JEE Journal of Ecological Engineering

Journal of Ecological Engineering, 2027, 28(1), 444–454
https://doi.org/10.12911/22998993/242701
ISSN 2299–8993, License CC-BY 4.0

Received: 2026.10.25
Accepted: 2026.11.16
Published: 2026.12.01

Variations of calcium oxide and moringa stem charcoal as catalysts in the preparation of biodiesel made from used cooking oil

I Wayan Bandem Adnyana[1*], Tjokorda Gde Tirta Nindhia[1], Ni Made Suaniti[2], Rusmansyah[3], Ni Pt. Pande Mirah Surya Dewi[3]

[1] Department of Mechanical Engineering, Faculty of Engineering, Udayana University, Bukit Jimbaran Campus Street, Badung, 80361, Bali, Indonesia
[2] Department of Chemistry, Faculty of Mathematic and Natural Sciences, Udayana University, Bukit Jimbaran Campus Street, Badung, Bali 80361, Bali, Indonesia
[3] Department of Chemistry Education, Faculty of Teacher Training and Education Lambung Mangkurat University, Banjarmasin South Kalimantan, Indonesia
* Corresponding author's e-mail: bandem.adnyana@unud.ac.id

ABSTRACT

The ingredients to make biodiesel environmentally friendly are oil, alcohol, and catalysts to accelerate the reactions that occur, namely esterification and transesterification reactions. The heterogeneous catalyst calcium oxide as in previous research can be combined with Moringa stem powder with a 1:1 ratio so that biodiesel can be obtained. The purpose of this research is analysed the esters in biodiesel from used cooking oil and calcium oxide catalysts that are varied with and without Moringa stem powder based on weight ratio. The analytical methods used were proximate, bomb calorimeter, FTIR, and GC-MS. The results of the analysis of biodiesel from used cooking oil using moringa stem charcoal at a carbonisation temperature of 650 °C and a holding time of 120 minutes with a size > 180 Mesh ≤ 100 Mesh, contained the most volatile compounds compared to the variation of calcium oxide and Moringa stem charcoal 1:1. This result is sup-ported by FTIR, the presence of ester-specific functional groups and GC-MS detected fatty acid ethyl esters including hexadecanoic acid ethyl ester, heptadecanoic acid ethyl ester, and other carboxylic acids. These compounds as volatile compounds were also detected to be the highest by proximate analysis and supported by their calorific value by bomb calorimeter.

Keywords: calcium oxide, moringa charcoal, biodiesel, used cooking oil.

INTRODUCTION

The rapid growth of global energy consumption continues to intensify pressure on conventional fossil fuel reserves. As fossil fuels become increasingly limited and environmentally burdensome, the search for renewable, sustainable, and low-emission alternatives has become a critical priority (Azni et al., 2023; Hasan et al., 2026). Biodiesel has emerged as one of the most promising renewable fuels due to its biodegradability, low toxicity, and favourable combustion characteristics (Monika et al., 2023; Zheng & Cho, 2025). In Indonesia, where energy demand consistently rises each year, reliance on petroleum-based fuels has led to periodic increases in fuel prices and heightened concerns regarding long-term energy security (Mardiana et al., 2020; Pambudi et al., 2023). These challenges reinforce the urgency of developing efficient and affordable biodiesel production technologies.

Used cooking oil represents an abundant, inexpensive, and environmentally advantageous feedstock for biodiesel synthesis (Srithejas et al., 2025). The widespread consumption of fried foods in Indonesia produces substantial volumes

of waste cooking oil that, if improperly disposed of, threatens both public health and environmental quality. Converting this waste material into biodiesel not only support waste minimization and circular economy principles but also provides a low-cost strategy for renewable fuel production. However, the presence of impurities such as free fatty acids (FFA), water, and degradation products necessitates an effective pre-treatment and catalytic process to ensure high biodiesel yield and quality (Osman et al., 2024).

Catalysts play a central role in enhancing the efficiency of esterification and transesterification reactions in biodiesel production (Naseef & Tulaimat, 2025). While homogeneous catalysts such as sulphuric acid and potassium hydroxide are commonly used, they pose several disadvantages, including corrosiveness (Mayuni et al., 2015) difficulty in catalyst recovery, and increase wastewater generation (Sentanuhady et al., 2020). In contrast, heterogeneous catalysts such as calcium oxide (CaO) offer several advantages: they are reusable, environmentally benign, and capable of simplifying downstream processing (Faruque et al., 2020). Previous studies have demonstrated that CaO-based catalysts can achieve high conversion rates; however; their activity is influenced by factors such as surface area, porosity, and the presence of synergistic support materials (Al Alwan et al., 2025; Macheli et al., 2025). Calcium heterogeneous catalysts have potential for further development (Mazaheri et al., 2021).

Biomass-derived charcoals have attracted significant interest as catalyst supports due to their porosity, renewability, and availability. Moringa (Moringa oleifera) stem charcoal, in particular, has shown promising adsorptive properties in the purification of used cooking oil (Aisyah et al., 2012). Prior research indicates that activated charcoal from moringa stems can significantly reduce free fatty acid content and peroxide values, improving the suitability of waste oil for biodiesel synthesis (Cervera-Chiner et al., 2024; Fernandes et al., 2015). Moringa seed oil has high oxidative stability, with an oleic acid content of over 60 per cent compared with oils from other plants (Omonhinmin et al., 2020). Combining CaO with moringa stem charcoal may enhance catalytic activity through improved dispersion, larger surface area, and increased active site accessibility.

Although previous studies have explored CaO Catalysts combined with moringa stem charcoal in fixed ratios (Suaniti, Adnyana, & Ratnayani, 2021), systematic investigations into various of the catalyst composition and preparation conditions remain limited. In particular, the influence of different proportions of CaO and moringa stem charcoal, as well as variations in meshing temperature during catalyst preparation, has not been comprehensively evaluated. Understanding these variables is crucial for optimizing catalyst performance and improving biodiesel yield from used cooking oil.

Therefore, this study aims to examine the effect of varying compositions of CaO and moringa stem charcoal on the catalytic efficiency in biodiesel production from used cooking oil. By analysing biodiesel characteristics and yield under different catalyst formulations and preparation conditions, this study seeks to contribute to the development of an efficient, sustainable, and cost-effective heterogeneous catalyst system for waste-based biodiesel production.

This study demonstrates the successful production of biodiesel from used cooking oil through ethanol-based esterification and transesterification using CaO and CaO-Moringa stem charcoal catalysts.

MATERIALS AND METHODS

Materials

The materials used in this research are used cooking oil from fried chicken sellers, phosphoric acid, ethanol pro analysis), calcium oxide, and moringa stem powder. Equipment included: glassware, a set for esterification reaction, and a furnace.

Method for preparing moringa stems into charcoal: moringa stems with a diameter of approximately 10 cm were selected, stripped of their bark, cut into 2 cm lengths and split into small pieces. They were then dried for a week out of direct sunlight, before being carbonised by placing the material in an oxygen-free reactor and heating it until charcoal formed. The charcoal in the reactor was left to cool for 24 hours, then sieved to the required size and stored in separate sealed plastic bags, ready for proximate analysis.

Methods

Biodiesel preparation method according to Adnyana et al. (2024); Adnyana & Suaniti (2019), biodiesel was produced from used cooking oil obtained after chicken frying through a two-step

process comprising acid-catalysed esterification followed by transesterification, with variations in catalyst composition applied during the transesterification stage. In the esterification step, 100 mL of used cooking oil was mixed with 20 mL of ethanol and 0.5 mL of phosphoric acid and placed in a two-neck round-bottom flask equipped with a magnetic stirrer, condenser and thermometer. The reaction mixture was continuously stirred and heated at 60 °C for 1 h. After completion, the mixture was allowed to cool and subsequently transferred into a separating funnel, where it was left to stand overnight to allow phase separation. The upper layer containing ethyl esters was collected and washed with heated distilled water to remove residual acid and impurities. The transesterification process was conducted under the same reaction for all biodiesel samples, differing only in the type and particle size of the catalyst employed. The esterified oil obtained from the first step was reacted with ethanol in the presence of the designated catalyst at 60 °C for 1 h under continuous stirring. For biodiesel 1, CaO was used as the catalyst. Biodiesel 2, 3, and 4 were produced using a composite catalyst consisting of CaO and Moringa stem charcoal in a 1:1 ratio, where the charcoal was carbonized at 650 °C with a holding time of 120 min and sieved into different particle sizes, namely > 180 mesh ≤ 100 mesh (biodiesel 2), > 315 mesh ≤ 180 mesh (biodiesel 3), ≤ 315 mesh (biodiesel 4). Biodiesel 5 was synthesized using CaO combined with Moringa stem charcoal with a particle size of > 180 mesh ≤ 100 mesh. After completion of the transesterification reaction, the reaction mixture was allowed to settle to achieve phase separation, and the upper ethyl ester layer was collected. Calcium chloride ($CaCl_2$) was added to remove residual moisture, followed by filtration to obtain purified biodiesel. Analytical methods for moringa stem powder or biodiesel using Bomb calorimeter, proximate analysis, Fourier transform infra red (FTIR), gas chromatography-mass spectrometry (GC-MS).

Bomb calorimeter was 1341 Plain Jacket Bomb Calorimeter. The solid-fuel gros calorimeter value (GCV) or high heating value (HHV) was determined using a Parr 1341 oxygen bomb calorimeter in accordance with ASTM D5865. ASTM D5865 reports GCV; therefore, the bomb calorimeter results are identified as GCV rather than low heating value (LHV). Proximate analysis by TGA701 series thermogravimetric analysis. Conforms to the following product specifications – low voltage directive 2006/95/EC and EMC directive 2004/108/EC. The specific parameters measured are moisture content, volatile matter, ash and fixed carbon. FTIR – IRPrestige-21 (CE) Shimadsu, serial number A21005002919. Analysis of the functional groups of the putative volatile compounds formed, such as the ester groups formed in biodiesel. GC-MS – Shimadsu 2010, The oven temperature is programmed as follows: 80 °C, held for 2 minutes; then increased by 10 °C per minute until it reaches 270 °C, held for 10 minutes, injection temperature 250 °C, injection mode splitless, sampling time 1 minute, linear velocity, pressure 79,5 kPA, total flow 122 mL/min, column flow 1,18 ml/min, linear velocity 40 cm/sec, and split ratio 100. GC-MS analysis to determine the types and percentages of ester compounds (fatty acid ethyl esters) formed in biodiesel. All measurements were carried out once, and a sample volume of 1 µL was injected into the GC-MS injector.

RESULTS AND DISCUSSION

Types of biodiesel

Biodiesel made from used cooking oil with ethanol reagent and phosphoric acid catalyst was the same during esterification process and transesterification process in addition to ethanol using CaO catalyst (biodiesel 1), CaO and Moringa stem charcoal 1: 1 carbonisation temperature of 650 °C at a holding time of 120 minutes, the mesh size varied: size > 180 mesh ≤ 100 mesh (biodiesel 2), size > 315 mesh ≤ 180 mesh (biodiesel 3), size ≤ 315 mesh (biodiesel 4), and moringa stem charcoal size > 180 mesh ≤ 100 mesh (biodiesel 5).

The calorific and proximate properties

The results of calorific and proximate analysis values (Figure 1), analysis and separation of possible detected compounds (Figure 2). The variation in catalyst com-position and particle size significantly influenced the calorific and proximate properties of biodiesel produced from used cooking oil, as illustrated in Figure 1. Biodiesel synthesized using CaO as a single catalyst (biodiesel 1) exhibited moderate higher heating value (HHV) and lower heating value (LHV), confirming the catalytic capability of CaO in promoting the transesterification reaction with ethanol;

however, the resulting energy content was lower than that obtained when CaO was combined with Moringa stem charcoal. The introduction of Moringa stem charcoal as co-catalyst with CaO (biodiesel 2, 4, and 5) led to a consistent improvement in calorific values, indicating a synergistic interaction between basic active sites of CaO and the porous carbon structure of the charcoal (Buchori et al., 2021). Unlike conventional CaO-based catalysts reported in recent studies, which primarily rely on single active phases, the present work introduces a dual-function system where CaO provides basic catalytic sites while Moringa stem charcoal enhances structural and adsorption properties. This combines approach offers a distinct pathway for improving catalyst efficiency and distinguishes this study from previously reported biomass-derived CaO catalysts. This finding is in line with recent studies demonstrating that CaO supported on carbon-based materials improves catalytic stability, enhances surfaces area, and reduces catalyst deactivation due to better dispersion of actives sites (Aleman-Ramirez et al., 2021; Dong et al., 2025). A heterogeneous catalyst with added charcoal (Suaniti, Adnyana, & Nindhia, 2021) produces biodiesel with a yield of over 90 percent (Foroutan et al., 2021). The synergism enhances surface area, improves reactant adsorption, and facilitates more efficient contact between triglycerides, ethanol, and catalytic sites, thereby promoting the formation of fatty acid ethyl esters. This synergistic behavior aligns with recent developments in heterogeneous catalysis, where supported CaO systems and modified catalysts (e.g., CaO-metal oxides or CaO-biochar composites) have been reported to significantly enhance catalytic activity, achieving biodiesel yields up to 99% under optimized conditions (Adnyana & Suaniti, 2015). However, the use of Moringa stem-derived carbon as a support remains rarely explored, highlighting the novelty of the present study.

Among the composite catalysts, biodiesel 5, produced using CaO combined with Moringa stem, charcoal at particles size > 180 mesh ≤ 100 mesh, exhibited the highest HHV and LHV values, suggesting that this particle size range provides an optimal balance between surface area availability and catalytic accessibility (Aleman-Ramirez et al., 2021; Dong et al., 2025). In terms of proximate analysis, notable differences in moisture and volatile contents were observed across the samples. Biodiesel 1 showed relatively high moisture content, which may be attributed to residual water generated during esterification and less effective adsorption during the reaction process, potentially compromising combustion efficiency and storage stability (Foroutan et al., 2021). The incorporation of Moringa stem charcoal in the CaO-based catalyst system resulted in reduced moisture content in biodiesel 2 and 4, while biodiesel 5 demonstrated the lowest moisture level, likely due to the enhanced water adsorption capability of the charcoal's micro and

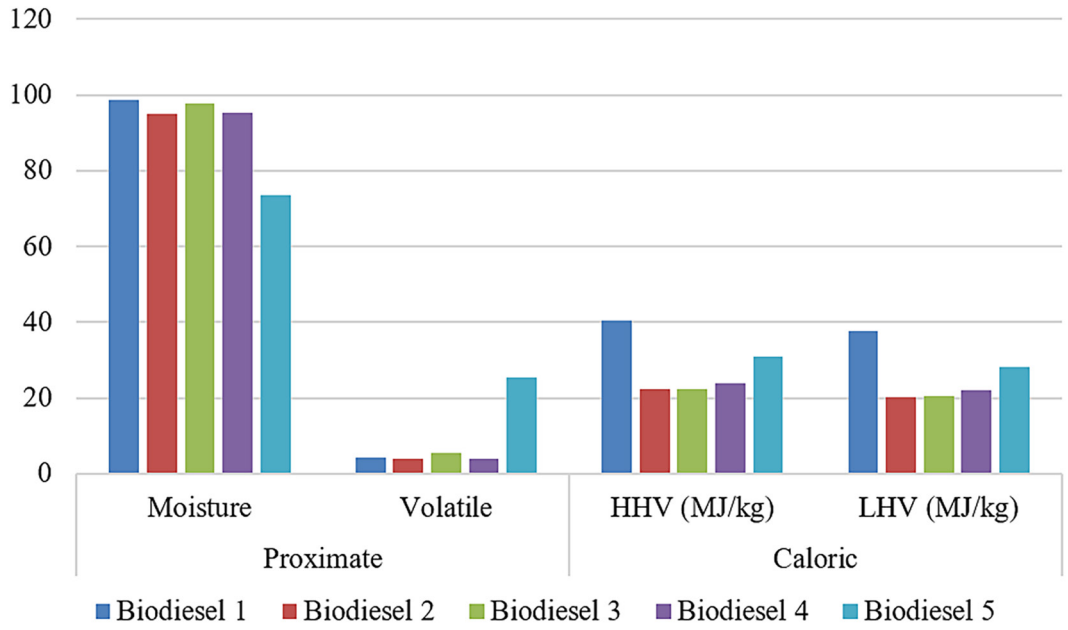

Figure 1. Calorific and proximate values of tested types of biodiesel

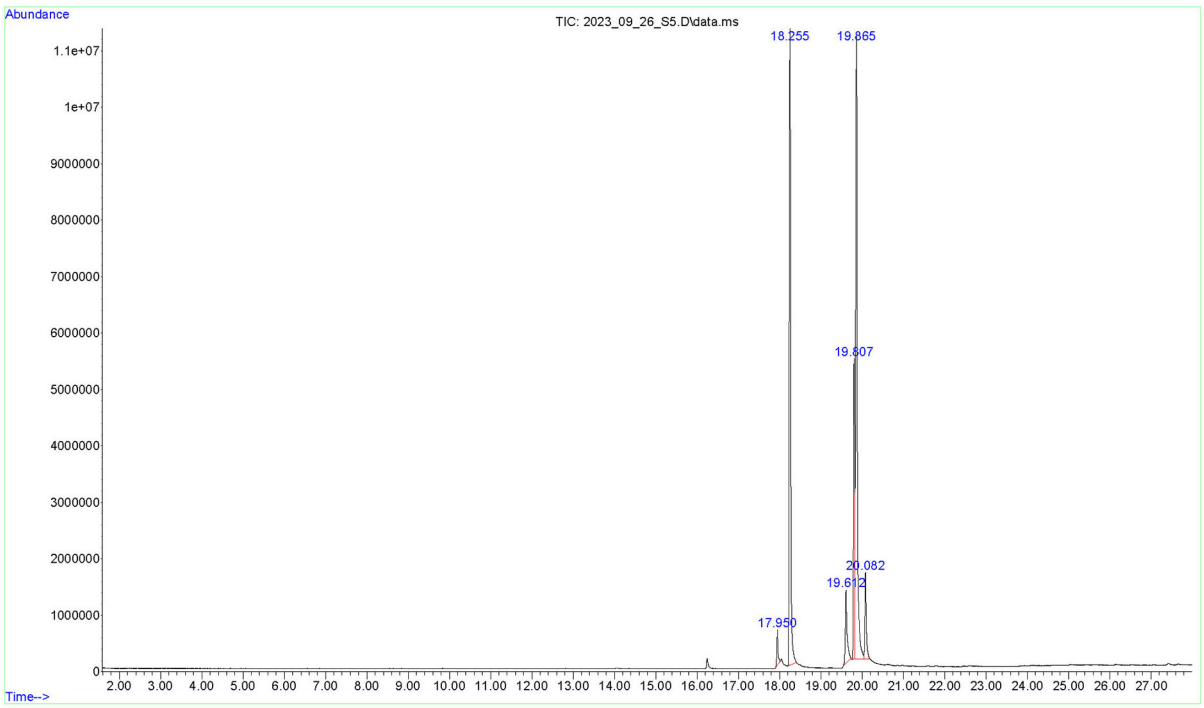

Figure 2. Chromatogram GC-MS of biodiesel 5 (database/Willey 09 TH.L)

mesoporous structure. Reduced moisture content is favourable for biodiesel quality as it minimizes corrosion risks and improves ignition behaviour. Conversely, volatile matter content increased with the addition of Moringa stem charcoal, with biodiesel 5 showing a markedly higher volatile fraction compared to CaO-only biodiesel, indicating improved ignition characteristics and a more complete conversion of triglycerides into ethyl ester compounds. Furthermore, catalyst particle size was found to play a crucial role in determining biodiesel quality, as finer particles increase the effective surface area and improve mass transfer between reactants, leading to enhances calorific values and more favourable proximate properties; however, excessively fine particles may present challenges in catalyst separation and reuse (Adnyana & Suaniti, 2015, 2020).

FTIR analysis

FTIR analysis (Figures 3 and 4) respectively as functional groups in charcoal at a holding time of 120 minutes, there is a similarity of spectrograms with the same functional groups but different absorption and all types of biodiesel exhibit similar spectrograms with the presumption of the same functional group containing carbonyl (C=O) as a marker of ester formation. This is supported by the formation of FAME in the spectrum region from 1300 to 1060 cm^{-1} (Yuan et al., 2014; Zhang, 2012). Intramolecular O-H hydrogen bonding at the spectral region of 3376 cm^{-1}. This bond forms when a hydrogen atom simultaneously interacts with two different electronegative atoms located within the same molecule (Samuel et al., 2023; Sangeetha et al., 2020). C-H stretching bond as alkane or alkyl group at 2923 and 2852 cm^{-1} (Zik et al., 2020). These spectroscopic findings are consistent with calorific and proximate analysis results, confirming that the improved fuel properties observed in biodiesel samples are directly linked to the successful formation of ester compounds. The consistency between FTIR, GC-MS, and fuel property analysis strengthens the reliability of the results and indicates the catalyst modification plays a crucial role in determining both chemical composition and fuel performance.

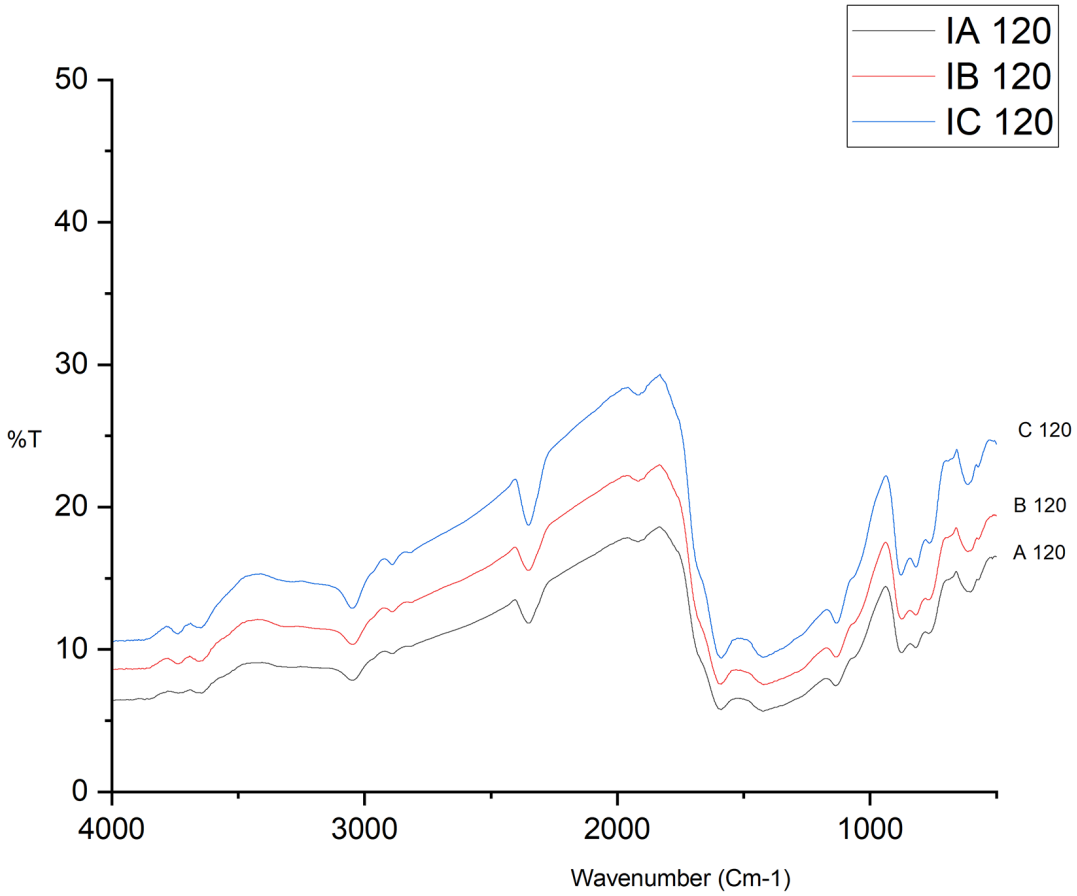

Figure 3. Similarity of functional groups of Moringa stem charcoal at 120 °C holding time at various mesh sizes by FTIR

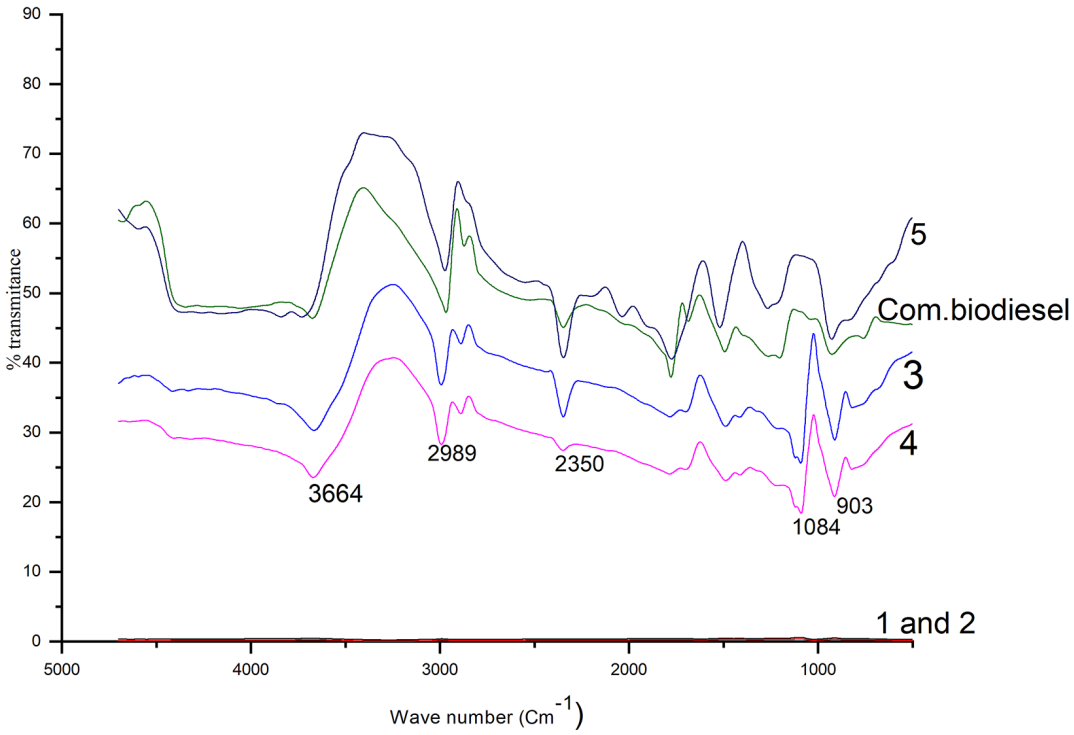

Figure 4. Functional groups at specific wave numbers in biodiesel 1, 2, 3, 4, 5 compared to commercial biodiesel by FTIR

GC-MS analysis

The results of the analysis of biodiesel from used cooking oil using moringa stem charcoal at a carbonisation temperature of 650 °C and a holding time of 120 minutes with a size > 180 mesh ≤ 100 mesh, contained the most volatile compounds compared to the variation of CaO and Moringa stem charcoal (the ratio 1:1) separation of the presumptive compounds contained using Moringa stem charcoal catalyst as shown in Figure 2. Complete data such as the presumptive percentages and ester types at the retention time of each biodiesel sample tested are shown in Table 1.

The results indicate the successful synthesis of biodiesel from used cooking oil through ethanol-based transesterification using several catalyst formulations, including CaO alone and combinations of CaO with Moringa stem charcoal. The positive formation of biodiesel was confirmed through the detection of ester compounds, which constitute the primary chemical components of fatty acid ethyl esters (FAEE). The presence of these ester fractions indicates that the transesterification reaction proceeded effectively across all catalyst variations, with Moringa stem charcoal contributing notably to the reaction behaviour. This aligns with previous findings indicating that biomass-derived heterogeneous catalysts have the potential to enhance biodiesel production efficiency while maintaining environmental sustainability (Adekanbi & Olugasa, 2022).

Across all samples analysed, the dominant compounds detected were esters particularly oleic-based esters characterised by the presence carbonyl (C=O) groups and methyl or ethyl functional groups. These observations are consistent with the typical ester profiles reported in biodiesel studies by Puspitasari et al. (2024); Sisca et al. (2021), who also identified methyl oleate as a major constituent in biodiesel derived from waste oils. The predominance of oleic-type esters is especially advantageous because oleic esters contribute to improved fuel performance, including better oxidative stability, favourable cold-flow properties, and more efficient combustion, as emphasized by Koria & Nithya (2012). Therefore, the high oleic ester content observed in this study suggests that the biodiesel produced exhibits promising fuel characteristics suitable for practical applications.

The chromatographic behaviour of the biodiesel samples further supports these findings. Fatty acid methyl esters (FAME), particularly oleic, linoleic, and linolenic acids, were effectively separated within approximately 40 minutes using High-Performance Liquid Chromatography (HPLC), as demonstrated in related study by Syed (2017). Although the present study employed GC-MS rather than HPLC, the clear separation of ester peaks and the diversity of ester group detected reflect similar compositional complexity. These results also highlight that the catalyst type and the presence of Moringa stem charcoal influence the ester distribution, with charcoal-containing catalysts producing more diverse and volatile esters. Such diversity is often associated with enhanced transesterification dynamics, likely due to the porous structure, surface functional groups, and adsorption capacity inherent to carbonised biomass materials.

Despite the successful formation of biodiesel, the study indicated opportunities for improving conversion efficiency and yields. In particular, the use of precipitated calcium carbonate as a precursor for producing high-purity CaO may enhance catalytic reactivity, reduce side reactions, and support faster attainment of equilibrium in the transesterification process. Previous research supports the notion that catalyst purity and surface area play crucial roles in determining biodiesel yield and ester profile uniformity, suggesting that

Table 1. The retention time and percent of ester compounds in biodiesel 1, 2, 3, 4, and 5

Retention time (minutes)	Percentage of ester as volatile compound					Kinds of compound
	1	2	3	4	5	
17.95					1,58	n palmitate acid
18.26	45.19	49.14	46.59	44.04	35.24	Ethyl palmitate
19.61					4.93	Palmitate acid
19.81				7.26 (ethyl linoleate)	13.53	Oleic acid
19.87	54.81	50.86	53.41	48.7	39.91	9,12-Octadecadienoic acid
20.08					4.81	Heptadecanoic acid ethyl ester

optimising catalyst synthesis could significantly advance process efficiency.

From an application perspective, the biodiesel produced in this study demonstrates ester compositions that are compatible with existing biodiesel standards. This is further supported by findings from Sentanuhady et al. (2020), who reported that biodiesel blends such as B20 show satisfactory performance in diesel engines while offering environmental benefits. Given the high oleic ester content and the presence of well-formed FAEE compounds, the biodiesel generated here holds potential for use in similar fuel blending applications, contributing to ongoing efforts to reduce reliance on fossil duels.

Overall, the results underscore that employing ethanol as a solvent and incorporating Moringa stem charcoal as a catalytic support provides a promising pathway for producing high-quality biodiesel from waste oil feedstocks. The clear formation of ester compounds, favourable oleic acid dominance, and the potential for further catalyst optimisation, collectively suggest that this approach aligns well with global initiatives targeting sustainable, low cost, and environmentally friendly biodiesel production. Future research focusing on improving catalyst synthesis, optimising reaction conditions, and scaling the process could further enhance the viability and efficiency of this method for broader industrial applications.

These results can be improved, as reported in the literature, by using nanocatalysts; adjusting the reaction time, the oil-to-methanol ratio and the reaction temperature can increase the recovery rate (Foroutan et al., 2025). The experimental results exceeded predictions, with a yield of over 99% achieved using a bifunctional CoFe/biochar/CaO catalyst at a methanol-to-oil ratio of 16:1, a catalyst loading of 3% by weight, and a temperature of 73 °C for 157 minutes (Xia et al., 2024). A CaO catalyst, calcined at 900 °C for 3 hours, was used to produce biodiesel from various volume ratios of used cooking oil to pure diesel, ranging from B10 to B-100 (Hamid et al., 2023). CaO is also used in the production of biodiesel from used cooking oil, and the biodiesel yield can be increased by more than 90 per cent through the addition of ZnO and TiO_2. The catalysts were used at 3 per cent of the catalyst weight, at 65 °C, with a 6:1 methanol-to-oil ratio and a reaction time of 3 hours (Kedir et al., 2023). The yield of biodiesel in the form of methyl esters from waste cooking oil (WCO) using a coconut husk biochar catalyst produced by impregnation with an H_2SO_4 solution was found to be less than 90%. The catalyst concentration was 10 wt%, the oil-to-alcohol molar ratio was 1:76, and the reaction temperature was 60°C. The measured parameters: density, viscosity, iodine value and acid value complied with national biodiesel standards (Sofyan et al., 2024). Sr-Zn oxide catalysts have also been successfully used for the production of biodiesel with a yield of over 90 per cent, with a molar ratio of ZnO to SrO of 0.6, through the addition of 11 per cent by weight of oleic acid (Liu et al., 2024).

CONCLUSIONS

The results of the analysis of biodiesel from used cooking oil using moringa stem charcoal at a carbonisation temperature of 650 °C and a holding time of 120 minutes with a size > 180 mesh ≤ 100 mesh, contained the most volatile compounds compared to the variation of CaO and Moringa stem charcoal 1:1.) and other comparisons. In the current study, is close to biodiesel by FTIR supported by proximate with the most volatile content and calorific value. GC-MS of samples 1 and 4 are similar to the content of suspected compounds as volatile compounds in the form of esters, namely fatty acid ethyl ester. GC-MS in a different laboratory for sample 5 is also similar to the content of suspected compounds as volatile compounds in the form of esters, namely fatty acid ethyl ester.

The results indicate that the incorporation of Moringa stem charcoal significantly improves catalyst performance, particularly in terms of calorific value, moisture reduction, and volatile compound formation. Furthermore, FTIR and GC-MS analyses confirmed the formation of fatty acid ethyl esters, indicating effective conversion of triglycerides into biodiesel. These findings highlight the potential of combining CaO with biomass-derived carbon materials as an alternative and sustainable catalytic system for biodiesel production. To better understand the significance of these findings, the effect of catalyst composition, particle size, and the role of Moringa stem charcoal are discussed in relation to recent developments in heterogeneous biodiesel catalyst.

Acknowledgements

This work is part of a research project, Udayana's leading research supported by research and service institutions Udayana University. The contract number B/1.796/UN14.4.A/PT.01.03/2023.

REFERENCES

1. Adekanbi, M. L., & Olugasa, T. T. (2022). Utilizing cashew nut shell liquid for the sustainable production of biodiesel: A comprehensive review. *Cleaner Chemical Engineering*, *4*, 100085. https://doi.org/10.1016/j.clce.2022.100085
2. Adnyana, I. W. B., & Suaniti, N. M. (2015). Analysis ethyl ester in biodiesel of raw material waste coconut oil and arak. *2nd International Conference on Engineering of Tarumanagara (ICET 2015)*, 22–23. https://api.semanticscholar.org/CorpusID:100733286
3. Adnyana, I. W. B., & Suaniti, N. M. (2019). Ultimate analysis and acid value of biodiesel from waste oil and ethanol. *IOP Conference Series: Materials Science and Engineering*, *508*, 012097. https://doi.org/10.1088/1757-899X/508/1/012097
4. Adnyana, I. W. B., & Suaniti, N. M. (2020). Proximate analysis of biodiesel from used cooking oil using a combination catalyst of CaO and Moringa seed powder (Moringa oleifera L.). *Seminar Nasional Sains Dan Teknologi*, 71-75 (in Indonesian).
5. Adnyana, I. W. B., Suaniti, N. M., & Lie, D. (2024). *Utilization of Moringa stem as a CaO catalyst mixer in making biodiesel*. 020019. https://doi.org/10.1063/5.0208099
6. Aisyah, S., Yulianti, E., & Fasya, A. G. (2012). Reduction in peroxide value and free fatty acids (FFA) during the bleaching process of used cooking oil using activated carbon from Moringa oleifera (Moringa oleifera Lamk) pods activated with NaCl. *ALCHEMY*, (in Indonesian). https://doi.org/10.18860/al.v0i0.1669
7. Al Alwan, B., Alamri, S., El Jery, A., Shah, M., & Sahlabji, T. (2025). Development of novel mussel-shell-derived CaO-based transition metal catalysts for efficient microwave-assisted biodiesel production. *Processes*, *13*(2), 522. https://doi.org/10.3390/pr13020522
8. Aleman-Ramirez, J. L., Moreira, J., Torres-Arellano, S., Longoria, A., Okoye, P. U., & Sebastian, P. J. (2021). Preparation of a heterogeneous catalyst from moringa leaves as a sustainable precursor for biodiesel production. *Fuel*, *284*, 118983. https://doi.org/10.1016/j.fuel.2020.118983
9. Azni, M. A., Md Khalid, R., Hasran, U. A., & Kamarudin, S. K. (2023). Review of the effects of fossil fuels and the need for a hydrogen fuel cell policy in Malaysia. *Sustainability*, *15*(5), 4033. https://doi.org/10.3390/su15054033
10. Buchori, L., Anggoro, D. D., & Ma'ruf, A. (2021). Biodiesel synthesis from the used cooking oil using CaO catalyst derived from waste animal bones. *Chemistry & Chemical Technology*, *15*(4), 583–590. https://doi.org/10.23939/chcht15.04.583
11. Cervera-Chiner, L., Pageo, S., Juan-Borrás, M., García-Mares, F. J., Castelló, M. L., & Ortolá, M. D. (2024). Fatty acid profile and physicochemical properties of Moringa oleifera seed oil extracted at different temperatures. *Foods*, *13*(17), 2733. https://doi.org/10.3390/foods13172733
12. Dong, Z., Dong, K., Li, H., Zhang, L., & Wang, Y. (2025). Progress and challenges in the process of using solid waste as a catalyst for biodiesel synthesis. *Molecules*, *30*(15), 3243. https://doi.org/10.3390/molecules30153243
13. Faruque, M. O., Razzak, S. A., & Hossain, M. M. (2020). Application of heterogeneous catalysts for biodiesel production from microalgal oil—A review. *Catalysts*, *10*(9), 1025. https://doi.org/10.3390/catal10091025
14. Fernandes, D. M., Sousa, R. M. F., de Oliveira, A., Morais, S. A. L., Richter, E. M., & Muñoz, R. A. A. (2015). Moringa oleifera: A potential source for production of biodiesel and antioxidant additives. *Fuel*, *146*, 75–80. https://doi.org/10.1016/j.fuel.2014.12.081
15. Foroutan, R., Foroughi, M., Tutunchi, A., Ramavandi, B., Terrón, D., & Pazos, M. (2025). Production of biodiesel from waste cooking oil and non-edible M. oleifera oil utilizing a CaO/$CuFe_2O_4$/$LaTiO_3$ Perovskite@Na bifunctional heterogeneous nanocatalyst. *Journal of Environmental Chemical Engineering*, *13*(4), 117261. https://doi.org/10.1016/j.jece.2025.117261
16. Foroutan, R., Mohammadi, R., Razeghi, J., & Ramavandi, B. (2021). Biodiesel production from edible oils using algal biochar/CaO/K2CO3 as a heterogeneous and recyclable catalyst. *Renewable Energy*, *168*, 1207–1216. https://doi.org/10.1016/j.renene.2020.12.094
17. Hamid, A., Jakfar, A., Romaniyah, S. B., Febriana, I. D., Abdullah, M., Rahmawati, Z., & Prasetyoko, D. (2023). Transesterification of waste cooking oil using CaO catalyst derived from Madura limestone for biodiesel production and its application in diesel engine. *Automotive Experiences*, *6*(1), 80–93. https://doi.org/10.31603/ae.7879
18. Hasan, M. A., Ridwan, M., Akter, S., Pattak, D. C., & Biswas, M. K. (2026). The distinguished role of fossil fuel, alternative and nuclear energy on the environmental sustainability of Brazil: A STIRPAT analysis with ARDL approach. *Nuclear*

Engineering and Technology, *58*(3), 104005. https://doi.org/10.1016/j.net.2025.104005

19. Kedir, W. M., Wondimu, K. T., & Weldegrum, G. S. (2023). Optimization and characterization of biodiesel from waste cooking oil using modified CaO catalyst derived from snail shell. *Heliyon*, *9*(5), e16475. https://doi.org/10.1016/j.heliyon.2023.e16475
20. Koria, L., & Nithya, G. (2012). Analysis of Datura stramonium Linn. biodiesel by gas chromatography - mass spectrometry (gc-ms) and influence of fatty acid composition on the fuel related characteristics. *Journal of Phytology*, *4*(1 SE-Research Article). https://updatepublishing.com/journal/index.php/jp/article/view/2751
21. Liu, S., Li, Z., Han, K., Wang, Y., Niu, S., Liu, J., Zhu, J., & Zheng, Y. (2024). Biodiesel production from waste cooking oil through transesterification catalyzed by the strontium-zinc bifunctional oxides. *Chemical Engineering and Processing - Process Intensification*, *200*, 109777. https://doi.org/10.1016/j.cep.2024.109777
22. Macheli, L., Malefane, M. E., & Jewell, L. L. (2025). Waste-derived calcium oxide catalysts in biodiesel production: Exploring various waste sources, deactivation challenges, and improvement strategies. *Bioresource Technology Reports*, *29*, 102021. https://doi.org/10.1016/j.biteb.2025.102021
23. Mardiana, S., Saragih, F., & Huseini, M. (2020). Forecasting gasoline demand in Indonesia using time series. *International Journal of Energy Economics and Policy*, *10*(6), 132–145. https://doi.org/10.32479/ijeep.9982
24. Mayuni, S. N., Suaniti, N. M., & Manuaba, I. B. P. (2015). Characterization of biodiesel from used cooking oil using bioethanol from sugarcane juice as a reagent. *CAKRA KIMIA (Indonesian E-Journal of Applied Chemistry)*, *Vol 3 No 3 (2015)*, 75-83 (in Indonesian). https://ojs.unud.ac.id/index.php/cakra/article/view/20284/13410
25. Mazaheri, H., Ong, H. C., Amini, Z., Masjuki, H. H., Mofijur, M., Su, C. H., Anjum Badruddin, I., & Khan, T. M. Y. (2021). An overview of biodiesel production via calcium oxide based catalysts: Current state and perspective. *Energies*, *14*(13), 3950. https://doi.org/10.3390/en14133950
26. Monika, Banga, S., & Pathak, V. V. (2023). Biodiesel production from waste cooking oil: A comprehensive review on the application of heterogenous catalysts. *Energy Nexus*, *10*, 100209. https://doi.org/10.1016/j.nexus.2023.100209
27. Naseef, H. H., & Tulaimat, R. H. (2025). Transesterification and esterification for biodiesel production: A comprehensive review of catalysts and palm oil feedstocks. *Energy Conversion and Management: X*, *26*, 100931. https://doi.org/10.1016/j.ecmx.2025.100931
28. Omonhinmin, C., Olomukoro, E., Ayoola, A., & Egwim, E. (2020). Utilization of Moringa oleifera oil for biodiesel production: A systematic review. *AIMS Energy*, *8*(1), 102–121. https://doi.org/10.3934/energy.2020.1.102
29. Osman, A. I., Nasr, M., Farghali, M., Rashwan, A. K., Abdelkader, A., Al-Muhtaseb, A. H., Ihara, I., & Rooney, D. W. (2024). Optimizing biodiesel production from waste with computational chemistry, machine learning and policy insights: A review. *Environmental Chemistry Letters*, *22*(3), 1005–1071. https://doi.org/10.1007/s10311-024-01700-y
30. Pambudi, N. A., Firdaus, R. A., Rizkiana, R., Ulfa, D. K., Salsabila, M. S., Suharno, & Sukatiman. (2023). Renewable energy in Indonesia: current status, potential, and future development. *Sustainability*, *15*(3), 2342. https://doi.org/10.3390/su15032342
31. Puspitasari, P., Pramono, D. D., Fiansyah, D. N., Permanasari, A. A., Mufti, N., & Razak, J. A. (2024). Biodiesel production from waste cooking oil using calcium oxide derived from scallop shell waste. *Clean Energy*, *8*(2), 113–126. https://doi.org/10.1093/ce/zkae005
32. Samuel, H. S., Nweke-Maraizu, U., & Etim, E. E. (2023). Understanding intermolecular and intramolecular hydrogen bonds: Spectroscopic and computational approaches. *Journal of Chemical Reviews*, *5*(4), 439–465. https://doi.org/10.48309/jcr.2023.407989.1235
33. Sangeetha, K., Rajina, S. R., Marchewka, M. K., & Binoy, J. (2020). The study of inter and intramolecular hydrogen bonds of NLO crystal melaminium hydrogen malonate using DFT simulation, AIM analysis and Hirshfeld surface analysis. *Materials Today: Proceedings*, *25*, 307–315. https://doi.org/10.1016/j.matpr.2020.01.526
34. Sentanuhady, J., Majid, A. I., Prashida, W., Saputro, W., Gunawan, N. P., Raditya, T. Y., & Muflikhun, M. A. (2020). Analysis of the effect of biodiesel B20 and B100 on the degradation of viscosity and total base number of lubricating oil in diesel engines with long-term operation using ASTM D2896 and ASTM D445-06 methods. *TEKNIK*, *41*(3), 269–274. https://doi.org/10.14710/teknik.v41i3.32515
35. Sisca, V., Tanjung, D.., Syukri, Zilfa, & Jamarun, N. (2021). Catalytic activity of precipitated calcium carbonate for biodiesel production. *Rasayan Journal of Chemistry*, *14*(03). https://doi.org/10.31788/RJC.2021.1436167
36. Sofyan, M. I., Mailani, P. J., Setyawati, A. W., Sulistia, S., Suciati, F., Hauli, L., Putri, R. A., Ndruru, S. T. C. L., Mawarni, R. S., Meliana, Y., Nurhayati, N., & Joelianingsih, J. (2024). Use of sulfuric acid-impregnated biochar catalyst in making of biodiesel from waste cooking oil via leaching method. *Bulletin of Chemical Reaction Engineering & Catalysis*, *19*(1), 160–170. https://doi.org/10.9767/bcrec.20113
37. Srithejas, K., Athreya, V., Prajwal, P. S., Achar, R.

R., & Vadiraj, K. T. (2025). Assessment of waste cooking oil-based biodiesel blend: Properties, performance and optimal blend ratio. *Journal of Ecological Engineering*, *26*(10), 200–210. https://doi.org/10.12911/22998993/205597

38. Suaniti, N. M., Adnyana, I. W. B., & Nindhia, T. G. T. (2021). Ester group detection of biodiesel from used cooking oil with sulphuric and toluene sulphuric acid catalysts. *Key Engineering Materials*, *877*, 153–159. https://doi.org/10.4028/www.scientific.net/KEM.877.153
39. Suaniti, N. M., Adnyana, I. W. B., & Ratnayani, O. (2021). Characterization and identification of fatty acid ethyl esters from refined used cooking oil as biodiesel by using spectroscopic techniques approach. *Key Engineering Materials*, *877*, 172–179. https://doi.org/10.4028/www.scientific.net/KEM.877.172
40. Syed, M. B. (2017). Analysis of biodiesel by high performance liquid chromatography using refractive index detector. *MethodsX*, *4*, 256–259. https://doi.org/10.1016/j.mex.2017.07.002
41. Xia, S., Tao, J., Zhao, Y., Men, Y., Chen, C., Hu, Y., Zhu, G., Chu, Y., Yan, B., & Chen, G. (2024). Application of waste derived magnetic acid-base bifunctional CoFe/biochar/CaO as an efficient catalyst for biodiesel production from waste cooking oil. *Chemosphere*, *350*, 141104. https://doi.org/10.1016/j.chemosphere.2023.141104
42. Yuan, T., Akochi-Koble, E., Pinchuk, D., & de Voort, F. (2014). FTIR on-line monitoring of biodiesel transesterification. *International Journal of Renewable Energy and Biofuels*, 1–13. https://doi.org/10.5171/2014.178474
43. Zhang, W.-B. (2012). Review on analysis of biodiesel with infrared spectroscopy. *Renewable and Sustainable Energy Reviews*, *16*(8), 6048–6058. https://doi.org/10.1016/j.rser.2012.07.003
44. Zheng, F., & Cho, H. M. (2025). Study on biodiesel production: feedstock evolution, catalyst selection, and influencing factors analysis. *Energies*, *18*(10), 2533. https://doi.org/10.3390/en18102533
45. Zik, N. A. F. A., Sulaiman, S., & Jamal, P. (2020). Biodiesel production from waste cooking oil using calcium oxide/nanocrystal cellulose/polyvinyl alcohol catalyst in a packed bed reactor. *Renewable Energy*, *155*, 267–277. https://doi.org/10.1016/j.renene.2020.03.144