KAMPUS AKADEMIK PUBLISHER
Jurnal Ilmiah Penelitian Mahasiswa
Vol.3, No.1 Februari 2025
e-ISSN: 3025-5465; p-ISSN: 3025-7964, Hal 451-461
DOI: https://doi.org/10.61722/jipm.v3i.734

Utilization of Waste Cooking Oil as Biodiesel for Portable Stoves: Comparison of Homogeneous and Heterogeneous Catalysts

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Abstract. *This research investigates the performance comparison between homogeneous (NaOH) and heterogeneous (CaO) catalyst in biodiesel production from waste cooking oil, specifically focusing on their application as fuel for portable stoves. The study examines the effects of catalyst type with NaOH concentrations of 1%, 2%, and 3%, and CaO concentrations of 4% and 6%, along with methanol-to-oil molar ratios (1:6 and 1:12) on biodiesel yield, product color, and flame characteristics. Results show that NaOH catalyst achieved higher yields (92.30%) at 3% concentration with a 1:6 methanol-to-oil ratio, while CaO catalyst reached maximum yields of 42.00% at 6% concentration with a 1:12 ratio. NaOH-catalyzed biodiesel consistently produced clear yellow coloration, whereas CaO-catalyzed biodiesel showed varying clarity depending on process conditions. In portable stove applications, NaOH-catalyzed biodiesel demonstrated superior performance with faster combustion rates (0.0607 ml/second) and blue flames, compared to CaO-catalyzed biodiesel's slower combustion (0.0412 ml/second) and yellowish-red flames.*

Keywords: *Biodiesel, Waste Cooking Oil, Portable Stove, NaOH, CaO*

Received September 30, 2024; Revised Oktober 30, 2024;Desember 28, 2024
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Introduction

Indonesia faces significant challenges in terms of energy security, with a high dependence on fossil fuels. Data from the Ministry of Energy and Mineral Resources (ESDM) indicates that national energy consumption is still dominated by fossil fuels, which account for 87.5% of the total energy use (Ministry of ESDM, 2024). The development of bioenergy, particularly biodiesel, has emerged as a strategic solution to reduce dependence on fossil fuels and achieve the national renewable energy mix target of 23% by 2025 (Ministry of ESDM, 2024).

As the world's largest palm oil producer, Indonesia holds significant potential for biodiesel development. Palm oil, which is used as the base for cooking oil, generates waste in the form of waste cooking oil, which can be utilized as a raw material for biodiesel production. Waste cooking oil has a high free fatty acid content but can be converted into biodiesel through a transesterification process. The resulting biodiesel has characteristics comparable to conventional diesel, with advantages such as a higher cetane number (45-67 compared to 40-55 for fossil diesel) and lower exhaust emissions (ASTM International, 2022).

Table 1. Comparison of standards between biodiesel and fossil diesel, according to American Standard for Testing and Materials (ASTM)

Fuel Property	Diesel	Biodiesel
Standard Method	ASTM D975	ASTM D6751
Fuel compositition	Hydrocarbon (C10-C21)	FAME (C12-C22)
Cetane number	40-55	48-60
Density (g/cm^3)	0.85	0.88
Cloud Point (^{0}C)	-15 to 5	-3 to 12
Flash Point (^{0}C)	60-80	100-170
Pour point (^{0}C)	-20 to -15	-15 to 5
Carbon content (wt%)	87	77
Hydrogen content (wt%)	13	12
Oxygen content (wt%)	0	11
Sulphur content (wt%)	0.05	0.05
Water content (wt%)	0.05	0.05

Various studies have demonstrated the potential of waste cooking oil as a raw material for biodiesel production. A study by Rahman et al. (2023) showed that biodiesel derived from waste cooking oil meets the SNI 7182:2015 standard, with a calorific value of 39.5 MJ/kg and a kinematic viscosity of 4.5 mm²/s (Rahman et al., 2023). Another study by Wijaya et al. (2022) revealed that process optimization through the selection of the appropriate catalyst could increase biodiesel yield to as high as 95% (Wijaya et al., 2022).

Catalyst selection plays a crucial role in biodiesel production. Homogeneous catalysts, such as NaOH and KOH, have long been used due to their high reactivity, achieving conversions above 90% in relatively short reaction times (1-2 hours) (Hidayat et al., 2023). However, these catalysts are difficult to separate from the product and generate significant wash water waste. In contrast, heterogeneous catalysts like CaO offer advantages in ease of separation and potential reuse up to five cycles, although they require longer reaction times (3-4 hours) (Kumar & Sharma, 2022; Lee et al., 2023).

Although extensive research on biodiesel production has been conducted, comprehensive studies comparing the effectiveness of homogeneous and heterogeneous catalysts in processing waste cooking oil remain limited, particularly in their application as a fuel for portable stoves. Portable stoves are an important option in emergency situations or regions that lack access to gas networks, making the use of biodiesel as an alternative, more environmentally friendly fuel worthy of further exploration (Rahman et al., 2023).

This study aims to compare the performance of homogeneous (NaOH) and heterogeneous (CaO) catalysts in biodiesel production from waste cooking oil, focusing on evaluating the effect of catalyst type and concentration on biodiesel yield, analyzing the physical characteristics of the produced biodiesel, particularly its color quality, and assessing the performance of the resulting biodiesel as a fuel for portable stoves through combustion rate and flame characteristics analysis. The research employs various catalyst concentrations and methanol-to-oil molar ratios.

2. Methods

2.1. Materials

Waste cooking oil as the main raw material was collected from restaurants, houses, and shops within Jambi City, Indonesia. Technical grade methanol (99%) was used for methyl ester conversion. Sodium hydroxide (NaOH) was used as a homogeneous catalyst and calcium oxide (CaO) was used as a heterogeneous catalyst for the biodiesel process. These chemicals were analytical grade and purchased from Merck Millipore.

2.2. Transesterification

Waste cooking oil was filtered to remove solid particles and heated at 100-110°C for 30 minutes to reduce water content. The WCO was allowed to cool until it reached 40°C. Various weights of catalysts (NaOH 1%, 2%, 3% and CaO 4% & 6%) were prepared for the reaction; the percentage weight of catalysts was based on oil weight. The transesterification was carried out in a 500 ml three-neck glass flask as a reactor connected with a reflux condenser. The reactor was placed on a heating plate by Thermo Scientific and stirred using a magnetic stirrer at 700-750 rpm. NaOH pellets and CaO powders were added to methanol before being poured into the reactor containing WCO heated up to 70°C for 1 hour; the ratio of WCO to methanol was 1:6 and 1:12 by volume. After the transesterification process, excess methanol was separated through a distillation process for 45 min at a 65-70°C temperature range. The separation of biodiesel and glycerol used a separating funnel which was left to settle for 24 hours. The biodiesel was washed using distilled water at 50°C to remove residual catalyst and methanol, repeated 3-4 times until the product was clean. The biodiesel was then heated again at 100-110°C to remove residual water.

$$\text{Yield (\%)} = \frac{V_{\text{Biodiesel}}}{V_{\text{WCO}}} \times 100\%$$

2.3. Portable Stove Application of Biodiesel

The produced biodiesel was subjected to application testing using a portable stove. The portable stove was constructed with three main components: the stove unit, blower system, and biodiesel storage channel. A blower mechanism was incorporated to supply excess air, thereby enhancing combustion efficiency. The portable stove's dimensional specifications comprised an outside diameter of 15 cm and a height of 16 cm, with graphite iron serving as the primary construction material. 2D illustration as shown below:

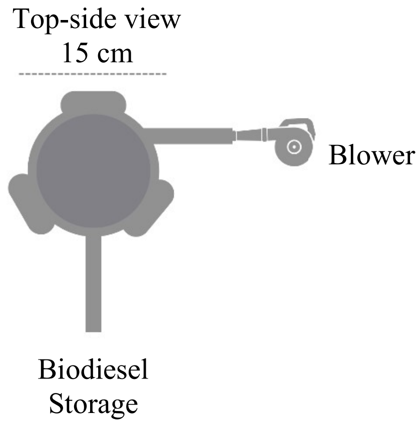

Fig 1. 2D Illustration Portable Stove

3. Result and Discussion

This research aims to evaluate the effect of the molar ratio of oil to methanol, catalyst concentration, and the type of catalysts (homogeneous and heterogeneous) on the yield, color, and flame duration of biodiesel produced using a portable stove. The homogeneous catalyst used is NaOH, while the heterogeneous catalyst is CaO. Biodiesel production is carried out using conventional methods, with the initial stage involving the analysis of molecular weight, free fatty acids, density, and viscosity. This analysis helps determine the physical and chemical properties of waste cooking oil, which serves as the raw material for biodiesel production through esterification and transesterification reactions. The biodiesel produced through the transesterification process was comprehensively analyzed to assess key parameters, including yield percentage, color variation, and ignition time. Additionally, the flame color generated when the biodiesel was used in a portable stove was observed to evaluate the fuel's combustion quality and efficiency under real-world conditions.

3.1. The Impact of Catalyst Variations and Catalyst Proportions on Biodiesel Yield

In a transesterification reaction, the catalyst works to lower the activation energy, so that at a certain temperature, the reaction rate constant becomes larger (Titik, Mas'udah, and Santosa 2023). This study discusses the biodiesel yield using two types of catalysts - NaOH (homogeneous) and CaO (heterogeneous) at various catalyst concentrations and methanol to oil ratios (1:6 and 1:12) shown in Figure 1. The biodiesel yield shows a strong dependence on the catalyst concentration and the methanol to oil ratio at NaOH catalyst. The biodiesel yield at a ratio of 1:6 increases steadily, peaking at 92.30% with 3% NaOH. This indicates that 3% NaOH is the optimal concentration under this condition. The biodiesel yield at a ratio of 1:12 initially rises, reaching 80.95% at 2% NaOH, but declines to 71.00% at 3%. This suggests that an excessive amount of NaOH can negatively impact the reaction efficiency at higher methanol-to-oil ratios. If too much catalyst is added, this can cause soap formation, which will ultimately reduce the yield obtained. A similar observation was also made in the study conducted by Syarifuddin on the synthesis of biodiesel from soybean oil (Oko et al. 2021)

The CaO catalyst exhibits significantly lower yields compared to NaOH. The biodiesel yield at a ratio of 1:6 remains low across all concentrations, with a maximum yield of 28.20% at 6% CaO. The yield improves slightly at a ratio 1:12, reaching 42.00% at 6% CaO, but still falls short of the performance achieved with NaOH. This aligns with the theory that homogeneous catalysts such as NaOH are more widely used in the biodiesel industry than heterogeneous catalysts like CaO, as the transesterification reaction with NaOH yields higher conversion rates. The benefits of using heterogeneous catalysts like CaO include its abundant natural availability, no side reactions, ease of separation from the reaction products, and the possibility of reuse after activation (Pasae, Bulo, and Ivonne 2019). Yuhelson's research also confirmed this by comparing the performance of CaO as a heterogeneous catalyst with that of a homogeneous catalyst in biodiesel production (Yuhelson et al. 2015). In the case of heterogeneous catalysts, the yield increases as the molar ratio of methanol to oil rises. This is due to the fact that an increase in methanol concentration or moles shifts the equilibrium toward the production of biodiesel (Prihanto and Irawan 2018).

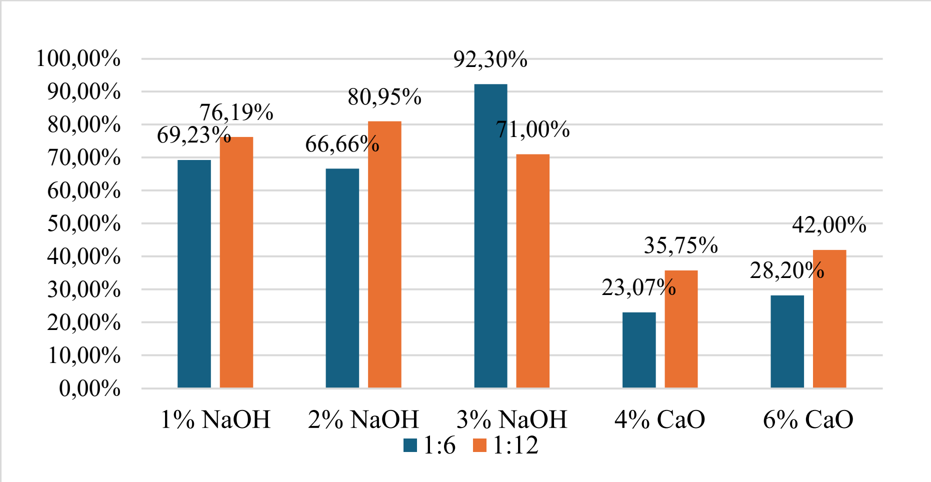

Fig. 2 Biodiesel Yield Comparison by Catalyst Type and Concentration

3.2. The Impact of Catalyst Variation and Catalyst Proportion on Biodiesel Color

The biodiesel color resulting from the use of NaOH (homogeneous catalyst) and CaO (heterogeneous catalyst) at varying concentrations and methanol-to-oil ratios (1:6 and 1:12) exhibits notable differences, as summarized at Table 1. The biodiesel color produced using NaOH (homogeneous catalyst) and CaO (heterogeneous catalyst) at different concentrations and methanol-to-oil ratios (1:6 and 1:12) shows clear differences.

Table 2. Biodiesel Color by Catalyst Type and Concentration

Catalyst Type	% Catalyst	Biodiesel Color	
		1:6	1:12
NaOH	1%	Clear Yellow	Clear Yellow
	2%	Clear Yellow	Clear Yellow
	3%	Clear Yellow	Clear Yellow
CaO	4%	Clear Yellow	Cloudy Yellow
	6%	Cloudy Yellow	Clear Yellow

Biodiesel made with NaOH consistently exhibited a Clear Yellow color across all catalyst concentrations (1%, 2%, and 3%) and both methanol-to-oil ratios. This consistency indicates efficient transesterification and minimal impurities, making NaOH highly effective for biodiesel production and ensuring uniform product quality. The color obtained is similar to the findings in Chandrika's research, which examined the impact of alkali catalyst concentration and the oil-to-methanol weight ratio on biodiesel production from waste cooking oil (Dwi Chandrika et al. 2023).

Biodiesel produced with CaO shows variations in clarity. At a methanol-oil ratio of 1:6, the use of 4% CaO produces Clear Yellow biodiesel, but increasing the concentration to 6% causes the biodiesel to become Cloudy Yellow. This may be due to an imperfect transesterification reaction, which produces a mixture of biodiesel and triglycerides that have not fully reacted, resulting in cloudiness. It can also be caused by imperfect purification, where the CaO catalyst is not fully separated, leaving small particles that make the biodiesel unclear. Therefore, optimizing purification through repeated washing to remove residual catalyst, glycerol, and impurities is necessary, as demonstrated in the study by (Lestari et al. 2021). At a 1:12 ratio, biodiesel with 4% CaO appears Cloudy Yellow, but increasing the concentration to 6% improves clarity to Clear Yellow, indicating that higher methanol levels can enhance reaction efficiency and reduce by-products.

(a) (b) (c) (d)

Fig 3. Biodiesel Color by Catalyst Type and Concentration (a) NaOH 1%; (b) CaO 4% (a); (c) NaOH 2%; (d) CaO 6%

The biodiesel produced with NaOH exhibited a higher level of clarity compared to that produced with CaO. The turbidity in the CaO biodiesel indicates possible issues, such as reduced reactivity or difficulties in separating the catalyst. Improving reaction parameters, like reaction time, temperature, or methanol concentration, could help enhance CaO's performance. This emphasizes the importance of choosing the right catalyst and optimizing reaction conditions to achieve biodiesel with the desired physical properties and high quality.

3.3. The application of biodiesel as fuel for portable stoves

Biodiesel serves as an innovative alternative energy source for portable stove fuel, catering to cooking needs. Its high calorific value ensures it can efficiently provide the heat required for cooking. Furthermore, biodiesel stands out for its low residue production and eco-friendly characteristics compared to other fuel options (Plata, Ferreira-Beltrán, and Gauthier-Maradei 2022). The performance of the homogeneous catalyst NaOH and the heterogeneous catalyst CaO was evaluated in biodiesel production using a methanol-to-waste cooking oil molar ratio of 1:12. A total of 17 ml of the resulting biodiesel was tested as fuel for a portable stove, with the results presented in Table 2 and figure 3.

Table 2. Results of the catalyst comparison test for portable stove performance.

Type of catalyst	Volume (ml)	Time (Second)	Flame color
Homogen (NaOH)	17	280	Blue flames
Heterogen (CaO)	17	413	Yellowish red flames

For the 17 ml of biodiesel with NaOH as homogeneous catalyst used, the combustion time lasted 4 minutes and 40 seconds with combustion rate is 0,0607 ml/seconds, whereas with CaO as a heterogeneous catalyst, the reaction time took much longer, namely 6 minutes and 53 seconds with combustion rate is 0,0412 ml/seconds. This difference in reaction time demonstrates the higher reactivity and efficiency of the NaOH catalyst compared to CaO. The faster reaction time for NaOH suggests its suitability for applications requiring rapid biodiesel production. In contrast, the slower reaction time for CaO may indicate challenges such as lower catalytic activity or additional time needed for mass transfer between the phases.

(a)

(b)


Fig 4. The flame of biodiesel on a portable stove produced with (a) a NaOH catalyst compared to that produced with (b) a CaO catalyst

Biodiesel made with homogeneous catalysts like NaOH generates a blue flame when burned on a portable stove. This blue flame signifies a more efficient combustion process, where the interaction between biodiesel and oxygen occurs optimally. As a result, it produces maximum heat energy and minimizes the emission of combustion residues. This highlights the superiority of homogeneous catalysts in producing fuel with higher combustion efficiency (Ansar et al. 2020).

On the other hand, biodiesel synthesized with heterogeneous catalysts like CaO produces a red flame when burned. The red flame indicates an inefficient combustion process, where the chemical reaction is less optimal, leading to the formation of more residues such as unburned carbon and other particles. This inefficiency is often attributed to the inherent limitations of heterogeneous catalysts in the transesterification process, which in turn affects the overall quality of the biodiesel produced (Rahman et al. 2016).

4. Conclusion

This study demonstrates significant performance differences between homogeneous (NaOH) and heterogeneous (CaO) catalysts in biodiesel production from waste cooking oil. NaOH consistently outperformed CaO, achieving high yields of 92.30% at 3% catalyst concentration with a 1:6 methanol-to-oil ratio, while CaO reached only 42.00% yield at 6% concentration with a 1:12 ratio. NaOH-catalyzed biodiesel exhibited superior quality with consistent clear yellow coloration and efficient combustion characteristics, producing blue flames and faster combustion rates (0.0607 ml/second) in portable stove applications. While CaO showed lower performance with varying product clarity and less efficient combustion (0.0412 ml/second with yellowish-red flames), its benefits of easy separation and reusability warrant further research to enhance its practical viability through improved reaction parameters and purification methods.

Acknowledge

The authors would like to acknowledge the financial support from LPPM (Lembaga Penelitian dan Pengabdian kepada Masyarakat) Universitas Jambi and Study Program of Chemical Engineering, Faculty of Science and Technology, Universitas Jambi for providing the laboratory facilities to conduct this research. We also extend our gratitude to Nazarudin, S.Si, M.Si, Ph.D for his valuable suggestions and assistance in proof-reading the manuscript draft. Additionally, we thank the students of Bioenergy Engineering Technology who have conducted this research excellently.

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