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Synthesis and Application of CaO-MgO Catalyst from Dolomite for Biodiesel Production

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Abstract

Dependence on dwindling fossil fuels drives the development of biodiesel as a renewable alternative energy. However, the use of homogeneous catalysts, which are difficult to separate, non-reusable, and generate waste, remains a major obstacle. This review aims to examine the potential of dolomite-based heterogeneous catalysts (CaO–MgO) as a more sustainable solution. These catalysts are synthesized through the calcination of dolomite an abundant carbonate mineral with main components of $CaCO_3$ and $MgCO_3$ and can be modified by adding Fe_2O_3, Fe_3O_4, SiO_2, or Na doping to enhance catalytic activity, surface area, and bifunctional properties. Various vegetable oil feedstocks such as Crude Palm Oil (CPO), used cooking oil, tamanu oil, and canola oil have been successfully converted into biodiesel via transesterification (and simultaneous esterification-transesterification) using these catalysts, yielding biodiesel >90% with quality that meets national and international standards. Thus, the synthesis of CaO–MgO catalysts from dolomite promises an effective, economical, and environmentally friendly application for large-scale biodiesel production.

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INTRODUCTION

Energy, an absolute necessity as the driving force for facilities and infrastructure supporting human life, is still largely generated from fossil fuels, which are limited, non-renewable, and less environmentally friendly. The current supply of fossil fuels is lower than the high demand (85%), leading to an increase in fossil fuel imports due to growth in the industrial sector and population in Indonesia (Khatibi et al., 2021).

Indonesia's final energy consumption in 2022 was recorded at 1.18 billion barrels of oil equivalent (BOE), an increase of 28.31% compared to the previous year, 2021, which was 924.19 million BOE. The largest energy consumption came from fossil-based oil fuels, amounting to 477.82 million BOE. According to the International Energy Agency (IEA), 81.7% of global energy consumption comes from fossil fuels, and energy demand is projected to increase by 53% by the end of 2030 to meet energy needs (Khalit et al., 2020). With continuously increasing demand amid depleting fossil energy reserves, it must be immediately balanced with the provision of renewable alternative energy such as biofuels, including bioethanol, biogas, biodiesel, and others (Mansir et al., 2018; Afsharizadeh & Mohsennia, 2019).

Biodiesel is one of the best alternative energies because it is clean, renewable, biodegradable, environmentally friendly, non-toxic, and can be produced from various renewable sources (Pandit & Fulekar, 2017). Additionally, it can reduce carbon monoxide emissions by about 50% and carbon dioxide emissions by up to 78%, has low sulfur content, a high flash point, and is easily degradable (Ramos et al., 2019). Biodiesel is generally produced through a transesterification reaction between triglycerides found in fatty acids such as vegetable oils, animal fats, or waste containing fatty acids, with short-chain alcohols like methanol, using a catalyst (Hadiyanto et al., 2020; Dharma et al., 2016).

Vegetable oils or animal fats contain triglycerides and fatty acids as their constituent components, making them suitable as raw materials for biodiesel, which is biodegradable, non-toxic, and sulfur-free. These advantages can be applied in engines with consideration of certain requirements such as viscosity and density. High viscosity and density can lead to poor fuel atomization and increased combustion delay, while cetane number is also an important indicator for the performance and characterization of fuel in diesel engines (Dey et al., 2021).

Variations in parameters such as alcohol-to-oil ratio, reaction time, reaction temperature, catalyst concentration, agitation speed, and free fatty acid (FFA) content also affect the quality of the final biodiesel product. Several steps that can be taken to produce biodiesel with optimum conversion include pre-treatment such as degumming to reduce gum or resin content from crude palm oil (Serrano-Bermúdez et al., 2021), esterification to reduce FFA content (Hadiyanto et al., 2020; Tran et al., 2019), as well as purification and water removal processes (Velez et al., 2019). Many researchers suggest that the free fatty acid content in vegetable oils to be transesterified should have an acid value of $<0.5\%$, and all materials must be free of water because water can react with the catalyst, reducing the catalyst amount.

In biodiesel production from vegetable oil or animal fat raw materials, a catalyst is required to accelerate the transesterification reaction. A good catalyst material for the transesterification reaction should be easily separable from the product, non-corrosive, and stable against deactivation or further reactions (Li et al., 2013; Hwa et al., 2017). The catalysts commonly used are acidic or basic catalysts, which can be in liquid (homogeneous) or solid (heterogeneous) phases. Heterogeneous catalysts are currently being developed because their use facilitates easier catalyst separation compared to homogeneous catalysts. Heterogeneous catalysts, especially those based on biomass and nano materials, offer more environmentally friendly, cost-effective, and reusable future solutions compared to conventional homogeneous catalysts (Changmai et al., 2020). Homogeneous catalysts provide high conversion but are difficult to separate, while heterogeneous catalysts are more environmentally friendly, though their activity is lower (Budiman and Samik, 2023; Wahyudin et al., 2018).

Several researchers have developed these solid-phase catalysts, such as calcium oxide (CaO) catalysts from various types of seafood shells or magnesium oxide (MgO) catalysts from various materials. However, these catalysts are still applied separately, meaning CaO alone and MgO alone. It is known that the use of these solid-phase catalysts provides high biodiesel conversion, reaching up to 99%. Therefore, the synthesis of CaO and MgO catalysts as a unified, interconnected material is conducted to enhance application effectiveness. To produce solid-phase CaO and MgO catalysts that are bound together, dolomite is chosen as the raw material because it is a material with the chemical formula $CaMg(CO_3)_2$ (Suprapto et al., 2016). Dolomite availability in Indonesia is abundant, and its economic value is relatively low, making it necessary to develop dolomite into products with higher economic value (Hwa et al., 2017).

The selection of dolomite-based CaO–MgO catalysts as the focus of this review is driven by the urgent need for sustainable and economically viable solutions in biodiesel production. While biodiesel offers a renewable alternative to fossil fuels, the widespread use of conventional homogeneous catalysts is hampered by their non-reusability, difficult separation, and significant chemical waste generation. Dolomite, an abundant and low-cost natural mineral composed of $CaCO_3$ and $MgCO_3$, presents a highly promising alternative. Upon calcination, it yields a heterogeneous CaO–MgO catalyst system that not only exhibits high activity and stability in transesterification reactions but also embodies the principles of green chemistry by utilizing a widely available resource. This review specifically addresses critical gaps in understanding by exploring how synthesis methods can be optimized, how effective and versatile these catalysts are across different feedstocks, and what challenges remain for their large-scale application. Therefore, the objective is to consolidate current research, evaluate performance, and outline a clear pathway for developing dolomite-based catalysts into practical, efficient, and sustainable tools for the future of biodiesel production.

METHOD

This research uses a qualitative descriptive approach to discuss the topic reviewed in this article. According to (Hanyfah et al., 2022), there are two techniques in the qualitative descriptive approach: field studies and literature studies. This research employs the literature study technique using the Systematic Literature Review (SLR) method to search for literature related to the topic under review.

The SLR begins by determining the problem to be discussed. The topic of this research is the potential synthesis of CaO-MgO catalysts based on dolomite and its application in the transesterification process in biodiesel production. The first step is to select relevant literature that discusses this topic within the specified limitations. The Publish or Perish (PoP) application assists in searching for journal literature related to this research. Once the literature has been collected, the next step is to search for details of other literature to obtain information on the subject being sought.

The first step is to select a theme for review. The theme "Potential synthesis of CaO-MgO catalysts based on dolomite and its application in the transesterification process in biodiesel production" is the research subject. The keywords "CaO-MgO catalyst" and "biodiesel production" were used to search for articles in Scopus and Google Scholar through the Publish or Perish (PoP) application. From 2015 to 2025, the number of articles was limited to 200 articles.

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) method was used to screen the collected articles. After initial screening, comparable articles (n=134) were found. Subsequently, articles that did not align with the research topic and articles that were in the form of final project reports, theses, or undergraduate theses were reduced to 45 articles. Next, from 32 articles, 4 were further excluded because their scope was not biodiesel production, leaving 28 articles. From these 28 articles, 22 articles were selected for detailed review, analysis, and in-depth examination, as they were relevant to the research theme. The following is a diagram of the stages carried out in conducting the literature study through PoP.

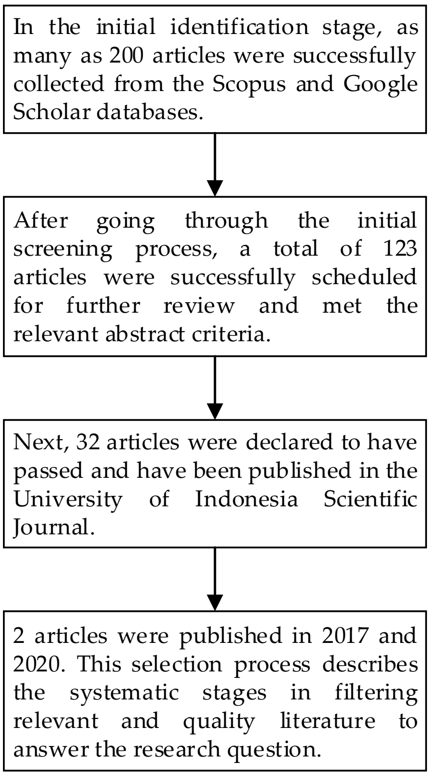

Figure 1. Flowchart of the Article Screening Process in the Systematic Literature Review Stage (n = number of articles). Source: (Hanyfah et al., 2022)

RESULTS AND DISCUSSION

Result

A filtering process using the Publish or Perish (PoP) application yielded 22 journal articles related to the potential synthesis of dolomite-based CaO-MgO catalysts and their application in the transesterification process for biodiesel production.

Table 1. Previous Research Related to Biodiesel Production

Author/ Year	Title	Objective	Results
Devi, Nurhayati & Linggawati (2015)	Biodiesel Production from CPO via Esterification with H_2SO_4 Catalyst and Transesterification with CaO Catalyst from Blood Clam Shells	To utilize CaO from waste blood clam shells as a transesterification catalyst for biodiesel after H_2SO_4 esterification	Biodiesel can be efficiently produced from CPO using esterification (H_2SO_4) and transesterification (CaO from blood clam shells) stages. The best conditions were obtained with an acid catalyst weight of 2 g, oil:methanol ratio of 1:24,

Author/ Year	Title	Objective	Results
			resulting in 67.41% biodiesel yield. The utilization of waste blood clam shells as a catalyst supports economic and environmental aspects in biodiesel production.
Ristianingsih, Hidayah and Sari (2015)	Making Biodiesel from Crude Palm Oil (CPO) as an Alternative Fuel through Direct Transesterification Process	To examine the effect of CPO:ethanol ratio (1:3–1:6) and NaOH catalyst weight (0.25–1%) on biodiesel yield and its physical properties.	Highest yield of 65.38% at a 1:3 ratio, 1% catalyst. Biodiesel met SNI standards for viscosity, pour point, density, but flash point was still low due to residual ethanol.
Abdulloh et al (2017)	Modification of Gresik's Dolomite to CaO•MgO Nanocomposite as a Catalyst for Synthesis of Biodiesel from Tamanu Oil	To prove that locally modified dolomite can become an effective CaO•MgO nano catalyst for biodiesel production from non-edible oil (tamanu oil)	Gresik dolomite was successfully modified into CaO•MgO nanocomposite via co-precipitation method. The catalyst has nano size (~53 nm), strong base, and high activity in transesterification of tamanu oil. Best conditions obtained at 65 °C, methanol:oil ratio 1:30, catalyst 1 g, for 5 hours → nearly 98% conversion. CaO•MgO catalyst is potential for biodiesel production, although further optimization is needed to suppress the influence of $Ca(OH)_2$.
Kusyanto and Hasmara (2017)	Utilization of Rice Husk Ash as a Heterogeneous Catalyst in Making Biodiesel from Palm Oil	To utilize calcined rice husk ash impregnated with KOH as a heterogeneous catalyst, and to determine the effect of catalyst mass variation on the conversion of palm oil into biodiesel and the quality of the produced biodiesel	Rice husk ash impregnated with KOH proved to function as a heterogeneous catalyst in making biodiesel from palm oil, with a yield of 67% and quality meeting biodiesel standards. Although the result is still limited, this research opens opportunities for utilizing rice husk waste as an environmentally friendly catalyst, and further optimization is suggested to increase yield to near 90%.
Hafiz, Helwani, Saputra (2017)	Synthesis of Solid Base Nanomagnetic CaO/Iron Powder Catalyst for Transesterification Reaction of Off Grade Palm Oil into Biodiesel	To synthesize a solid base nanomagnetic CaO/iron powder catalyst via impregnation method, and to study the effect of CaO:iron powder ratio and calcination temperature on catalyst characteristics and its performance in the transesterification reaction of off grade palm oil into biodiesel	The solid base nanomagnetic CaO/iron powder catalyst was successfully synthesized and showed high performance in the transesterification reaction of off grade palm oil. Optimum conditions were obtained at an 80:20 ratio and calcination temperature of 850°C, with a biodiesel yield of 81.32% and quality meeting SNI 7182:2015 standard.
Nugraha, Helwani, Saputra (2017)	Use of Fly Ash Catalyst Impregnated with CaO from $Ca(NO_3)_2$ in the Transesterification	To develop a CaO/fly ash catalyst to increase biodiesel yield from off-grade palm oil	The CaO/fly ash catalyst produced biodiesel according to SNI with an optimum yield of 61.72% at 60°C, 8:1 ratio, and

Author/ Year	Title	Objective	Results
	Stage of Off-grade Palm Oil into Biodiesel	and to find the optimum reaction conditions	catalyst concentration of 7%. The most dominant factor affecting yield is catalyst concentration. Utilizing fly ash effectively adds value to industrial waste while supporting environmentally friendly catalysts.
Rasouli & Esmaeili (2019)	Characterization of MgO nanocatalyst to produce biodiesel from goat fat using transesterification process	To prove that MgO nanocatalyst is highly effective for converting goat fat into high-quality biodiesel according to international standards	MgO nanocatalyst is effective for transesterification of goat fat with high yield (93%). Nano size (5.5 nm) and mesoporous properties enhance catalytic activity. Biodiesel–diesel blends (B75–B100) best fit international standards. Constraint: pure biodiesel has high pour & cloud points → not suitable in cold temperatures.
Widayat, Putra & Nursafitri (2019)	Preparation of α-Fe_2O_3–Al_2O_3 Catalysts and Catalytic Testing for Biodiesel Production	To synthesize and evaluate the performance of α-Fe_2O_3–Al_2O_3 catalysts derived from iron sand for biodiesel production from waste cooking oil	Hematite (α-Fe_2O_3) can be successfully synthesized from iron sand via precipitation and calcination methods. α-Fe_2O_3 and α-Fe_2O_3–Al_2O_3 catalysts are effective for producing good quality biodiesel from waste cooking oil, with the best result obtained from pure α-Fe_2O_3 catalyst at a calcination temperature of 700 °C.
Murguía-Ortiz et al. (2021)	Na-CaO/MgO dolomites used as heterogeneous catalysts in canola oil transesterification for biodiesel production	To prove that Na-doped dolomite can be an effective and economical heterogeneous catalyst for biodiesel production, with high conversion and potential for industrial application	Mexican dolomite can be modified into Na-CaO/MgO as an efficient heterogeneous catalyst for biodiesel production from canola oil. Na addition enhances basic properties and biodiesel conversion. This catalyst offers economic potential due to reusability, although further research is still needed for reusability optimization.
Febriana (2022)	Utilization of Madura Limestone as a Catalyst in Making Biodiesel from Nyamplung Oil	To utilize limestone from Pamekasan, Madura, as a source of CaO catalyst for the transesterification reaction of nyamplung oil (Calophyllum inophyllum) into biodiesel, while studying the characteristics of the catalyst resulting from high-temperature calcination using XRD, FTIR, and SEM-EDX methods and evaluating biodiesel results with GC-MS	Research results show that calcining limestone at 900°C produces CaO with crystal characteristics according to XRD, although not yet pure due to the formation of $Ca(OH)_2$ and $CaCO_3$ from air exposure. SEM-EDX analysis showed solid morphology resembling blocks and prisms with particle sizes around 10 µm. Transesterification reaction of nyamplung oil with 4% CaO catalyst at 60°C and methanol:oil ratio of 16:1 for 1 hour produced a biodiesel yield of 54% and conversion of 49%, proving the

Author/ Year	Title	Objective	Results
			potential of local Madura limestone as a cheap heterogeneous catalyst for biodiesel production.
Saleh (2022)	Making Biodiesel from Crude Palm Oil (CPO) Conducted via Esterification and Transesterification Stages	To produce biodiesel from CPO through esterification (H_2SO_4) to reduce FFA, followed by transesterification (KOH)	Biodiesel from CPO can be effectively produced through two reaction stages (esterification–transesterification). Test results show the produced biodiesel has density, viscosity, and water content that meet national standards, making it suitable as an alternative fuel.
Widayat et al (2023)	Preparation of MgO-CaO/SiO_2 Catalyst from Dolomite and Geothermal Solid Waste for Biodiesel Production	To develop a heterogeneous catalyst based on MgO-CaO/SiO_2 made from dolomite and geothermal solid waste for biodiesel production from waste cooking oil.	The MgO-CaO/SiO_2 catalyst from dolomite and geothermal waste can improve the quality and yield of biodiesel from waste cooking oil. Subsequent research is suggested to explore catalyst acidity/basicity characterization and reaction kinetics.
Cantika, Zulfikar & Rusli (2023)	Synthesis of Ethylenediamine Modified Chitosan Beads for Biodiesel Production Catalyst: A Preliminary Study	To develop a heterogeneous catalyst based on chitosan (CS) modified with ethylenediamine (EDA) and epichlorohydrin (ECH) for the transesterification reaction of palm oil into biodiesel, and to evaluate the performance and reusability of the catalyst.	The CS/ECH/EDA catalyst was successfully synthesized, is stable, environmentally friendly, reusable, and shows great potential as a heterogeneous catalyst for palm oil-based biodiesel production.
Anindita, Permana, & Said (2023)	Synthesis and Characterization of CaO/K_2O Catalyst from Limestone for Biodiesel Production	To synthesize and characterize a heterogeneous CaO/K_2O catalyst from limestone via KOH impregnation method, and to test its performance in the transesterification reaction of waste cooking oil into biodiesel.	The CaO/K_2O catalyst was successfully synthesized from limestone via KOH impregnation method. This catalyst has high basicity, porous morphology, and good crystallinity. Activity tests show a significant increase in biodiesel yield (65.2%) compared to pure CaO, so the CaO/K_2O catalyst has potential for use in environmentally friendly biodiesel production from waste cooking oil.
Rachmadona et al (2023)	Biodiesel Production from Crude Palm Oil (CPO) using Lipase and Low-Concentration Ethanol	To use immobilized Thermomyces lanuginosus lipase as a transesterification catalyst for CPO with low-concentration ethanol.	The enzymatic transesterification method using immobilized lipase and low-concentration ethanol successfully produced biodiesel from CPO with a fairly good yield. Improving parameters such as increasing ethanol concentration can increase conversion and reduce hydrolysis interference, making this process more efficient and environmentally friendly.

Author/ Year	Title	Objective	Results
Mulyadi, Meidinariasty, & Taufik (2023)	Making Biodiesel from Off Grade CPO Using KOH Catalyst with Microwave Radiation Method	To accelerate the production of biodiesel from off grade CPO using KOH and microwave heating.	Microwave radiation with KOH catalyst can accelerate biodiesel production from off grade CPO. Process parameters (methanol ratio and reaction time) significantly affect yield and biodiesel quality. The produced biodiesel quality generally meets SNI standards, specifically density, flash point, and acid number; however, viscosity and water content need improvement with purification optimization.
Widayat et al (2024)	Preparation $CaO/MgO/Fe_3O_4$ Magnetite Catalyst and Catalytic Test for Biodiesel Production	To research the synthesis and testing of $CaO/MgO/Fe_3O_4$ nanomagnetic catalyst made from dolomite and iron sand for producing biodiesel from waste cooking oil.	The $CaO/MgO/Fe_3O_4$ nanomagnetic catalyst is effective and sustainable for biodiesel production from waste cooking oil. The combination of natural waste materials (dolomite and iron sand) offers an environmentally friendly approach to waste management while producing clean fuel.
Widayat et al (2024)	Synthesis, Characterization and Testing of $CaO-MgO/Fe_2O_3$ Catalyst from Dolomite and Iron Sand for Making Biodiesel from Used Cooking Oil	To develop and test a heterogeneous $CaO-MgO/Fe_2O_3$ catalyst made from dolomite and iron sand, to see its characteristics and performance in producing biodiesel from used cooking oil.	The $CaO-MgO/Fe_2O_3$ catalyst was successfully synthesized from dolomite and iron sand, functioning well as a bifunctional catalyst (basic side from CaO-MgO for transesterification, acidic side from Fe_2O_3 for esterification). Optimal combination (3:1 ratio, calcination temperature 900°C) produced biodiesel with quality according to national standards.
Buchori (2025)	Biodiesel Production Using Simultaneous Esterification–Transesterification Method from Waste Cooking Oil with CaO/Fe_2O_3 Bifunctional Catalyst	To produce biodiesel from waste cooking oil using a simultaneous esterification–transesterification method with a CaO/Fe_2O_3 bifunctional catalyst from eggshells & Fe_2O_3.	The CaO/Fe_2O_3 bifunctional catalyst from waste eggshells is effective for biodiesel production from WCO using the simultaneous esterification–transesterification method. Best conditions were obtained at catalyst calcination 800 °C and reaction time 4 hours, producing biodiesel quality according to SNI and supporting the utilization of waste into renewable energy.
Nurdianty, Usman, Rahmalia (2025)	Determination of Optimum Conditions for Biodiesel Synthesis from Bulk Palm Oil Using Red Mud-CaO Catalyst	To determine the optimum conditions for biodiesel synthesis from bulk palm oil using a red mud-CaO heterogeneous catalyst, by examining the effect of red mud:CaO ratio, catalyst percentage, and reaction time on methyl ester conversion,	This research proves that the red mud-CaO catalyst can be used effectively for biodiesel synthesis from bulk palm oil, with optimum conditions at a 1:1 ratio, 5% catalyst, and 2 hours reaction time. The biodiesel product is rich in methyl oleate and methyl palmitate, and catalyst quality is

Author/ Year	Title	Objective	Results
		while characterizing the resulting catalyst with XRD, XRF, FTIR, and GC-MS.	supported by XRD, XRF, and FTIR analysis results, so the utilization of red mud and clay bath waste has the potential to be an environmentally friendly solution for biodiesel production.
Eldwita, Octhaviana, and Rusdianasari (2025)	Production of Biodiesel from Sunflower Oil using Base Catalysts	To study biodiesel production from sunflower oil using base catalysts by highlighting the effect of catalyst amount, temperature, reaction time, stirring speed, and molar ratio of methanol to oil.	Results show that optimum conditions were obtained at a 6:1 molar ratio, 1% catalyst concentration, and 60 °C temperature with rapid stirring, producing biodiesel with high yield; while microwave use did not always significantly increase yield. Overall, sunflower oil proves potential as an environmentally friendly biodiesel feedstock with high efficiency under proper operating conditions.

Research on biodiesel production has been extensively conducted using various catalysts, both domestically and internationally, to explore the synthesis of CaO-MgO catalysts based on dolomite and their application in transesterification. Early studies such as Devi, Nurhayati & Linggawati (2015) demonstrated the potential of CaO catalysts derived from blood clam shell waste, achieving a biodiesel yield of 67.41% and highlighting the economic and environmental advantages of heterogeneous catalysts. In the same year, research by Ristianingsih et al. (2015) using a NaOH catalyst only reached a yield of 65.38% and faced challenges with low flash point.

Significant progress occurred in 2017, when Abdulloh et al. successfully modified Gresik dolomite into a CaO•MgO nanocomposite with nearly 98% conversion, while Hafiz et al. and Nugraha et al. developed nanomagnetic CaO/iron powder (yield 81.32%) and CaO/fly ash (yield 61.72%) catalysts, respectively. Kusyanto & Hasmara (2017) also utilized rice husk ash with a yield of 67%, opening opportunities for agricultural waste utilization. Collectively, these studies reveal that CaO-based catalysts, especially when combined with MgO or supporting materials, offer high catalytic activity, ease of separation, recycling potential, thereby forming an important foundation for more economical dolomite-based catalysts development.

Research advancements have continued with increasingly diverse catalyst and feedstock exploration. In 2019, Rasouli & Esmaeili demonstrated the effectiveness of MgO nanocatalysts with a 93% yield for goat fat, despite challenges in cold temperatures, while Widayat et al. (2019) successfully synthesized α-Fe_2O_3 catalysts from iron sand. The trend of catalyst modification and combination strengthened further, as shown by Widayat et al. (2023, 2024) with MgO-CaO/SiO_2 catalysts from dolomite and geothermal waste (yield 92.63%) and nanomagnetic CaO/MgO/Fe_3O_4 catalysts.

Murguía-Ortiz et al. (2021) reinforced the potential of Na-doped dolomite as an effective and reusable catalyst. Meanwhile, research using CPO feedstock also expanded, encompassing chitosan-based catalysts (Cantika et al., 2023), lipase enzymes (Rachmadona et al., 2023), and microwave heating (Mulyadi et al., 2023).

Recent studies such as Buchori (2025) and Nurdianty et al. (2025) continue to optimize bifunctional catalysts and waste utilization, while Eldwita et al. (2025) evaluated sunflower oil. The synthesis of these various studies highlights that dolomite-based (CaO-MgO) catalysts offer competitive advantages including local raw material availability, high performance, and a sustainable approach compared to many alternatives, while simultaneously identifying gaps for further optimization.

Table 2. Summary of Previous Research Related to Biodiesel Production

Author	Catalyst	Vegetable Oil	Yield	Complies with SNI
Devi, Nurhayati & Linggawati (2015)	CaO (blood clam shells) + H_2SO_4	CPO	67.41%	Yes
Ristianingsih, Hidayah & Sari (2015)	NaOH	CPO	65.38%	Partial (low flash point)
Midiyarti, Nurhayati & Muhdarina (2016)	CaO (blood clam shells)	Waste cooking oil	Not specified	Yes
Abdulloh et al. (2017)	CaO•MgO nanocomposite (dolomite)	Tamanu oil	~98% (conversion)	Unclear
Kusyanto & Hasmara (2017)	CaO/rice husk ash + KOH	Palm oil	67%	Yes
Hafiz, Helwani & Saputra (2017)	Nanomagnetic CaO/iron powder	Off-grade CPO	81.32%	Yes
Nugraha, Helwani & Saputra (2017)	CaO/fly ash	Off-grade CPO	61.72%	Yes
Rasouli & Esmaeili (2019)	MgO nanocatalyst	Goat fat	93%	Yes (international)
Widayat et al. (2019)	α-Fe_2O_3, α-Fe_2O_3–Al_2O_3	Waste cooking oil	86.78%	Yes
Murguía-Ortiz et al. (2021)	Na–CaO/MgO (dolomite)	Canola oil	High (not detailed)	Yes
Febrina (2022)	CaO (Madura limestone)	Calophyllum inophyllum oil	54% (conversion 49%)	Unclear
Saleh (2022)	H_2SO_4 + KOH	CPO	Not specified	Yes
Widayat et al. (2023)	MgO–CaO/SiO_2 (dolomite + geothermal waste)	Waste cooking oil	92.63%	Yes
Cantika, Zulfikar & Rusli (2023)	Chitosan/EDA/ECH	CPO	Not specified	Yes
Anindita, Permana & Said (2023)	CaO/K_2O (limestone)	Waste cooking oil	65.2%	Yes
Rachmadona et al. (2023)	Lipase (enzymatic)	CPO	61.67%	Yes
Mulyadi, Meidinariasty & Taufik (2023)	KOH + microwave	Off-grade CPO	Not specified	Partial (SNI, but viscosity & water content not met)
Widayat et al. (2024a)	CaO/MgO/Fe_3O_4 nanomagnetic	Waste cooking oil	86.78–92.63%	Yes
Widayat et al. (2024b)	CaO–MgO/Fe_2O_3 (dolomite + iron sand)	Waste cooking oil	54.25%	Yes
Buchori (2025)	CaO/Fe_2O_3 (eggshells)	Waste cooking oil	82%	Yes
Nurdianty, Usman & Rahmalia (2025)	Red mud–CaO	Bulk palm oil	100% (full conversion)	Yes
Eldwita, Octhaviana & Rusdianasari (2025)	Base catalyst (unspecified)	Sunflower oil	High (not detailed)	Yes

Based on the summary of various studies, biodiesel has been successfully produced using diverse types of catalysts and feedstocks from both vegetable oils and animal fats. Homogeneous catalysts such as NaOH, KOH, and H_2SO_4 can produce biodiesel with a fairly good yield, but they have limitations in terms of separation, reusability, and environmental impact. Conversely, heterogeneous catalysts based on CaO, MgO, and modifications using dolomite, fly ash, rice husk ash, and even nanomagnetic materials, demonstrate superior performance with high yields, quality meeting SNI standards, as well as economic and sustainability benefits due to their reusability and utilization of natural waste.

Specifically, CaO–MgO catalysts from dolomite have proven to be promising as they provide high conversion (up to >90% under optimum conditions), are environmentally friendly, and are supported by the abundant availability of mineral raw materials in Indonesia. Considering the potential of CPO as a strategic national biodiesel feedstock, the application of CaO–MgO catalysts offers significant prospects for sustainable biodiesel production in the future, while also supporting the achievement of renewable energy targets and reducing dependence on fossil fuels.

Discussion

The comprehensive analysis of previous research underscores a significant paradigm shift in biodiesel catalysis, moving from conventional homogeneous systems toward advanced heterogeneous catalysts, with dolomite-derived CaO-MgO composites emerging as a particularly promising frontier (Eldwita, Octhaviana & Rusdianasari, 2025). Homogeneous catalysts like NaOH and H_2SO_4, while achieving moderate yields (65.38% for NaOH), are fundamentally limited by their corrosiveness, difficult separation, generation of chemical waste, and inability to be reused, which inflates both economic and environmental costs. In stark contrast, the reviewed studies demonstrate that heterogeneous catalysts, especially those based on CaO and its composites, address critical short-comings (Nurdianty, Usman & Rahmalia, 2025).

The foundational work on CaO from waste sources like blood clam shells (67.41% yield) established the potential for waste-to-value conversion. However, the true catalytic breakthrough is exemplified by the modification of natural dolomite into advanced nanomaterials. For instance, Abdulloh et al. (2017) achieved near-complete conversion (~98%) using a CaO•MgO nanocomposite, highlighting the synergistic effect when these two basic oxides are combined at the nanoscale.

This synergy enhances active site density, surface area, and stability. The subsequent development of magnetically separable catalysts (e.g., CaO/iron powder, 81.32% yield) and waste-supported systems (e.g., CaO/fly ash, CaO/rice husk ash) further embeds the principles of the circular economy into catalyst design, transforming industrial and agricultural byproducts into valuable catalytic materials. Thus, the evolution from simple CaO to engineered dolomite-based nanocomposites represents a critical advancement, offering a pathway to catalysts that are not only highly active and selective but also separable, reusable, and derived from abundant, low-cost mineral and waste resources (Nugraha, Helwani & Saputra, 2017).

Delving deeper into the mechanistic and applied promise, dolomite-based CaO-MgO catalysts exhibit superior performance due to their intrinsic strong basicity, thermal stability post-calcination (800–1000 °C), and the bifunctionality achieved through strategic modifications. The high yield of biodiesel from various feedstocks—93% for goat fat using MgO nanocatalysts, 92.63% for waste cooking oil using MgO-CaO/SiO_2, and 82% for simultaneous esterification-transesterification using a CaO/Fe_2O_3 bifunctional catalyst, validates their versatility and efficiency.

The incorporation of dopants (e.g., Na in Murguía-Ortiz et al., 2021) or secondary phases (e.g., Fe_2O_3, SiO_2) creates bifunctional or supported catalysts that can simultaneously tackle esterification of free fatty acids and transesterification of triglycerides, crucial for processing low-grade feedstocks like waste cooking oil or off-grade CPO. This addresses a major industrial hurdle.

For Indonesia, where CPO is a strategic commodity and dolomite reserves are abundant, this catalyst system presents a uniquely synergistic solution for sustainable biodiesel production. It aligns national resource wealth with advanced material science, potentially reducing reliance on imported catalysts and fossil fuels. However, the transition to industrial scale requires focused research on long-term catalyst reusability, regeneration protocols, and precise optimization of reaction parameters for largevolume continuous processes. By mastering these aspects, dolomite-based CaO-MgO catalysts can evolve from a high-performance laboratory material into a cornerstone technology for a circular, low-carbon bioeconomy, directly supporting national energy security and decarbonization goals.

CONCLUSION

This review consolidates critical research to demonstrate the significant potential of dolomite-derived CaO–MgO catalysts in advancing sustainable biodiesel production. By systematically analyzing their effectiveness across various feedstocks, the study provides a compelling case for shifting from conventional homogeneous catalysts to this more sustainable heterogeneous alternative. The primary impact lies in its contribution to developing a cost-effective, environmentally friendly, and industrially scalable catalyst technology. Utilizing an abundant natural mineral like dolomite directly addresses economic and waste-management challenges, thereby supporting national energy independence and renewable energy targets, particularly in palm oil-producing regions like Indonesia.

The novel insight from this review is the identification of dolomite not merely as a source of CaO, but as a unique precursor for a synergistic CaO–MgO composite with inherent advantages. The calcination process unlocks strong basicity and thermal stability, while strategic modifications (e.g., with Fe_2O_3 or SiO_2) introduce enhanced bifunctionality and surface properties not found in single-oxide catalysts. This positions the modified dolomite-based catalyst as a versatile and superior material capable of efficiently processing diverse and low-cost feedstocks, including high free-fatty-acid oils. The conclusion underscores that the future novelty lies in optimizing this integrated system for industrial-scale application, focusing on improving reusability, reaction kinetics, and process intensification to bridge the gap between laboratory success and commercial implementation.

RECOMMENDATION

To harness the full potential of dolomite-derived CaO-MgO catalysts for sustainable biodiesel production in Indonesia, future efforts should adopt a holistic and systematic research and development framework. It is imperative to conduct rigorous optimization studies focusing on key reaction parameters, such as methanol-to-oil molar ratio, catalyst loading, reaction temperature, and duration, specific to Indonesian CPO and its derivatives, to establish standardized and efficient operational protocols. Concurrently, research must prioritize enhancing the catalyst's longevity and reusability by investigating its stability over multiple cycles, developing effective regeneration methods, and engineering its physicochemical properties, such as porosity and mechanical strength, to withstand industrial process conditions. A concerted transition from laboratory-scale batch processes to continuous pilot-scale systems is essential to validate economic feasibility, assess environmental impacts via life-cycle analysis, and identify integration pathways within existing refinery infrastructure. This should be supported by collaborative partnerships among academia, industry, and government to align technical development with supportive policies, incentive mechanisms, and national renewable energy targets, thereby transforming this catalytic innovation into a cornerstone of Indonesia’s energy independence and low-carbon future.

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