

Low-Cost Dolomite Catalyst for Sustainable Biodiesel Production from Kapok Seed Oil

Salma Avia Pratidina¹

Arif Hidayat^{*,1}

¹Department of Chemical Engineering, Faculty of Industrial Technology, Universitas Islam Indonesia, Yogyakarta 55584, Indonesia

*e-mail: arif.hidayat@uii.ac.id

Submitted 23 June 2025

Revised 11 August 2026

Accepted 15 August 2026

Abstract. This study investigated dolomite as a low-cost heterogeneous catalyst for microwave-assisted biodiesel production from kapok seed oil (KSO). Dolomite was thermally activated at 900 °C for 4 h to convert carbonate phases into catalytically active CaO–MgO oxides. Catalyst characterization using XRD, nitrogen adsorption–desorption, EDS, and Hammett indicators confirmed the formation of crystalline oxide phases, mesoporous characteristics, and an increased surface area from 0.7190 to 1.2676 m²/g. Calcination increased total basicity from 3.23 to 9.90 mmol/g. Transesterification was performed under microwave irradiation by varying reaction temperature, methanol-to-oil molar ratio, and catalyst loading. The highest biodiesel yield (89%) was obtained at 60 °C, a methanol-to-oil molar ratio of 12:1, and a catalyst concentration of 7.5 wt%. The GC–MS analysis confirmed the formation of fatty acid methyl esters dominated by methyl linoleate, methyl palmitate, methyl oleate, and methyl stearate. The biodiesel produced from KSO exhibited physicochemical properties that met the standards of SNI 7182 and ASTM D6751 for measured parameters. However, catalyst reusability decreased from 89% to 65% after four cycles, indicating progressive deactivation.

Keywords: Biodiesel, CaO catalyst, Dolomite, Heterogeneous Catalyst, Kapok Seed Oil, Transesterification

INTRODUCTION

Global energy demand continues to rise, while fossil fuel resources shrink and discoveries diminish. Biodiesel, a renewable monoalkyl ester produced through esterification or transesterification of triglycerides, offers a promising alternative. Many types of edible oil, including rapeseed (Nowicki *et al.*, 2016), corn (Sirajuddin *et al.*, 2015), sunflower (Dahdah *et al.*, 2020), soybean (Wu *et al.*, 2016), palm oil (Pradana *et al.*, 2017), coconut (Qiu *et al.*, 2016)(Qiu *et*

al., 2016), and rice bran oil (Hidayat *et al.*, 2018), have been investigated as raw materials for biodiesel synthesis. Sustainability concerns about using edible oils have prompted a shift toward non-edible feed stock. Furthermore, feedstock cost is a key factor in biodiesel feasibility; non-edible oils reduce production costs and improve competitiveness with petroleum diesel. *Ceiba pentandra* is a non-edible oilseed and contains 20–25% oil by weight. In 2015, Indonesia was estimated to have 100,500 hectares of kapok plantations and could

produce approximately 110 kg of seeds per hectare. This has the potential to produce over 10 million liters annually. Given these facts, developing kapok seed oil (KSO) as an economical raw material for biodiesel production appears to be a promising research direction.

Biodiesel production from edible oils typically involves NaOH or KOH as homogeneous base catalysts. When free fatty acids are present, NaOH or KOH can form soap through neutralization, thereby consuming catalysts and reducing biodiesel yield. Homogeneous catalysts also have several limitations, including the need for advanced separation processes, the generation of large volumes of wastewater, and the high cost of recovery and reuse (Mandari and Devarai, 2021; Mulyatun *et al.*, 2022)(Mandari & Devarai, 2022; Mulyatun *et al.*, 2022). Heterogeneous catalysts can address limitations associated with homogeneous catalysts. Several recent studies have investigated the performance of heterogeneous catalysts in biodiesel synthesis. Various type of solid catalysts have been examined using different types of raw materials such as zeolites (Hidayat *et al.*, 2018; Hidayat and Sutrisno, 2018), metals oxides (Castro *et al.*, 2014; Hájek *et al.*, 2017), clays (Negm *et al.*, 2017; Zatta *et al.*, 2013), alumina (Ramesh *et al.*, 2019; Silveira Junior *et al.*, 2019), hydrotalcite (Nowicki *et al.*, 2016), biomass-based catalyst (Chen *et al.*, 2015; Farabi *et al.*, 2019; Hidayat and Sutrisno, 2017; Pradana *et al.*, 2018, 2017).

Among heterogeneous base catalysts, alkaline earth metal oxides, particularly CaO and MgO, attract much attention because they are inexpensive, strongly basic, and relatively simple to prepare. CaO provides strong basic sites for methanol activation into methoxide species, whereas MgO may

improve structural stability and contribute moderate basicity. However, catalytic performance depends not only on composition but also on crystallinity, surface area, pore accessibility, particle size, active-site density, and resistance to deactivation (Gardy *et al.*, 2019; Widayat *et al.*, 2023). Dolomite, a natural carbonate mineral mainly composed of $\text{CaMg}(\text{CO}_3)_2$, is a suitable precursor for CaO–MgO-based heterogeneous catalysts. During calcination, dolomite decomposes, releasing CO_2 and forming mixed oxide phases that provide basic sites during transesterification. The coexistence of calcium and magnesium species may contribute to strong basicity with good structural stability (Makarevičienė *et al.*, 2025; Šlinkšienė *et al.*, 2024). Using local dolomite is important for sustainable biodiesel production because it links catalyst development to local resource availability. Locally sourced mineral catalysts can reduce dependence on imported catalysts.

In addition to selecting locally sourced catalysts, the heating method significantly impacts biodiesel production. Conventional heating transfers energy from the reactor wall to the reaction mixture, which can generate a temperature gradient and slow heat transfer in a multiphase system containing oil, methanol, and a solid catalyst. Microwave-assisted transesterification offers more efficient heat transfer because microwave irradiation can promote rapid volumetric heating through dipole rotation and ionic conduction. Microwave irradiation can increase contact between methanol, oil, and the solid catalyst, accelerate mass transfer, and reduce the time required to achieve the effective reaction temperature. In a heterogeneous catalysis system, the reaction occurs at the interface between the immiscible liquid phase and the solid active

sites during microwave irradiation. Microwave irradiation can reduce external heat transfer barriers and enhance the formation of reactive methoxide species on the surface of the base catalyst (Devasan *et al.*, 2023; Silviana *et al.*, 2022).

Dolomite has been extensively studied as a heterogeneous basic catalyst for biodiesel production because it can produce active sites after calcination. Various studies have shown that dolomite performs well with many types of edible oil. Jindapon and Ngamcharussrivichai obtained 99.9 wt% FAME from refined palm oil at 60 °C, with a 10 wt% catalyst, a methanol-to-oil ratio of 30:1, and a reaction time of 60 minutes, after calcining the dolomite at 800 °C for 3 hours (Jindapon & Ngamcharussrivichai, 2018). (Jindapon & Ngamcharussrivichai, 2018) Šlinkšienė *et al.* demonstrated the reusability of dolomite in rapeseed oil. The initial yield of 98.66 wt% remained at 97.23 wt% after six thermal regeneration cycles at 850 °C (Šlinkšienė *et al.*, 2024). Gaide *et al.* reported that the butanolysis of rapeseed oil using dolomite calcined at 850 °C for 4 hours required more severe conditions, namely 110 °C, a catalyst loading of 5.24 wt%, a butanol-to-oil ratio of 13.72:1, and a reaction time of 8 hours, yielding 94.89–95.9% (Gaide *et al.*, 2021). Modifying dolomite also improves catalytic performance. Niu *et al.* developed Ce/dolomite by calcining at 800 °C for 3 hours, impregnating with cerium, and activating at 550 °C for 4 hours. In palm oil transesterification, a catalyst concentration of approximately 5 wt%, a methanol-to-oil ratio of 15:1, a temperature of 65 °C, and a reaction time of 2 hours resulted in a yield of 97.21% (Niu *et al.*, 2020). Zhao *et al.* used La-dolomite for palm oil. They achieved a yield of 98.7% at 65 °C, with a catalyst loading of 7 wt%, a methanol-to-oil ratio of 18:1, and a reaction

time of 180 minutes, although the activation duration at 800 °C was not reported in detail (Zhao *et al.*, 2019). Dolomite catalysts have also been investigated for biodiesel production using feedstocks from non-edible oils. Çakırca *et al.* used *Chlorella protothecoides* microalgal oil with a 30% CaO/dolomite catalyst calcined at 850 °C for 2 hours. At 65 °C, with a 3 wt% catalyst, a methanol-to-oil ratio of 6:1, and a reaction time of 3 hours, the FAME content reached 90% (Çakırca *et al.*, 2019). Widiarti *et al.* reported converting waste cooking oil using dolomite-derived CaO aided by *Sapindus rarak* extract. The catalyst was calcined at 800 °C for 3 hours and yielded 92.40% at 65 °C, with a 5 wt% catalyst, an oil-to-methanol ratio of 1:9, and a reaction time of 3 hours (Widiarti *et al.*, 2024) (Widiarti *et al.*, 2024). Process intensification approaches have also yielded interesting results. Temur Ergan *et al.* used dolomite calcined at 840 °C for 3 hours in an enhanced microwave system for canola oil. At 65 °C, with a 5 wt% catalyst, a methanol-to-oil ratio of 9:1, and a reaction time of 2 hours, the yield reached 99.1%, significantly higher than that achieved by conventional heating (Temur Ergan *et al.*, 2022). Sudalai *et al.* Click or tap here to enter text. extended the application of dolomite to *Pongamia pinnata* oil and achieved a yield of 92.3% at 75 °C, a methanol:oil ratio of 20:1, a catalyst concentration of approximately 5 wt%, and a reaction time of 9 hours, although the calcination conditions were not specified (Sudalai *et al.*, 2024).

A literature review shows that the use of dolomite catalysts for biodiesel production from non-food feedstocks remains limited. Therefore, using abundant, low-cost dolomite for the transesterification of kapok seed oil is relevant to expanding biodiesel production from more sustainable non-food

feedstocks. This research focused on integrating the use of locally sourced kapok seed oil as a non-edible feedstock with dolomite as a low-cost, naturally abundant mineral for recoverable basic catalysis. This study lies not only in combining kapok seed oil with a dolomite catalyst but also in the microwave-assisted transesterification process. Microwave irradiation offers advantages in biodiesel production, including rapid heating, faster biodiesel yields, significantly lower energy consumption, and improved contact between methanol, oil, and the solid catalyst. These factors enable more efficient biodiesel production than conventional heating. The study also evaluates catalyst reusability and identifies deactivation as a primary challenge for operational sustainability. The study examined the influence of catalyst concentration, reaction temperature, and methanol-to-oil molar ratio on biodiesel yield. The study also evaluated reusability to determine whether the catalyst can retain activity over repeated cycles, which is essential for assessing practical feasibility.

MATERIALS AND METHODS

Materials

Dolomite was collected from natural sources. Deionized water was used for washing. Methanol was used as the reactant. Kapok seed oil served as the biodiesel feedstock. Kapok seed oil was extracted using solvent extraction with n-hexane, which is highly selective for non-polar lipids. Initially, dried kapok seeds were finely ground to increase the surface area for solvent contact. Approximately 50 g of the ground seeds were placed in a Soxhlet extractor and refluxed with 300 mL of n-hexane for 6 hours. The resulting oil-solvent mixture was then rotary-

evaporated at 40°C to remove the solvent and obtain kapok seed oil.

Dolomite Catalyst Preparation

Dolomite was washed with deionized water to eliminate organic pollutants and impurity particles. The washed dolomite was dried at 105°C for 12 hours in an oven to eliminate moisture. After drying, the dolomite was pulverized through a ball mill and sieved using a 100–200 mesh sieve to produce a uniform particle-size distribution. Calcination of the powder was conducted at 900°C for 4 hours in a muffle furnace to convert carbonate compounds into active oxide forms: calcium oxide (CaO) and magnesium oxide (MgO), with the release of CO₂ gas. The calcined dolomite was stored in a desiccator to prevent rehydration by water vapor, because CaO is hygroscopic.

Catalyst Characterization

The Crystal Structure of Porous Materials was examined using X-Ray Diffraction (XRD). The instrument used was a Rigaku SmartLab X-ray Diffractometer for crystalline structure characterization of porous materials. Equipped with a Cu K α radiation source ($\lambda = 1.5406 \text{ \AA}$), it operates at 40 kV and 30 mA, using a θ – 2θ configuration and a D/teX Ultra 250 detector. Scans typically run from 5° to 90° 2θ with a step of 0.02°. The pore size, pore volume, and surface area distribution of the porous materials were measured using a Quantachrome NOVA 2200e. Operating with nitrogen gas at –196°C, the specific surface area was determined by the BET method, while pore volume and average pore diameter were determined using the BJH methods. It supports multi-point analysis, with relative pressure ranging from 0.05–0.3 (P/P_0), with degassing performed at 100–300°C under vacuum. Energy-dispersive X-ray

Spectroscopy (EDS) is an important technique for determining the elemental composition of porous materials. EDS analysis was performed using an Oxford Instruments X-Max 20 EDS system integrated with a JEOL JSM-6510LA Scanning Electron Microscope. The system uses a wide-area silicon drift detector (SDD) with a resolution of approximately 125 eV at Mn K α . Operating in high vacuum with an accelerating voltage range of 10–20 kV, EDS captures characteristic X-ray emissions resulting from electron-matter interactions. Quantitative and semi-quantitative analyses were processed using AZtec software, which allows real-time elemental mapping and spot analysis. Basic strength of solid materials was determined through the Hammett indicator method as a qualitative measurement tool. It employs organic indicators with known H_0 values in non-aqueous solvents. A color change upon contact with the material indicates that the surface basicity exceeds the indicator's H_0 value. Common indicators include phenolphthalein ($H_0 = +9.8$) and 4-nitroaniline ($H_0 = +18.4$). This classifies basic sites as strong, moderate, or weak, offering valuable insight into catalyst performance.

Catalytic Performance Test

Kapok seed oil was used as the raw material in the transesterification reaction. Microwaves were used to assist the experiments. A two-neck flask reactor, equipped with a reflux condenser and a temperature indicator, was placed on a magnetic hot plate stirrer. Methanol and a certain amount of catalyst were added to the flask, heated while stirring at 500 rpm, and kapok seed oil was slowly introduced. The reaction was run for 1 hour. After the reaction was complete, the catalyst was separated by vacuum filtration and centrifugation. The

reaction mixture was placed in a separating funnel and allowed to stand for 24 hours. The glycerol layer was isolated, and the methyl ester layer was heated at 80°C to remove residual methanol.

Product Analysis

Biodiesel yield was determined as the ratio of the weight of biodiesel produced to the weight of initial oil used, using the following equation Eq. 1; (Ajala *et al.*, 2020)(Ajala *et al.*, 2021)

$$\text{Biodiesel Yield (\%)} = \left(\frac{\text{Weight of biodiesel produced}}{\text{Weight of KSO used}} \right) \times 100\%$$

Biodiesel composition was identified using a Shimadzu GCMS-QP2010 SE equipped with a GC-2010 Plus gas chromatograph.

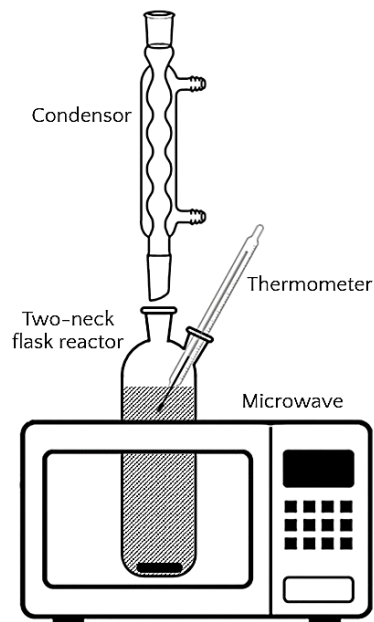


Fig. 1: Catalytic performance test apparatus

Catalyst Reusability

The calcined dolomite catalyst was reused in several reaction cycles to evaluate its stability and activity over time. The

calcined dolomite catalyst's reusability was assessed under constant reaction conditions, including 7.5% catalyst loading, a methanol-to-oil molar ratio of 1:12, a reaction time of 60 minutes, and 60°C temperature. After the reaction, the remaining catalyst was immediately reused in subsequent esterification cycles under identical conditions.

RESULTS AND DISCUSSION

Physicochemical Properties of Dolomite Catalysts

The crystalline phase of raw dolomite and dolomite catalysts were examined using X-ray diffraction (XRD) analysis. Figure 2 (a) presents the XRD pattern of the raw dolomite before thermal activation. Several sharp and intense diffraction peaks at approximately $\theta = 18.6^\circ$, 29.4° , 32.0° , 36.0° , 47.2° , 50.8° , and 59.0° indicate the presence of well-crystallized phases. The sharp diffraction at a 2θ angle of 29.4° is attributed to the plane of calcite (CaCO_3). Meanwhile, the peaks at 47.2° and 50.8° can be attributed to CaO (lime phase). The presence of calcium and magnesium compounds as dominant crystal phases indicates dolomite's potential to produce catalytically active basic oxides through activation. These oxides are well known for their strong basic nature, which enhances the catalytic performance in base-catalyzed reactions such as transesterification for biodiesel production. The XRD patterns in Figure 2 (b) illustrate the crystallographic characteristics of the dolomite-based catalyst after thermal activation. The diffractograms show several sharp and intense peaks, indicating a well-crystallized material. The characteristic peaks appearing at 36.0° , 42.6° , and 62.4° are consistent with the reflections of magnesium oxide (MgO), while the peaks

at 32.0° , 47.2° , and 53.0° can be attributed to calcium oxide (CaO).

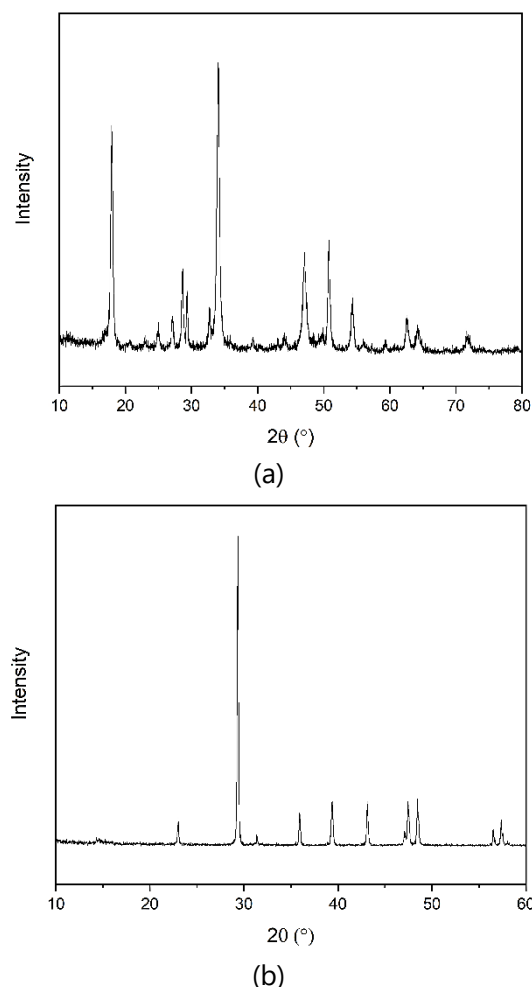


Fig. 2: X-Ray diffraction pattern of (a) raw Dolomite; and (b) Dolomite catalyst

The disappearance of some diffraction patterns in dolomite after thermal activation indicates that the thermal treatment successfully converted the original carbonate matrix into catalytically active oxide phases. These oxides are known for their strong basicity, which helps facilitate base-catalyzed transesterification and other reactions requiring basic active sites. The sharp diffraction peaks indicate high crystallinity, which improves thermal and structural stability during catalytic operation. In addition, MgO contributes to a higher surface area and dispersion of active sites, while CaO

acts as a strong base, increasing the reactivity of the catalytic material.

Figure 3 (a) illustrates the nitrogen adsorption-desorption isotherm curves, which exhibit Type IV behavior, characteristic of mesoporous materials according to the IUPAC classification. The Type IV isotherm is characterized by initial adsorption showing the formation of monolayers to multilayers at relatively low pressures ($P/P_0 < 0.3$), followed by a significant increase in the adsorption volume at intermediate pressures due to capillary condensation within the mesopores. The relatively small initial adsorption at low P/P_0 indicates that micropores do not dominate this material. The sharp increase in adsorption volume as P/P_0 approaches 0.9–1.0 confirms the presence of mesopores. The hysteresis curve along the desorption path further confirms the presence of mesoporous structures. The observed hysteresis curve resembles type H3, which is associated with plate-shaped materials and slit-shaped pores.

As shown in Figure 3(b), the nitrogen adsorption-desorption isotherm mirrors the trend in Figure 3(a). According to IUPAC classification, this is identified as a Type IV isotherm, typical of mesoporous materials. The curve demonstrates a sigmoidal trend, with a steady rise in adsorbed volume at $P/P_0 < 0.3$ (low relative pressure), followed by a steeper increase as the relative pressure approaches unity. The curve trend illustrates layered adsorption followed by capillary condensation in the mesopores. Hysteresis is observed between the adsorption and desorption branches at medium to high relative pressures, indicating the presence of mesopores. The hysteresis profile is categorized as type H3, which is often associated with slit-shaped or plate-like pores. The H3 type hysteresis indicates a wider and less uniform pore structure. Both

N₂ isotherm curves of raw and calcined dolomite show that the materials have a mesoporous structure with slit-shaped pores, so they have high potential for use in applications such as catalysis, adsorption, and separation.

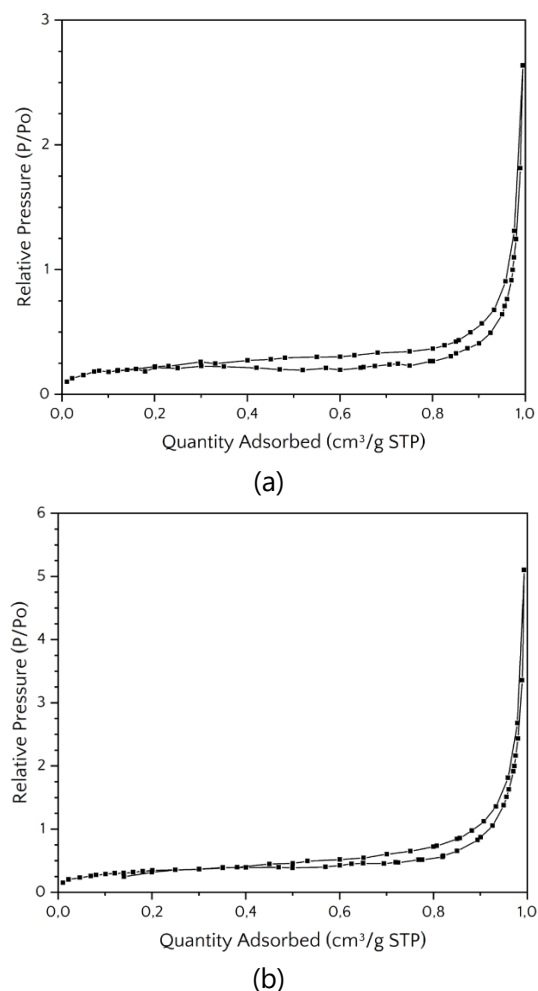


Fig. 3: Nitrogen adsorption-desorption isotherm profile of: (a) raw dolomite; and (b) dolomite catalyst

The physicochemical characteristic of raw and calcined dolomite is summarized in Table 1. The key parameters such as average pore size diameter, specific surface area, and total pore volume are crucial for evaluating the properties of porous materials, particularly in applications involving heterogeneous catalysis, adsorption, and energy storage. The nitrogen adsorption–

desorption results for raw and calcined dolomite are summarized in Table 1. Upon calcination, all three measured parameters increased significantly, indicating the development of a more favorable porous structure for catalytic applications.

The specific surface area of raw dolomite was recorded at $0.7190 \text{ m}^2\cdot\text{g}^{-1}$, which increased substantially to $1.2676 \text{ m}^2\cdot\text{g}^{-1}$ after calcination. This enhancement can be attributed to the thermal decomposition of carbonate phases (CaCO_3 and MgCO_3) into their respective oxides (CaO and MgO), which induces the formation of voids and disordered structures, increasing the accessible surface area. Higher specific surface area is favorable in catalytic systems as it provides more active sites for reactant adsorption and surface reactions, ultimately improving catalytic efficiency.

Table 1. Physicochemical characteristics of raw and calcined dolomite

Samples	BET surface area ($\text{m}^2\cdot\text{g}^{-1}$)	Average pore diameter (nm)	Cumulative pore volume ($\text{cm}^3\cdot\text{g}^{-1}$)
Raw Dolomite	0.7190	22.834	$4.078\cdot 10^{-3}$
Calcined Dolomite	1.2676	24.8995	$7.891\cdot 10^{-3}$

In parallel, the average pore diameter also increased from 22.83 nm to 24.89 nm after calcination. According to the IUPAC classification, this pore size range falls within the mesoporous region (2–50 nm), which is highly desirable in catalysis because it balances molecular diffusion and surface accessibility. The slight enlargement of pore diameter after calcination may result from sintering effects during the thermal treatment, which leads to the coalescence of smaller pores into larger mesopores, thereby

facilitating the transport of larger molecules within the pore network.

The total pore volume also showed a remarkable increase from $4.078 \times 10^{-3} \text{ cm}^3\cdot\text{g}^{-1}$ in raw dolomite to $7.891 \times 10^{-3} \text{ cm}^3\cdot\text{g}^{-1}$ in calcined dolomite. This expansion in pore volume supports the formation of additional porosity, likely from the removal of volatile components and carbonate decomposition. Increased pore volume is advantageous in adsorptive processes and storage applications, such as gas adsorption, where it directly influences the material's uptake capacity.

Collectively, these changes demonstrate that calcination significantly modifies the textural properties of dolomite, transforming it into a more porous and catalytically active material. The shift toward a mesoporous structure with improved surface area and pore volume suggests enhanced potential for use in transesterification reactions for biodiesel production, CO_2 capture, or as a base catalyst in various organic syntheses. Moreover, the presence of medium-sized mesopores is advantageous for reactions involving bulky molecules, reducing diffusion limitations and improving turnover frequency. The BET parameter underscores the transformation of Dolomite's physicochemical characteristics due to thermal activation. These modifications not only reflect the evolution of mesoporosity but also highlight the suitability of calcined dolomite for deployment in advanced catalytic and environmental applications.

The basicity of raw and calcined dolomite catalysts was evaluated using Hammett's indicator method, as presented in Table 2. Basicity and total basicity are important parameters affecting catalyst performance in the transesterification reaction for biodiesel production. Raw

dolomite showed basicity in the range of $7.2 < H^- \leq 9.8$, indicating a weak to moderate basic sites. The basic strength in this range is attributed to the surface hydroxyl groups or bicarbonate species, which have limited nucleophilic character and are less effective in abstracting protons from alcohol molecules during transesterification. Calcined dolomite showed much higher basicity in the range of $12.2 < H^- < 15.0$, corresponding to strong basic sites. This is mainly due to the formation of highly reactive O^{2-} species on the surface due to the thermal decomposition of dolomite into CaO and MgO phases. These strong basic sites are essential for enhancing methanol deprotonation, thereby increasing the rate of methoxide ion formation, a key intermediate in biodiesel synthesis.

The total basicity of raw dolomite was 3.23 mmol/g, increasing substantially to 9.90 mmol/g after calcination. The more than threefold increase in basic sites was driven by thermal activation, which generated surface-active oxygen species and removed adsorbed CO_2 or water that could block active sites. The increase in both basic strength and basic site concentration after calcination indicated a significant improvement in dolomite's catalytic potential for the transesterification reaction. Stronger basic sites would facilitate the initial activation of methanol while also promoting sustained reaction kinetics, leading to higher biodiesel yields. Furthermore, higher basicity (in mmol/g) provided more reactive sites per unit mass, increasing overall catalytic efficiency. However, very strong basicity ($H^- > 15.0$) can also cause side reactions such as saponification, which can reduce the biodiesel yield and complicate product purification. The basic strength values observed in calcined dolomite (H^- up to 15.0) remain within the optimal threshold to achieve high

activity without significant side reactions, making it a promising candidate for heterogeneous catalysis in biodiesel production.

Table 2. The dolomite and dolomite catalyst characteristics

Samples	Basic strength(H^-)	Total basicity (mmoles/gr)
Raw Dolomite	$7.2 < H^- < 9.8$	3.23
Dolomite catalyst	$12.2 < H^- < 15.0$	9.9

The elemental composition of raw dolomite and its calcined derivative was characterized using Energy-Dispersive X-ray Spectroscopy (EDS), with the resulting spectra and quantified data presented in Figure 4. The analysis reveals significant changes in elemental distribution before and after thermal activation, providing insight into the material's structural and chemical transformation.

The EDS spectrum of raw dolomite shows that the material is primarily composed of calcium (Ca), carbon (C), and oxygen (O), with weight concentrations of 64.63 wt%, 19.19 wt%, and 16.18 wt%, respectively. This composition is consistent with the theoretical formula of dolomite, $CaMg(CO_3)_2$. However, magnesium was not detected in this analysis—possibly due to EDS limitations in detecting lighter elements or due to partial substitution of Mg^{2+} by Ca^{2+} in the mineral lattice.

The high carbon and oxygen contents indicate the presence of carbonate species, confirming that the material exists in its carbonate form, which is typical of naturally occurring dolomite. The stoichiometric balance of C and O further supports the presence of carbonate groups (CO_3^{2-}), which

are thermally unstable and tend to decompose under high-temperature conditions. This carbonate-rich structure implies relatively low basicity, making raw dolomite catalytically inactive or less effective for base-catalyzed reactions such as transesterification.

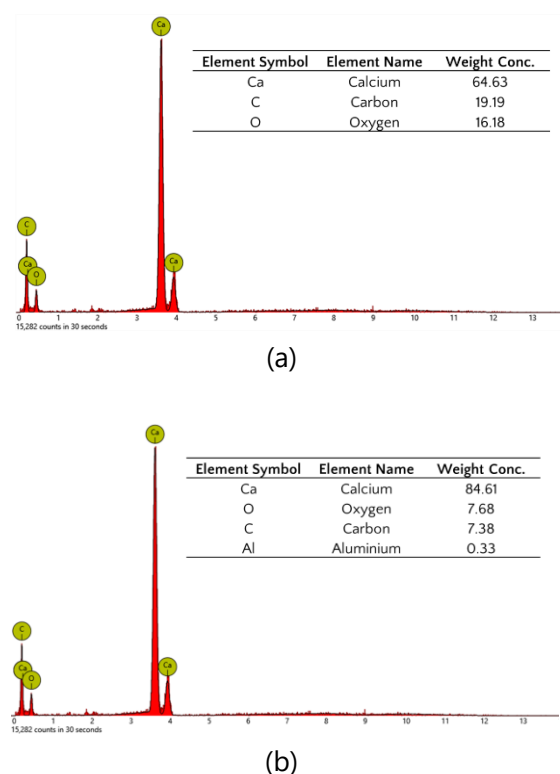


Fig. 4: Energy-dispersive X-ray spectroscopy (EDS) of (a) raw dolomite; and (b) dolomite catalyst

After thermal treatment, the material exhibits significant compositional changes. The calcium content increases sharply to 84.61 wt.%, while the carbon and oxygen contents drop to 7.38 wt.% and 7.68 wt.%, respectively. These reductions reflect the decomposition of carbonate groups into calcium oxide (CaO) and the evolution of CO₂ during calcination, a well-documented transformation in dolomitic materials (Zabeti *et al.*, 2009). The conversion of CaCO₃ to CaO is a crucial step that enhances the material's basic properties and catalytic performance.

These elemental changes have significant implications for catalytic applications. The increase in CaO content leads to a higher density of surface basic sites, which are essential for facilitating nucleophilic attacks in biodiesel production. The decrease in carbon content further confirms the successful removal of thermally unstable carbonate groups, increasing the material's thermal stability and reactivity (Boey *et al.*, 2011). Moreover, the reduced oxygen content aligns with CO₂ loss, corroborating the thermal transformation pathway of dolomite under calcination.

Overall, the EDS results demonstrate a clear transformation of dolomite from a carbonate-dominated structure to an oxide-rich catalyst through calcination. The marked increase in calcium content and concurrent loss of carbonate species confirms the formation of CaO as the dominant phase, which is desirable for heterogeneous base catalysis. These findings validate the potential of thermally activated dolomite as an efficient, low-cost solid base catalyst, particularly for applications such as biodiesel synthesis.

Performance Test Temperature Effect

Figure 5 illustrates the effect of reaction temperature on biodiesel yield. As observed, the biodiesel yield increases progressively with rising reaction temperature, ranging from 30°C to 60°C. At 30°C, the yield is approximately 64%, which increases to 75% at 40°C. At 50°C, the yield increases to around 81%, and the highest yield of approximately 89% is obtained at 60°C. This trend indicates that elevated temperatures enhance the transesterification reaction, likely due to increased molecular motion and collision frequency between triglyceride and alcohol

molecules. Higher temperatures reduce oil viscosity, improve mass transfer, and accelerate the reaction rate. Moreover, at higher temperatures, the activation energy barrier is more easily overcome, leading to improved conversion rates.

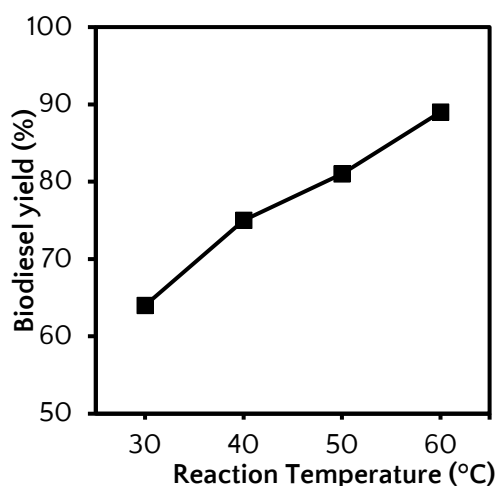


Fig. 5: Temperature effect on biodiesel yield

However, while the graph shows a positive correlation between temperature and biodiesel yield up to 60°C, excessively high temperatures (typically above the boiling point of methanol, ~64.7°C) may cause methanol evaporation, reducing reaction efficiency and causing economic loss. Therefore, optimization should balance between maximizing yield and minimizing energy and methanol loss. Overall, the results suggest that increasing the reaction temperature up to 60°C significantly enhances biodiesel production efficiency, highlighting the importance of temperature control in transesterification processes.

Mole Ratio of Oil to Methanol Effect

One crucial factor influencing biodiesel yield is the mole ratio of oil to methanol. Mole ratio is the ratio between the number of moles of oil and the number of moles of methanol. The mole ratio was used to shift

the reaction toward biodiesel formation. Figure 6 presents the influence of the mole ratio of oil to methanol on biodiesel yield. The data indicates that increasing the methanol content relative to oil enhances biodiesel production efficiency. At a molar ratio of 1:3, the yield is approximately 71%. This value increases slightly to around 74% at a 1:6 ratio. A more significant improvement is observed at the 1:9 ratio, reaching approximately 85%, and the highest yield of approximately 89% is achieved at the 1:12 ratio.

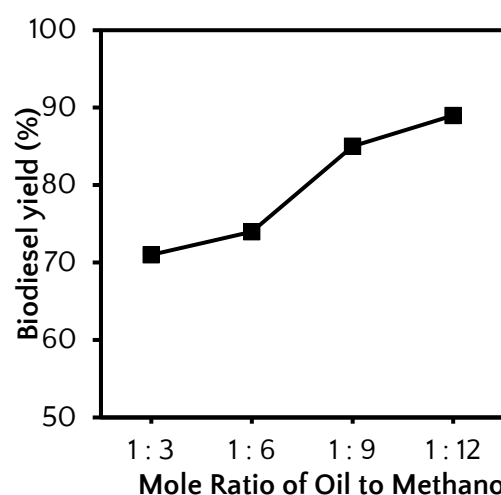


Fig. 6: Mole ratio of methanol to oil effect on biodiesel yield

This trend can be attributed to the nature of the transesterification reaction, which is reversible. According to Le Chatelier's principle, using an excess amount of methanol shifts the reaction equilibrium toward the formation of more methyl esters (biodiesel), thus improving the yield. In addition, a higher methanol concentration enhances the solubility of glycerol, the reaction by-product, reducing its inhibitory effect on the catalyst and overall reaction rate. Nevertheless, excessively high methanol quantities, while beneficial to yield, may create additional separation and purification burdens. Recovering and recycling excess

methanol is necessary to maintain economic and sustainable processes. Therefore, while the 1:12 ratio provides the maximum yield in this study, optimization must consider both conversion efficiency and downstream processing requirements.

Catalyst Concentration Effect

Catalyst concentration is an important operating parameter affecting biodiesel yield during the transesterification reaction. The f CaO and MgO phases in calcined dolomite provide strong basic sites that contribute to its catalytic activity by facilitating methanol activation and subsequent triglyceride conversion. The catalyst concentration is varied in the range of 1–7.5% weight of Dolomite catalyst.

Figure 7 illustrates the effect of varying catalyst concentration (expressed as weight percent of oil) on biodiesel yield. The data indicates a consistent upward trend in biodiesel yield as the catalyst concentration increases from 1 wt% to 7.5 wt%. At 1 wt% catalyst concentration, the biodiesel yield is approximately 70%. This increases to about 75% at 2.5 wt%, then rises more significantly to approximately 84% at 5 wt%. The highest yield, nearly 89%, is achieved at a catalyst concentration of 7.5 wt%. The observed yield increase with higher catalyst concentration is attributed to more active catalytic sites available for the transesterification reaction, which facilitates the conversion of triglycerides into methyl esters. Higher catalyst concentration enhances reaction kinetics by promoting methanol activation and accelerating biodiesel formation. However, while the yield continues to improve up to 7.5 wt%, it is important to recognize that beyond a certain threshold, further increases in catalyst concentration may not yield proportionally higher

conversion. In industrial-scale applications, excessive catalyst use can lead to practical drawbacks, including increased soap formation, higher viscosity, separation difficulties, and additional costs for catalyst recovery and purification.

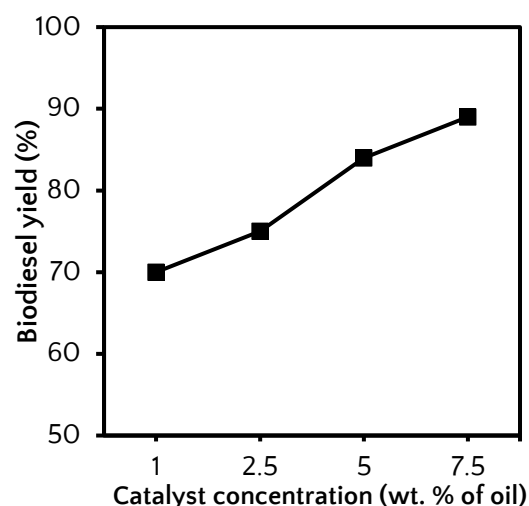


Fig. 7: Catalyst concentration effect on biodiesel yield

Reusability Test

Figure 8 illustrates the performance test of dolomite catalyst in four consecutive transesterification cycles using the same operating conditions (reaction temperature of 60°C, mole ratio of methanol to oil of 12: 1, and catalyst concentration of 7.5 wt%). Fresh catalyst yielded 89% biodiesel. In the second cycle, the biodiesel yield decreased to 76 wt%, indicating deactivation or loss of catalytic active sites, which is generally due to partial fouling, leaching, or accumulation of organic residues on the catalyst surface. Further use in the third and fourth cycles showed a significant decrease in biodiesel yield to 68 and 65 %, respectively. This significant decrease indicates a significant reduction in catalytic efficiency with repeated reuse, which may be due to structural degradation or adsorption of irreversible reaction byproducts. Despite this decrease,

the catalyst maintained a biodiesel content above 65 wt% during the reuse cycles, indicating relatively good stability and reusability under the operating conditions tested. The test results demonstrate the dolomite catalyst's capability for multiple reaction cycles under the same operating conditions. However, a regeneration or reactivation step is necessary to maintain the catalyst performance.

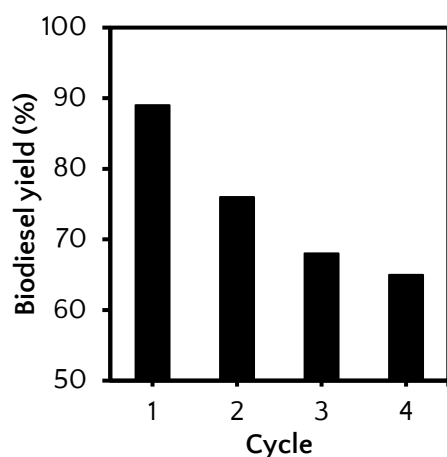


Fig. 8: Reusability of dolomite catalyst for four consecutive cycles

The decline in activity after four consecutive cycles is related to changes in the number and strength of CaO–MgO base sites. Catalyst deactivation can occur due to leaching of active Ca species into the methanol phase. In addition, CaO and MgO may undergo hydration and carbonation, forming Ca(OH)_2 , Mg(OH)_2 , and CaCO_3 , which lower surface basicity and suppress methoxide ion formation. Catalyst activity can also decline because glycerol, partial glycerides, soaps, and other organic species adsorb on the surface, blocking active sites and obstructing pore accessibility. Consequently, washing followed by re-calcination can be considered an effective regeneration approach to remove deposited organic species and restore the catalytically

active oxide phases (Hu *et al.*, 2023; Niu *et al.*, 2020; Šlinkšienė *et al.*, 2024).

Figure 9 shows the GC-MS results for biodiesel produced using kapok seed oil. The GC-MS evaluation of biodiesel synthesized from kapok seed oil demonstrated a characteristic elution pattern with several methyl ester compounds predominantly detected between 38 and 46 minutes of retention time. The highest intensity peak, appearing around 40.2 minutes, is attributed to methyl linoleate, a primary unsaturated fatty acid methyl ester (FAME). Notable peaks also include methyl palmitate (~38.9 min), methyl oleate (~40.5 min), and methyl stearate (~42.1 min). These findings confirm effective transesterification of the original triglycerides. The dominance of unsaturated FAMEs reflects promising fuel qualities, particularly in cold-flow behavior and oxidative resistance. Compound identification was supported by spectral matching with reference libraries.

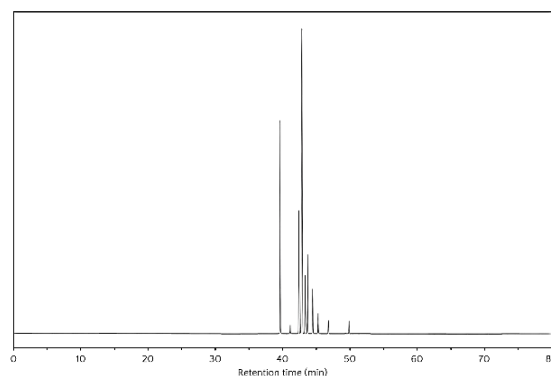


Fig. 9: GC-MS results for biodiesel produced using kapok seed oil

The physicochemical properties of KSO biodiesel produced using the low-cost dolomite catalyst are presented in Table 3 and compared with KSO biodiesel, ASTM D6751, and EN 14214 standards. The density and kinematic viscosity of KSO were 861 kg/m^3 and $4.9 \text{ mm}^2/\text{s}$, respectively, both of which are

within the acceptable limits of the standards. The values indicate that the produced biodiesel has suitable flow behavior, adequate volumetric energy characteristics, and favorable atomization performance for application in compression-ignition diesel engines (Aslan, 2023). The acid value of KSO was 0.39 mg KOH/g, below the maximum permitted value, indicating a low residual free fatty acid level and reduced potential for corrosion in fuel injection systems and engine parts. In addition, the calorific value of 40.82 MJ/kg further confirms that KSO biodiesel can provide sufficient energy output when used as an alternative diesel fuel. Meanwhile, the cetane number of 56 suggests improved ignition quality (Zhang *et al.*, 2025). The compliance of biodiesel derived from kapok seed oil with international fuel quality standards indicates that dolomite catalyst, when used in conjunction with microwave irradiation, is effective in producing biodiesel that can be used in conventional diesel

engines. The low water content of 0.002 wt% indicates moderate unsaturation, storage stability, and reduced risks of corrosion or hydrolysis. The compliance of biodiesel derived from kapok seed oil with international fuel quality standards indicates that the dolomite catalyst, when used with microwave irradiation, effectively produces biodiesel suitable for conventional diesel engines.

CONCLUSIONS

The study successfully demonstrated the viability of synthesizing biodiesel from non-edible kapok seed oil over a dolomite heterogeneous catalyst under microwave-assisted transesterification conditions. The optimal reaction parameters—60 °C temperature, 1:12 methanol-to-oil molar ratio, and 7.5 wt% catalyst loading—yielded a maximum biodiesel conversion of 89%, meeting the specifications set by SNI 7182 and ASTM D6751. GC–MS analysis of the biodiesel composition confirmed successful conversion of the KSO feedstock into fatty acid methyl esters (FAMES). However, catalyst reusability declined significantly after four cycles, with yields dropping from 89 to 65%, primarily due to catalyst deactivation and fouling. This highlights a key limitation in long-term operational stability and necessitates further research on catalyst regeneration strategies and surface modification to enhance durability.

The study underscores the potential of natural dolomite as a cost-effective and eco-friendly catalyst for biodiesel production, particularly suitable for regions with abundant kapok seed resources. This work contributes to sustainable energy transition efforts by leveraging locally available materials and green processing methods.

Table 3. Comparison of KSO biodiesel physicochemical properties with standards (SNI 7182, ASTM D6751)

Properties	KSO biodiesel (this research)	SNI 7182	ASTM D6751
Density (kg/m ³)	861	850– 890	860–900
Kinematic viscosity mm ² /s	4.9	2.3–6.0	1.9–6.0
Acid value	0.39	< 0.4	< 0.5
Cetane number	56	51 (min)	45 (min)
Calorific value (MJ/kg)	40.82	-	35 (min)
Water content	0.002	< 0.003 5	< 0.005

Future studies should focus on improving the catalyst's lifecycle performance, evaluating scalability in continuous reactor systems, and conducting techno-economic and life cycle assessments (LCA) to validate its industrial feasibility and positive environmental impact.

STATEMENT OF AUTHOR CONTRIBUTIONS

Salma Avia Pratidina: experimental work, writing, project administration, review & editing; Arif Hidayat: writing original draft, methodology, formal analysis, investigation, conceptualization, supervision, writing, review, and editing.

DECLARATION OF CONFLICTS OF INTEREST

The authors declare no known financial or personal relationships that might have impacted the research findings reported in this paper.

ACKNOWLEDGEMENT

The authors thank the Chemical Engineering Department, Universitas Islam Indonesia, for the support and facilities provided throughout this research.

REFERENCES

Ajala, E. O., Ajala, M. A., Odetoeye, T. E., Aderibigbe, F. A., Osanyinpeju, H. O., and Ayanshola, M. A., 2020. "Thermal modification of chicken eggshell as heterogeneous catalyst for palm kernel biodiesel production in an optimization process." *Biomass Convers. Biorefinery*, 11, 2599–2615.
<https://doi.org/10.1007/S13399-020-00636-X>
 Aslan, V., 2023. "Fuel characterization, engine

performance characteristics and emissions analysis of different mustard seed biodiesel: An overview." *J. Biotechnol.*, 370, 12–30.
<https://doi.org/10.1016/J.JBIOTEC.2023.05.006>
 Boey, P. L., Maniam, G. P., and Hamid, S. A., 2011. "Performance of calcium oxide as a heterogeneous catalyst in biodiesel production: A review." *Chem. Eng. J.*, 168, 15–22.
<https://doi.org/10.1016/J.CEJ.2011.01.009>
 Çakırca, E. E., Tekin, G. N., İlgen, O., and N Akın, A., 2019. "Catalytic activity of CaO-based catalyst in transesterification of microalgae oil with methanol." *Energy & Environ.*, 30, 176–187.
<https://doi.org/10.1177/0958305X18787317>
 Castro, C. S., Garcia, L. C. F., and Assaf, J. M., 2014. "The enhanced activity of Ca/MgAl mixed oxide for transesterification." *Fuel Process. Technol.*, 125, 73–78.
<https://doi.org/10.1016/J.FUPROC.2014.03.024>
 Chen, G. Y., Shan, R., Shi, J. F., and Yan, B. B., 2015. "Transesterification of palm oil to biodiesel using rice husk ash-based catalysts." *Fuel Process. Technol.*, 133, 8–13.
<https://doi.org/10.1016/J.FUPROC.2015.01.005>
 Dahdah, E., Estephane, J., Haydar, R., Youssef, Y., El Khoury, B., Gennequin, C., Aboukaïs, A., Abi-Aad, E., and Aouad, S., 2020. "Biodiesel production from refined sunflower oil over Ca–Mg–Al catalysts: Effect of the composition and the thermal treatment." *Renew. Energy*, 146, 1242–1248.
<https://doi.org/10.1016/J.RENENE.2019.06.171>

-
- Devasan, R., Ruatpuia, J. V. L., Gouda, S. P., Kodgire, P., Basumatary, S., Halder, G., and Rokhum, S. L., 2023. "Microwave-assisted biodiesel production using bio-waste catalyst and process optimization using response surface methodology and kinetic study." *Sci. Rep.*, 13, 2570-. <https://doi.org/10.1038/s41598-023-29883-4>
- Farabi, M. S. A., Ibrahim, M. L., Rashid, U., and Taufiq-Yap, Y. H., 2019. "Esterification of palm fatty acid distillate using sulfonated carbon-based catalyst derived from palm kernel shell and bamboo." *Energy Convers. Manag.*, 181, 562–570. <https://doi.org/10.1016/J.ENCONMAN.2018.12.033>
- Gaide, I., Makareviciene, V., Sendzikiene, E., and Kazancev, K., 2021. "Natural Rocks–Heterogeneous Catalysts for Oil Transesterification in Biodiesel Synthesis." *Catalysts*, 11(3), 384. <https://doi.org/10.3390/CATAL11030384>
- Gardy, J., Rehan, M., Hassanpour, A., Lai, X., and Nizami, A. S., 2019. "Advances in nano-catalysts based biodiesel production from non-food feedstocks." *J. Environ. Manage.*, 249, 109316. <https://doi.org/10.1016/J.JENVMAN.2019.109316>
- Hájek, M., Kocík, J., Frolich, K., and Vávra, A., 2017. "Mg-Fe mixed oxides and their rehydrated mixed oxides as catalysts for transesterification." *J. Clean. Prod.*, 161, 1423–1431. <https://doi.org/10.1016/J.JCLEPRO.2017.05.199>
- Hidayat, A., Mukti, N. I. F., Handoko, B., and Sutrisno, B., 2018. "Biodiesel production from rice bran oil over modified natural zeolite catalyst." *Int. J. Technol.*, 9, 400–411. <https://doi.org/10.14716/IJTECH.V9I2.1084>
- Hidayat, A., and Sutrisno, B., 2018. "Free fatty acids esterification on palm oil sludge using zirconia-supported Indonesian natural zeolite as heterogeneous catalyst." *Orient. J. Chem.*, 34, 2464–2470. <https://doi.org/10.13005/ojc/340531>
- Hidayat, A., and Sutrisno, B., 2017. "Esterification free fatty acid in sludge palm oil using $\text{ZrO}_2/\text{SO}_4^{2-}$ - Rice husk ash catalyst." *AIP Conf. Proc.*, 1840. <https://doi.org/10.1063/1.4982275/794482>
- Hu, M., Pu, J., Qian, E. W., and Wang, H., 2023. "Biodiesel Production Using MgO - CaO Catalysts via Transesterification of Soybean Oil: Effect of MgO Addition and Insights of Catalyst Deactivation." *Bioenergy Res.*, 16(4), 2398–2410. <https://doi.org/10.1007/S12155-023-10580-Z>
- Jindapon, W., and Ngamcharussrivichai, C., 2018. "Heterogeneously catalyzed transesterification of palm oil with methanol to produce biodiesel over calcined dolomite: The role of magnesium oxide." *Energy Convers. Manag.*, 171, 1311–1321. <https://doi.org/10.1016/J.ENCONMAN.2018.06.068>
- Makarevičienė, V., Gaidė, I., Sendžikienė, E., and Gumbytė, M., 2025. "The Potential of Dolomite as a Heterogeneous Catalyst in Biodiesel Synthesis: A Review." *Energies*, 18, 2920. <https://doi.org/10.3390/EN18112920>
- Mandari, V., and Devarai, S. K., 2021. "Biodiesel Production Using Homogeneous, Heterogeneous, and Enzyme Catalysts via Transesterification and Esterification Reactions: a Critical Review." *Bioenergy Res.*, 15(2), 935–961. <https://doi.org/10.1007/S12155-021-10580-Z>
-

-
- 10333-W
- Mulyatun, M., Prameswari, J., Istadi, I., and Widayat, W., 2022. "Production of non-food feedstock based biodiesel using acid-base bifunctional heterogeneous catalysts: A review." *Fuel*, 314, 122749. <https://doi.org/10.1016/J.FUEL.2021.122749>
- Negm, N. A., Sayed, G. H., Yehia, F. Z., Habib, O. I., and Mohamed, E. A., 2017. "Biodiesel production from one-step heterogeneous catalyzed process of Castor oil and Jatropha oil using novel sulphonated phenyl silane montmorillonite catalyst." *J. Mol. Liq.*, 234, 157–163. <https://doi.org/10.1016/J.MOLLIQ.2017.03.043>
- Niu, S., Zhang, X., Ning, Y., Zhang, Y., Qu, T., Hu, X., Gong, Z., and Lu, C., 2020. "Dolomite incorporated with cerium to enhance the stability in catalyzing transesterification for biodiesel production." *Renew. Energy*, 154, 107–116. <https://doi.org/10.1016/J.RENENE.2020.03.003>
- Nowicki, J., Lach, J., Organek, M., and Sabura, E., 2016. "Transesterification of rapeseed oil to biodiesel over Zr-doped MgAl hydrotalcites." *Appl. Catal. A Gen.*, 524, 17–24. <https://doi.org/10.1016/J.APCATA.2016.05.015>
- Pradana, Y. S., Hidayat, A., Prasetya, A., and Budiman, A., 2018. "Application of Coconut-Shell Activated Carbon as Heterogeneous Solid Catalyst for Biodiesel Synthesis." *Defect Diffus. Forum*, 382, 280–285. <https://doi.org/10.4028/WWW.SCIENTIFIC.NET/DDF.382.280>
- Pradana, Y. S., Hidayat, A., Prasetya, A., and Budiman, A., 2017. "Biodiesel production in a reactive distillation column catalyzed by heterogeneous potassium catalyst." *Energy Procedia*, 143, 742–747. <https://doi.org/10.1016/J.EGYPRO.2017.12.756>
- Qiu, T., Guo, X., Yang, J., Zhou, L., Li, L., Wang, H., and Niu, Y., 2016. "The synthesis of biodiesel from coconut oil using novel Brønsted acidic ionic liquid as green catalyst." *Chem. Eng. J.*, 296, 71–78. <https://doi.org/10.1016/J.CEJ.2016.03.096>
- Ramesh, A., Palanichamy, K., Tamizhdurai, P., Umasankar, S., Sureshkumar, K., and Shanthi, K., 2019. "Sulphated Zr-Al₂O₃ catalysts through jatropha oil to green-diesel production." *Mater. Lett.*, 238, 62–65. <https://doi.org/10.1016/J.MATLET.2018.11.158>
- Silveira Junior, E. G., Perez, V. H., Reyero, I., Serrano-Lotina, A., and Justo, O. R., 2019. "Biodiesel production from heterogeneous catalysts based K₂CO₃ supported on extruded γ-Al₂O₃." *Fuel*, 241, 311–318. <https://doi.org/10.1016/J.FUEL.2018.12.074>
- Silviana, S., Anggoro, D. D., Hadiyanto, H., Salsabila, C. A., Aprilio, K., Utami, A. W., Sa'adah, A. N., and Dalanta, F., 2022. "A Review on the Recent Breakthrough Methods and Influential Parameters in the Biodiesel Synthesis and Purification." *Int. J. Renew. Energy Dev.*, 11, 1012–1036. <https://doi.org/10.14710/ijred.2022.43147>
- Sirajuddin, M., Tariq, M., and Ali, S., 2015. "Organotin(IV) carboxylates as an effective catalyst for the conversion of corn oil into biodiesel." *J. Organomet. Chem.*, 779, 30–38.
-

-
- <https://doi.org/10.1016/J.JORGANCHEM.2014.12.019>
- Šlinkšienė, R., Paleckienė, R., Gaidė, I., Makarevičienė, V., and Sendžikienė, E., 2024. "The Regeneration of Dolomite as a Heterogeneous Catalyst for Biodiesel Production." *Catalysts*, 14, 139. <https://doi.org/10.3390/CATAL14020139>
- Sudalai, S., Devanesan, M. G., and Arumugam, A., 2024. "Dolomite as A Potential Source of Heterogenous Catalyst for Biodiesel Production from Pongamia pinnata." *Nat. Environ. Pollut. Technol.*, 23, 2391–2396. <https://doi.org/10.46488/NEPT.2024.v23i04.042>
- Temur Ergan, B., Yilmazer, G., and Bayramoğlu, M., 2022. "Fast, High Quality and Low-Cost Biodiesel Production using Dolomite Catalyst in an Enhanced Microwave System with Simultaneous Cooling." *Cleaner Chem. Eng.*, 3, 100051. <https://doi.org/10.1016/J.CLCE.2022.100051>
- Widayat, W., Maheswari, N. T., Fitriani, W., Buchori, L., Satriadi, H., Kusmiyati, K., and Ngadi, N., 2023. "Preparation of MgO-CaO/SiO₂ catalyst from dolomite and geothermal solid waste for biodiesel production." *Int. J. Renew. Energy Dev.*, 12, 541–549. <https://doi.org/10.14710/IJRED.2023.51573>
- Widiarti, N., Holilah, H., Bahruji, H., Nugraha, R. E., Suprpto, S., Ni'mah, Y. L., and Prasetyoko, D., 2024. "Coprecipitation and hydrothermal synthesis of CaO from dolomite in the presence of Sapindus rarak extract for biodiesel production: catalysts characterization and optimization." *RSC Adv.*, 14, 23332–23340.
- <https://doi.org/10.1039/D4RA03489A>
- Wu, L., Wei, T. Y., Tong, Z. F., Zou, Y., Lin, Z. J., and Sun, J. H., 2016. "Bentonite-enhanced biodiesel production by NaOH-catalyzed transesterification of soybean oil with methanol." *Fuel Process. Technol.*, 144, 334–340. <https://doi.org/10.1016/J.FUPROC.2015.12.017>
- Zabeti, M., Wan Daud, W. M. A., and Aroua, M. K., 2009. "Activity of solid catalysts for biodiesel production: A review." *Fuel Process. Technol.*, 90, 770–777. <https://doi.org/10.1016/J.FUPROC.2009.03.010>
- Zatta, L., Ramos, L. P., and Wypych, F., 2013. "Acid-activated montmorillonites as heterogeneous catalysts for the esterification of lauric acid acid with methanol." *Appl. Clay Sci.*, 80–81, 236–244. <https://doi.org/10.1016/J.CLAY.2013.04.009>
- Zhang, Y., Chen, C., Xie, E., Hu, M., Fu, G., Wang, Y., Li, L., Yan, X., Zhang, Z., and Wu, G., 2025. "Production of biodiesel through the transesterification of Jatropha seed oil catalyzed by S-1 and TS-1 zeolite supported molybdenum catalysts." *Front. Chem. Sci. Eng.*, 19, 74–. <https://doi.org/10.1007/S11705-025-2584-8>
- Zhao, S., Niu, S., Yu, H., Ning, Y., Zhang, X., Li, X., Zhang, Y., Lu, C., and Han, K., 2019. "Experimental investigation on biodiesel production through transesterification promoted by the La-dolomite catalyst." *Fuel*, 257, 116092. <https://doi.org/10.1016/J.FUEL.2019.116092>
-