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Emission and Fuel Properties Analysis of Jatropha and UCO Biodiesel Blends for Combustion Applications

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Abstract
This study investigates the production, characterization, and emission performance of biodiesel blends derived from Jatropha Methyl Ester (JME) and Used Cooking Oil Methyl Ester (UCOME). Biodiesel was produced through a two-step transesterification process, resulting in an average yield of 94.3% for JME and 92.0% for UCOME from 9.6 liters of crude oil. Production cost analysis revealed that crude Jatropha oil constituted 83% of the total cost per liter, while UCO contributed only 5.8%, indicating significant economic advantages for waste-based feedstock. Physical properties of the biodiesel blends were assessed and compared to EN 590 (diesel) and EN 14214 (biodiesel) standards. Results showed that increasing biodiesel content in blends raised viscosity, density, specific gravity, and surface tension, while reducing calorific value. Despite these variations, all blends remained within acceptable biodiesel standard limits, making them suitable for industrial burner applications. SO_2 emissions were evaluated using combustion tests across lean, stoichiometric, and rich conditions. Compared to conventional diesel fuel (CDF), B25 UCOME achieved the highest SO_2 reduction of 69% under lean, 58.1% under stoichiometric, and 90.9% under rich conditions. These reductions are attributed to the inherently lower sulphur content in biodiesel. The findings demonstrate the environmental and economic potential of biodiesel blends, particularly UCOME, as cleaner and cost-effective alternatives to fossil fuels in combustion systems.

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1. Introduction

The growing concern over the environmental impact of fossil fuels has accelerated the search for alternative, renewable energy sources. Among the many options, biodiesel has gained considerable attention due to its biodegradability, renewability, and lower emissions profile. Derived from biological sources such as vegetable oils and animal fats, biodiesel presents a viable substitute for conventional diesel in various combustion systems, especially in stationary industrial burners and power generation applications (Demirbas, 2009; Mata et al., 2010; Muhibbuddin et al., 2025b). Jatropha curcas oil is one of the most promising non-edible feedstocks for biodiesel production due to its high oil content and adaptability to marginal lands (Achten and Jeukendrup, 2003; Nizar et al., 2025b; Rosdi et al., 2025a). Several studies have demonstrated that Jatropha Methyl Ester (JME) possesses favorable physicochemical properties, such as higher cetane number and flash point, and lower sulphur content compared to conventional diesel (Muchlis et al., 2025a, 2025b; Sardjono et al., 2025). However, its relatively high production cost remains a challenge, mostly attributed to the cost of crude Jatropha oil.

On the other hand, Used Cooking Oil (UCO) has emerged as a cost-effective and environmentally friendly biodiesel feedstock. Since UCO is a waste material, its utilization helps reduce disposal issues while offering significantly lower raw material costs (Maulana et al., 2025; Muhtadin et al., 2025; Rosdi et al., 2025c). Biodiesel derived from UCO shows competitive fuel properties and substantially reduced production costs compared to virgin oil sources (Canakci and Sanli, 2008; Sanli et al., 2015). The transesterification process, particularly the two-step acid-base method, has been widely adopted to convert high Free Fatty Acid (FFA) oils like UCO into biodiesel. This approach reduces soap formation and improves yield efficiency (Iqbal et al., 2025; Jalaludin et al., 2025; Xiaoxia et al., 2025). The success of this method depends on multiple parameters, including methanol-to-oil ratio, catalyst concentration, temperature, and reaction time. Researchers have consistently optimized these variables to achieve biodiesel yields above 90% in laboratory-scale setups.

Beyond fuel production, the evaluation of biodiesel blends in combustion systems is critical to assess their practical applicability. Previous combustion studies have shown that biodiesel can significantly reduce emissions of harmful gases such as carbon monoxide (CO), unburned hydrocarbons (HC), and sulphur dioxide (SO_2), due to its oxygenated nature and negligible sulphur content (Febrina and Anwar, 2025; Rosli et al., 2025; Sumarno et al., 2025). Nevertheless, an increase in nitrogen oxides (NOx) emissions has been reported in certain conditions, which requires further analysis depending on fuel blends and combustion parameters.

This study aims to compare the production yield, fuel properties, and SO_2 emission characteristics of JME and UCOME blends with conventional diesel fuel (CDF) under various combustion conditions. It also explores the economic viability of each biodiesel source by analyzing production costs at the laboratory scale. The findings from this research are expected to contribute valuable insights into the feasibility of implementing biodiesel blends in industrial combustion systems, with an emphasis on environmental and cost efficiency.

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. Compressed air was supplied by a blower to the burner. The thermocouples were attached in holes on top of the combustion chamber and were connected to the data logger. For data collection of emission, gas analyser tube was mounted at the exit of the combustion chamber.

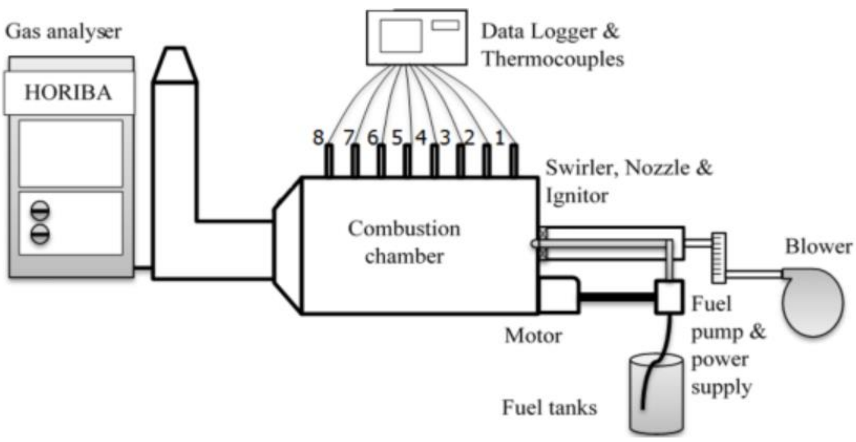


Fig. 1. Combustion experiment setup

Thermocouple and Thermocouple Reader Data Logger

In general, thermocouple is a sensor used to measure temperature. It is made of two wire legs from two different metal that are joined together at one end, creating a junction. When the junction experiences an adjustment in temperature, a voltage will be produced and interpreted by a data logger. Data logger converts the voltage to temperature in the form of digitally data. In this experiment, instrument used to determine the wall temperature of the combustion chamber were type-K thermocouple. It was placed at the eight holes on top of combustion chamber. The type-K thermocouple is economical, precise, and reliable and has a wide temperature range from -270˚C to 1260˚C. As for reader to the thermocouple, data logger was used as an addition instrument. In this case, Graphtec GL220 midi logger was used to read signal; voltage, created from the thermocouple and converts it to temperature value. Appendix B2 shows the specification of Graphtec GL220 midi logger. **Figs 2** and **3** show the typeK thermocouple and the data logger used in this experiment.

Fig. 2. Type-K thermocouple

Fig. 3. Graphtec GL220 Logger

3. Result & Discussion

Preparation of Biodiesel from Crude Oil

Fig. 4 shows sample of JME and UCOME produced. Both methyl esters were produced by conversion from crude oil via two-step transesterification process. In term of physical appearances, both biodiesels have darker colour compared to diesel fuel due to their crude oils' colour.

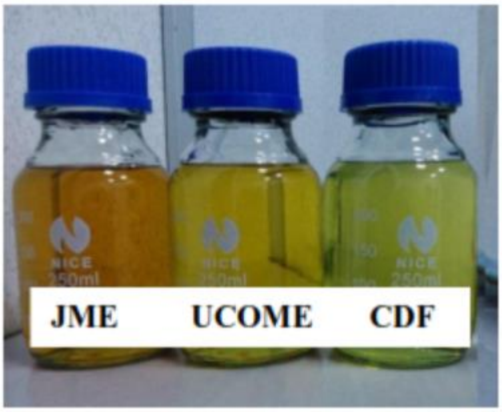


Fig. 4. Sample of JME, UCOME and CDF

JME and UCOME Yield Percentage

Yield or conversion rate is a ratio of quantity product produced to amount provided at first. In 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 1** shows conversion rate and yield for biodiesel production.

Table 1: Yield of jatropha and used cooking oil biodiesels production

No	JME conversion rate	Yield		No	UCOME conversion rate	Yield
1	1010 ml / 1200 ml	84.2%		1	1020 ml / 1200 ml	85.0%
2	1040 ml / 1200 ml	86.7%		2	1055 ml / 1200 ml	87.9%
3	1080 ml / 1200 ml	90.0%		3	1100 ml / 1200 ml	91.7%
4	1070 ml / 1200 ml	89.2%		4	1050 ml / 1200 ml	87.5%
5	1165 ml / 1200 ml	97.1%		5	1070 ml / 1200 ml	89.2%
6	1095 ml / 1200 ml	91.3%		6	1130 ml / 1200 ml	94.2%
7	1135 ml / 1200 ml	94.6%		7	1080 ml / 1200 ml	90.0%
8	1045 ml / 1200 ml	87.1%		8	1070 ml / 1200 ml	89.2%

Considering the best 3 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 3 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 is depending on parameters such as ratio of methanol to crude oil, ratio of catalyst, reaction temperature and time. Human error factor during handling the product also considered as one of the contributions to total conversion rate. However, in this study, major factor that give big effect on yield is formation of soup though post treatment process. To minimize the soup formation, unpurified methyl ester must be treated gently and shake slowly in separation funnel.

Biodiesel Production Cost

Table 2 shows estimation of biodiesel production cost of 1-litre jatropha and used cooking oil biodiesel. The cost accountable the material utilized in two-step transesterification process within lab scale range. Nevertheless, a correct calculation shall include material, electricity, apparatus, consumable equipment and labour cost. Generally, these costs have minor impact and decline as the production scale range is getting larger. It is stated that 60-75% of biodiesel production cost is from cost of feedstock or crude oil (Canakci and Van Gerpen, 2003; Muzakki and Putro, 2025; Nizar et al., 2025a; NOOR et al., 2025). UCO on the other hand are much cheaper, could be collected national wide at Ringgit Malaysia (RM) 0.50 – 1.00 (Manan, 2015; Harian, 2015). There do not have any standard and specification of UCO as it would be treated as high FFA oil and require a two-step transesterification process to convert it to biodiesel.
Table 2 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 recycle product, hence the price is cheaper.

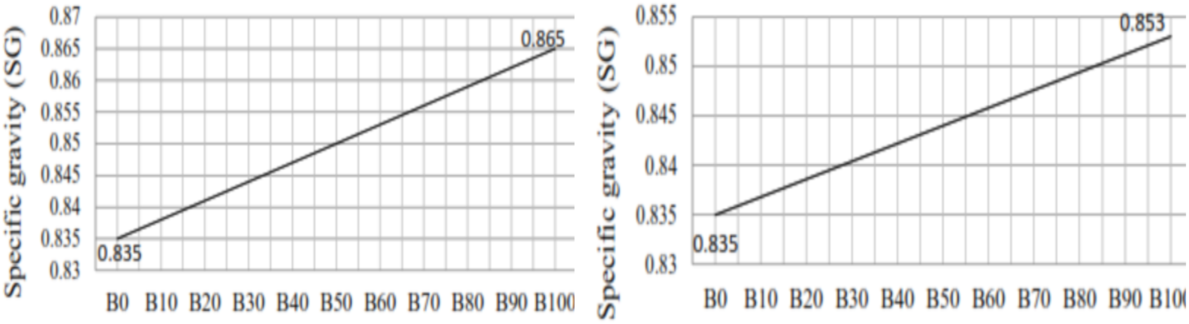
Table 2 Biodiesel production cost (material) per litre in Ringgit Malaysia (RM)

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

Blending process to produce jatropha and used cooking oil biodiesel blends were carried at Gas Turbine Combustion Research Group laboratory. Blending machine or mixer was used to blend CDF with biodiesel according to amount and composition required as presented in **Table 2**. **Fig. 5** shows the sample of test fuels. **Fig 6** shows graph of specific gravity plotted to estimate the blends homogenously during blending process.

Fig. 5. Sample of test fuels



(a) Jatropha biodiesel blends (b) Used cooking oil biodiesel blends

Figure 6: Specific gravity versus biodiesel blends

Kinematic Viscosity

Kinematic viscosity test was conducted with an Anton Paar SVM3000 Stabinger Viscometer at 40°C complied with the ASTM D7042 measuring standard. It was repeated twice due to viscometer accuracy. **Table 3** shows the kinematic viscosity of the fuels tested. From the table, kinematic viscosity of CDF is the lowest among all other fuels which is 3.5 mm^2 /s. The viscosity of the fuels gets higher as the percentage of biodiesel increases in the blend. Due to biodiesel has heavier in term of density, viscosity of biodiesel fuel is also more viscous than CDF.

Table 3: Kinematic viscosity of fuels

Fuel	Average Kinematic Viscosity (mm^2/s)
CDF	3.5020
B5 JME	3.5802
B15 JME	3.6795
B25 JME	3.7110
B100 JME	4.4761
B5 UCOME	3.5833
B15 UCOME	3.6520
B25 UCOME	3.7511
B100 UCOME	4.5184

Summary of Physical Properties of Fuels

The fuel physical properties acquired are compared to the diesel standard (EN 590) and biodiesel standard (EN 14214). **Table 4** shows the summary of the test fuels physical properties. The droplet size diameter in biodiesel and diesel are almost the same between 750 to 950 microns, which negligibly small, but the difference between them is only their chemical structures. Their chemical structures contribute to main reason to their differences in terms of physical properties (Almardhiyah et al., 2025; Khan et al., 2016; Pranoto et al., 2025). From **Table 4**, it is observed that biodiesels have lower calorific value which indicate they contain lower energy as compared to diesel. Viscosity is a characteristic of fuel's resistance to flow. A fuel with very high viscosity will destruct the fuel injector then vaporise poorly, resulting in high quantity of carbon build up (Mufti et al., 2025; Rosdi et al., 2025b; Selvakumar et al., 2025b). Referring to the table, biodiesel blends are slightly viscous compared to diesel. Despite high viscosity, both B100 biodiesels produced complied to biodiesel standard EN14214. Surface tension is the molecules force of attraction, affecting fuel atomization in combustion (Fitriyana et al., 2025; Khalisha et al., 2025; Muhibbuddin et al., 2025a). Biodiesel's surface tension is higher than diesel. As surface tension increases, fuel atomization degrades. Besides surface tension and viscosity, density and specific gravity of biodiesel blends is increase with the increases of biodiesel content in diesel fuel. Therefore, it can be concluded that jatropha and used cooking oil biodiesel blends have lesser calorific value but then slightly more viscous, have higher density, specific gravity and surface tension. Overall, all test fuels were confirmed in the range stated in biodiesel standard EN 14214. This is to confirm that these fuels are acceptable for industrial burner application.

Table 4. Summary of Fuel Physical Properties

Physical Properties	Density (kg/m^3)	Specific Gravity	Kinematic Viscosity (mm^2/s)	Surface Tension (mN/m)	Calorific Value (kJ/kg)
EN 590	820-845	-	2.0-4.5	-	-
Diesel (CDF)	830.1	0.835	3.5020	29.5	45.29
B5 JME	833.8	0.839	3.5802	29.7	44.83
B15 JME	837.4	0.840	3.6795	29.9	44.21
B25 JME	841.0	0.843	3.7110	30.1	43.59
B100 JME	868.0	0.865	4.4761	31.6	39.52
B5 UCOME	827.4	0.836	3.5833	29.7	44.93
B15 UCOME	830.5	0.837	3.6520	29.9	44.35
B25 UCOME	833.5	0.840	3.7511	30.0	43.73
B100 UCOME	858.7	0.853	4.5184	32.1	39.50
EN 14214	860-900	-	3.5-5.0	-	-

Sulphur Dioxide (SO_2)

Sulphur dioxide (SO_2) is one of the harmful, major emissions from fossil fuel combustion at industries and power plants. SO_2 is principally formed by combustion wall temperature and oxygen content in the fuel. **Fig. 7** shows the amount of SO_2 produced by CDF, B5 JME, B15 JME, B25 JME, B5 UCOME, B15 UCOME and B25 UCOME test fuels at various equivalence ratios.

From Figure 4.16, alike NOx, SO2profile has an inverse vertical parabolic trend. The maximum SO_2 produced was at the stoichiometric region where oxygen supplied in the fuel and the combustion wall temperature was optimal to execute a complete combustion. CDF produced the highest SO_2 which is 14 ppm. Biodiesel application can reduce SO_2 formed as suggested by many researchers (Abdul Rahim et al., 2016; Bahagia et al., 2025; Sawarimuthu and Jaâ, 2008). This is due to biodiesel and its crude oil normally content lower sulphur compared to CDF. The amount of SO_2 in this region which B5 JME output was 7 ppm, B15 JME was also 7 ppm, B25 JME was 6 ppm, B5 UCOME was 10 ppm, B15 UCOME was 7 ppm too and B25 UCOME was 6 ppm.

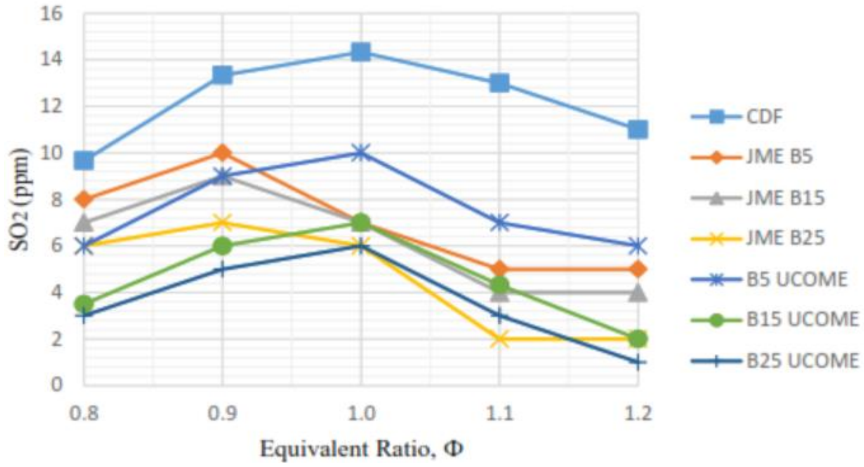


Fig. 7. Emission of SO2 for test fuels

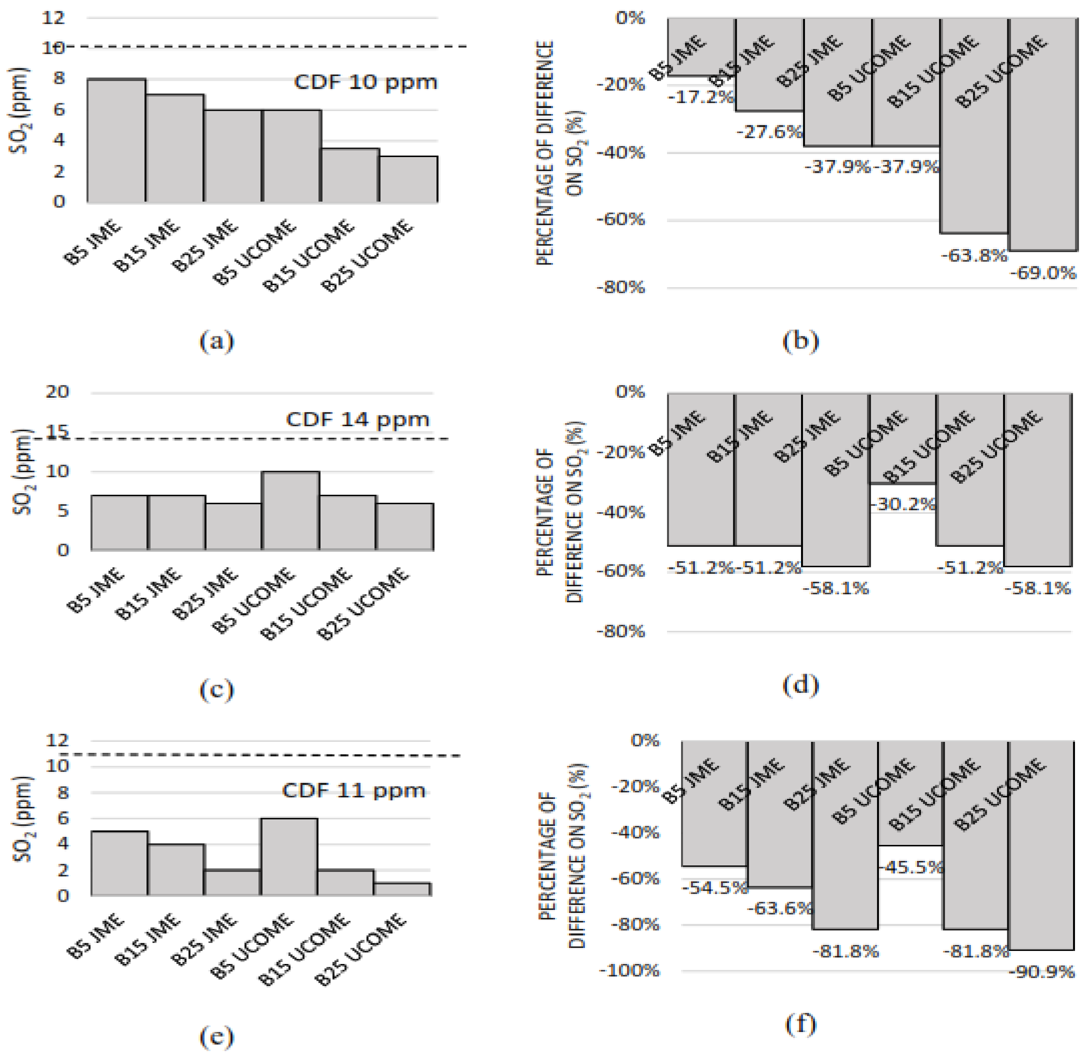


Fig. 8. Emission of SO_2 at specific equivalence ratio and percentage of difference on SO_2 emission relative to CDF fuel (a) SO_2 at lean condition, (b) percentage of difference on SO_2 at lean condition, (c) SO_2 at stoichiometric condition, (d) percentage of difference on SO_2 at stoichiometric condition, (e) SO_2 at rich condition, (f) percentage of difference on SO_2 at rich condition

Considering emission at lean, stoichiometric and rich conditions during combustion of each test fuels, comparison with CDF were made as shown in **Fig. 8** (a), (c) and (e). The value of CDF was from experiments conducted and were used as baseline to compare with other test fuels. **Fig. 8** (b), (d) and (f) show reduction percentage of test fuels SO_2 emission relative to CDF at lean, stoichiometric and rich conditions. From **Fig. 8** (b), (d), and (f) the largest reduction percentage of SO_2 emission relative to CDF was 69% by B25 UCOME at lean condition, 58.1% by both B25 JME and B25 UCOME at stoichiometric, whereas in rich condition 90.9% drop by B25 UCOME respectively. It is observed that increasing of the percentage of biodiesel in a fuel, leads to higher reduction of SO_2 formation compared to diesel SO_2 emission. In lean condition, too much air causes the mixture to be diluted with air, suppressing the reaction between sulphur and oxygen (Gani et al., 2025a; Irhamni et al., 2025; Yana et al., 2025). In the fuel rich region, the production of SO_2 declined due to the change of other particulate matter such as hydrogen and cobalt sulphate, thus reducing SO_2 (Gani et al., 2025b; Maghfirah et al., 2025; Selvakumar et al., 2025a). Generally, the SO_2 production of biodiesel blends are significantly lesser than CDF due to their low sulphur content in its fuel.

4. Conclusion

This study successfully demonstrated the production and evaluation of biodiesel from Jatropha Methyl Ester (JME) and Used Cooking Oil Methyl Ester (UCOME) through a two-step transesterification process. The average biodiesel yield achieved was 94.3% for JME and 92.0% for UCOME. Cost analysis showed that Jatropha oil accounted for 83% of the total production cost per liter, whereas UCO contributed only 5.8%, highlighting the economic advantage of using waste-based feedstock. The physical properties of the biodiesel blends, including kinematic viscosity, density, and specific gravity, increased with higher biodiesel content, while the calorific value slightly decreased. Nevertheless, all test fuels complied with biodiesel standard EN 14214, confirming their suitability for industrial combustion applications. Combustion emission analysis revealed significant reductions in sulphur dioxide (SO_2) emissions compared to conventional diesel fuel (CDF). The highest SO_2 reduction was observed in B25 UCOME, with a 69% decrease under lean condition, 58.1% under stoichiometric, and 90.9% under rich condition. These results emphasize the environmental benefit of biodiesel blends in reducing harmful emissions due to their lower sulphur content. Overall, the findings confirm that JME and UCOME biodiesel blends offer a viable and cleaner alternative to fossil fuels, with promising environmental and economic performance for industrial burner applications.

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