

Performance evaluation of ethanol-derived waste cooking oil biodiesel in a forced-draft commercial burner system

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Abstract: The improper disposal of waste cooking oil (WCO) presents significant environmental challenges, yet its potential as a renewable fuel remains underutilized. This study optimized the conversion of WCO into biodiesel through a two-step esterification and transesterification process and evaluated its performance in a commercial burner system compared to liquefied petroleum gas (LPG). The process employed acid-catalyzed esterification followed by alkaline transesterification using ethanol and potassium hydroxide, with ethanol-to-oil molar ratios of 11:1, 12:1, and 13:1. The 13:1 ratio was identified as optimal, yielding 165.85 g of crude biodiesel per 100 g of oil with reduced glycerol formation. Physicochemical characterization revealed a flash point of 160°C and a calorific value of 35.65 MJ/kg, satisfying key ASTM D6751 requirements. However, the density of 0.9756 g/mL exceeded the standard range, suggesting the presence of residual ethanol and the need for improved post-treatment purification. Performance testing showed that the biodiesel-fueled burner heated 1 L of water in 381.33 s, compared to 420.67 s for LPG, demonstrating enhanced heating performance. The system achieved a thermal efficiency of 19.46% and a specific fuel consumption of 1.48 MJ/L. Emission analysis confirmed complete combustion, with carbon monoxide levels of 22.3 ppm and zero hydrocarbon emissions. The improved performance is attributed to the use of a forced-draft burner system, which enhances fuel atomization and combustion stability. Overall, the results demonstrate that transesterified WCO is a viable and cleaner alternative to conventional fossil fuels, offering a practical waste-to-energy solution for small-scale commercial cooking applications.

Keywords : waste cooking oil; biodiesel; ethanol-based transesterification; forced-draft burner; combustion performance

1. Introduction

Waste cooking oil (WCO) represents a significant environmental concern due to the large quantities generated worldwide each year [1], [2], [3], [4], [5], [6]. In urban areas such as the Cogon Night Market in Cagayan de Oro City, Philippines, street food vendors often dispose of used oil into sinks and drainage systems because of limited access to proper waste management. This practice contributes to water pollution, odor emissions, and drainage blockage, leading to environmental degradation and public health risks. Despite being commonly treated as waste, WCO has strong potential as a renewable energy source, particularly for biodiesel production [7], [8], [9], [10]. However, effective local collection and utilization systems remain limited. Transesterification has been widely recognized as the most effective method for converting vegetable oils into biodiesel [11], [12]. This process involves reacting oil with an alcohol in the presence of a catalyst to produce fatty acid esters [13]. Methanol is commonly used due to its low cost; however, it is toxic and hazardous, whereas ethanol

offers a safer and renewable alternative despite its higher cost [14]. A major challenge in using WCO as feedstock is its high water and free fatty acid (FFA) content, which can lead to saponification and reduced biodiesel yield, thereby necessitating pretreatment processes such as esterification [15], [16]. Furthermore, process parameters, including the alcohol-to-oil molar ratio, significantly influence biodiesel production efficiency [17], [18].

Recent studies have also explored the combustion behavior and practical applications of biodiesel fuels. The presence of oxygen in biodiesel molecules promotes more complete combustion compared to raw vegetable oils; however, higher viscosity, incomplete atomization, and limited air–fuel mixing in simple burner systems may still lead to localized soot formation and affect flame characteristics [19]. In addition, previous research has primarily focused either on biodiesel production or on its application in automotive compression ignition engines, with limited attention given to its use in small-scale commercial heating systems. Although some studies have investigated burner designs for biomass-based fuels [20], challenges remain in directly applying WCO-derived biodiesel in commercially available burner systems, particularly in terms of airflow regulation and combustion stability.

Therefore, a critical research gap exists in integrating biodiesel production from waste cooking oil (WCO) with its direct application and performance evaluation in commercial burner systems. This study addresses this gap by systematically evaluating transesterified WCO in a commercially available burner, integrating a controlled two-step ethanol-based conversion process with thermal and emission performance assessment. The primary aim of this study is to convert waste cooking oil into biodiesel and evaluate its effectiveness as a clean-burning fuel in a commercial burner system. In doing so, this research contributes to environmental sustainability by transforming waste into a valuable energy resource while offering a practical alternative to conventional fossil-based fuels. Accordingly, the specific objectives of this study are as follows:

1. To conduct the transesterification of waste cooking oil and evaluate its conversion efficiency into biodiesel suitable for clean combustion.
2. To characterize the physicochemical properties of the produced biodiesel and assess its compliance with ASTM D6751 standards.
3. To evaluate the performance of a commercial burner fueled with biodiesel in terms of flame stability, fuel consumption, thermal efficiency, and emissions.
4. To compare the heating performance of biodiesel with liquefied petroleum gas (LPG) under controlled conditions.

To further guide the investigation, the following research questions are formulated:

1. How do different ethanol-to-oil molar ratios (11:1, 12:1, and 13:1) affect biodiesel yield from high-FFA WCO using a two-step conversion process?
2. What are the physicochemical properties of the produced biodiesel, and does it comply with ASTM D6751 standards?
3. How does the produced biodiesel perform in a commercial burner in terms of fuel consumption, thermal efficiency, and emissions?
4. How does its heating performance compare with that of conventional LPG?

2. Material and methods

2.1 Research setting and sample collection

The study was conducted in a controlled laboratory environment at the Chemistry Department, University of Science and Technology of Southern Philippines (USTP), Cagayan de Oro Campus.

Waste cooking oil (WCO) was collected from street food vendors at the Cogon Night Market with permission from the City Economic Enterprises and Business Development Administration (CEEEDA), ensuring a consistent and regulated collection process.

2.2 Materials and equipment

Ethanol (C_2H_5OH), potassium hydroxide (KOH) as the alkaline catalyst, and sulfuric acid (H_2SO_4) for acid-catalyzed pretreatment were used in the biodiesel production process. The burner system was designed using Autodesk Fusion 360 software. The analytical instruments used included an ENERAC 700AV gas analyzer for emission measurements, a Parr 1341 oxygen bomb calorimeter for calorific value determination, a Cleveland open-cup tester for flash point analysis, and a Suntext TS-1 pH meter for pH measurement. A blower (Model YD9733HBL, DC brushless, 12 V, 2.94 A) was used in the burner assembly to regulate airflow.

2.3 Pretreatment of WCO via esterification

The pretreatment of WCO via esterification is illustrated in Figure 1. Due to the high free fatty acid (FFA) content of waste cooking oil (WCO), an acid-catalyzed esterification process was performed. The collected WCO was initially filtered using a coarse sieve to remove suspended solids and large impurities. The filtration process was repeated until visible debris was eliminated. The filtered oil was then heated at $110^\circ C$ for 3 h to remove moisture and subsequently cooled to approximately $60^\circ C$ prior to the reaction. A mixture of ethanol and sulfuric acid (H_2SO_4) was added, with the acid concentration set at 0.25 wt% relative to the oil mass. The reaction mixture was stirred for 60 min and allowed to settle for 2 h to reduce the FFA content prior to transesterification[19], [21].

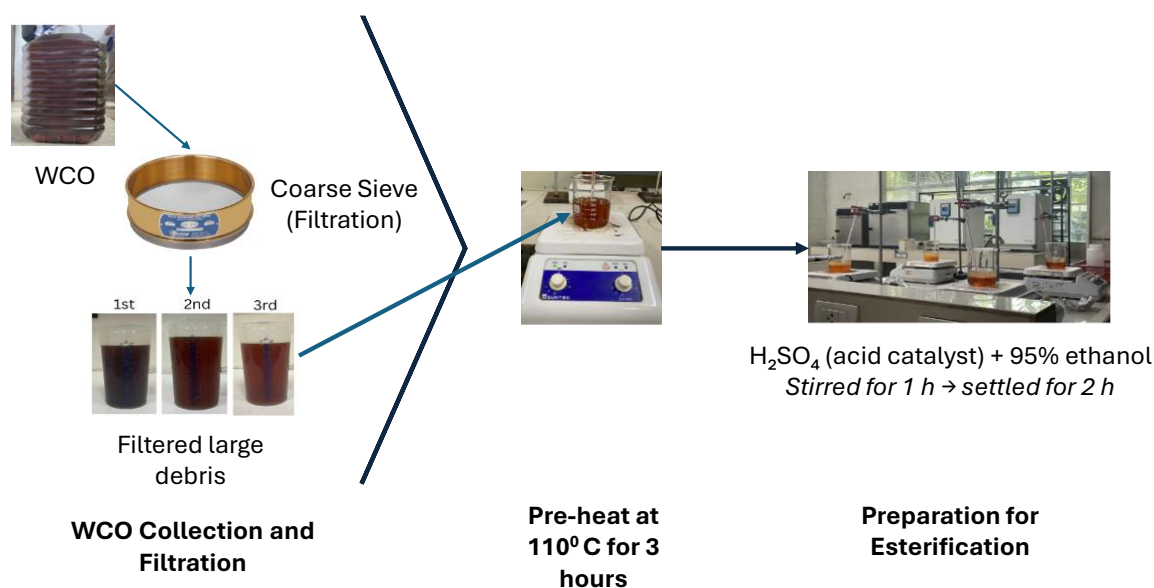


Figure 1. Pretreatment of WCO via esterification, including filtration, heating at $110^\circ C$, and acid-catalyzed esterification using H_2SO_4 and ethanol

2.4 Transesterification process

The transesterification process is illustrated in Figure 2. An ethoxide solution was prepared by dissolving 2.5 g of KOH in ethanol. The pretreated oil was heated to approximately $50^\circ C$ under continuous stirring. The ethoxide solution was then added to the heated oil, and the reaction was

carried out at 50–60°C using ethanol-to-oil molar ratios of 11:1, 12:1, and 13:1. After the reaction, the mixture was transferred to a separatory funnel and allowed to settle overnight, resulting in phase separation into biodiesel (upper layer) and glycerol (lower layer) [13], [19], [21].

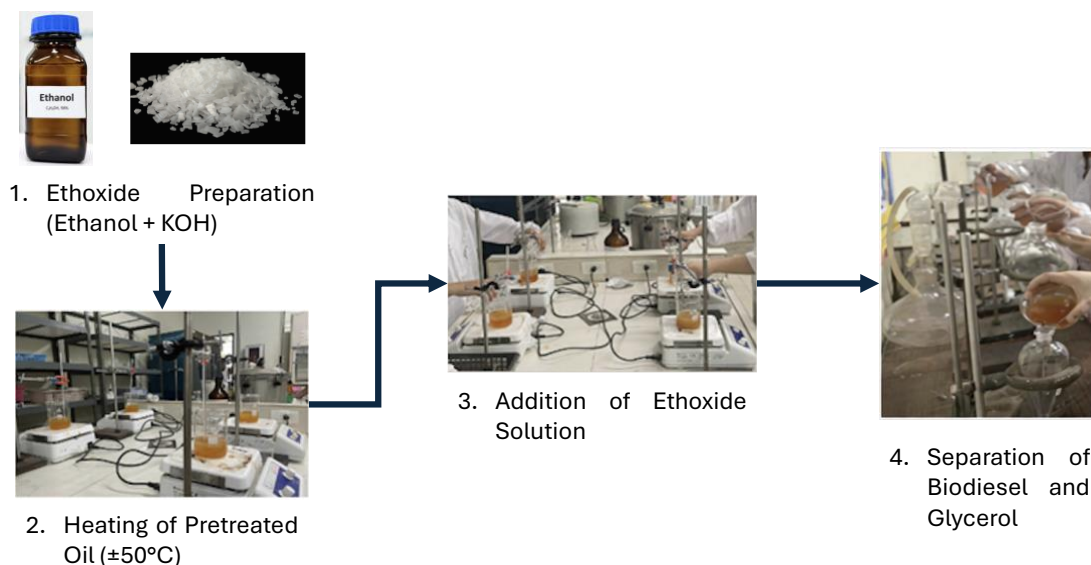


Figure 2. Transesterification process showing ethoxide preparation, heating of oil, reaction at 50–60°C, and phase separation into biodiesel and glycerol

2.5 Physicochemical characterization of biodiesel

The physicochemical characterization of biodiesel is presented in Figure 3. Several key properties of the produced biodiesel were evaluated, including flash point, calorific value, pH, and emission characteristics. The flash point of the biodiesel was determined using a Cleveland open-cup tester to assess fuel safety during handling and storage. The calorific value was measured using a bomb calorimeter, which determines the heat released during complete combustion of the fuel. The pH value of the biodiesel sample was measured using a pH electrode connected to a digital meter to evaluate its acidity or alkalinity. In addition, emission analysis was conducted using an ENERAC Model 700 gas analyzer. Parameters such as combustion efficiency, gas concentrations, and combustion ratios were recorded during the test runs.

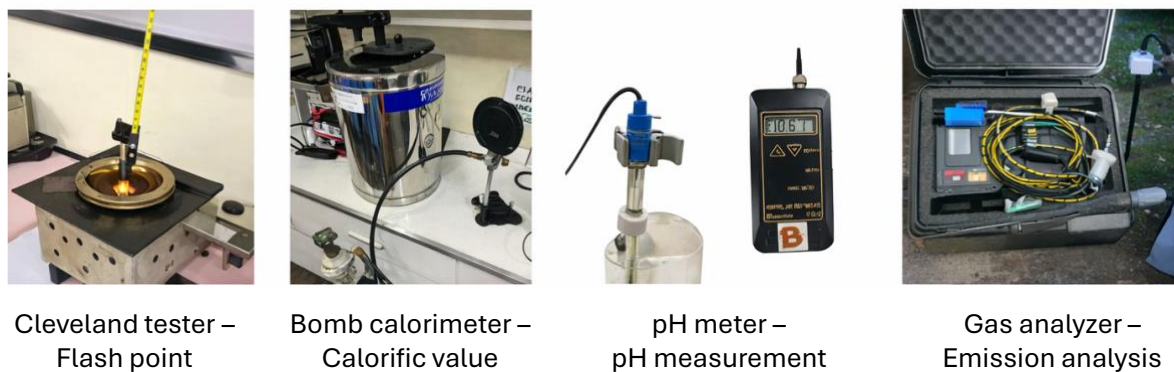


Figure 3. Physicochemical characterization of biodiesel: (A) flash point measurement, (B) calorific value determination, (C) pH measurement, and (D) emission analysis

2.6 Experimental evaluation of biodiesel combustion performance

The experimental evaluation of biodiesel combustion performance is presented in Figure 4. The test was conducted using a chimney-equipped burner, a boiling test of 1 L water to assess heating efficiency, and a flame duration test to evaluate combustion stability.

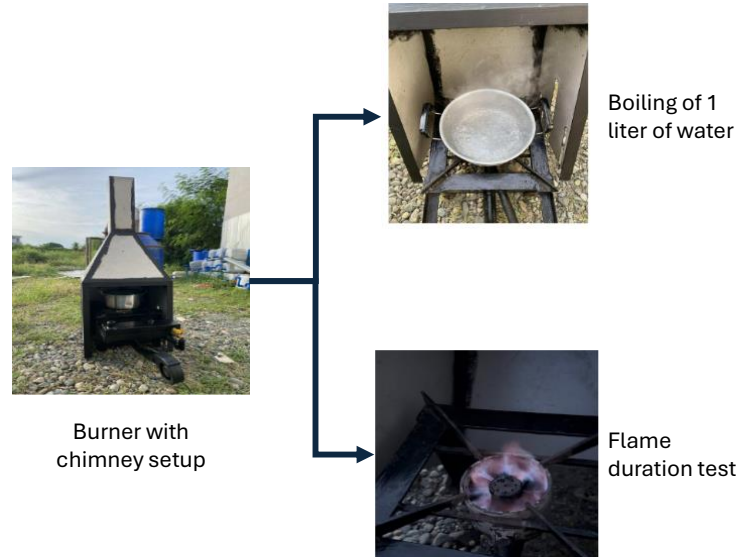


Figure 4. Experimental evaluation of biodiesel combustion performance using a chimney-equipped burner, boiling test, and flame stability test

2.7 Data analysis and calculations

To determine the required reagent quantities and evaluate the performance of the produced biodiesel, stoichiometric and thermodynamic calculations were applied.

2.1.1 Stoichiometric calculations

The number of moles of oil (η_{oil}) was calculated based on the ratio of oil mass to its molar mass, as expressed in Equation (1).

$$\eta_{oil} = \frac{\text{mass of oil (g)}}{\text{molar mass of oil (g/mol)}} \quad (1)$$

where the molar mass of oil was assumed to be 884 g/mol.

The mass of ethanol required for the transesterification process was determined based on the selected molar ratio (R), as shown in Equation (2).

$$m_{EtOH} = \eta_{oil} \times R \times 46.07 \quad (2)$$

where R represents the ethanol-to-oil molar ratio (11, 12, or 13), and 46.07 g/mol is the molar mass of ethanol.

The theoretical yield of biodiesel was estimated using stoichiometric relationships, as presented in Equation (3).

$$m_{theoretical} = \eta_{oil} \times R \times \text{Molar Mass of Biodiesel (g/mol)} \quad (3)$$

where 3 represents the stoichiometric conversion factor, and 310 g/mol is the molar mass of biodiesel.

For the pretreatment stage, the required mass of sulfuric acid was calculated based on its weight percentage relative to the oil mass, as given in Equation (4).

$$m_{H_2SO_4} = (\text{wt}\% H_2SO_4) \times (\text{Mass of Oil}) \quad (4)$$

where the acid concentration used was 0.25 wt%.

2.1.2 Physicochemical property calculation

The density of the produced biodiesel (ρ_{ave}) was determined from the ratio of its average mass to volume, as expressed in Equation (5).

$$\rho_{ave} = \frac{m_{ave}}{v_{ave}} \quad (5)$$

2.1.3 Combustion performance analysis

The air–fuel ratio (AFR) was calculated to evaluate combustion characteristics, as shown in Equation (6).

$$A/F = \frac{(n_{air}) \times (MW_{air})}{(n_{fuel}) \times (MW_{fuel})} \quad (6)$$

where n represents the number of moles and MW is the molecular weight.

The fuel consumption rate was determined as the ratio of fuel consumed to combustion time, as presented in Equation (7).

$$\text{Fuel Consumption Rate} = \frac{\text{Mass of Fuel Consumed}}{\text{Time}} \quad (7)$$

The firepower, defined as the rate of energy released during combustion, was calculated using Equation (8).

$$P_{fire} = m_{fuel} \times \text{Calorific Value} \quad (8)$$

The total energy input during the boiling process was determined as the product of firepower and boiling time, as shown in Equation (9).

$$Q_{input} = P_{fire} \times t_{boiling} \quad (9)$$

The useful heat energy absorbed by the water was calculated using Equation (10).

$$Q_{output} = m \times C_p \times \Delta T \quad (10)$$

where $m = 1$ kg and $C_p = 4.186$ kJ/kg°C

Finally, the thermal efficiency and specific fuel consumption were calculated using Equations (11) and (12), respectively:

$$\text{Thermal Efficiency} = \frac{\text{Energy Output}}{\text{Energy Input}} \times 100\% \quad (11)$$

$$\text{Specific Fuel Consumption} = \frac{\text{Total Energy Supplied}}{\text{Volume of water Boiled}} \quad (12)$$

3. Results and discussion

3.1 Optimization of ethanol-to-oil molar ratio

To maximize biodiesel production, three ethanol-to-oil molar ratios (11:1, 12:1, and 13:1) were investigated. The influence of these ratios on biodiesel and glycerol production is presented in Table 1.

Table 1. Production of glycerol and biodiesel at varying molar ratios

Molar Ratio	Glycerol (g)	Biodiesel (g)
11:1	77.10	98.58
12:1	69.42	123.70
13:1	32.43	165.85

The results show a clear positive correlation between molar ratio and biodiesel yield. The 13:1 ratio produced the highest crude biodiesel yield (165.85 g) and the lowest glycerol production (32.43 g). The measured biodiesel mass exceeding the initial oil input (100 g) is attributed to residual ethanol present in the unwashed organic phase. This observation supports the principle that excess alcohol shifts the equilibrium toward product formation [22]. Therefore, the 13:1 molar ratio was selected for subsequent experiments.

3.2 Conversion efficiency

Figure 5 demonstrates that the conversion efficiency reached a maximum of 86.39% at Batch 2 and decreased at higher molar ratios. This decline is attributed to the co-solvent effect of excess ethanol, which increases the solubility of glycerol in the ester phase and hinders phase separation. High concentrations of unreacted alcohol promote the formation of stable emulsions, reducing the measurable yield and potentially shifting the reversible reaction equilibrium [23].

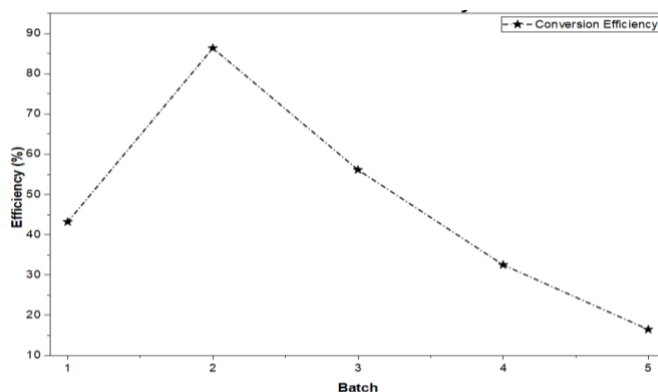


Figure 5. Conversion efficiency of biodiesel production

3.3 Physicochemical characterization of biodiesel

The physicochemical properties of the produced biodiesel are summarized in Table 2.

Table 2. Physicochemical properties of WCO biodiesel

Parameter	ASTM D6751 Limit	Value	Unit
Density (40°C)	0.860–0.900	0.9756	g/mL
Flash Point	>130	160	°C
Calorific Value	35–45	35.65	MJ/kg
pH Level	–	10.63	–

The density of 0.9756 g/mL exceeds ASTM standards, likely due to oxidation products and residual ethanol. The flash point (160°C) indicates safe handling, while the calorific value (35.65 MJ/kg) falls within acceptable limits. The pH value of 10.63 indicates alkaline characteristics, which may be attributed to residual catalyst (KOH) remaining in the biodiesel due to the absence of a washing process.

3.4 Combustion performance evaluation

3.4.1 Boiling performance and flame stability

A boiling test showed that biodiesel heated 1 L of water in 381.33 s, compared to 420.67 s for LPG, indicating improved heating performance. The flame behavior is illustrated in Figure 6. Stable flame conditions were achieved within 30.41 s, demonstrating consistent combustion performance. The fuel depletion phase lasted 952.06 s, followed by a post-combustion phase of 364.47 s, indicating sustained heat release throughout the combustion process.

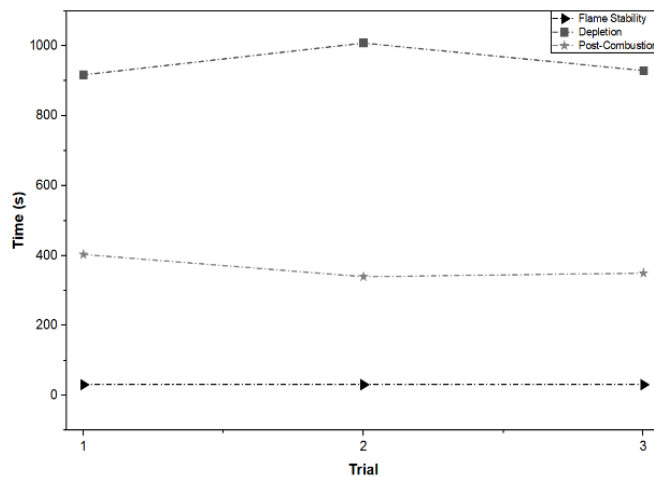


Figure 6. Flame duration test phases showing ignition, steady combustion, and depletion stages

3.4.2 Thermal efficiency and fuel consumption

The burner analysis metrics are presented in Table 3. The thermal efficiency was calculated as 19.46%, which is typical for open-flame systems. The specific fuel consumption (SFC) was 1.48 MJ/L, comparable to LPG (1.38 MJ/L). The calculated firepower of 3.875 kW indicates the rate of energy release during combustion, while the total energy supplied (1,475.65 kJ) and energy absorbed by water

(287.85 kJ) further support the observed thermal efficiency of the system. These values confirm that a significant portion of heat is lost to the environment, which is typical in open-flame combustion systems.

Table 3. Burner analysis metrics

Parameter	Value	Unit
Fuel consumption	0.401	L/hr
Firepower	3.875	kW
Energy supplied	1,475.65	kJ
Energy absorbed by water	287.85	kJ

3.4.3 Emission characteristics

The emission results are presented in Table 4. The high air–fuel ratio indicates an extremely lean mixture. This promotes complete combustion, as evidenced by zero hydrocarbon emissions (0 ppm HC), but reduces thermal efficiency due to heat loss from excess air. This behavior is consistent with lean combustion systems, where excess air improves emission quality but lowers flame temperature.

Table 4. Gas analyser results

Parameter	Average value	Unit
Combustion efficiency	42.5	%
Stack temperature	123.7	°C
Carbon monoxide (CO)	22.3	ppm
Hydrocarbons (HC)	0	ppm
Air/Fuel ratio	274.0	–

3.5 Specific fuel consumption comparison

The comparison of fuel performance is shown in Figure 7. The biodiesel burner achieved an SFC of 1.48 MJ/L. Variations in fuel consumption are influenced by viscosity and atomization behavior, which affect heat transfer efficiency. The higher viscosity of biodiesel leads to larger droplet formation, reducing atomization efficiency and influencing combustion performance.

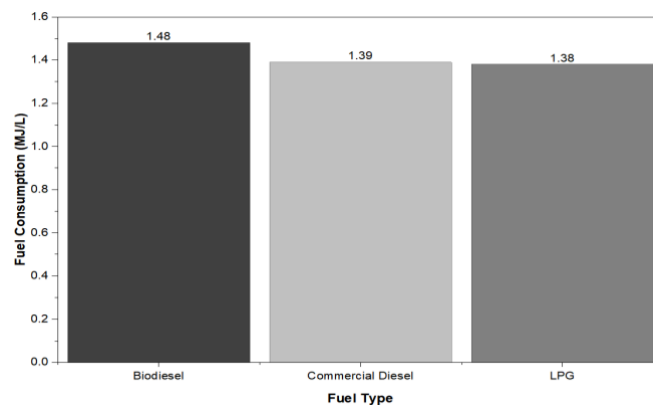


Figure 7. Specific fuel consumption of biodiesel, commercial diesel and LPG

3.6 Discussion

The results demonstrate that WCO biodiesel produced via ethanol-based transesterification can be effectively utilized as an alternative fuel for small-scale burner applications. Despite its lower calorific value (35.65 MJ/kg) compared to conventional fossil fuels such as diesel (~42–45 MJ/kg), the biodiesel exhibited competitive and, in some aspects, superior practical performance. Notably, the boiling test results revealed that the biodiesel burner achieved faster heating (381.33 s) compared to LPG (420.67 s), indicating improved heat transfer performance. This finding contrasts with conventional studies, where LPG typically outperforms biodiesel due to its higher flame temperature and cleaner combustion [19]. The improved performance observed in this study is attributed to the integration of a forced-air blower system, which enhances atomization of the fuel and heat transfer efficiency. Similar findings have been reported in forced-draft combustion systems, where improved mixing significantly enhances the performance of high-viscosity biofuels [20].

In terms of fuel production, the optimization results indicate that increasing the ethanol-to-oil molar ratio enhances biodiesel yield, with the 13:1 ratio producing the highest output. This is consistent with previous studies showing that excess alcohol shifts the reversible transesterification equilibrium toward ester formation [21], [24]. However, the observed decline in conversion efficiency at excessive ethanol concentrations supports the co-solvent effect, where excess alcohol increases glycerol solubility in the ester phase and hinders phase separation [25], [26]. From a physicochemical perspective, the biodiesel met several ASTM D6751 criteria, particularly in terms of flash point and calorific value. However, the density exceeded the standard range, which is consistent with previous findings on WCO biodiesel [27], [28], [29], [30]. This deviation is attributed to residual impurities and unremoved ethanol due to the absence of post-treatment processes such as washing and drying.

The combustion analysis further revealed that the system operated under an extremely lean air–fuel ratio (274.0), significantly higher than the stoichiometric requirement (~12.5:1). While this condition ensured complete combustion, as evidenced by zero hydrocarbon emissions, it also introduced thermodynamic inefficiencies. The excess air acted as a heat sink, reducing flame temperature and contributing to the moderate thermal efficiency (19.46%). This trade-off between emission reduction and thermal efficiency has also been reported in forced-air combustion systems using alternative fuels [20].

This study contributes to the existing body of knowledge by demonstrating the practical applicability of ethanol-based WCO biodiesel in commercial burner systems used by street food vendors, rather than in internal combustion engines. Unlike conventional studies requiring burner modification, this work demonstrates that biodiesel can be used directly in existing commercial hardware. Additionally, the use of ethanol instead of methanol provides a safer and more sustainable production pathway, reducing reliance on fossil-derived alcohols and improving the environmental profile of the process. Several limitations were identified in this study. First, the effectiveness of the esterification process was not validated through standard FFA titration. Second, the absence of post-treatment processes such as washing and drying contributed to elevated density and potential impurities. Third, emission analysis was limited, as NO_x and SO_x were not measured due to equipment constraints. Finally, the study utilized a single burner configuration without exploring variations in air–fuel ratios or combustion chamber design.

4. Conclusion

This study explored the viability of repurposing waste cooking oil (WCO) as an alternative heating fuel for small-scale commercial applications. A two-step esterification and transesterification process

successfully converted high-FFA WCO into biodiesel, with the 13:1 ethanol-to-oil molar ratio yielding 165.85 g of raw product per 100 g of oil. Physicochemical characterization showed that the produced biodiesel exhibited a flash point of 160°C and a calorific value of 35.65 MJ/kg, satisfying key ASTM D6751 safety and energy requirements. However, the measured density of 0.9756 g/mL indicates the presence of residual ethanol, highlighting the need for improved post-treatment processes in future applications. During combustion testing in an active-draft commercial burner, the fuel exhibited stable combustion behavior. The system recorded a fuel consumption rate of 0.401 L/hr and a thermal efficiency of 19.47%. Emission analysis further indicated complete combustion, as evidenced by zero hydrocarbon emissions (0 ppm HC), although the system operated under an extremely lean air–fuel ratio. During combustion testing in an active-draft commercial burner, the fuel exhibited stable combustion behavior. The system recorded a fuel consumption rate of 0.401 L/hr and a thermal efficiency of 19.47%. Emission analysis further indicated complete combustion, as evidenced by zero hydrocarbon emissions (0 ppm HC), although the system operated under an extremely lean air–fuel ratio. Overall, the integration of WCO biodiesel with a forced-draft burner system effectively compensates for the fuel’s higher viscosity by enhancing atomization and combustion efficiency. These findings highlight the potential of WCO biodiesel as a practical waste-to-energy solution for localized commercial cooking applications.

Author’s declaration

Author contribution

Ma. Leona Maye B. Pepito: Conceptualization, supervision and validation. **Jasper V. Acierto:** Investigation, methodology and resources. **Katrina Mae S. Raiz:** Formal analysis, methodology and resources. **Lance Erroyl J. Sambaan:** Software, Investigation, and Visualization. **Alyssa Mae S. Tabasa :** Project administration, methodology and resources.

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Data availability

Data supporting the findings will be made available upon reasonable request to the corresponding author.

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Conflict of interest

The authors declare no conflict of interest in this research and publication.

Ethical clearance

Not applicable

AI statements

Artificial intelligence tools were not used in the design, data collection, analysis, or interpretation of results for this study. AI-assisted tools were used only for language editing and grammar refinement, without affecting the scientific content or conclusions of the manuscript.

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