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# Combustion and Emission Characteristics of Jatropha and UCO Biodiesel Blends in Burner System

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**Abstract**
This study investigates the combustion performance and emission characteristics of biodiesel blends derived from Jatropha Methyl Ester (JME) and Used Cooking Oil Methyl Ester (UCOME) in comparison to Conventional Diesel Fuel (CDF). Biodiesel was produced using a two-step transesterification process, producing high yields of 94.3% for JME and 92.0% for UCOME. Fuel blends were prepared at B5, B15, and B25 concentrations and tested in a lab-scale combustion chamber equipped with thermocouples and a gas analyzer. Key fuel properties such as specific gravity and calorific value were evaluated, showing that gravity increased with higher biodiesel content while calorific value decreased. For instance, CDF had the highest calorific value at 45.29 MJ/kg, whereas B100 biodiesels recorded lower values. Emissions analysis revealed that increasing biodiesel content significantly reduced NOx and CO emissions. At stoichiometric conditions (equivalence ratio 1.0), NOx emissions dropped from 61 ppm (CDF) to 51 ppm (B25 JME) and 52 ppm (B25 UCOME). CO emissions under the same conditions showed a reduction of up to 95.2% for B25 JME compared to CDF. The highest CO reduction occurred under stoichiometric combustion, while the most significant NOx reduction was observed at lean conditions, with B25 UCOME achieving a 40.5% decrease. These findings demonstrate the environmental advantage of biodiesel blends, particularly B25, which significantly reduces harmful emissions without compromising fuel performance.

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## 1. Introduction

The global demand for sustainable and environmentally friendly energy sources has accelerated the exploration and development of biofuels, particularly biodiesel. Derived from renewable biological resources, biodiesel offers a cleaner alternative to fossil fuels due to its biodegradability, non-toxicity, and significantly lower emissions. Various feedstocks such as vegetable oils, animal fats, and used cooking oil (UCO) have been successfully utilized in biodiesel production, contributing to energy diversification and waste reduction. Jatropha curcas has emerged as a promising non-edible oilseed crop for biodiesel production, especially in tropical regions. Several studies have shown that Jatropha Methyl Ester (JME) possesses fuel properties comparable to conventional diesel, including acceptable viscosity, cetane number, and calorific value (S. M. Rosdi, Maghfirah, et al., 2025; S. M. M. Rosdi et al., 2025; Selvakumar et al., 2025; Yadav et al., 2018). JME can be blended up to 20% with diesel without significant engine modification (Gani, Saisa, et al., 2025; Gani, Zaki, et al., 2025; Ghazali et al., 2025; Saleh & Selim, 2017). Moreover, its cultivation on marginal lands makes it an attractive feedstock without interfering with food supply chains.

Used Cooking Oil (UCO) has also gained attention as a low-cost and environmentally beneficial biodiesel feedstock. It addresses both waste management and fuel production simultaneously. Biodiesel from UCO exhibits reduced emissions of carbon monoxide (CO) and particulate matter (Alenezi et al., 2021; Fitriyana et al., 2025; Muhibbuddin, Hamidi, & Fitriyana, 2025; Rahman et al., 2025). However, the high free fatty acid (FFA) content in UCO often requires a two-step transesterification process to ensure high conversion efficiency (Alenezi et al., 2020; Iqbal et al., 2025; Nizar, Syafrizal, et al., 2025; Roslan et al., 2022). Combustion and emission characteristics are essential for evaluating biodiesel performance in real applications. Numerous studies have shown that biodiesel generally reduces CO, unburned hydrocarbons (HC), and sulfur oxides (SOx) due to its oxygen-rich nature and negligible sulfur content (Erdiwansyah, Mamat, Sani, Sudhakar, et al., 2019; Estevez et al., 2022; Jalaludin et al., 2025; Muhtadin et al., 2025). For instance, Lapuerta et al. (2008) reported that biodiesel blends reduced CO emissions by up to 60% compared to diesel, while NOx emissions could vary depending on fuel properties and combustion conditions.

However, NOx emissions remain a concern for biodiesel usage, often attributed to higher combustion temperatures and oxygen content in the fuel. Researchers such as Tat and Van Gerpen (2004) observed increased NOx emissions with higher biodiesel blends, though this effect can be mitigated through engine tuning or fuel formulation (Erdiwansyah, Mamat, Sani, & Sudhakar, 2019; Masera & Hossain, 2023; Muhibbuddin, Hamidi, Rashid, et al., 2025; Sumarno et al., 2025). Moreover, blending biodiesel in lower proportions, such as B5 to B25, has shown the potential to balance emission reductions without significantly altering engine performance. This study evaluates the fuel properties, combustion behaviour, and emission profiles of JME and UCOME blends in a lab-scale burner system. Specifically, the study focuses on B5, B15, and B25 blends to assess their practicality in reducing NOx, CO, and $SO_2$ emissions. The results are expected to contribute to the growing body of evidence supporting biodiesel as a viable and sustainable substitute for fossil diesel in stationary combustion applications.

The novelty of this study lies in its comparative analysis of biodiesel blends derived from both Jatropha Methyl Ester (JME) and Used Cooking Oil Methyl Ester (UCOME) under controlled combustion conditions using a lab-scale burner system, focusing on emissions at varying equivalence ratios (lean, stoichiometric, and rich). Unlike previous studies emphasising engine-based tests, this research highlights the emission behaviour in a combustion chamber, providing a clearer understanding of thermal and chemical interactions during fuel burning. Furthermore, the detailed quantification of emission reductions such as a 40.5% decrease in NOx and up to 95.2% reduction in CO demonstrates the effectiveness of biodiesel blends in minimizing environmental pollutants. This approach offers valuable insights for stationary applications and thermal systems utilizing renewable liquid fuels.

## 2. Methodology

The combustion experimental test rig set up for the liquid fuel burner is presented in **Fig. 1**. The burner and combustion chamber were aligned and fixed horizontally. A blower supplied compressed air to the burner. The thermocouples were attached in holes in the combustion chamber and connected to the data logger. For data collection of emissions, a gas analyser tube was mounted at the exit of the combustion chamber.

**Thermocouple and Thermocouple Reader Data Logger**

In general, the thermocouple is a sensor used to measure temperature. It is made of two wire legs from two metals joined together at one end, creating a junction. When the junction experiences a temperature adjustment, a data logger will produce and interpret a voltage. The data logger converts the voltage to temperature as digital data. In this experiment, the instrument used to determine the wall temperature of the combustion chamber was a type-K thermocouple. It was placed at the eight holes on top of the combustion chamber. The type-K thermocouple is economical, precise, and reliable and has a wide temperature range from -270˚C to 1260˚C. A data logger was used as an additional instrument for the reader to the thermocouple. In this case, the Graphtec GL220 midi logger was used to read the signal; voltage was created from the thermocouple and converted to temperature value. Appendix B2 shows the specifications of the Graphtec GL220 MIDI logger. **Fig. 2** and **3** show the type K thermocouple and the data logger used in this experiment.

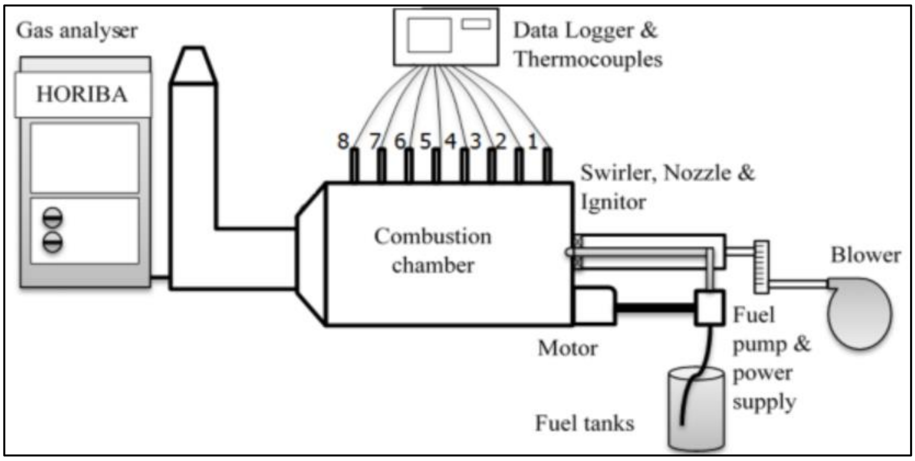


**Fig. 1**. Combustion experiment setup

**Fig. 2**. Type-K thermocouple

Figure 3.17 Graphtec GL220 Logger

## 3. Result & Discussion

**Gas Analyser**

The primary purpose of a gas analyser is to measure the emission concentration from the combustion of the fuel. This gas analyser needed to be run earlier before experimenting to warm up and stabilise the reading before it could be used to collect the emission reading from the combustion test. This experiment used a gas analyser from the Horiba ENDA 5000 stack gas analysis system to measure NOx, CO and $SO_2$ emissions. **Fig. 4** shows the Horiba ENDA 5000 gas analyser used. **Table 1** shows the range of the gas analyser.

**Fig. 4**. Horiba ENDA 5000 series of stack gas analysis system

**Table 1**. Gas analyser Horiba ENDA 5000 range

| Gas measured | Range | Measurement Method |
|---|---|---|
| Nitrogen Oxide ($NO_2$) | 200-5000 ppm | NDIR |
| Sulfur Dioxide ($SO_2$) | 200-5000 ppm | NDIR |
| Carbon Monoxide (CO) | 200-5000 ppm | NDIR |

**Preparation of Biodiesel from Crude Oil**

**Fig. 5** shows a sample of JME and UCOME produced. Both methyl esters were converted from crude oil via a two-step transesterification process. In terms of physical appearance, both biodiesels have darker colours than diesel fuel due to their crude oils' colour.


**Fig. 5**. Sample of JME, UCOME and CDF

**JME and UCOME Yield Percentage**

Yield or conversion rate is a ratio of the quantity of product produced to the amount provided at first. In the Gas Turbine Combustion Research Group laboratory, eight batches of 1200 ml two-step transesterification process were done to produce biodiesel. From the production, for every 9.6 litres of crude oils, the yield percentage of JME is 94.3%, whereas UCOME is 92.0%. **Table 2** shows the conversion rate and yield for biodiesel production.

**Table 2**. Yield of jatropha and used cooking oil biodiesel production

| No | JME conversion rate | Yield | UCOME conversion rate | Yield |
|---|---|---|---|---|
| 1 | 1010 ml / 1200 ml | 84.2% | 1020 ml / 1200 ml | 85.0% |
| 2 | 1040 ml / 1200 ml | 86.7% | 1055 ml / 1200 ml | 87.9% |

| No | JME conversion rate | Yield | UCOME conversion rate | Yield |
|---|---|---|---|---|
| 3 | 1080 ml / 1200 ml | 90.0% | 1100 ml / 1200 ml | 91.7% |
| 4 | 1070 ml / 1200 ml | 89.2% | 1050 ml / 1200 ml | 87.5% |
| 5 | 1165 ml / 1200 ml | 97.1% | 1070 ml / 1200 ml | 89.2% |
| 6 | 1095 ml / 1200 ml | 91.3% | 1130 ml / 1200 ml | 94.2% |
| 7 | 1135 ml / 1200 ml | 94.6% | 1080 ml / 1200 ml | 90.0% |
| 8 | 1045 ml / 1200 ml | 87.1% | 1070 ml / 1200 ml | 89.2% |

Considering the best three yields from batch 5, batch 6 and batch 7 of jatropha conversion, average yield = (97.1 + 91.3 + 94.6) / 3 = 94.3%. As well as considering the best three yields from batch 3, batch 6 and batch 7 of used cooking oil conversion, average yield = (91.7 + 94.2 + 90) / 3 = 92.0%. The conversion rate of biodiesel production depends on parameters such as the ratio of methanol to crude oil, ratio of catalyst, reaction temperature and time. While handling the product, the human error factor contributes to the total conversion rate. However, in this study, the primary factor that significantly affects yield is the formation of soup through the post-treatment process. To minimize the soup formation, unpurified methyl ester must be treated gently and shaken slowly in the separation funnel.

**Biodiesel Production Cost**

**Table 3** shows the estimation of biodiesel production cost of 1-litre jatropha and used cooking oil biodiesel. The cost was accountable for the material utilized in the two-step transesterification process within the lab scale range. Nevertheless, a correct calculation shall include material, electricity, apparatus, consumable equipment and labour costs. Generally, these costs have a minor impact and decline as the production scale range increases. It is stated that 60-75% of biodiesel production cost is from the cost of feedstock or crude oil (Canakci & Sanli, 2008; Daud et al., 2023; Mata et al., 2010; Sumbodo et al., 2025).

On the other hand, UCO is much cheaper and can be collected nationwide at Ringgit Malaysia (RM) 0.50 – 1.00 (Nizar, Yana, et al., 2025; S. M. Rosdi, Ghazali, et al., 2025; Tutur & Mat Daud, 2022; Yusop et al., 2022). UCO has no standards and specifications as it would be treated as high FFA oil and require a two-step transesterification process to convert it to biodiesel. **Table 3** proved that 83% of jatropha biodiesel production cost covered the crude oil cost, whereas used cooking oil only costs 5.8% of its biodiesel production cost. It is known because of used cooking oil is a used and recycled product. Hence the price is cheaper.

**Table 3**. Biodiesel production cost (material) per litre in Ringgit Malaysia (RM)

| Material | Quantity | Cost for JME (RM) | Cost for UCOME (RM) |
|---|---|---|---|
| Crude Oil | 1 litre | 80.00 | 1.00 |
| Methanol, MeOH | 750 ml | 8.70 | 8.70 |
| Acid Sulfuric, $H_2SO_4$ | 15 ml | 0.23 | 0.23 |
| Potassium Hydroxide, KOH | 9.1 g | 0.50 | 0.50 |
| Distilled Water | 7.5 litre | 6.82 | 6.82 |
| Total material cost (RM) | | 96.25 | 17.25 |

**Blending Test Fuels**

Gas Turbine Combustion Research Group laboratory carried out the blending process to produce jatropha and used cooking oil biodiesel blends. **Fig. 6** shows the sample of test fuels. **Fig. 7** shows a graph of specific gravity plotted to estimate the homogenous blends during the blending process.


**Fig. 6**. Sample of test fuels

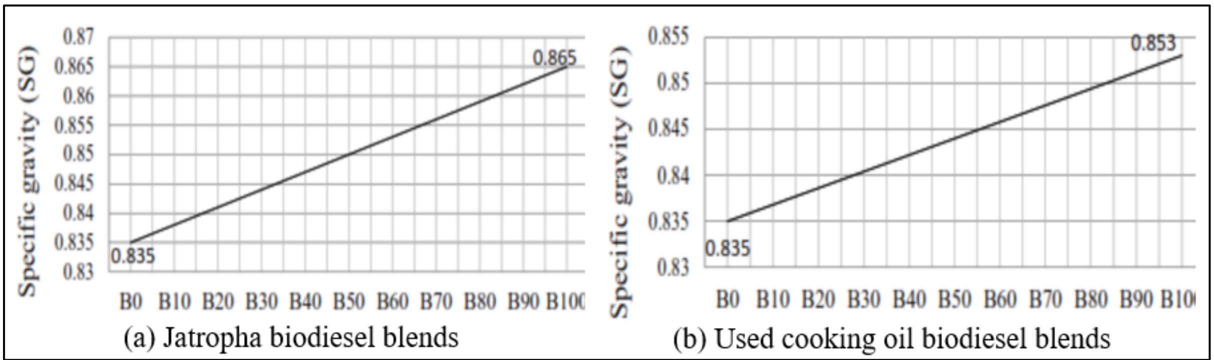


**Fig. 7**. Specific gravity versus biodiesel blends

**Specific Gravity**

A specific gravity test was conducted during the blending process in this study to determine the physical properties of the fuels. A hydrometer was used as per ASTM D891 specific gravity measuring standard procedure. **Table 4** shows the specific gravities of the test fuels with the lowest SG CDF with a value of 0.835. The table shows that each blend fuel has a higher SG than diesel and lower than their B100 SG. As the proportion of biodiesel increases in a blend, the specific gravity of the fuel increases, too. It follows the density trend, where biodiesel is heavier than CDF. Thus, the trend is similar.

**Table 4**. The specific gravity of fuels

| Fuel | Density (kg/m3) |
|---|---|
| CDF | 830.1 |
| B5 JME | 833.8 |
| B15 JME | 837.4 |
| B25 JME | 841.0 |
| B100 JME | 868.0 |
| B5 UCOME | 827.4 |
| B15 UCOME | 830.5 |
| B25 UCOME | 833.5 |
| B100 UCOME | 858.7 |

**Calorific Value**

Calorific value is also known as the heating value of fuel in terms of the quantity of heat that can be produced in a unit weight or volume during combustion. Calorific value is also defined as the energy content of a fuel and, thus, its efficiency (Verduzco et al., 2011). Energy content is one of the most notable properties of fuel. For instance, a fuel with a higher calorific value will give better combustion performance than a lesser calorific value. A calorific value property test was conducted using the IKA

C2000 bomb calorimeter, which complies with the ASTM D240 measuring standard. It was performed twice, sometimes more, where these values are acceptable if the differences are less than 1000J/g. **Table 5**. shows the calorific value of the fuels tested in this study. It is observed that CDF has the highest calorific value, 45.29 kJ/kg, among the fuels tested, whereas B100 biodiesels have the lowest calorific value among its blends.

**Table 5**. The calorific value of fuels

| Fuel | Calorific Value (kJ/kg) |
|---|---|
| CDF | 45.29 |
| B5 JME | 44.83 |
| B15 JME | 44.21 |
| B25 JME | 43.59 |
| B100 JME | 39.52 |
| B5 UCOME | 44.93 |
| B15 UCOME | 44.35 |
| B25 UCOME | 43.73 |
| B100 UCOME | 39.50 |

It suggested that the calorific value decreases as a higher percentage of biodiesel in the fuel was applied. CDF has the highest energy content compared to B100 JME and B100 UCOME. As the rate of biodiesel in a blend decreases, the quantity of energy content as its B100 biodiesel lowers the calorific value.

**Gaseous Emissions**

Gaseous emissions produced during the combustion of test fuels were to contrast the effectiveness and feasibility of biodiesel in replacing fossil fuels. The types of exhaust emissions considered were nitrogen oxides (NOx), carbon monoxide (CO) and sulphur dioxide ($SO_2$). Those gases are the primary pollutants that harm the environment and affect human health. The emissions volume produced was measured in parts per million (ppm) using a gas analyser connected at the exhaust end of the combustion chamber.

**Nitrogen Oxide (NOx)**

NOx is a product of nitrogen and oxygen reactions. Throughout combustion, NOx is formed with nitrogen and oxygen at high temperatures (Strakey et al., 2006). **Fig. 8** shows the amount of NOx generated by combusting CDF, B5 JME, B15 JME, B25 JME, B5 UCOME, B15 UCOME and B25 UCOME test fuels at various equivalence ratios. The pattern of NOx formation concentration can be observed in **Fig. 8**. NOx formation increased during combustion from lean to stoichiometric condition, reached peak at stoichiometric and declined back towards the fuel-rich region combustion. The trend of NOx produced is relatively similar for all test fuels. At the fuel-lean region, equivalence ratios of 0.8 and 0.9, NOx produced were small due to an abundant amount of oxygen in the lean region. This region was diluted with air, reducing NOx formation during combustion. Vice versa, at equivalence ratios 1.1 and 1.2, there was more fuel than air in the fuel-rich region. This means there was less oxygen in the air to react with fuel to form NOx (Daud et al., 2022b; Houshfar et al., 2012; Maulana et al., 2025; S. M. Rosdi, Yasin, et al., 2025). NOx is affected by oxygen concentration in the fuels and the wall temperature at various equivalence ratios.

From **Fig. 9**, the most considerable amount of NOx produced by all test fuels was at equivalence ratio 1.0, stoichiometric condition. The value of each peak was 61 ppm for CDF, followed by 60 ppm for both B5 JME and B5 UCOME, B15 UCOME 55 ppm, B15 JME 54 ppm, B25 UCOME 52 ppm and B25 JME with 51 ppm NOX produced. Considering emission at lean, stoichiometric and rich conditions during the combustion of each test fuel, comparisons with CDF were made, as shown in **Fig. 9** (a), (c) and (e). The values of CDF were from experiments conducted and were used as a baseline to compare with other test fuels. **Fig. 9** (b), (d) and (f) show a reduction in the percentage of test fuel NOx emission relative to CDF at lean, stoichiometric and rich conditions. The reduction of NOx from CDF to other biodiesel blends was significant, with the highest emission drop compared to CDF at lean condition by

B25 UCOME with a 40.5% reduction, as shown in **Fig. 9** (b). It is observed that the reduction is proportional to the percentage of biodiesel in a blend. As the percentage of biodiesel increases in fuel, NOX formation is reduced. This can be explained by the physical properties of biodiesel studied. The biodiesel blends were lower in calorific value but higher in kinematic viscosity than CDF. Therefore, their heating value was also lower. Thus, lowering their wall temperature through combustion impeded the formation of NOx, which needed a high combustion wall temperature.

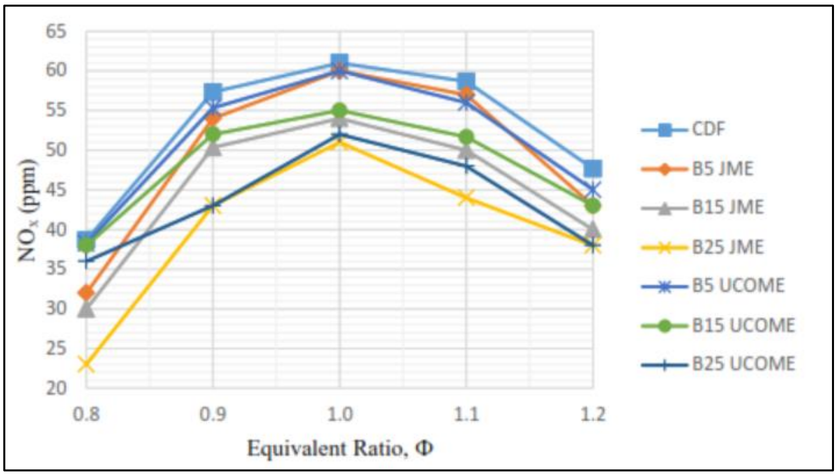


**Fig. 8**. Emission of NOx for test fuels

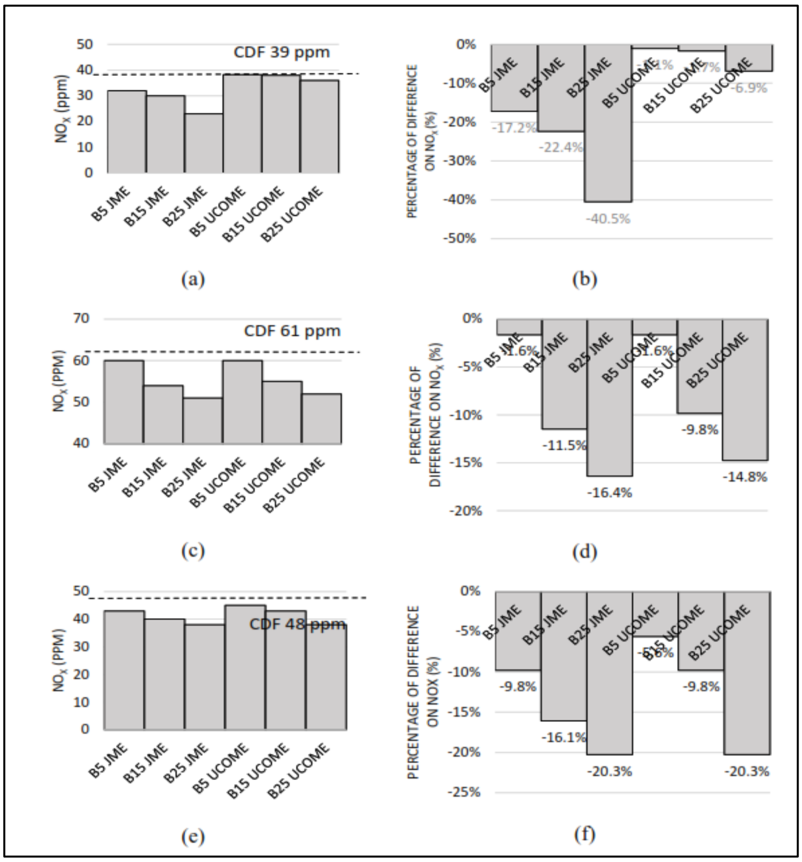


**Fig. 9.** Emission of NOX at specific equivalence ratio and percentage of difference on NOX emission relative to CDF (a) NOX at lean condition, (b) percentage of difference on NOX at lean condition, (c) NOX at stoichiometric condition, (d) percentage of difference on NOX at stoichiometric condition, (e) NOX at rich condition, (f) percentage of difference on NOX at rich condition

On the other hand, having higher kinematic viscosity only degraded their atomization, and the oxygen molecules were too short and scarce to react correctly with the nitrogen in the air that reserved the production of NOx. NOx emissions slightly increase depending on cetane number (Daud et al., 2022c, 2022a; Khan et al., 2016).

**Carbon Monoxide (CO)**

Carbon monoxide (CO) was formed due to incomplete fuel combustion, mainly affected by the combustion wall temperature (Malik et al., 2022; Muchlis, Efriyo, Rosdi, Syarif, et al., 2025; Sardjono et al., 2025; Tomomewo & Oni, 2025). Incomplete combustion occurs when there is insufficient oxygen. Hence, the combustion process generates CO concentration from inadequate oxygen supply. **Fig. 10** shows the amount of CO produced by combustion of CDF, B5 JME, B15 JME, B25 JME, B5 UCOME, B15 UCOME and B25 UCOME test fuels at various equivalence ratios.

From **Fig. 10**, the CO emission trend is vertically parabolic. The minimum CO formed from all the test fuels was at an equivalent ratio of 1.0. This stoichiometric region denotes complete combustion, where all the carbon content in the fuel was well burnt, leaving no carbon leftovers. Considering emission at lean, stoichiometric and rich conditions during the combustion of each test fuel, comparisons with CDF were made, as shown in **Fig. 11** (a), (c) and (e). The values of CDF were from experiments conducted and were used as a baseline to compare with other test fuels. **Fig. 11** (b), (d) and (f) show a reduction in the percentage of test fuel CO emission relative to CDF at lean, stoichiometric and rich conditions. **Fig. 11** (d), relative to CDF in stoichiometric conditions, shows the most significant emission reduction compared to lean and rich conditions, from 42.9% to 95.2%. In the fuel-rich region, the increase of oxygen content in the test fuel means that the carbon and hydrogen contents were lower. The results suggest that utilizing biodiesel blends helps reduce CO produced during combustion, similar to those reported by other researchers (Abu-Hamdeh et al., 2020; Muchlis, Efriyo, Rosdi, & Syarif, 2025; Pourhoseini et al., 2021).

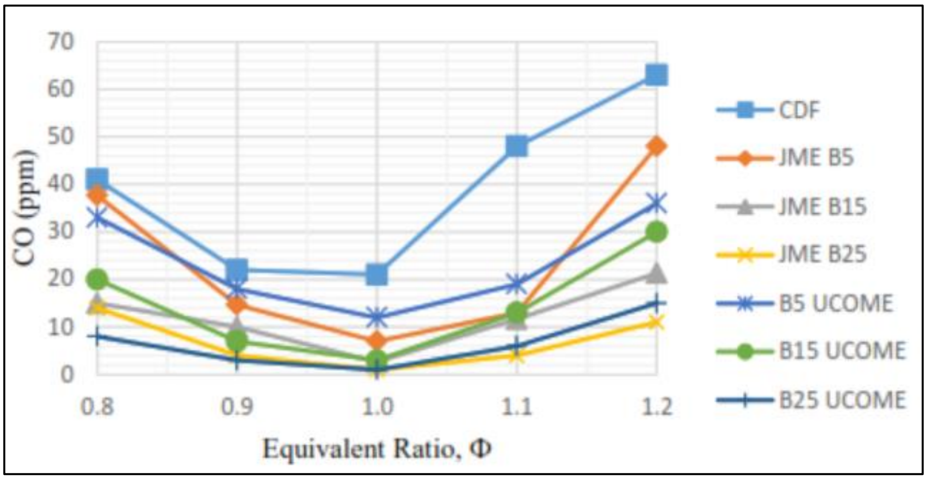


**Fig. 10.** Emission of CO for test fuels

**Fig. 11** (b), (d) and (f) show a reduction percentage of test fuels CO emission relative to CDF. The highest percentage drop compared to diesel occurred during combustion of B25 UCOME, 80.5% at lean condition, and B25 JME with 95.2% reduction at stoichiometric condition and 82.5% drop at rich condition by B25 JME. The smallest reduction percentage compared to diesel fuel had occurred using B5 JME and B5 UCOME, with a reduction of 8.1% at lean condition, 42.9% reduction by B5 UCOME at stoichiometric condition and 23.8% at rich condition correspondingly. The reduction is proportional to the percentage of biodiesel in a blend; as the percentage of biodiesel increases in fuel, the reduction of CO formation is more significant. In addition, an increment in combustion wall temperature resulted from an increase in the reactivity of the carbon and oxygen, consequently producing more CO than the combustion in the stoichiometric region. In the fuel-lean condition, air diluted the mixture of fuel and air, causing a slower oxidation rate, thus generating more CO (Daud et al., 2021; Jamil et al., 2021; Zakiyuddin et al., 2021).

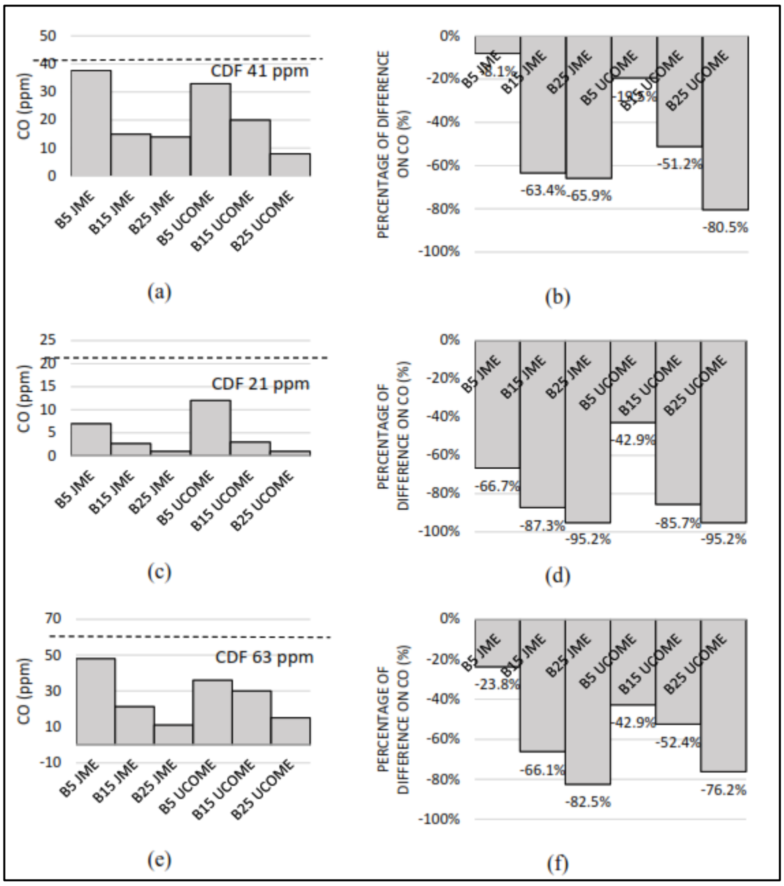


**Fig. 11.** Emission of CO at specific equivalence ratio and percentage of difference on CO emission relative to CDF fuel (a) CO at lean condition, (b) the percentage of difference on CO at lean condition, (c) CO at stoichiometric condition, (d) the percentage of difference on CO at stoichiometric condition, (e) CO at rich condition, (f) percentage of difference on CO at rich condition

## 4. Conclusion

The experimental investigation demonstrated that biodiesel blends derived from Jatropha Methyl Ester (JME) and Used Cooking Oil Methyl Ester (UCOME) are promising alternatives to conventional diesel fuel (CDF) in terms of combustion performance and emission reduction. The biodiesel production through a two-step transesterification process yielded 94.3% for JME and 92.0% for UCOME, confirming the method's efficiency. Fuel property analysis showed that as the biodiesel percentage increased in the blends, the specific gravity also increased, ranging from 0.835 (CDF) to values above 0.860 for B25 blends. Meanwhile, calorific value decreased with higher biodiesel content, with CDF recording the highest value of 45.29 MJ/kg and B100 biodiesels showing the lowest values, consistent with their lower energy content. Combustion emission results showed a clear emission reduction trend with an increasing biodiesel ratio. At stoichiometric conditions (equivalence ratio 1.0), NOx emissions decreased from 61 ppm (CDF) to 52 ppm (B25 UCOME) and 51 ppm (B25 JME). The most significant NOx reduction was 40.5% at lean conditions using B25 UCOME. For CO emissions, reductions reached up to 95.2% at stoichiometric conditions with B25 JME compared to CDF. These outcomes indicate that blending up to 25% biodiesel can significantly reduce NOx and CO emissions while maintaining feasible combustion characteristics, supporting using JME and UCOME as sustainable, low-emission biofuels.

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