

Performance-Emission Trade-off Analysis of *Luffa cylindrica* Biodiesel Diesel Blends in a Single Cylinder Direct Injection Compression Ignition Engine

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*Abstract- The growing demand for sustainable energy and the environmental impacts associated with fossil fuel combustion have intensified research into alternative fuels such as biodiesel. Biodiesel derived from non-edible feedstocks has gained attention due to its potential to reduce emissions while maintaining engine performance. However, limited studies have explored the performance emission trade-offs of underutilized feedstocks such as *Luffa cylindrica*, particularly across varying engine operating conditions. This study investigates the performance and emission characteristics of *Luffa cylindrica* biodiesel diesel blends (B5–B100) in a single-cylinder, four-stroke, direct injection compression ignition engine. Engine performance was evaluated under variable load conditions, while emission characteristics (NO_x, CO, CO₂, and HC) were analysed at engine speeds of 1200 rpm, 1500 rpm, and 1800 rpm. The results show that brake power increased with engine load for all fuels, with conventional diesel exhibiting the highest performance. Among the biodiesel blends, B5 demonstrated performance characteristics closest to diesel, making it the most suitable blend for maintaining engine output. In contrast, higher blends resulted in reduced performance due to lower calorific value and higher viscosity. Emission analysis revealed that biodiesel blends significantly reduced carbon monoxide and hydrocarbon emissions, with B20 exhibiting the most favourable emission profile. However, nitrogen oxides emissions increased with increasing biodiesel concentration due to higher combustion temperatures. The findings highlight a clear performance emission trade-off in the use of *Luffa cylindrica* biodiesel blends. While B5 is optimal for performance, B20 offers better emission reduction, indicating that blend selection should be based on specific operational and environmental priorities. This study demonstrates the viability of *Luffa cylindrica* as a sustainable biodiesel feedstock for compression ignition engines.*

Keywords: *Biodiesel; *Luffa cylindrica*; CI engine; emissions; performance; alternative fuels*

I. INTRODUCTION

The increasing global demand for energy and the environmental challenges associated with fossil fuel consumption have intensified the search for sustainable and renewable energy alternatives. Compression ignition (CI) engines are widely used in transportation and industrial sectors due to their high efficiency and durability; however, their reliance on petroleum-based diesel contributes significantly to greenhouse gas emissions and environmental degradation. The combustion of fossil fuels releases pollutants such as carbon monoxide (CO), nitrogen oxides (NO_x), and unburnt hydrocarbons (HC), which are major contributors to climate change and air pollution (Haung et al., 2012; Demirbas, 2009).

Biodiesel has emerged as a promising alternative fuel for CI engines due to its renewable nature, biodegradability, and compatibility with existing diesel engines. It is typically produced from vegetable oils or animal fats through transesterification and exhibits physicochemical properties similar to conventional diesel fuel (Chozhavendha et al., 2020; Janaun & Ellis, 2010). Several studies have reported that biodiesel can be used in diesel engines with little or no modification while offering advantages such as reduced CO and HC emissions and improved lubricity (Xue et al., 2011; Fazal et al., 2011; Azad et al., 2015). However, biodiesel combustion is often associated with certain limitations, including higher viscosity, lower calorific value, and increased NO_x emissions, particularly at higher blend ratios (Fazal et al., 2011; Pinzi et al., 2013). These conflicting characteristics highlight the need for a balanced evaluation of biodiesel blends to determine optimal performance and emission outcomes.

Most existing studies have focused on conventional feedstocks such as palm oil, soybean oil, and other edible or widely utilized non-edible oils, with comparatively limited attention given to underutilized plant resources (Amigun et al., 2011); Nouadjep et al.). The exploration of alternative feedstocks is essential to ensure sustainability and avoid competition with food resources. *Luffa cylindrica*, a tropical plant commonly found in many regions, represents a promising yet underexploited feedstock for biodiesel production. The plant is often considered agricultural waste despite its oil-bearing seeds and potential for energy applications (Achigan-Dako et al., 2011); Mazali & Alves, 2005). Previous research has demonstrated that biodiesel derived from luffa seed oil possesses acceptable fuel properties and can be blended with diesel for use in CI engines (Adeola et al. (2016); Bamgboye & Oniya, 2012).

Although numerous studies have investigated biodiesel performance and emissions using various feedstocks, there remains limited understanding of the combined performance and emission behaviour of *Luffa cylindrica* biodiesel blends in compression ignition engines. In particular, insufficient attention has been given to the trade-off between engine performance and emission characteristics across different blend ratios, which is critical for practical engine applications and energy policy decisions.

Therefore, this study aims to experimentally evaluate the performance and emission characteristics of *Luffa cylindrica* biodiesel–diesel blends (B5–B100) in a single-cylinder direct injection CI engine. The study specifically investigates the performance emission trade-off associated with varying blend ratios, highlighting the comparative advantages of lower blends (e.g., B5) in terms of engine performance and moderate blends (e.g., B20) in terms of emission reduction. The findings contribute to the growing body of knowledge on sustainable alternative fuels and provide insights into the practical viability of *Luffa cylindrica* biodiesel in compression ignition engines.

II. MATERIALS AND METHODS

2.1 Biodiesel Production

Biodiesel used in this study was produced from *Luffa cylindrica* seed oil through a two-step process involving oil extraction and transesterification. The seeds were collected, cleaned, and dried to remove impurities and moisture prior to extraction. Oil extraction was carried out using a solvent extraction technique, which is known to provide higher oil recovery compared to mechanical methods (Bhuiya et al., 2020; Mwaurah et al., 2020).

The extracted oil was subsequently subjected to transesterification using methanol in the presence of a base catalyst (potassium hydroxide, KOH). This process converts triglycerides into fatty acid methyl esters (FAME) and glycerol as a by-product, improving the fuel properties of the oil for engine applications (Janaun & Ellis, 2010; Farouk et al., 2024). Excess methanol was employed to shift the reaction equilibrium towards biodiesel formation, while controlled temperature and agitation ensured efficient conversion.

Following the reaction, the biodiesel was separated from glycerol, washed to remove residual catalyst and impurities, and dried to eliminate moisture. The final product was evaluated to ensure compliance with established biodiesel standards such as ASTM D6751, confirming its suitability for use in compression ignition engines (ASTM, 2003; Raj et al., 2022).

2.2 Fuel Blends

Biodiesel diesel blends were prepared on a volumetric basis using the produced *Luffa cylindrica* biodiesel and conventional petroleum diesel. The blends were designated as B5, B10, B15, B20, B25, and B100, representing 5%, 10%, 15%, 20%, 25%, and 100% biodiesel content, respectively, with the balance being diesel fuel.

Blending was carried out under ambient laboratory conditions by thoroughly mixing the required proportions of biodiesel and diesel to ensure homogeneity. The use of volumetric blending is widely adopted in biodiesel studies due to its simplicity and reproducibility in engine applications

(Kaisan et al., 2020; Pinzi et al., 2013). Prior to engine testing, each blend was visually inspected to ensure phase stability and absence of separation.

The selected blend ratios were chosen to evaluate the effect of increasing biodiesel concentration on engine performance and emission characteristics, with particular emphasis on identifying optimal blends for practical engine operation. Lower blends such as B5 are typically associated with minimal changes in fuel properties, while higher blends (e.g., B20 and above) introduce more pronounced effects due to increased oxygen content and altered physicochemical characteristics (Xue et al., 2011; Azad et al., 2015).

2.3 Engine Setup

The engine performance and emission tests were conducted using a single-cylinder, four-stroke, direct injection (DI) compression ignition engine. The engine has a rated power output of 6.6 kW and is designed to operate on conventional diesel fuel. Direct injection engines are widely used in experimental biodiesel studies due to their high thermal efficiency and suitability for evaluating fuel combustion characteristics (Heywood, 1988; Xue et al., 2011).

The engine was coupled with appropriate instrumentation for measuring performance parameters, including brake power, fuel consumption, and exhaust gas temperature. Torque was applied using a loading system, allowing the engine to operate under variable load conditions. The engine speed was controlled and maintained at predefined values of 1200 rpm, 1500 rpm, and 1800 rpm during testing.

A data acquisition system was used to monitor and record engine parameters in real time. The experimental setup ensured steady-state operating conditions before data collection to minimize fluctuations and improve measurement accuracy. The configuration of the test rig enabled consistent comparison of different fuel blends under identical operating conditions.

2.4 Experimental Procedure

The experimental investigation was carried out to evaluate the performance and emission characteristics

of *Luffa cylindrica* biodiesel diesel blends under controlled engine operating conditions. Prior to each test, the engine was allowed to run for a sufficient period to attain steady-state conditions, ensuring consistent temperature and stable operation.

For performance evaluation, the engine was operated under variable load conditions by adjusting the applied torque. The load was varied within the operating range of the engine, and corresponding performance parameters such as brake power, brake-specific fuel consumption (BSFC), brake thermal efficiency (BTE), brake mean effective pressure (BMEP), and exhaust gas temperature (EGT) were recorded. This approach enables the assessment of fuel behaviour under realistic engine loading conditions, which is critical for practical applications (Kaisan et al., 2020; Idris et al., 2023).

For emission analysis, the engine was operated at constant speeds of 1200 rpm, 1500 rpm, and 1800 rpm. At each speed, exhaust emissions including nitrogen oxides (NO_x), carbon monoxide (CO), carbon dioxide (CO₂), and unburnt hydrocarbons (HC) were measured for all fuel blends. The selection of multiple engine speeds allows for the evaluation of combustion behaviour and emission formation under varying operating conditions (Xue et al., 2011; Azad et al., 2015).

Each experiment was repeated to ensure consistency of results, and average values were recorded for analysis. The same procedure was followed for all fuel blends (B5–B100) to ensure uniformity and enable direct comparison of performance and emission characteristics across different biodiesel concentrations.

2.5 Emission Measurement

Exhaust gas emissions were measured using a calibrated exhaust gas analyser connected to the engine exhaust system. The analyser was used to quantify the concentrations of nitrogen oxides (NO_x), carbon monoxide (CO), carbon dioxide (CO₂), and unburnt hydrocarbons (HC) under steady-state operating conditions.

During each test, the probe of the gas analyser was inserted into the exhaust stream, and sufficient time was allowed for the readings to stabilize before

recording the values. Measurements were taken at engine speeds of 1200 rpm, 1500 rpm, and 1800 rpm for all fuel blends to ensure consistency and comparability. The use of exhaust gas analysers for evaluating engine emissions is widely adopted in biodiesel research due to their reliability and ability to provide real-time data (Xue et al., 2011; Yasin et al., 2017).

To minimize experimental error, multiple readings were taken for each operating condition, and average values were used in the analysis. The measurement procedure ensured that all tests were conducted under similar environmental and operating conditions, thereby enhancing the accuracy and repeatability of the results.

III. RESULTS AND DISCUSSION

3.1 Engine Performance under Variable Load

Figure 1 Brake power variation with engine load for diesel and *Luffa cylindrica* biodiesel diesel blends (B5–B100).

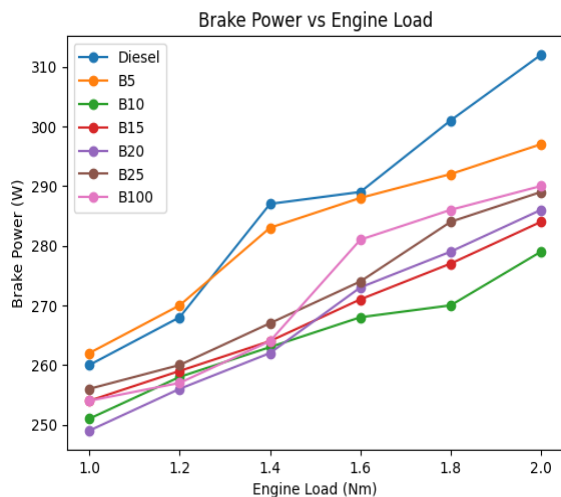


Figure 1 illustrates the variation of brake power (BP) with engine load for diesel and *Luffa cylindrica* biodiesel–diesel blends. As expected, brake power increased with increasing engine load for all fuel samples due to the higher fuel input and improved combustion at elevated loading conditions. This trend is consistent with the typical behavior of compression ignition engines reported in previous studies (Xue et al., 2011; Idris et al., 2023).

At all load conditions, conventional diesel exhibited the highest brake power, serving as the performance baseline. However, among the biodiesel blends, B5 demonstrated brake power values closest to diesel, particularly at moderate load conditions. This can be attributed to the relatively lower viscosity and higher calorific value of B5 compared to higher biodiesel blends, which enhances fuel atomization and combustion efficiency within the cylinder (Pinzi et al., 2013).

As the biodiesel concentration increased from B10 to B100, a gradual reduction in brake power was observed. This reduction is primarily associated with the lower heating value and higher viscosity of biodiesel, which can lead to poorer atomization and incomplete combustion at higher blend ratios. The increased fuel density and reduced volatility of higher blends further contribute to delayed combustion and reduced energy output (Azad et al., 2015; Mofijur et al., 2014).

In addition, the oxygenated nature of biodiesel promotes more complete combustion; however, this advantage does not fully compensate for the reduced calorific value at higher blend ratios. Consequently, blends such as B20, B25, and B100 exhibited lower brake power compared to B5 and diesel across the tested load range.

Overall, the results indicate that lower biodiesel blends, particularly B5, provide engine performance characteristics comparable to conventional diesel, making them suitable for applications where power output is a critical requirement. However, increasing biodiesel content introduces a trade-off between fuel properties and engine performance, which becomes more evident at higher blend ratios.

3.2 Emission Characteristics at Varying Engine Speeds

The variation of exhaust emissions with engine speed for diesel and *Luffa cylindrica* biodiesel blends is presented in Figures 2–5. The results highlight the influence of biodiesel concentration and engine speed on emission formation, reflecting the combustion characteristics of oxygenated fuels.

3.2.1 Nitrogen Oxides (NO_x) Emissions

Figure 2 Variation of nitrogen oxides (NO_x) emissions with engine speed for diesel and *Luffa cylindrica* biodiesel diesel blends.

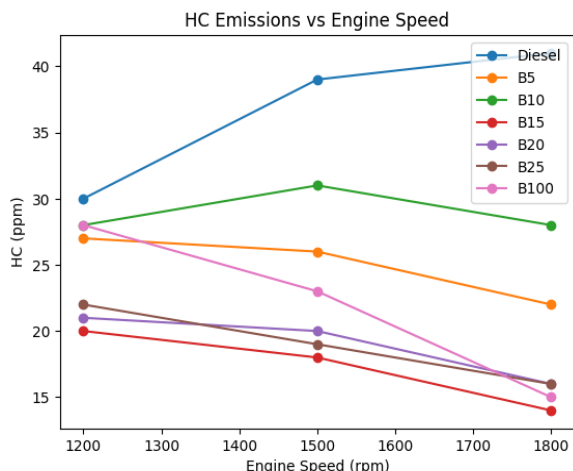
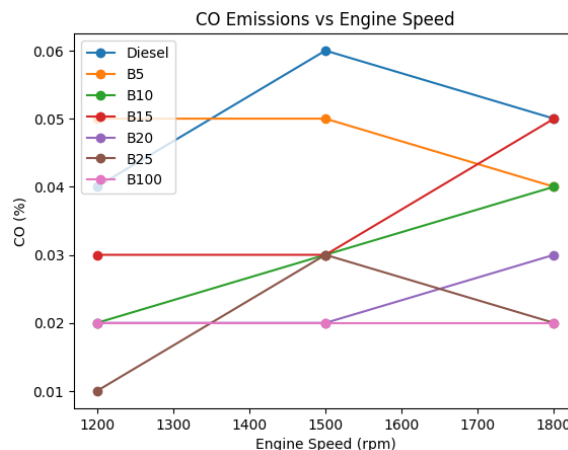


Figure 2 shows the variation of NO_x emissions with engine speed for all fuel blends. It is observed that biodiesel blends generally produced higher NO_x emissions compared to conventional diesel across the tested speed range. Diesel exhibited the lowest NO_x values, decreasing slightly with increasing engine speed.

In contrast, blends such as B5, B10, B25, and B100 showed significantly higher NO_x emissions, with peak values observed at higher speeds. B20 exhibited moderate NO_x levels relative to other biodiesel blends, indicating more balanced combustion behaviour. The increase in NO_x emissions with biodiesel blends can be attributed to the inherent oxygen content of biodiesel, which enhances combustion efficiency and promotes higher in-cylinder temperatures. Elevated combustion temperatures accelerate thermal NO_x formation through the Zeldovich mechanism, leading to increased NO_x emissions (Xue et al., 2011; Pinzi et al., 2013). Additionally, improved oxidation due to oxygenated fuel structure contributes to more complete combustion, further raising peak flame temperatures.

3.2.2 Hydrocarbon (HC) Emissions

Figure 3 Variation of unburnt hydrocarbon (HC) emissions with engine speed for diesel and *Luffa cylindrica* biodiesel diesel blends.



The variation of unburnt hydrocarbon emissions with engine speed is presented in Figure 3. Diesel fuel exhibited the highest HC emissions across all speeds, indicating relatively incomplete combustion compared to biodiesel blends. A significant reduction in HC emissions was observed for all biodiesel blends, with B15, B20, and B25 showing the lowest values, particularly at higher engine speeds. The reduction in HC emissions is primarily due to the oxygenated nature of biodiesel, which facilitates more complete oxidation of fuel during combustion. As engine speed increased, HC emissions generally decreased for biodiesel blends. This trend is associated with improved turbulence and air–fuel mixing at higher speeds, which enhances combustion efficiency and reduces the formation of unburnt hydrocarbons (Azad et al., 2015; Mofijur et al., 2014).

3.2.3 Carbon Monoxide (CO) Emissions

Figure 4. Variation of carbon monoxide (CO) emissions with engine speed for diesel and *Luffa cylindrica* biodiesel diesel blends.

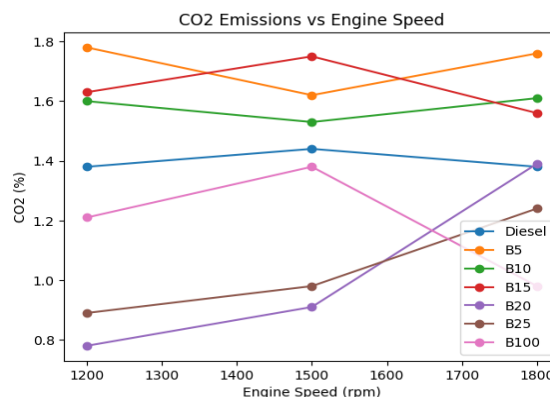


Figure 4 illustrates the variation of carbon monoxide emissions with engine speed. Diesel fuel exhibited comparatively higher CO emissions, particularly at intermediate engine speeds, indicating incomplete combustion under certain operating conditions.

Biodiesel blends demonstrated lower CO emissions overall, with B20 and B25 showing the most significant reductions. The reduction in CO emissions is attributed to the presence of oxygen in biodiesel molecules, which promotes more complete oxidation of carbon during combustion.

Although slight fluctuations were observed across different speeds, the general trend indicates that increasing biodiesel content leads to a reduction in CO emissions. This finding is consistent with previous studies, which report improved combustion efficiency and reduced carbon monoxide formation in biodiesel-fueled engines (Xue et al., 2011; Fazal et al., 2011).

3.2.4 Carbon Dioxide (CO₂) Emissions

The variation of carbon dioxide emissions with engine speed is shown in Figure 5. CO₂ emissions exhibited a relatively stable trend for diesel fuel, with slight variations across the tested speeds.

For biodiesel blends, CO₂ emissions showed a mixed behaviour depending on blend ratio and engine speed. In some cases, higher CO₂ emissions were observed, indicating more complete combustion, while in others, lower values were recorded due to differences in carbon content and fuel composition. Biodiesel generally contains lower carbon content compared to petroleum diesel, which can result in reduced CO₂ emissions on a volumetric basis. However, improved combustion efficiency associated with oxygenated fuels can increase CO₂ formation as a product of complete oxidation (Pinzi et al., 2013). This explains the observed variations across different blends and operating conditions.

3.3 Performance Emission Trade-off Analysis

The evaluation of *Luffa cylindrica* biodiesel diesel blends reveals a clear trade-off between engine performance and emission characteristics. While lower biodiesel blends tend to preserve engine performance, higher blends improve emission

profiles due to their oxygenated nature. This trade-off is critical in determining the most suitable blend for practical engine applications.

From the performance analysis, B5 demonstrated brake power values closest to conventional diesel across the tested load conditions, indicating minimal deviation from baseline engine performance. The relatively low biodiesel content in B5 ensures that key fuel properties such as calorific value, viscosity, and volatility remain similar to those of diesel, thereby maintaining efficient fuel atomization and combustion. As a result, B5 can be considered the most favourable blend in terms of engine performance. In contrast, emission analysis showed that biodiesel blends significantly reduced carbon monoxide (CO) and unburnt hydrocarbon (HC) emissions compared to diesel. These reductions are attributed to the inherent oxygen content of biodiesel, which enhances oxidation reactions and promotes more complete combustion (Xue et al., 2011; Fazal et al., 2011). Among the blends, B20 consistently exhibited lower CO and HC emissions while maintaining relatively stable behaviour across different engine speeds.

However, the use of biodiesel blends resulted in increased nitrogen oxides (NO_x) emissions, particularly at higher blend ratios. This increase is primarily due to higher combustion temperatures and improved oxidation processes associated with oxygenated fuels, which favour NO_x formation through thermal mechanisms (Pinzi et al., 2013). Although B20 showed higher NO_x emissions than diesel, its values remained lower than those observed for higher blends such as B25 and B100, indicating a moderate and acceptable increase.

The combined evaluation of performance and emissions suggests that no single blend simultaneously optimizes all engine parameters. Instead, a compromise must be achieved depending on operational priorities. B5 offers superior engine performance with minimal power loss, making it suitable for applications where performance is critical. Conversely, B20 provides a more favourable emission profile, significantly reducing CO and HC emissions while maintaining acceptable performance levels.

Therefore, the results highlight that B5 and B20 represent two optimal points along the performance emission spectrum. B5 is recommended for performance-oriented applications, whereas B20 is more suitable for environmentally conscious applications where emission reduction is prioritized. This trade-off underscores the importance of selecting appropriate biodiesel blend ratios based on specific operational and environmental requirements.

IV. CONCLUSION

This study evaluated the performance and emission characteristics of *Luffa cylindrica* biodiesel–diesel blends (B5–B100) in a single-cylinder direct injection compression ignition engine under varying operating conditions. The results demonstrated that biodiesel blends influence engine behaviour in terms of both performance and emissions, with effects strongly dependent on blend ratio.

Brake power increased with engine load for all fuels, with conventional diesel exhibiting the highest values. Among the biodiesel blends, B5 showed performance characteristics closest to diesel, indicating that lower blend ratios can be used without significant compromise in engine output. However, increasing biodiesel concentration resulted in a gradual reduction in performance due to lower calorific value and higher viscosity.

Emission analysis revealed that biodiesel blends significantly reduced carbon monoxide (CO) and unburnt hydrocarbon (HC) emissions compared to diesel, confirming improved combustion efficiency associated with oxygenated fuels. Conversely, nitrogen oxides (NO_x) emissions increased with higher biodiesel content due to elevated combustion temperatures. Among the tested blends, B20 provided the most balanced emission profile, achieving notable reductions in CO and HC while maintaining moderate NO_x levels.

Overall, the findings highlight a clear performance emission trade-off in the use of *Luffa cylindrica* biodiesel blends. B5 is recommended for applications requiring high engine performance, while B20 is more suitable for reducing exhaust emissions. The study demonstrates that *Luffa cylindrica* biodiesel is

a viable alternative fuel for compression ignition engines and offers potential for sustainable energy applications.

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