Biodiesel Synthesis on Transesterification of Used Cooking Oil Using Modified Clay Catalyst: Temperature Effect Study

Janviter Manalu, Ilham Salim, Himawan, Janed Sriwati Labagai, Adi Mara, Deni Fajar Fitriyana,
Samsudin Anis, Rozanna Dewi, Januar Parlaungan Siregar, Heri Yudiono, Nurharniza Abdul Rahman

***Abstract*— The transesterification of waste cooking oil (WCO) into biodiesel was performed using a modified clay catalyst. The catalyst was synthesized by treating Merauke clay with an 8M HCl solution for dealumination, then fused NaOH pellets at a NaOH-to-clay ratio of 0.8. The solution was then adjusted to a pH of 11.5 and underwent hydrothermal treatment at 140°C for 48 hours. The dealumination process was characterized using X-ray fluorescence (XRF), while surface area analysis and X-ray diffraction (XRD) were employed to investigate the properties of the resulting zeolite. Transesterification reactions were carried out at temperatures of 55°C, 65°C, 75°C, and 85°C, with a catalyst-to-waste cooking oil-to-methanol ratio of 1.0:20.0:13.3, and a reaction time of 6 hours. The liquid samples were analyzed using gas chromatography-mass spectrometry (GC-MS). The XRF analysis revealed that the dealumination process resulted in a clay composition consisting of 34.77% silicon and 5.67% aluminum. The modified clay (MC) exhibited a surface area of 5.5685 m^2/g, a pore volume of 0.0126 cm^3/g, and a pore diameter of 8.871 nm. XRD analysis showed a significant change in the mineral composition, with gismondine recognized as the predominant phase. During the transesterification process, increasing the temperature did not lead to the highest conversion. The optimal conversion of 85 wt% to methyl ester was achieved at 65°C.**

***Index Terms*— clay, modified, transesterification, temperature, biodiesel**

I. INTRODUCTION

Frequent utilization of cooking oil leads to its degradation, marked by increased concentrations of free fatty acids, peroxides, and the generation of chemicals such as ketones, aldehydes, and free radicals. The chemical alterations diminish the quality of the oil, making it unsuitable for further usage. Consequently, this oil is designated as used cooking oil (UCO) [1].

Fig. 1. Sources of Waste Cooking Oil

Used cooking oil (UCO) is often reused for cooking despite its associated health risks, while others dispose of it improperly, leading to what is classified as waste cooking oil (WCO). Various sources, including households, restaurants, catering services, and industrial kitchens, generate WCO daily (Figure 1) [2], [3].

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Janviter Manalu is a Professor of Natural Resources and Environment Study Program, Universitas of Cenderawasih, Jayapura, Indonesia (corresponding author to provide phone: +62967-574124; fax: +62967-574125; e-mail: manalujanviter10@gmail.com).

Ilham Salim is an Assistant Professor of Chemistry Department, Faculty of Mathematics and Natural Science, University of Cenderawasih, Jayapura, Indonesia (e-mail: ilhamkimia@yahoo.com).

Himawan is an undergraduate student of Chemistry Department, Faculty of Mathematics and Natural Science, University of Cenderawasih, Jayapura, Indonesia (e-mail: himawahim.11@gmail.com).

Janed Sriwati Labagai is an undergraduate student of Chemistry Department, Faculty of Mathematics and Natural Science, University of Cenderawasih, Jayapura, Indonesia (e-mail: ilhamkimia@yahoo.com).

Adi Mara is an Assistant Professor of Chemistry Department, Faculty of Mathematics and Natural Science, University of Cenderawasih, Jayapura, Indonesia (e-mail: ilhamkimia@yahoo.com).

Deni Fajar Fitriyana is an Assistant Professor of Mechanical Engineering, Universitas Negeri Semarang, 50229 Indonesia (e-mail: deniifa89@mail.unnes.ac.id).

Samsudin Anis is a Professor of Mechanical Engineering, Universitas Negeri Semarang, 50229 Indonesia (e-mail: samsudin_anis@mail.unnes.ac.id).

Rozanna Dewi is an Associate Professor at the Chemical Engineering, Malikussaleh University, Lhokseumawe 24353, Aceh, Indonesia (e-mail: rozanna.dewi@unimal.ac.id).

Januar Parlaungan Siregar is an Associate Professor in the Faculty of Mechanical and Automotive Engineering Technology at Universiti Malaysia Pahang Al-Sultan Abdullah, Malaysia (e-mail: januar@ump.edu.my).

Heri Yudiono is a Professor of Mechanical Engineering, Universitas Negeri Semarang, 50229 Indonesia (e-mail: heri_yudiono@mail.unnes.ac.id).

Nurharniza Abdul Rahman is an Associate Professor in the Department of Civil Engineering, Faculty of Engineering and Quantity Surveying at INTI International University, Malaysia (e-mail: nurharniza.rahman@newinti.edu.my).

The improper disposal of WCO, particularly in water bodies and drainage systems, poses a serious environmental concerns as it leads to pollution and reducing water quality [3]–[5]. The formation of an oil layer on the surface of water can induce significant damage due to the resultant physical, biological, and chemical transformations. The oil rapidly disperses over the water's surface, resulting in oxidation and other detrimental processes. Over time, oil that accumulates on the seabed can annihilate marine life, altering entire ecosystems. The amalgamation of oil and water elevates the chemical oxygen demand (COD), leading to reduced oxygen availability for aquatic organisms. As oil degrades, harmful by-products are assimilated by marine organisms and ultimately enter our food supply via the food chain. Disposing of WCO in landfills is equally detrimental. The oil infiltrates the earth, posing a risk of contaminating groundwater, which is an essential source of drinking water [3]–[5].

The reutilization of WCO in culinary applications presents inherent concerns. Prolonged heating of oil leads to its degradation and the formation of deleterious chemicals. Such degradation leads to rancid lipids, which are not only unappealing but may also contribute to serious health issues, including premature aging, elevated steroid levels, and increased body weight [3]–[5]. Proper WCO management is crucial for mitigating environmental damage and promoting sustainability. An effective solution is converting WCO into biodiesel. The conversion of waste into useful products is an important step in increasing the economic value of waste while minimizing the negative impact on the environment (Figure 2). [6]–[15].

Fig. 2. Pathways to Sustainable Waste Management

A catalyst can chemically transform the triglycerides in WCO via esterification or transesterification [16]–[19]. This mitigates waste disposal challenges and facilitates renewable energy generation and environmental conservation. A catalyst accelerates chemical reactions without undergoing any changes itself. Biodiesel, derived from oilseeds or animal fats, is a renewable fuel that can be preserved for future utilization. It is a more environmentally sustainable alternative to fossil fuels, as it is devoid of sulfur. Biodiesel is significantly more environmentally benign than petroleum diesel, exacerbating air pollution. Biodiesel can be engineered to exhibit superior lubricating qualities compared to petroleum diesel, which generally results in reduced emissions. As interest in sustainable alternative fuels rises, biodiesel is gaining prominence in academic research and industry sectors [20].

Biodiesel production can be catalyzed through esterification or transesterification reactions, both of which are recognized methods for establishing biodiesel [21]. The method of transesterification for biodiesel production generally categorizes catalysts into three distinct groups: homogeneous, heterogeneous, and biological [22], [23]. The selection of an appropriate catalyst for biodiesel production via transesterification plays a critical role in influencing the efficiency, economic viability, and environmental sustainability of the process. Homogeneous, heterogeneous, and biological catalysts each present unique benefits and limitations. A comprehensive understanding of these catalytic systems is essential for optimizing biodiesel production and promoting the advancement of sustainable energy technologies (Figure 3).

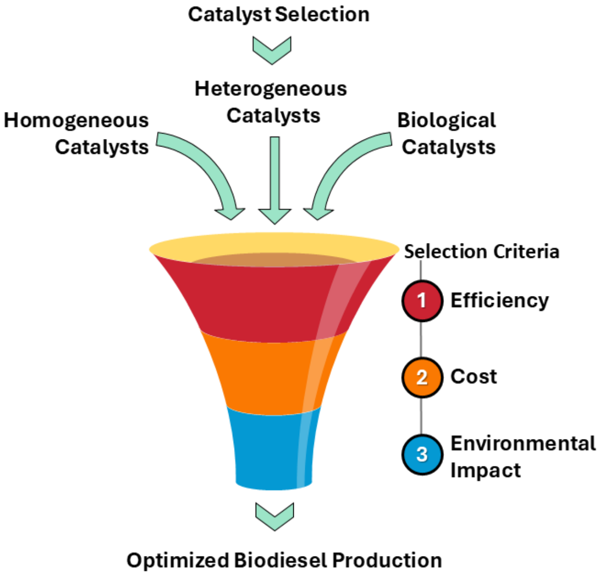


Fig. 3. Catalyst Selection in Biodiesel Production

Generally, in esterification, acid catalysts such as H_2SO_4, HF, H_3PO_4 or HCl [24] interact with triglycerides, producing biodiesel and water [25]. Base catalysts such as NaOH or KOH may be employed in transesterification [26], [27]. Nonetheless, these catalysts exhibit significant corrosiveness, rendering their application a safety issue. Consequently, alternatives are being investigated [28], [29]. Transesterification is a widely utilized technique due to its efficacy and ease of management. In this process, triglycerides undergo a reaction with methanol and are subjected to heating in the presence of a catalyst to yield biodiesel and glycerol [30]–[32].

There are many methods to perform transesterification, with base catalysts being the most common. However, these methods have disadvantages, including cleaning requirements and waste disposal that contribute to environmental pollution. Therefore, heterogeneous catalysts are preferred over homogeneous catalysts because of their lower price, corrosion resistance, simplicity of separation, potential for reuse and recycling, sustainability, and enhanced durability (Figure 4). [17], [33]–[37]. Zeolites, which are classified as heterogeneous catalysts, have been widely utilized in the industry due to their economic and ecological environment concerns, high specific surface area, and porosity within the industry [38]–[42].

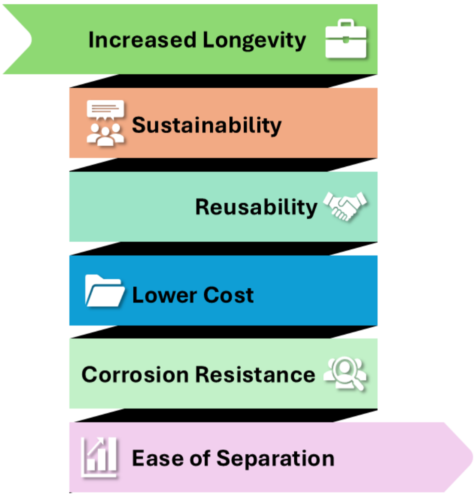


Fig. 4. Advantages of Heterogeneous Catalysts

The most noticeable advantage of zeolites, among others, is their ability to withstand several applications since they do not need to be discarded after use like liquid catalysts do. This advantage makes zeolites a better alternative in the production of biodiesel. Zeolites are crystalline materials that can be synthesized from silica and alumina containing raw materials like clay, for example, Merauke clay from Papua, Indonesia. However, we must process the clay to remove any non-catalytic matters. This step is usually achieved through the process of treating the clay with concentrated HCl and fusing with the NaOH pellets to the point when free alumina and silica are obtained. Such materials can be applied to synthesize zeolites [43]–[45]. Zeolite synthesis is known to occur through hydrothermal treatment at temperatures ranging from 25 °C to 150 °C [46].

Recently, there has been a trend in utilizing clay as a solid catalyst in the production of biodiesel due to its cost-effectiveness and eco-friendliness. After extensive applications, clay catalysts have been noted for their ability to maintain activity and for being the most straightforward catalyst to extract from the final product [47]–[50]. Nevertheless, there is limited knowledge about using clay flats as a porous catalyst for WCO.

In another study, biodiesel production from WCO was performed using montmorillonite clay K-30, achieving a yield of 78.4% under optimal conditions: 90°C, 180 minutes, a 12:1 molar ratio of methanol to oil, and 3% catalyst [51]. The ease of separating solid catalysts from the reaction mixture through simple filtration is a significant advantage. Their reusability plays a significant role in minimizing costs and mitigating environmental contamination. There is a growing focus on solid materials such as zeolites and clay minerals as substitutes for conventional liquid catalysts. These materials are more readily recoverable and do not necessitate significant washing post-use [52]. This study aims to produce biodiesel using waste cooking oil (WCO) with catalytically modified clay, while also analyzing the influence of temperature on biodiesel yield. This research corresponds with multiple United Nations Sustainable Development Goals (SDGs), specifically SDG 7 (Affordable and Clean Energy) by promoting renewable energy sources and SDG 12 (Responsible Consumption and Production) by tackling waste management and advocating for the recycling of waste cooking oil. The application of eco-friendly catalysts like clay contributes to the progress of SDG 13 (Climate Action) by alleviating the environmental impacts associated with biodiesel production and supporting efforts to decrease greenhouse gas emissions.

II. MATERIALS AND METHODS

Figure 5 illustrates the materials utilized in this study. The clay used in this study was obtained from Merauke, Papua, Indonesia.

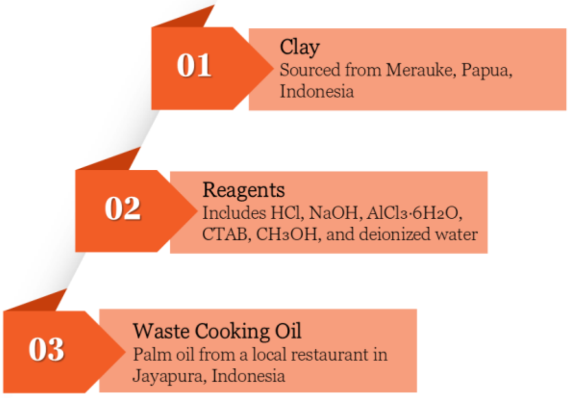


Fig. 5. Materials Utilized in This Study

The chemicals used were 37% hydrochloric acid, NaOH pellets, aluminum trichloride hexahydrate, and cetyltrimethylammonium bromide from Aldrich. Distilled water was obtained from the Chemistry Laboratory of the Department of Chemistry, University of Cenderawasih, Jayapura, Indonesia. The waste cooking oil (WCO) used in the experiments was palm oil sourced from a local restaurant in Jayapura.

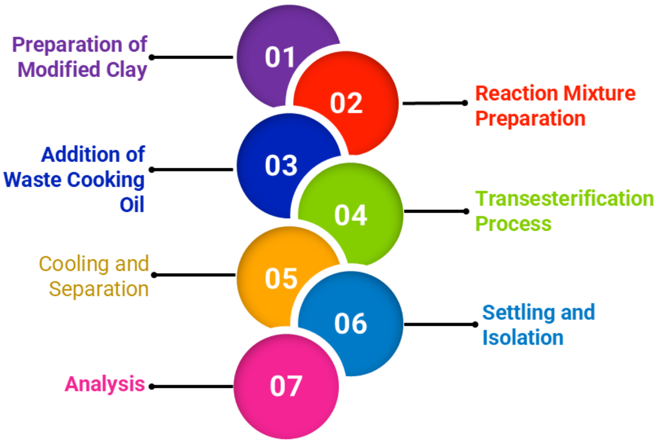


Fig. 6. Experimental setup

The experimental setup for this study is shown in Figure 6. The initial procedure for preparing the clay involved water washing, which followed by oven drying at 120°C for a duration of four hours. The clay was then soaked in water and pulverized to a 100-mesh size. Next, 50 g of the clay was added to 100 mL of 8M hydrochloric acid, and the mixture was boiled at 100°C for six hours. The clay underwent a washing process with deionized water until achieving a neutral pH, followed by drying in an oven at 120°C for a duration of four hours. The dealuminated clay was treated with NaOH at a 0.8:1 ratio of NaOH to clay, and the mixture was heated to 500°C for four hours.

In the final step, 10 g of the clay obtained from the fusion process was mixed with 1.2 g of $AlCl_3 \cdot 6H_2O$ and 1.2 g of CTAB. The mixture was stirred at room temperature for 48 hours after adding distilled water to raise the pH to 11.5. The mixture showed hydrothermal treatment subsequently at 140°C for 48 hours. The modified clay (MC) underwent a series of treatments, including successive washing with deionized water until reaching a pH of 6, followed by filtration, drying in an oven at 120 °C for 4 hours, and calcination at 350 °C for 3 hours.

During the transesterification process, the WCO was first mixed with the modified clay (without fusion). The reaction was carried out in a 250 mL double-necked flask equipped with a reflux condenser and a thermometer. In the flask, 20 g of methanol and 1.5 g of the synthesized catalyst were added, followed by heating the mixture to 55°C while stirring with a magnetic stirrer. Once the temperature reached 55°C, 30 g of WCO was added, and the mixture was stirred for 6 hours. Transesterification reactions were also conducted at 65°C, 75°C, and 85°C for comparison. After the reaction, the mixture was cooled, and the solid catalyst was separated from the liquid phase containing glycerol and methyl ester. The liquid phase was transferred to a separating funnel and allowed to settle for 30 hours. After settling, the crude methyl ester fraction was isolated and weighed. The crude methyl ester was then analyzed by gas chromatography-mass spectrometry (GC-MS).

III. RESULTS AND DISCUSSIONS

To convert clay into zeolite with Si/Al ratios of approximate values 5:1, knowing the silicon and aluminum levels in the clay post-dealumination is crucial. Clay is composed of a complex of silica and alumina-silica and other impurities, which may be organic in nature. The predominant minerals found in clay are aluminum phyllosilicates, which may also contain iron, magnesium, alkali metals, and other cations. Inert components like silica and organic impurities can be detrimental to the catalytic process. Thus, they must be eliminated to enhance the efficiency of the catalyst.

The treatise also includes the cut of the core aggregated clay having Si, Al forming similar groups towards acid metals in the presence of 8M HCl solution: Al, Fe^2, Mn from structures which include organic ones and disperse impurities during the clay dealumination and decatenation process. This enables for the complete destruction of the clay's structural integrity at specific temperatures; however, there are instances where the caustic fails to separate the clay into free silica and aluminum which is a requirement of zeolite synthesis.

X-ray Fluorescence Analysis and XRF of clay were also undertaken after this dealumination process, revealing that the clay contains 34.77% of silicon and 5.67% of aluminum. To achieve the desired Si/Al ratio of around five, additional aluminum in the form of pentahydrate chloride, $AlCl_3 \cdot 6H_2O$, was used. The synthesized zeolite, which in this study refers to modified clay, was subjected to nitrogen adsorption analysis to determine its surface area, pore volume, and pore diameter. The results showed a surface area of 5.5685 m²/g, a pore volume of 0.0126 cm³/g, and a pore diameter of 8.871 nm. The pore diameter falls within the range of mesopores, suggesting that the synthesized zeolite exhibits mesoporous characteristics.

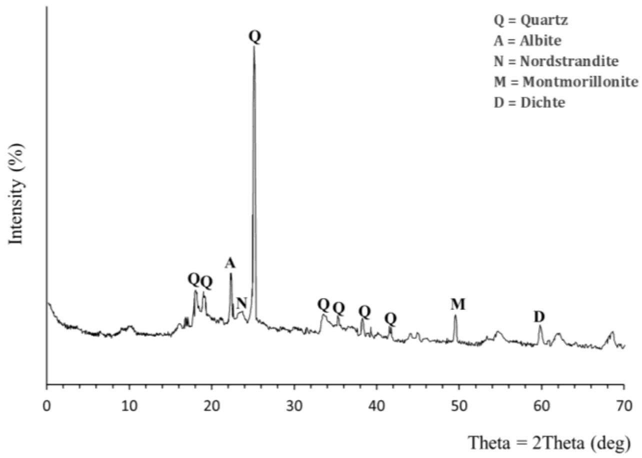


Fig. 7. Diffractogram of Merauke clay before modification

Figure 7 illustrates the X-ray diffraction (XRD) pattern for the unmodified clay. The analysis revealed that the clay sourced from Merauke contained several minerals, including Quartz (SiO_2), Albite ($NaAlSi_3O_8$), Dickite ($Al_2Si_2(OH)_2$), Montmorillonite, and Nordstrandite ($Al(OH)_3$). Among these, Quartz was the most dominant mineral, as shown in Figure 8.

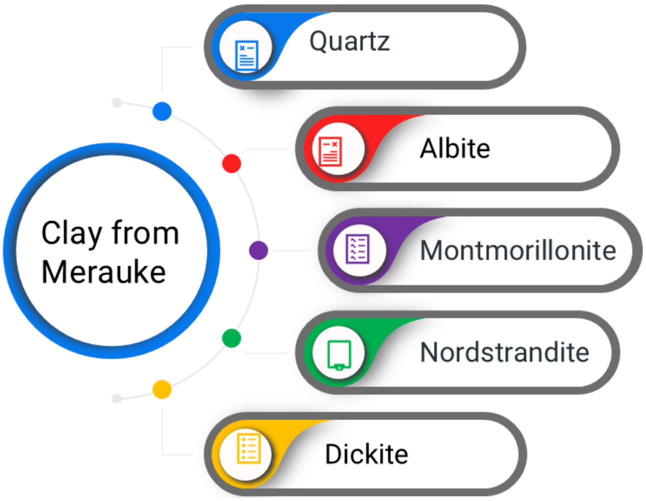


Fig. 8 Mineral Composition of Merauke Clay

Figure 9 shows the X-ray diffraction (XRD) analysis of the modified clay (MC), which reveals that the crystalline peaks are sharper and more intense in comparison to the unmodified clay, as seen in Figure 7. The highest peak occurred at $2\theta = 26.65$ degrees with an interplanar distance, d = 3.34 Å. The diffractogram analysis, based on the 2θ values, revealed the presence of several minerals, including:

- Quartz ($2\theta = 20.87°$, d = 4.26 Å, JCPDS No. 5-0490)
- Gismondine ($2\theta = 26.65°$, d = 3.34 Å, JCPDS No. 71-0962)
- Mordenite ($2\theta = 27.38°$, d = 3.25 Å, JCPDS No. 6-239)

Further 2θ values for Mordenite were observed at 27.96° (d = 3.19 Å), with Sodalite appearing at 31.69° (d = 2.82 Å, JCPDS No. 75-0709) [53], and further Mordenite peaks were noted at 45.41° (d = 1.99 Å), 45.56° (d = 1.99 Å), and 50.14° (d = 1.81 Å).

Based on these findings, it is anticipated that Gismondine zeolite will be the predominant mineral in the modified clay

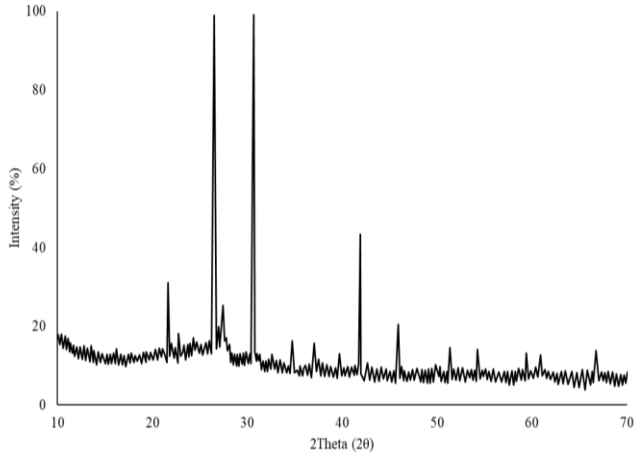


Fig. 9. Diffractogram of MC catalyst

Synthetic zeolites are classified under Faujasite and Gismondine. These zeolites are typically synthesized from materials such as clay, natural zeolite, fly ash, and volcanic ash, all of which contain fused silica and alumina in their composition. This eventually yields a blend of various types of zeolites. Gismondine, or more particularly, NaP zeolite, has been reported to have a molar Si/Al ratio of about 2-5 and is known for its capacity to selectively separate the small molecules, such as water, nitrogen, carbon dioxide and hydrogen [17−20], [54]–[58]. On the transesterification process, the MC catalyst and methanol were mixed before reacted with WCO. The aim is to form sodium ethoxide. The reaction can be written as follows:

$$MC + CH_3OH \rightarrow MC{-}OHCH_3^- + H^+$$

Co-methylation of the WCO with MC-OCH_3 involves catalysts containing modified clay (MC) with methanol. This intermediate then reacts with triglycerides in WCO to produce methyl esters. Biodiesel production (lipid transesterification with methyl ester = triglycerides + glycerin), usually employs heterogeneous catalysis as a trans-critical process. In this instance, we use a modified clay catalyst (MC). Figure 10 presents this process.

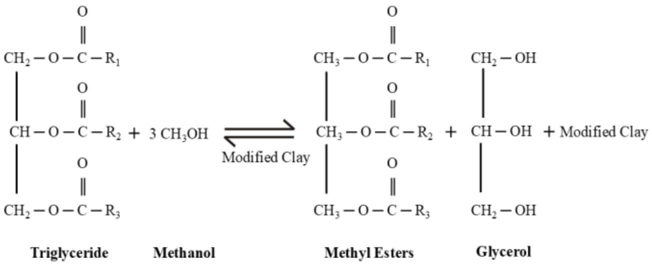


Fig. 10. Transesterification reaction using heterogeneous catalyst

The transesterification reaction creates a mixture where methyl esters rise to the top and glycerol, along with the solid catalyst, settles at the bottom. The methyl esters and glycerol are then separated. Since the catalyst is solid, it can be easily recovered for reuse. An investigation was conducted to study the effect of temperature on the transesterification of waste cooking oil (WCO) using the MC catalyst. The results of these experiments, which examine the effect of temperature variations on the reaction, are presented in Table 1.

Table 1.
Transesterification results of WCO using MC Catalyst at variation of temperature and reaction time of 6h

Temperature of Reaction (°C)	Weight of Catalyst (g)	Weight of Methanol (g)	Weight of WCO (g)	Conversion to Biodiesel [%(wt./wt.)]
55	1.5	20	30	25.87
65	1.5	20	30	85.31
75	1.5	20	30	34.78
85	1.5	20	30	31.18

The influence of temperature on the biodiesel production results is clearly shown in Figure 11. Temperature plays a major role in affecting the rate of transesterification. As the temperature escalates, the reactions accelerate, resulting in a heightened frequency of collisions within a specified timeframe. As a result, the conversion rate to the product accelerates markedly [59], [60]. A catalyst facilitates the acceleration of the process, thus allowing for quicker formation of biodiesel [34], [61], [62].

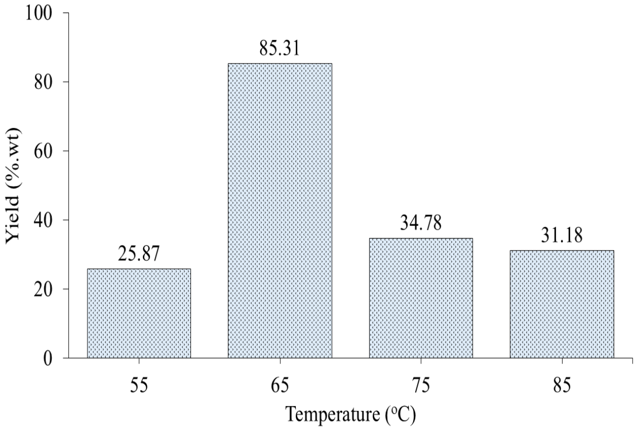


Fig. 11. Graph of Yield (%wt.) with Temperature of Reaction

As shown in the data presented in Table 1 and Figure 11, increasing the reaction temperature to 65°C results in a higher biodiesel yield. However, when the temperature goes above 65°C, the yield starts to drop, indicating that higher temperatures might harm the transesterification process, possibly because the degradation of reactants or the catalyst doesn't work well at those temperatures. This decrease is attributed to the fact that methanol, one of the reactants in the process, has a boiling point of 64.7°C [63], [64]. Once the temperature exceeds this point, excess methanol begins to evaporate, reducing the amount of methanol available for the reaction. Moreover, since the biodiesel formation process is exothermic, increasing the temperature beyond methanol's boiling point further reduces its availability as a reactant, leading to evaporation. Consequently, the transesterification process loses efficiency, leading to a reduction in the biodiesel yield.

Many investigations have shown 65°C as the ideal upper-temperature limit for maximizing biodiesel output in transesterification reactions utilizing cooking oil. Increased temperatures accelerate kinetics reaction by decreasing oil viscosity and enhancing molecular mobility, promoting more efficient interactions between triglycerides and alcohol molecules.

Wei et al. [65] found that biodiesel production can exceed 95% at about 65°C, which speeds up the reaction and helps the ingredients mix better, even though some solvent may evaporate at higher temperatures.

Takase et al. [66] noted an enhancement in biodiesel yields with an increase in temperature from 50°C to 60°C; however, yields started to diminish above 60°C, indicating that 60°C may be optimal for biodiesel production. Furthermore, Andrifar et al. [67] examined the transesterification of waste cooking oil (WCO) with heterogeneous alkali catalysts. It was shown that elevating the temperature to 55°C enhanced biodiesel yields; however, subsequent increases to 65°C resulted in a decline in yield, presumably due to methanol evaporation and adverse side reactions at elevated temperatures. Musa [68] also observed that although elevated temperatures can improve the conversion rate, temperatures over 60°C may diminish biodiesel yields due to methanol loss. On the other hand, Hindarso et al. [69] discovered that the peak conversion rate (99.35%) for making biodiesel from microalgal oils using microwave transesterification with MgO as a catalyst was attained at 60°C, supporting the idea that slightly lower temperatures can provide the best balance between higher biodiesel yields and less methanol loss.

Transesterification takes place at methanol boiling points and only operates effectively up to temperatures of about 64°C; this is the optimal temperature for transesterifications [70]. Reasonable temperatures should not cross this boundary, which shifts the optimal values downwards due to methanol loss through volatilization. Thermal elevation may speed up the transesterification process, but it's crucial not to surpass the methanol's boiling point during the reaction to avoid methanol waste [71]–[73]. The biodiesel produced in the transesterification reaction of waste cooking oil (WCO) at various temperature levels is illustrated in Figure 12.

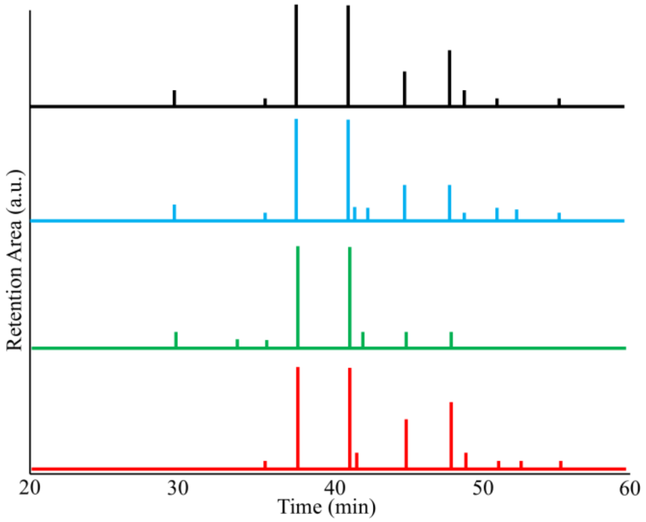


Fig. 12. GC-MS chromatograms of the transesterification product of WCO using the MC catalyst at different temperatures: a) 55°C, b) 65°C, c) 75°C, and d) 85°C.

The results of the transesterification reaction show clear differences in biodiesel production at temperatures of 55°C, 65°C, 75°C, and 85°C, as shown in the chromatograms. The peaks in the chromatograms reveal changes in the composition of the products at each temperature. At 65°C, the peaks exhibit greater concentration around a retention period of 40 minutes, suggesting an increased biodiesel yield. The peaks observed by around 45 minutes are comparatively smaller and less pronounced. This pattern reflects the amount of methyl esters produced at each temperature.

In Figure 12a, the chromatogram displays 13 distinct retention times, with the following compounds identified:

- 37.739 min: Hexadecanoic acid, methyl ester (22.65%)
- 41.134 min: 9.12-Hexadecanoic acid, methyl ester (3.87%)
- 41.256 min: 10-Octadecenoic acid, methyl ester (21.21%)
- 41.758 min: Octadecanoic acid, methyl ester (1.68%)
- 44.909 min: Octadecanoic acid, 2-hydroxy-1,3-propanediyl ester (15.93%)
- 45.167 min: Hexadecanoic acid, 2-hydroxy-1,3-propanediyl ester (3.15%)
- 47.979 min: 13-Octadecenal (18.78%)
- 48.242 min: 6-Tridecanol (2.65%)
- 48.386 min: Octadecanoic acid, 2-hydroxy-1,3-propanediyl ester (2.86%)
- 48.895 min: Di-n-octyl phthalate (1.52%)
- 51.208 min: 10-Nonadecanon (0.59%)
- 52.581 min: Hexadecanoic acid, 2-hydroxy-1,3-propanediyl ester (1.66%)
- 55.268 min: 10-Nonadecanon (2.44%)

The most common methyl esters identified were Hexadecanoic acid, methyl ester (22.65%), 10-Octadecenoic acid, methyl ester (21.21%), and 9.12-Hexadecanoic acid, methyl ester (3.87%).

In Figure 12b, the chromatogram reveals seven main retention times, with the following compounds:

- 34.012 min: Tetradecanoic acid, methyl ester (1.03%)
- 38.504 min: Hexadecanoic acid, methyl ester (37.61%)
- 41.858 min: Linoleic acid, methyl ester (10.24%)
- 42.043 min: 11-Octadecenoic acid, methyl ester (42.20%)
- 42.458 min: Octadecanoic acid, methyl ester (4.24%)
- 45.595 min: 2-Hydroxy-1,3-propanediyl ester (2.79%)
- 48.672 min: 9-Octadecenal (2.89%)

Here, the dominant compounds are 11-Octadecenoic acid, methyl ester (42.20%), hexadecanoic acid, methyl ester (37.61%), and linoleic acid, methyl ester (10.24%).

In Figure 12c, 18 retention times were detected, with major compounds including:

- 27.779 min: Hexadecane ester (0.68%)
- 29.563 min: Dodecanoic acid (5.82%)
- 37.261 min: 2-Heptadecanone (0.76%)
- 37.715 min: Hexadecanoic acid, methyl ester (23.61%)
- 38.850 min: 9-Octadecene (1.53%)
- 40.775 min: 8-Octadecanone (1.46%)
- 41.107 min: 9,12-Hexadecadienoic acid, methyl ester (5.98%)
- 41.231 min: 10-Octadecenoic acid, methyl ester (24.20%)
- 41.729 min: Octadecanoic acid, methyl ester (1.38%)
- 42.594 min: 1-Docosene (1.05%)
- 44.877 min: 10-Nonadecanone (3.41%)

- 47.950 min: Hexadecanoic acid, 2-hydroxy-1,3-propanediyl ester (10.83%)
- 48.871 min: Octadecanoic acid, 2-hydroxy-1,3-propanediyl ester (2.15%)
- 51.182 min: Di-n-octyl phthalate (0.82%)
- 52.549 min: 2-Tricosanone (0.76%)
- 55.235 min: Isooctanol (1.26%)

The most common methyl esters were 10-Octadecenoic acid, methyl ester (24.20%), Hexadecanoic acid, methyl ester (23.61%), and 9,12-Hexadecadienoic acid, methyl ester (5.98%).

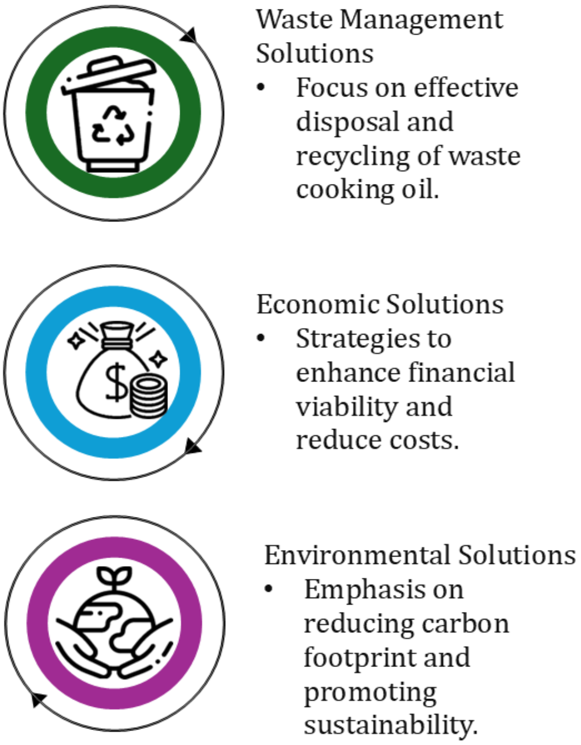
In Figure 12d, there were 13 detected retention times, which corresponded to the following compounds:

- 29.541 min: Dodecanoic acid (3.89%)
- 37.723 min: Hexadecanoic acid, methyl ester (23.86%)
- 40.788 min: 8-Octadecanone (1.40%)
- 41.119 min: 9,12-Hexadecadienoic acid, methyl ester (5.60%)
- 41.239 min: 10-Octadecenoic acid, methyl ester (23.64%)
- 41.741 min: Octadecanoic acid, methyl ester (1.49%)
- 44.549 min: 9-Octadecanone (2.60%)
- 44.892 min: Octadecanoic acid, 2-hydroxy-1,3-propanediyl ester (9.78%)
- 45.133 min: Hexadecanoic acid, 2-hydroxy-1,3-propanediyl ester (3.97%)
- 47.963 min: 9-Octadecen-1-ol (15.47%)
- 48.881 min: Di-n-octyl phthalate (2.19%)
- 51.186 min: 12-Tricosanone (1.13%)
- 55.245 min: 9-Octadecenal (1.67%)

The dominant methyl esters were Hexadecanoic acid, methyl ester (23.86%), 10-Octadecenoic acid, methyl ester (23.64%), and 9,12-Hexadecadienoic acid, methyl ester (5.60%).

This study demonstrates that biodiesel can be synthesized effectively via the transesterification of used cooking oil with a modified clay catalyst. Developing biodiesel from waste cooking oil (WCO) provides significant economic, environmental, and waste management advantages (Figure 13). This technology offers an eco-friendly method by recycling waste cooking oil, diminishing the quantity of refuse that would otherwise exacerbate landfill congestion. Improper disposal of WCO, particularly in water bodies and drainage systems, poses a significant environmental threat by contributing to pollution and reducing water quality [3]–[5]. Reducing waste cooking oil to biodiesel reduces pollutants and greenhouse gas emissions relative to traditional fossil fuels. Moreover, the utilization of renewable resources such as WCO diminishes dependence on fossil fuels, promoting a cleaner and more sustainable energy environment [74]–[78].

In addition to its environmental benefits, the production of biodiesel from waste cooking oil offers significant economic advantages. WCO serves as an economical feedstock that reduces production expenses, considering that feedstock typically accounts for 70-90% of biodiesel production expenditures. This cost reduction is substantial, rendering biodiesel production more economically feasible. The recycling of waste cooking oil reduces waste disposal expenses.



Waste Management Solutions
- Focus on effective disposal and recycling of waste cooking oil.

Economic Solutions
- Strategies to enhance financial viability and reduce costs.

Environmental Solutions
- Emphasis on reducing carbon footprint and promoting sustainability.

Fig. 13. The primary benefit of biodiesel production from waste cooking oil.

This approach mitigates the financial pressure on businesses, particularly in the oil and food industries, by efficiently addressing waste management challenges. Furthermore, the extensive utilization of biodiesel from waste cooking oil diminishes reliance on petroleum, thus fostering economic stability in energy markets. The production of biodiesel from waste cooking oil promotes the advancement of a circular economy by converting waste into a valuable energy source [79]. Substituting a fraction of petrochemical oil imports with biodiesel from waste cooking oil mitigates fossil fuel usage and lowers waste management expenses [74]–[78].

The conversion of waste cooking oil into biodiesel addresses both environmental and economic challenges, while also greatly improving waste management practices. The management of waste, particularly in urban settings, is becoming an increasingly pressing issue as the amount of waste produced continues to grow alongside the limitations of current disposal techniques. Inadequate disposal of WCO leads to environmental pollution and exerts significant pressure on waste management systems. Improper disposal of WCO could block drainage systems, contaminate water bodies, and pose health risks by promoting the proliferation of pathogenic microorganisms.

These challenges significantly strain waste management systems already grappling with the substantial volume and intricacy of contemporary waste streams. The transformation of waste cooking oil into biodiesel efficiently resolves this issue by facilitating sustainable waste management and recycling [17], [80]. This approach minimizes water and soil contamination while alleviating the pressure on waste management infrastructures. Thus, converting waste cooking oil into biodiesel represents a sustainable approach to waste-to-energy that addresses both waste management and energy production needs [74]–[78].

IV. CONCLUSIONS

Merauke clay was changed by adjusting its Si/Al ratio to about 5 through a series of steps, which included dealumination, fusion with NaOH pellets, and a hydrothermal reaction at 140°C for 48 hours. This modification resulted in the formation of various zeolite minerals, with gismondine zeolite being the most prominent. We subsequently employed the modified clay as a catalyst (MC catalyst) in the transesterification of waste cooking oil (WCO) to produce biodiesel. The MC catalyst exhibited a surface area of 5.5685 m^2/g, a pore volume of 0.0126 cm^3/g, and a pore diameter of 8.871 nm.

In the transesterification process, increasing the reaction temperature did not necessarily lead to the highest biodiesel conversion. The optimal conversion to methyl ester (85 wt.%) was achieved at 65°C. At this temperature, the predominant methyl ester compounds were 11-octadecenoic acid methyl ester (42.20%), hexadecanoic acid methyl ester (37.61%), and linoleic acid methyl ester (10.24%). These findings suggest that, despite variations in reaction temperature, 65°C was the most effective temperature for biodiesel production using the MC catalyst.

This study contributes to advancing sustainable energy solutions in line with the United Nations Sustainable Development Goals (SDGs), particularly SDG 7: Affordable and Clean Energy and SDG 12: Responsible Consumption and Production. The modification of Merauke clay to produce an efficient catalyst for biodiesel production from waste cooking oil supports efforts to enhance renewable energy sources and reduce environmental impacts. By utilizing waste materials, the process promotes cleaner energy production and supports SDG: Climate Action by reducing reliance on fossil fuels. Furthermore, the use of a locally sourced material like Merauke clay demonstrates a commitment to SDG 9: Industry, Innovation, and Infrastructure, encouraging innovation in sustainable technologies for biodiesel production.

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