics. The compression ratio of 17.7 is relatively high, typical for diesel engines, which rely on compression rather than spark ignition. A high compression ratio contributes to better thermal efficiency and fuel economy but requires stronger engine components to withstand the higher pressures.
Regarding performance output, the engine provides a continuous output of 7.82 kW at 2400 rpm, which reflects the maximum power it can deliver during prolonged operation without damage. Meanwhile, the rated output is slightly higher at 8.94 kW at the same engine speed (2400 rpm), representing the maximum power the engine can produce for short durations under optimal conditions. These values indicate that the YANMAR TF120M is a compact yet powerful engine suitable for small-scale energy conversion research, particularly for performance testing, combustion studies, and emission analysis. The YANMAR TF120M's specifications indicate a durable, efficient, and research-friendly diesel engine well-suited for controlled experiments involving alternative fuels, combustion efficiency, and emission measurements.

3. Result & Discussion

Figure 2 illustrates the CO_2 emissions (%) for various biodiesel–butanol fuel blends under different engine load conditions (25%, 50%, and 75%) at 1200 rpm. The tested fuel types include B5Bu5, B5Bu10, B10Bu5, B10Bu10, B15Bu5, and B15Bu10. Overall, the results indicate that CO_2 emissions decrease as engine load increases, especially for blends with higher biodiesel and butanol concentrations. This trend aligns with previous studies, which suggest that higher engine loads improve combustion efficiency, resulting in more complete combustion and reduced CO_2 emissions [18–21].
Among the fuel blends, B10Bu10 and B15Bu5 exhibited the highest CO_2 emissions at 25% engine load, reaching approximately 1.3%. However, as the load increased to 75%, emissions from these same blends significantly dropped to around 0.8% and 0.4%, respectively. On the other hand, B5Bu5 showed the lowest emission at 50% load (0.1%) and only a slight increase to 0.2% at 75% load, suggesting better combustion stability even at varying loads. The influence of butanol concentration also plays a significant role. For instance, comparing B10Bu5 to B10Bu10 at 25% load reveals a dramatic increase in CO_2 emission from 0.2% to 1.3% when butanol content is raised, indicating that excessive butanol at low loads may lead to incomplete combustion. Nevertheless, at 75% load, the CO_2 emissions from these two blends converge more closely (0.2% vs. 0.8%), implying improved combustion as load increases. A similar trend is observed for the B15 blends, where a higher butanol ratio (B15Bu10) results in slightly more CO_2 at higher loads (0.5%) compared to B15Bu5 (0.4%).

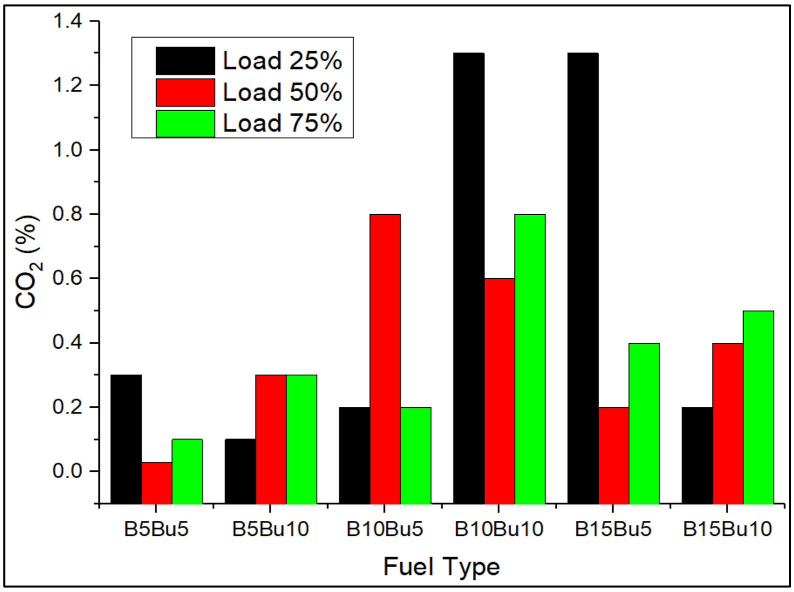

Figure 2: CO_2 Emissions for Engine Loads 1200 rpm

Based on the data, the blends B5Bu5 and B10Bu5 produce the lowest CO_2 emissions at 75% engine load (around 0.2%), indicating their potential as optimal blends for reducing emissions under heavy-duty operating conditions. This observation aligns with findings that low alcohol–biodiesel mixtures such as butanol blends improve combustion efficiency and minimise CO_2 formation, particularly at elevated loads due to enhanced oxygen availability and better fuel atomization [5,22–24]. In summary, both engine load and fuel composition significantly affect CO_2 emissions. Higher engine loads generally promote better combustion, reducing emissions, especially when using well-balanced biodiesel–butanol blends. B5Bu5 demonstrates the most favourable emission characteristics among the tested fuels across varying loads, making it a promising alternative for cleaner diesel engine operations.

Figure 3 shows the CO_2 emissions (%) of various biodiesel–butanol blends at different engine load conditions (25%, 50%, and 75%) operating at 1800 rpm. The results reveal a distinctive pattern in which CO_2 emissions generally increase with butanol addition, especially at medium engine loads (50%), but decrease slightly at higher loads (75%) for most fuel types. This phenomenon is consistent with observations, which noted that oxygenated fuels like butanol can enhance or hinder combustion depending on operating conditions such as load and speed [25–28]. Among all fuel types, B10Bu10 produced the highest CO_2 emission at 50% load, reaching approximately 2.1%, followed by B10Bu5 at around 1.5%. This suggests that increasing butanol content, especially at medium load, can lead to more complete combustion, generating higher CO_2 as a byproduct of efficient oxidation. However, the exact blend (B10Bu10) shows a notable decrease to 1.3% at 75% load, likely due to a leaner air-fuel mixture and enhanced thermal efficiency at higher operating speeds.

Interestingly, B5Bu5 and B5Bu10 exhibited more stable and lower CO_2 emissions across all load levels. For instance, B5Bu5 produced 1.1% at 25% load and gradually declined to 0.9% at 75%. B5Bu10 remained consistent at about 0.9% across 50% and 75% load conditions. This stability suggests that lower concentrations of both biodiesel and butanol provide a balanced combustion profile with less CO_2 production, as supported by [5,29–31], who emphasized the combustion benefits of low-level alcohol blends under varying engine loads.

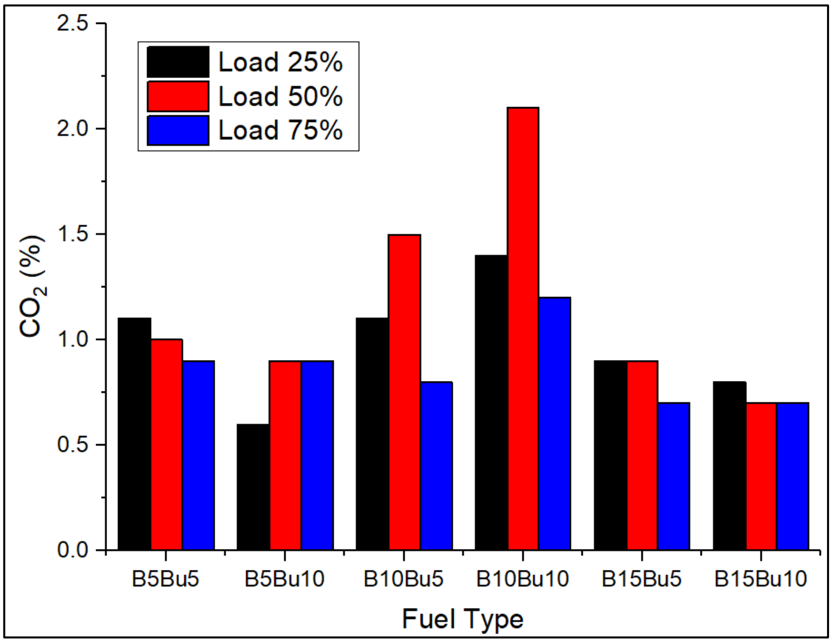

Figure 3: CO_2 Emissions for Engine Loads 1800 rpm

The emissions remain moderate across all load conditions at higher biodiesel content (B15Bu5 and B15Bu10). B15Bu5 produced CO_2 values of 1.0%, 1.0%, and 0.8% for 25%, 50%, and 75% loads, respectively, while B15Bu10 showed slightly lower emissions around 0.9%, 0.8%, and 0.8%. These results indicate that increasing biodiesel content may reduce CO_2 emissions somewhat at higher speeds, likely due to its higher cetane number promoting more complete combustion under full-load conditions.

The data suggest that engine speed and load significantly influence CO_2 emissions depending on the fuel blend. At 1800 rpm, medium-load conditions tend to produce the highest emissions, particularly for blends with moderate to high butanol content. Nevertheless, the B5Bu10 and B15Bu10 blend provide a favourable balance between performance and emissions, especially at higher engine loads. These findings reinforce that optimizing biodiesel–butanol ratios according to engine operating conditions is critical for reducing CO_2 emissions in diesel engines fueled with alternative biofuels.
Figure 4 presents the CO_2 emission profile for different biodiesel–butanol fuel blends at 2400 rpm under varying engine loads (25%, 50%, and 75%). At this higher engine speed, a general increase in CO_2 emissions is observed across all blends compared to lower-speed operations. This can be attributed to the elevated combustion temperature and pressure that improve oxidation and fuel breakdown, leading to increased CO_2 as a primary combustion product, consistent with the findings [32–35]. Among the tested fuels, B10Bu5 shows the highest CO_2 emission at 50% load, reaching approximately 4.2%, significantly higher than its emissions at 25% (around 2.3%) and 75% (around 2.5%). This pattern suggests that at mid-load conditions, the oxygen-enriched nature of butanol leads to more complete combustion and, thus, higher CO_2 formation. A similar but slightly lower trend is seen for B10Bu10, which emitted around 3.7% at 50% load and increased to nearly 3.9% at 75%, indicating sustained high combustion efficiency even at full load.

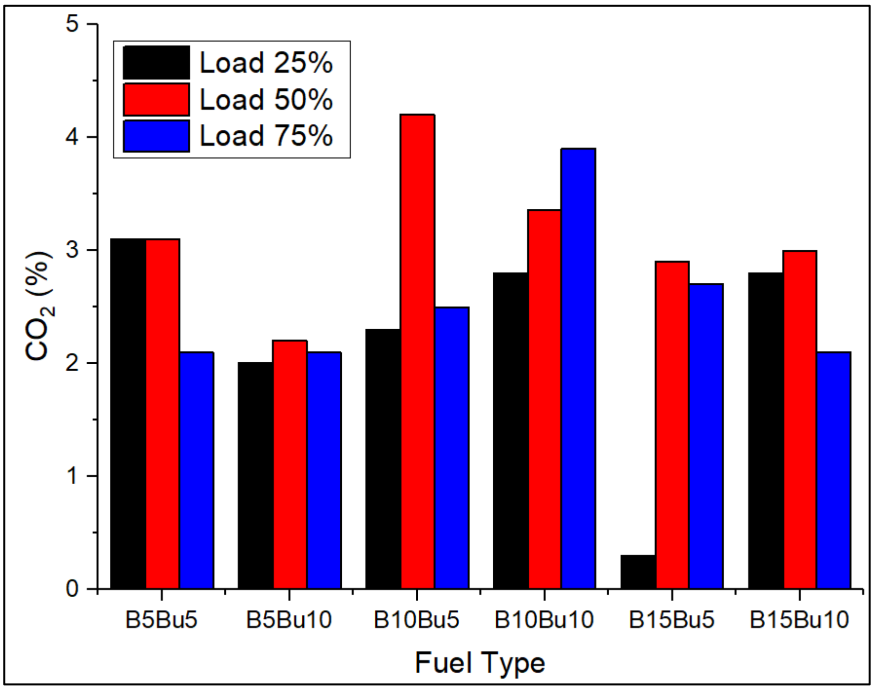

Figure 4: CO_2 Emissions for Engine Loads 2400 rpm

In contrast, B5Bu5 and B5Bu10 displayed relatively moderate emissions. B5Bu5 peaked at approximately 3.1% at 50% load but declined to 2.0% at 75%, showing an inverse relationship between load and emission. B5Bu10 showed stable emissions of 2.0% to 2.2% across all load conditions. These observations imply lower butanol concentrations in the fuel mixture can maintain balanced combustion with controlled CO_2 generation, particularly under high-speed operations. Hazar and Aydin (2010) reported that modest alcohol blends in biodiesel can reduce CO_2 emissions due to better volatility and evaporation characteristics. A fascinating result is observed for B15Bu5 at 25% load, where the CO_2 emission drops sharply to about 0.2%, a significant anomaly compared to its emissions at 50% and 75% loads (2.8% and 2.6%, respectively). This may indicate poor combustion or delayed ignition at low load and high biodiesel content, which could suppress CO_2 formation due to incomplete oxidation. However, such low values are not observed for B15Bu10, which showed consistent emissions around 2.8% to 2.9% at 25% and 50% loads, slightly decreasing to 2.1% at 75%.

Overall, this figure highlights that at higher engine speeds (2400 rpm), the CO_2 emission behaviour is compassionate to blend composition and engine load. The highest emissions are consistently found at 50% load, especially for blends with higher butanol content, reflecting optimized combustion conditions. Meanwhile, blends like B5Bu10 and B15Bu10 offer relatively moderate and consistent emissions, suggesting their potential as balanced biofuel options for high-speed diesel engine applications.

Figure 5 illustrates the variation of brake-specific fuel consumption (BSFC), expressed in g/kWh, across different biodiesel–butanol fuel blends under varying engine loads (25%, 50%, and 75%) at a constant engine speed of 1200 rpm. The BSFC values show a clear dependence on both the fuel blend composition and the engine load. At lower engine loads (25%), fuel consumption is generally higher due to inefficient combustion and increased friction losses. At the same time, BSFC tends to decline with increasing load due to better thermal efficiency and improved combustion conditions. This trend is supported by Lapuerta et al. (2008), who observed that BSFC typically decreases at higher loads when using biofuels, owing to more complete combustion. At 25% load, the lowest BSFC value is observed for the B15Bu10 blend at approximately 165 g/kWh, which indicates highly efficient combustion despite the higher percentage of oxygenated fuels. In contrast, the B15Bu5 blend shows a higher BSFC of nearly 195 g/kWh, while B10Bu5 and B5Bu5 register moderate values around 175–210 g/kWh. Interestingly, B5Bu10 and B10Bu10 display slightly better fuel efficiency than their respective 5% butanol counterparts, implying that an increase in butanol concentration may enhance atomization and volatility, thus supporting improved combustion even at low loads.

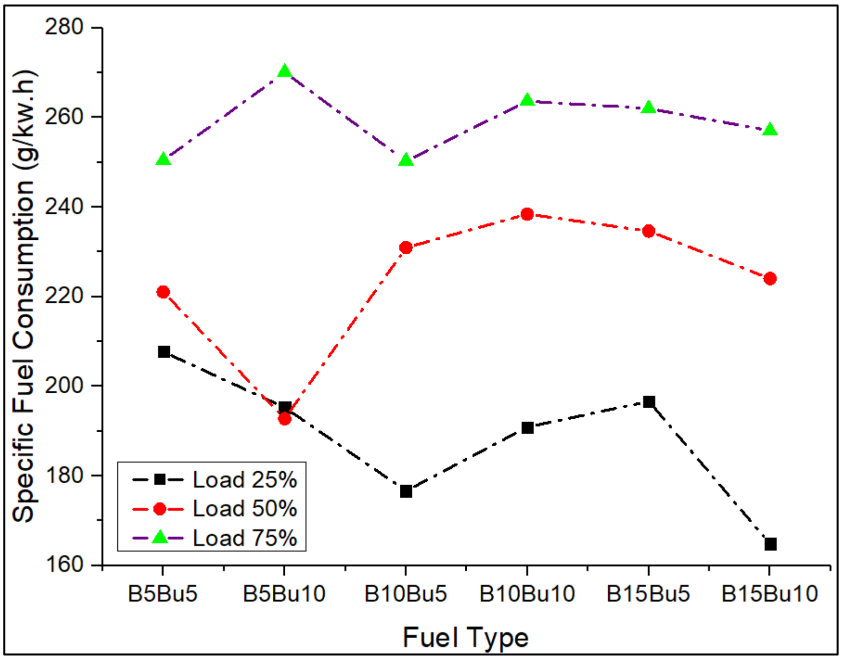

Figure 5: Brake Specific Fuel Consumption for Engine Loads 1200 rpm

At 50% load, all blends experience a slight increase in BSFC compared to 25% load, with values ranging from approximately 190 g/kWh (B5Bu10) to over 240 g/kWh (B10Bu10). The peak value for BSFC at this load is observed for B10Bu10, suggesting that an intermediate butanol content may not favour combustion at mid-loads, possibly due to a longer ignition delay and reduced cetane number of the blend. The lowest BSFC at 50% load is recorded by B5Bu10, which performs consistently well across load ranges, demonstrating its suitability for mid-load operations. At 75% engine load, BSFC values are generally higher than at lower loads, with a peak of around 270 g/kWh for B5Bu10 and B10Bu10. However, the B15Bu10 blend performs better, recording the lowest BSFC at around 250 g/kWh, reaffirming its superior combustion characteristics under high-load conditions. The increase in BSFC at 75% load, particularly for B5Bu10, may be attributed to increased fuel injection requirements to maintain power output, which offsets combustion efficiency gains.

The BSFC characteristics reveal that engine load and fuel composition significantly influence fuel efficiency. The B15Bu10 blend consistently shows lower BSFC across all load conditions, indicating superior combustion behaviour and thermal efficiency. This aligns with previous findings, emphasising that biodiesel blends with alcohol additives like butanol can enhance fuel economy when optimized correctly [36–39]. The data also suggest low to moderate butanol concentrations (5–10%) may be optimal under different engine loads, particularly when coupled with a higher biodiesel ratio.

Figure 6 displays brake-specific fuel consumption (BSFC) variation for different biodiesel–butanol blends at 1800 rpm under 25%, 50%, and 75% of engine loads. As expected, BSFC trends are influenced by fuel composition and engine load, with values ranging broadly between 110 g/kWh and 250 g/kWh. Lower BSFC values are generally associated with improved fuel efficiency, while spikes may indicate combustion inefficiencies or suboptimal fuel-air mixtures. At 25% load, the B5Bu5 blend recorded the lowest BSFC of approximately 110 g/kWh, highlighting efficient fuel use at a light load with a low butanol concentration. In contrast, B5Bu10 displayed a noticeable increase to around 150 g/kWh at the same load, indicating that increasing butanol content may reduce combustion efficiency at light engine loads, possibly due to butanol's lower cetane number and higher latent heat of vaporization. For blends with higher biodiesel content (B10Bu5 to B15Bu10), BSFC values under 25% load ranged between 150 and 180 g/kWh, with relatively stable trends.

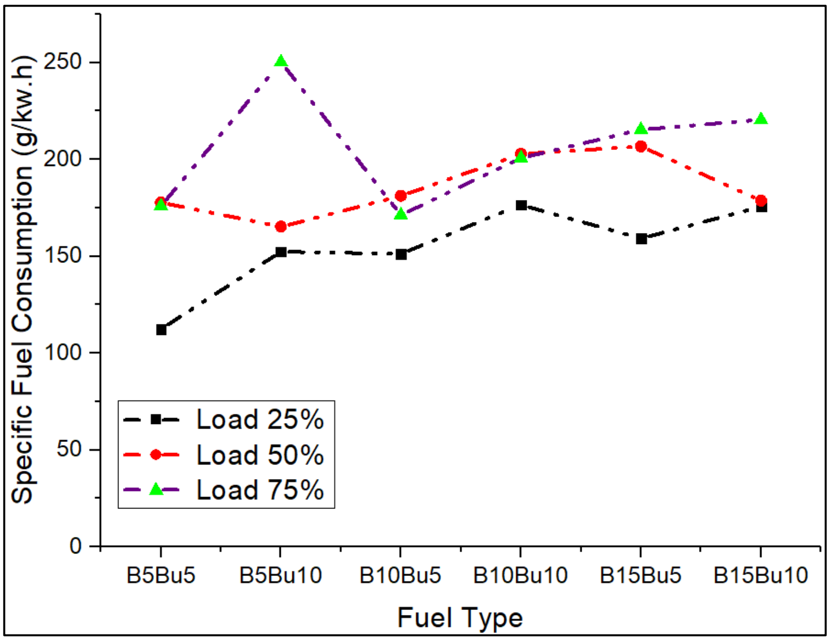

Figure 6: Brake Specific Fuel Consumption for Engine Loads 1800 rpm

Under 50% engine load, BSFC increased for most blends, peaking near 210 g/kWh for B15Bu5. The blend B5Bu10 maintained moderate efficiency with a value of approximately 160 g/kWh, slightly better than that of B10Bu10 and B15Bu5. Interestingly, B15Bu10 showed a reduced BSFC of around 170 g/kWh, suggesting that the combined effects of higher biodiesel and butanol contents may promote better combustion in mid-load scenarios. This observation is supported by the findings of Lapuerta et al. (2008), which suggest that alcohol–biodiesel blends can provide improved efficiency at moderate loads due to enhanced fuel-air mixing and oxygen availability. At 75% load, BSFC reached its highest level for B5Bu10, approximately 250 g/kWh, likely due to incomplete combustion or higher fuel injection requirements at high loads for blends with higher volatility. Conversely, B10Bu5, B10Bu10, and B15Bu10 maintained more stable and efficient values ranging from 190 to 210 g/kWh. Notably, the B10Bu5 blend achieved one of the lowest BSFC values at 75% load (~180 g/kWh), demonstrating its capability for maintaining efficient combustion under complete engine stress.

In summary, **Figure 6** illustrates that the most efficient blend at low load is B5Bu5, while B10Bu5 and B15Bu10 perform better under medium to high loads. These results suggest that fuel selection should be tailored to the expected load conditions of the engine to optimize fuel efficiency. The trends align with prior research, emphasizing that alcohol–biodiesel blends behave differently across operational ranges, and their effectiveness depends on precise ratio balancing and engine conditions [36,40–42].

Figure 7 presents the brake-specific fuel consumption (BSFC) in g/kWh for a series of biodiesel–butanol blends operated at 2400 rpm across three engine load conditions: 25%, 50%, and 75%. The data show that fuel consumption patterns vary significantly with engine load and fuel composition, highlighting the complex interplay between fuel properties and engine operating dynamics at higher rotational speeds. At 25% load, the B5Bu10 blend recorded the highest BSFC value of approximately 260 g/kWh, starkly contrasting to other blends such as B10Bu10, which displayed the lowest BSFC around 190 g/kWh. This result suggests that using 10% butanol with low biodiesel content may reduce combustion efficiency at light engine loads, likely due to delayed ignition and the evaporative cooling effect of butanol. Conversely, blends with higher biodiesel content, such as B10Bu10 and B15Bu10, exhibited more efficient fuel usage at low loads, indicating improved ignition and combustion stability.

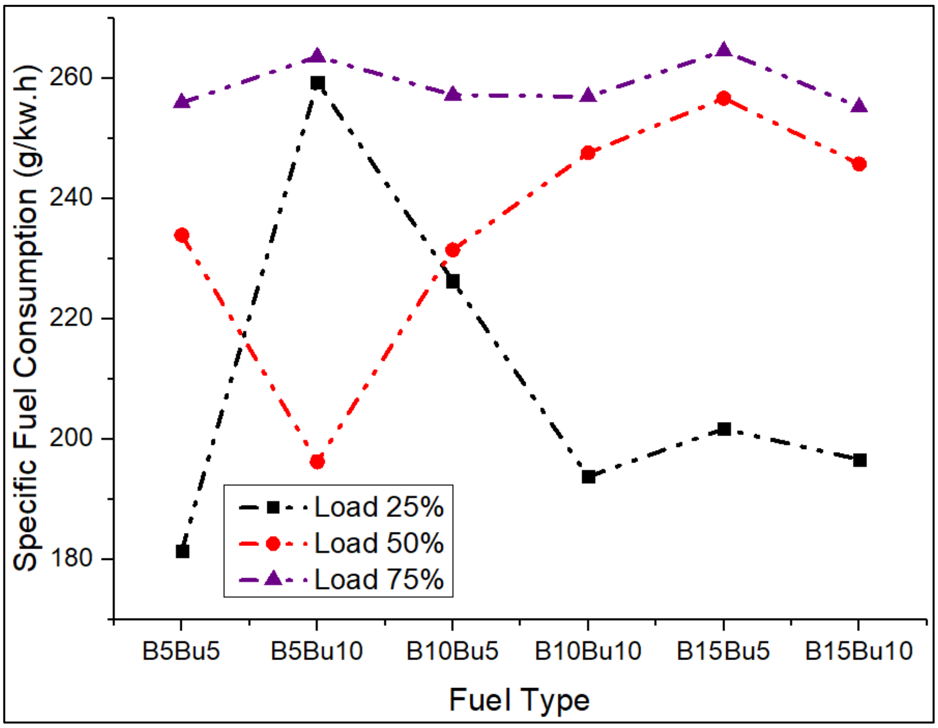

Figure 7: Brake Specific Fuel Consumption for Engine Loads 2400 rpm

At 50% load, most blends showed improved BSFC values, with B5Bu10 again demonstrating the most efficient performance at around 195 g/kWh. The B10Bu5 and B10Bu10 blends exhibited slightly higher values (230–250 g/kWh), while B15Bu5 peaked at approximately 255 g/kWh. The trend suggests moderate butanol content (5–10%) and 5% biodiesel may promote better atomization and combustion characteristics at medium loads, enhancing thermal efficiency. These observations are consistent with findings from Lapuerta et al. (2008), who reported that moderate alcohol additions in biodiesel blends could optimize BSFC by improving fuel-air mixing and increasing the oxygen content of the fuel. At full load (75%), BSFC values across all fuel blends remained high and relatively consistent, ranging between 250 and 265 g/kWh. B10Bu5, B10Bu10, and B15Bu5 hovered near the range's upper limit, indicating that high-speed, full-load operations demand more significant fuel input to maintain power output. Interestingly, B15Bu10 showed a slightly lower BSFC (~255 g/kWh), suggesting that this blend might provide a more favourable combustion balance at high load and speed conditions.

In summary, the BSFC data in **Figure 7** demonstrate that fuel blend composition and engine load level significantly affect fuel efficiency at 2400 rpm. The results highlight that B5Bu10 is particularly effective at medium load, while B10Bu10 and B15Bu10 offer superior efficiency under low-load and high-load conditions, respectively. These findings reinforce prior research, underscoring the importance of optimizing biodiesel–butanol ratios to match specific engine operating regimes to achieve maximum fuel economy and performance [36,43–45].

4. Conclusion

This study aimed to evaluate the effects of biodiesel–butanol fuel blends on CO_2 emissions and brake-specific fuel consumption (BSFC) under varying engine speeds and loads. The results demonstrate that the blend composition and operating conditions significantly affect both engine performance and environmental impact. Among the tested blends, B5Bu5 and B10Bu5 achieved the lowest CO_2 emissions of 0.2% at 75% engine load and 1200 rpm, indicating complete combustion at higher loads. Conversely, B10Bu10 recorded the highest CO_2 emission of 4.2% at 50% load and 2400 rpm, suggesting that mid-load conditions combined with high butanol content promote more complete oxidation but result in greater CO_2 output. Regarding fuel efficiency, B15Bu10 consistently demonstrated the lowest BSFC, reaching 165 g/kWh at 25% load and 1200 rpm, and maintained superior performance across other load conditions. In contrast, B5Bu10 exhibited the highest BSFC at approximately 260 g/kWh under the same load and 2400 rpm, indicating that excessive butanol may impair combustion at light engine loads. These findings confirm that well-balanced biodiesel–butanol blends, such as B10Bu5 and B15Bu10, offer optimal trade-offs between emission reduction and fuel efficiency. Therefore, selecting appropriate blend ratios tailored to engine speed and load conditions is crucial for advancing cleaner and more efficient diesel engine technologies.

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