Al-Kimia, 14-1-2026, 37-48
Available online at: http://journal.uin-alauddin.ac.id/index.php/al-kimia

Ultrasonic-Assisted Synthesis of Methyl Ester Sulfonate (MES) from Coconut Oil via Transesterification and Sulfonation Using Eggshell-Derived CaO Catalyst

Indah Nur Pramesti*, Muhammad Arga Iqbal, Rini Retnosari, Laurent Octaviana

Department of Chemistry, Faculty of Mathematics and Natural Sciences, Universitas Negeri Malang, Indonesia

Corresponding Author: indahnur.pramesti.fmipa@um.ac.id

Received: November, 11, 2025/Accepted: May, 22, 2026
doi:10.24252/al-kimia.v14i1.62602

Abstract: *The extensive use of commercial detergents containing Alkylbenzene Sulfonate (ABS) and Linear Alkylbenzene Sulfonate (LAS) has led to environmental concerns due to their poor biodegradability. This study aims to develop an environmentally friendly surfactant, Methyl Ester Sulfonate (MES), synthesized from coconut oil as a renewable feedstock using CaO catalyst derived from eggshell waste. The synthesis involved transesterification of coconut oil followed by sulfonation using $NaHSO_3$, conducted under both conventional and ultrasonic-assisted conditions. The CaO catalyst was prepared via calcination at 800°C and characterized using XRD and XRF to confirm its phase composition. The ultrasonic-assisted method significantly enhanced the sulfonation efficiency, producing the highest MES yield of 74.28% at 50°C with 2% CaO catalyst. The obtained MES exhibited a density of 0.854 g/mL, viscosity of 2.798 cSt, neutral pH, and surface tension reduction to 38.8 mN/m. FT-IR analysis confirmed the successful introduction of sulfonate groups into the methyl ester structure. These findings demonstrate that coconut oil-based MES synthesized using eggshell-derived CaO catalyst has strong potential as a sustainable and biodegradable surfactant for detergent formulations.*

Keyword: *CaO Catalyst, Coconut Oil, Green Surfactant, Methyl Ester Sulfonate, Ultrasonication*

INTRODUCTION

The global detergent industry has experienced rapid growth over the past decade. According to Precedence Research (2025), the global detergent chemicals market is projected to reach USD 157.83 billion by 2034, up from USD 68.53 billion in 2024, with a compound annual growth rate of 8.7%. This expansion is largely driven by increasing consumer purchasing power and lifestyle changes. However, most commercial detergents still rely on petroleum-based surfactants such as Alkylbenzene Sulfonate (ABS) and Linear Alkylbenzene Sulfonate (LAS), which are resistant to biodegradation and toxic to aquatic organisms, leading to serious environmental issues (Cowan-Ellsberry et al., 2014; Morrow & Piwoni, 1993).

Growing environmental awareness and stricter regulatory standards have encouraged the development of eco-friendly and biodegradable surfactants. Among these, Methyl Ester Sulfonate (MES) has gained considerable attention as a promising alternative to LAS. MES demonstrates excellent detergency, high washing performance even in hard water, and better biodegradability (Lim et al., 2019). The production of MES commonly utilizes renewable raw materials such as vegetable oils, which offer advantages in renewability, biodegradability, and lower carbon footprint compared to petrochemical sources (Tooy et al., 2025). Coconut oil, in particular, is a suitable feedstock due to its high lauric acid (C12:0)

content (45–53%), which contributes to superior foaming and cleaning properties (Suryani et al., 2020).

Catalyst selection plays a crucial role in the transesterification and sulfonation processes that govern MES synthesis. Conventional homogeneous catalysts such as NaOH and KOH provide high yields but are difficult to separate from the reaction mixture and cannot be reused. In contrast, heterogeneous catalysts such as calcium oxide (CaO) offer easier recovery and reusability (Boey et al., 2011). Eggshell waste, which contains over 94% calcium carbonate ($CaCO_3$), is an inexpensive and abundant source for CaO production via calcination (Oko & Feri, 2019). The use of eggshell-derived CaO aligns with the principles of green chemistry by transforming biowaste into a value-added catalyst while minimizing environmental impact.

Traditionally, the sulfonation of methyl esters requires prolonged heating under reflux, resulting in high energy consumption and extended reaction time. Ultrasonication has emerged as an effective alternative technique that enhances reaction rates through acoustic cavitation, generating localized hot spots with high temperature and pressure (Pasawan et al., 2022). This phenomenon improves mass transfer, accelerates reaction kinetics, and can significantly increase MES conversion. Previous studies have shown that ultrasonic-assisted sulfonation can enhance both yield and product quality, while simultaneously reducing energy consumption (Amaliah et al., 2021).

Building upon these insights, this study aims to synthesize Methyl Ester Sulfonate (MES) from coconut oil using CaO catalyst derived from eggshell waste through transesterification and sulfonation reactions under both conventional and ultrasonic-assisted conditions. The effects of reaction temperature and catalyst concentration on MES conversion were evaluated to determine the optimal synthesis parameters. This work provides a sustainable approach to surfactant production by integrating waste-derived catalysts and energy-efficient processing, contributing to the advancement of green chemistry and circular economy principles.

RESEARCH METHODS

Materials and Tools

The materials used in this study included coconut oil, sodium bisulfite ($NaHSO_3$, p.a., Merck), eggshell waste collected from Malang, distilled water, methanol (p.a., Smartlab), technical methanol, ethanol, sodium hydroxide (NaOH), 0.1 N potassium hydroxide (KOH), phenolphthalein (PP) indicator, thin-layer chromatography (TLC) plates, xylene, dichloromethane, ethyl acetate, and 10% sulfuric acid (H_2SO_4). All chemicals were of analytical or technical grade and used as received without further purification. The instruments used included X-Ray Diffraction (XRD, PANalytical), X-Ray Fluorescence (XRF, PANalytical), Fourier Transform Infrared (FT-IR) Spectroscopy (Shimadzu 8400S) and Gas Chromatography–Mass Spectrometry (GC–MS, Shimadzu QP2010 Plus).

Methods

Synthesis and Characterization of Calcium Oxide (CaO) Catalyst

Eggshell waste (approximately 1 kg) was thoroughly washed with distilled water to remove adhering impurities and the inner membrane. The cleaned shells were then dried at 105 °C for 3 hours, ground into fine powder, and sieved through a 100-mesh screen. The obtained powder was calcined in a muffle furnace at 800 °C for 3 hours to convert calcium carbonate ($CaCO_3$) into calcium oxide (CaO). The resulting catalyst was characterized using

XRF to determine its elemental composition and XRD to confirm the crystalline phases of CaO.

Synthesis of Methyl Ester (ME) from Coconut Oil via Transesterification Reaction

The transesterification process was carried out following the method described by Yohanes et al. (2022) with slight modifications (Yohanes Setyawan et al., n.d.). Initially, coconut oil and methanol were mixed at a molar ratio of 1:10, corresponding to 94.72 mL of coconut oil and 35.55 mL of methanol, and stirred until homogeneous. Subsequently, 1 wt% potassium hydroxide (KOH) catalyst (1 g) was added to the mixture, and the reaction was performed under reflux conditions at 60°C for 4 hours with continuous stirring using a magnetic stirrer.

After the reaction was complete, the mixture was allowed to settle, and the two layers formed were separated. The upper ester layer (methyl ester) was collected and washed several times with 50 mL of warm distilled water (≈50°C) to remove residual catalyst and impurities. The washed methyl ester was then heated at 100°C to remove remaining moisture. To ensure complete water removal, a small amount of anhydrous $MgSO_4$ was added, followed by centrifugation at 3000 rpm for 30 minutes to separate residual solids. The purified methyl ester was subsequently characterized using GC-MS to determine the composition of fatty acid methyl esters.

Synthesis of Methyl Ester Sulfonate (MES) via Sulfonation Using CaO Catalyst

The methyl ester obtained from the transesterification process was further converted into Methyl Ester Sulfonate (MES) through a sulfonation reaction. The reaction was carried out between methyl ester and the sulfonating agent sodium bisulfite ($NaHSO_3$) with a molar ratio of 1:1.5, corresponding to 10 g of methyl ester and 6.35 g of $NaHSO_3$. Calcium oxide (CaO) derived from eggshell waste was used as a heterogeneous catalyst, with varying concentrations of 1 wt%, 1.5 wt%, and 2 wt% relative to the methyl ester mass. Two reaction methods were employed: conventional reflux, conducted at 90°C for 3 hours, and ultrasonic-assisted sulfonation, performed at 50°C and 60°C for 60 minutes using an ultrasonic bath with a frequency of 40 kHz (Amaliah et al., 2021).

After completion of the reaction, the mixture was transferred into a separatory funnel to allow phase separation. The upper layer containing the crude MES product was collected for purification. The purification process aimed to remove residual $NaHSO_3$ and catalyst by adding 40% methanol, followed by heating at 55°C with continuous stirring for 1.5 hours. Excess methanol was subsequently removed through evaporation. A neutralization step was then conducted to adjust the pH of MES by dropwise addition of 20% NaOH solution at 55°C, while stirring at 450 rpm until the mixture reached a neutral pH (Amaliah et al., 2021). The resulting MES was analyzed using Thin Layer Chromatography (TLC) with ME as a reference. A silica gel plate was used as the stationary phase, while a mixture of methanol, dichloromethane, and ethyl acetate (45:45:1 v/v) served as the mobile phase. The FT-IR Spectroscopy was used to confirm the incorporation of sulfonate functional groups into the methyl ester structure.

Physical Characterization of Methyl Ester Sulfonate (MES)

The physical properties of the synthesized Methyl Ester Sulfonate (MES) were evaluated, including density, viscosity, pH, surface tension, yield, and emulsion stability.

Density

The density of MES was measured using a 5 mL pycnometer. The pycnometer containing the sample was weighed with an analytical balance (accuracy 0.0001 g), and the density was calculated by dividing the sample mass by its volume:

$$\text{Density} = \frac{\text{Mass of pycnometer + sample} - \text{Mass of empty pycnometer}}{\text{Sample volume}}$$

Yield

The yield of MES was determined as the percentage of the actual mass of the product relative to the theoretical mass:

$$\%\text{Yield} = \frac{\text{Mass of synthesized MES}}{\text{Theoretical mass}} \times 100\%$$

pH

The pH of MES was measured using a universal pH indicator. A portion of MES sample was placed in a beaker, and the indicator was immersed to determine the pH value.

Surface Tension

Surface tension was measured using a Du Noüy tensiometer. MES solution was placed in a petri dish, and a platinum ring was immersed. The ring was slowly lifted from the surface, and the scale reading was recorded.

Viscosity

Viscosity measurements were conducted using an Ostwald viscometer. First, distilled water was tested to establish a reference flow time. Then, the MES sample was measured similarly. The dynamic viscosity (μ) was calculated using:

$$\frac{\mu_{\text{water}}}{\mu_{\text{sample}}} = \frac{\rho_{\text{water}} \cdot t_{\text{water}}}{\rho_{\text{sample}} \cdot t_{\text{sample}}}$$

Kinematic viscosity (ν) in centistokes (cSt) was obtained by dividing dynamic viscosity by sample density:

$$\nu = \frac{\mu}{\rho}$$

Emulsion Stability

Emulsion stability was tested by mixing xylene and water (6:4 v/v) with 1% surfactant. The mixture was shaken until homogeneous and then allowed to separate. The time taken for phase separation was recorded (Iman et al., 2016).

RESULTS AND DISCUSSION

Synthesis and Characterization of Calcium Oxide (CaO) Catalyst

Calcium oxide (CaO) was synthesized from chicken eggshell waste as a sustainable source of heterogeneous catalyst. Initially, 1 kg of eggshells was thoroughly washed with distilled water to remove adhering dirt and the inner membrane, followed by drying at 105°C for 12 hours to reduce moisture content. The dried eggshells were then ground into a fine powder using a mechanical grinder to achieve uniform particle size, ensuring a homogeneous calcination process. The calcination step was carried out in a muffle furnace at 800°C for 4

hours to thermally decompose calcium carbonate ($CaCO_3$) into CaO, releasing CO_2 gas. The resulting greyish powder, shown in Figure 1, served as the synthesized CaO catalyst.



Figure 1. The Synthesized CaO Catalyst

The synthesized CaO catalyst was characterized using XRD and XRF to determine the phase composition and chemical purity [46]. The XRD pattern (Figure 2) confirmed that CaO is the dominant crystalline phase, consistent with JCPDS card 154-7349. Minor residual $CaCO_3$ was observed, likely due to local temperature variations or incomplete calcination. This observation aligns with previous studies showing that calcination temperature and duration significantly affect CaO phase purity (Cheng et al., 2021; Dewi et al., 2023; Syarif et al., 2025). The purity of CaO is critical because residual carbonate can reduce the basicity and catalytic efficiency, affecting downstream reactions.

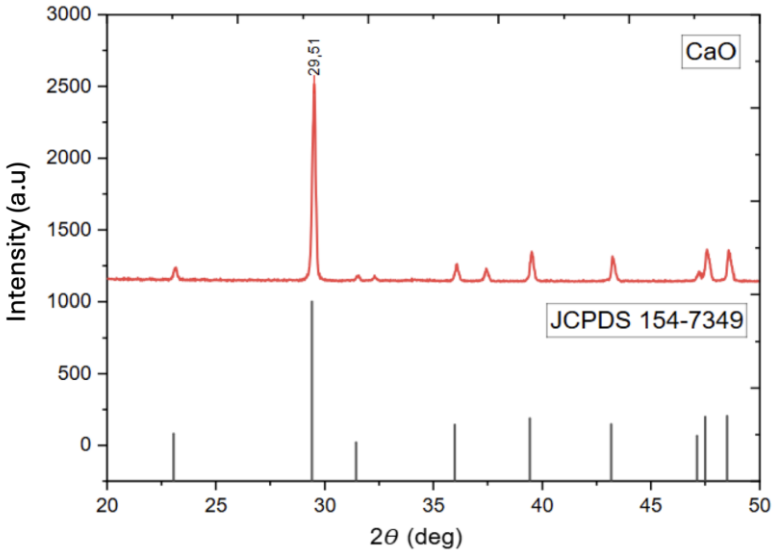


Figure 2. XRD Analysis of The Synthesized CaO Catalyst

X-ray fluorescence (XRF) analysis indicated that CaO accounted for 99.19% of the sample, with impurities such as Fe_2O_3, Co_3O_4, CuO, MoO_3, Er_2O_3, and Lu_2O_3 present in trace amounts (<1%) (Table 3). The high content of CaO suggests strong surface basicity, which is favourable for nucleophilic reactions like sulfonation. These results demonstrate that

eggshell-derived CaO is not only a high-purity, effective catalyst but also an environmentally friendly alternative to commercial CaO, offering valorization of biogenic waste in accordance with green chemistry principles (Dewi et al., 2023).

Table 1. XRF Oxida Composition of The Synthesized CaO Catalyst

Oxida	CaO	Fe_2O_3	Co_3O_4	CuO	MoO_3	Er_2O_3	Lu_2O_3
Concentration	99,19%	0,064%	0,063%	0,03%	0,41%	0,1%	0,13%

Synthesis of Methyl Ester (ME) from Coconut Oil via Transesterification Reaction

The transesterification of coconut oil to methyl ester (ME) was conducted under reflux using a basic catalyst (KOH). Methanol and the catalyst were pre-mixed before being introduced into the oil to facilitate the formation of methoxide ions (CH_3O^-), which act as nucleophiles attacking the carbonyl carbon of triglycerides. This reaction produces tetrahedral intermediates, subsequently forming diglycerides, monoglycerides, and finally methyl esters. The transesterification reaction is illustrated in Figure 3. The reaction efficiency was reflected in a high ME yield of 83.69%, indicating effective conversion of triglycerides into methyl ester.

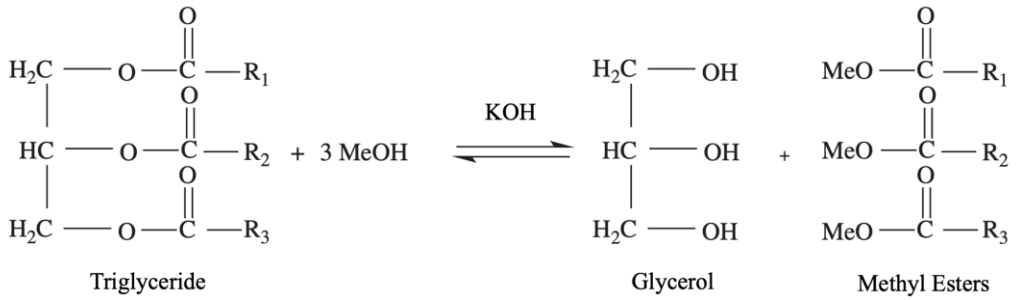


Figure 3. Transesterification Reaction

The composition of methyl esters (ME) was analyzed using GC–MS (Figure 4, Table 2). Methyl laurate (C12:0) was the major component (40.88%), followed by methyl myristate (C14:0, 21.10%) and methyl palmitate (C16:0, 10.71%). Minor saturated components included methyl caprylate (C8:0, 0.44%) and methyl caprate (C10:0, 8.40%), while unsaturated methyl esters such as methyl oleate (C18:1, 8.44%) and methyl linoleate (C18:2, 1.00%) were also detected. The predominance of medium-chain saturated fatty acids, particularly lauric acid, contributes to the oxidative stability and reactivity of the methyl ester product (Ecker et al., 2012; Makalalag et al., 2018).

Overall, the fatty acid profile of the synthesized ME demonstrates a composition suitable for further chemical modification, especially sulfonation to produce methyl ester sulfonate (MES). Approximately 83.16% of the methyl ester consisted of saturated fatty acids, while unsaturated fatty acids represented 9.44% of the total area. These compositional features confirm the high purity and quality of the ME product, establishing it as a reliable precursor for eco-friendly surfactant synthesis.

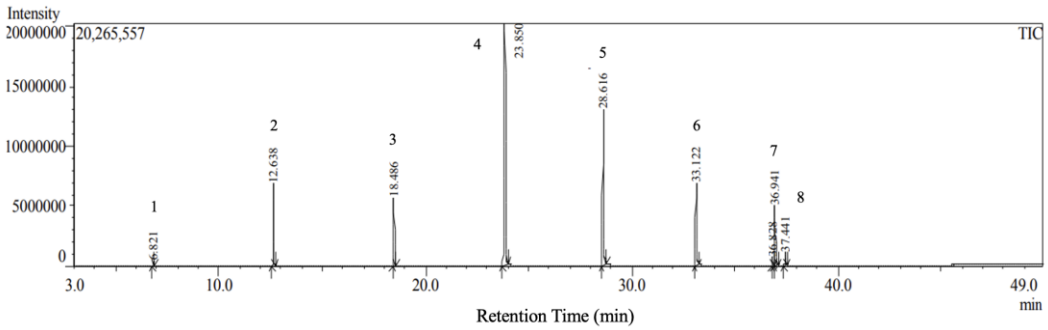


Figure 4. Chromatogram GC of Metil Ester from Coconut Oil

Tabel 2. GC-MS Analysis of Metil Ester from Coconut Oil

No. Peak	Retention Time (min)	Area (%)	[M⁺]	Compound Name
1	6.821	0.44	130	Methyl Caprylate (C8:0)
2	12.638	8.40	158	Methyl Caprate (C10:0)
3	23.850	40.88	214	Methyl Laurate (C12:0)
4	28.616	21.10	242	Methyl Myristate (C14:0)
5	33.122	10.71	270	Methyl Palmitate (C16:0)
6	36.828	1.00	294	Methyl Linoleate (C18:2)
7	36.941	8.44	296	Methyl Oleate (C18:1)
8	37.411	1.63	298	Methyl Stearate (C18:0)

Synthesis of Methyl Ester Sulfonate (MES) via Sulfonation Using CaO Catalyst

The conversion of methyl ester (ME) to methyl ester sulfonate (MES) was carried out using eggshell-derived CaO as a heterogeneous catalyst. Preliminary trials without a catalyst confirmed that sulfonation does not occur spontaneously, highlighting the necessity of catalysis. The sulfonation process was investigated under conventional reflux and ultrasonic-assisted conditions, with % conversion serving as a key metric to evaluate efficiency. The % conversion was calculated based on the ratio of the actual MES yield to the theoretical maximum yield.

The sulfonation reaction was carried out under both conventional reflux and ultrasonic-assisted conditions. In ultrasonic-assisted reactions, cavitation phenomena generate localized high temperature and pressure micro zones, which improve mass transfer, accelerate the diffusion of $NaHSO_3$ into the ME phase, and enhance contact between reactants. As shown in Table 3, the highest conversion (% conversion) of 74.28% was obtained at 50°C with 2% CaO catalyst under ultrasonication. Interestingly, increasing the reaction temperature to 60°C decreased conversion to 65.19%, likely due to side reactions such as ME degradation and formation of secondary products. These results indicate that excessive heat can reduce the overall efficiency of sulfonation, while moderate temperature combined with ultrasonication provides optimal reaction conditions (Penteado et al., 2018; Qadariyah et al., 2021; Yusuff et al., 2023).

Table 3. % Conversion of MES

Sulfonation Condition & Temperature	Catalyst Concentration (w/w %)	Conversion (%)
Conventional / Reflux (90°C/ 3 h)	1.0	66.20
	1.5	60.15
	2.0	67.12
Ultrasonication (50°C/ 1 h)	1.0	74.00
	1.5	71.91
	2.0	74.28
Ultrasonication (60°C/ 1 h)	1.0	57.81
	1.5	68.36
	2.0	65.19

The sulfonation involves nucleophilic substitution at the α-carbon (Cα) of the ester group, where the bisulfite ion (HSO_3^-) attacks the electrophilic carbon of the ester moiety (Figure 5). This reaction is facilitated by the inductive effect of the oxygen atom double bonded to the carbonyl carbon, which increases the electrophilicity of Cα. The addition of CaO provides basic surface sites that enhance HSO_3^- dissociation, strengthen nucleophilic attack, and minimize the formation of undesired free sulfonic acid by-products, thus increasing MES yield (Qadariyah et al., 2021).

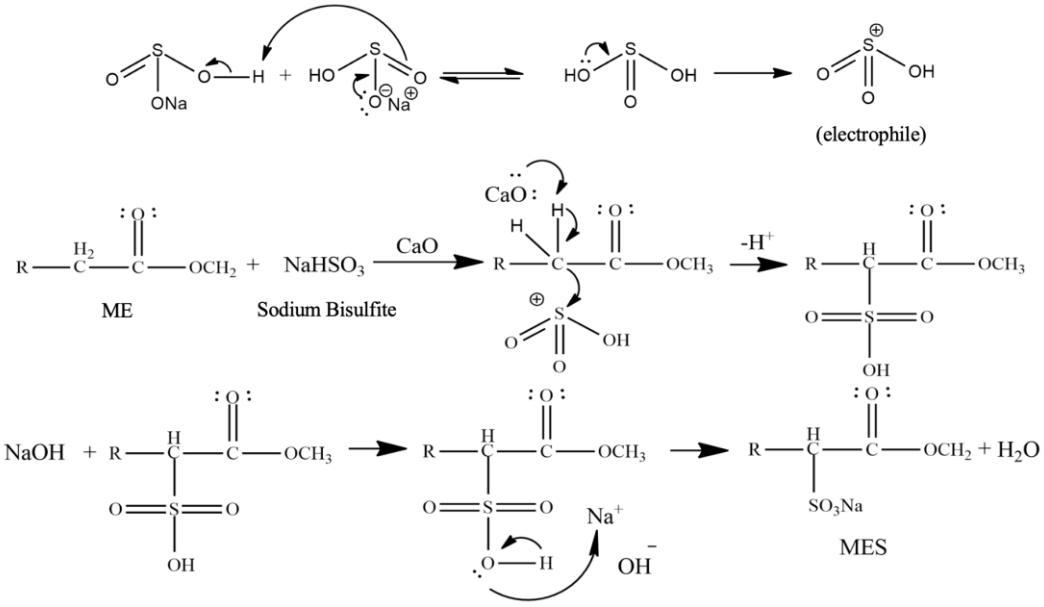


Figure 5. Proposed Mechanism of Sulfonation Reaction Using CaO Catalyst

The successful transformation of ME into MES was confirmed through Thin Layer Chromatography (TLC) and Fourier Transform Infrared (FT-IR) spectroscopy. TLC analysis showed a clear shift in Rf value from 0.75 (ME) to 0.45 (MES), indicating structural modification due to the incorporation of the sulfonate group (Figure 6). FT-IR spectra exhibited characteristic C=O stretching at 1741 cm^{-1} for the ester backbone and strong S=O

stretching bands at 1113.8–1015.46 cm^{-1}, confirming the presence of the sulfonate functionality (Figure 7). These findings demonstrate that CaO-catalyzed sulfonation under ultrasonication efficiently converts ME into high-purity MES with improved conversion efficiency, providing a sustainable approach for producing eco-friendly surfactants (Penteado et al., 2018; Qadariyah et al., 2021).

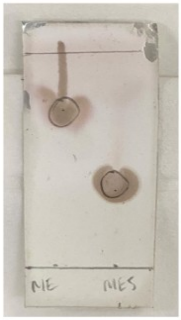


Figure 6. TLC Result of MES

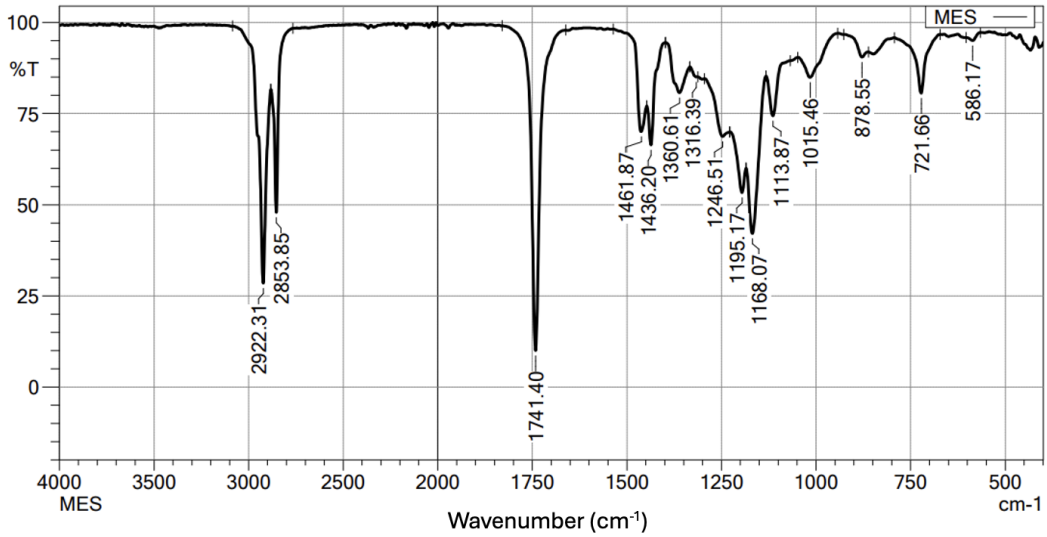


Figure 7. FT-IR Spectra of MES

Physical Characterization of Methyl Ester Sulfonate (MES)

The physicochemical properties of MES were evaluated to assess its suitability as a surfactant (Table 4). Ultrasonic-assisted synthesis improved emulsion stability (up to 103.10 minutes at 50°C and 1% catalyst), moderate viscosity (2.798–4.300 cSt), and density (0.827–0.875 g/mL) compared to conventional reflux methods. These properties indicate that MES possesses favorable rheological and interfacial characteristics for detergent applications.

The improved properties under ultrasonic-assisted conditions can be attributed to the enhanced homogeneity and finer dispersion of reactants during the reaction, which likely reduced product aggregation and increased surfactant activity. In contrast, higher temperatures (60°C) reduced emulsion stability, consistent with observed decreases in % conversion due to side reactions. Overall, the physicochemical analysis confirms that MES synthesized using eggshell-derived CaO exhibits desirable properties, including high

emulsion stability, suitable viscosity, and appropriate density, making it a promising eco-friendly surfactant for industrial applications.

Table 4. Physicochemical Properties of Methyl Ester Sulfonate (MES)

Sulfonation Condition & Temperature	Catalyst Concentration (w/w %)	Density (g/mL)	Viscosity (cSt)	Surface Tension (mN/m)	Emulsion Stability (min)
Conventional / Reflux (90°C / 3 h)	1.0	0.847	4.982	40.20	77.31
	1.5	0.886	3.826	39.40	74.59
	2.0	0.865	4.300	41.10	69.43
Ultrasonication (50°C / 1 h)	1.0	0.862	3.411	38.50	103.10
	1.5	0.827	3.615	41.10	78.24
	2.0	0.854	2.798	38.80	91.57
Ultrasonication (60°C / 1 h)	1.0	0.875	3.748	43.70	57.20
	1.5	0.862	3.677	42.60	83.19
	2.0	0.845	3.136	40.50	89.07

CONCLUSIONS

The CaO catalyst synthesized from eggshell waste proved effective for the synthesis of methyl ester sulfonate (MES), with the highest conversion of 74.28% achieved at 50°C and 2% catalyst loading using the ultrasonic-assisted method. Ultrasonication enhanced the yield compared to the conventional method, whereas higher temperatures reduced efficiency due to side reactions. These results demonstrate that coconut oil-based MES catalyzed by CaO derived from biogenic waste has strong potential as an eco-friendly surfactant for detergent applications. This study also highlights opportunities for further optimization of reaction time, reactant molar ratios, and catalyst regeneration to improve process efficiency and sustainability.

REFERENCES

Amaliah, D., Qadariyah, L., & Mahfud, M. (2021). The Production of Surfactant Anionic Methyl Ester Sulfonate (MES) from Virgin Coconut Oil (VCO) with Ultrasound-Assisted. *Journal of Physics: Conference Series*, *1845*(1). https://doi.org/10.1088/1742-6596/1845/1/012005

Boey, P. L., Maniam, G. P., & Hamid, S. A. (2011). Performance of calcium oxide as a heterogeneous catalyst in biodiesel production: A review. In *Chemical Engineering Journal* (Vol. 168, Issue 1, pp. 15–22). https://doi.org/10.1016/j.cej.2011.01.009

Cheng, H., Wei, J., Liang, M., Dai, S., Liu, X., Ma, L., Wang, H., & Lai, F. (2021). Calcium Glycerolate Catalyst Derived from Eggshell Waste for Cyclopentadecanolide Synthesis. *Frontiers in Chemistry*, *9*. https://doi.org/10.3389/fchem.2021.770247

Cowan-Ellsberry, C., Belanger, S., Dorn, P., Dyer, S., Mcavoy, D., Sanderson, H., Versteeg, D., Ferrer, D., & Stanton, K. (2014). Environmental safety of the use of major surfactant classes in North America. In *Critical Reviews in Environmental Science and*

Technology (Vol. 44, Issue 17, pp. 1893–1993). Taylor and Francis Inc. https://doi.org/10.1080/10739149.2013.803777

Dewi, D. K., Putri, V. M., Febriyanti, V., & Yudha, C. S. (2023). Calcination of Various Eggshell Wastes into CaO Heterogeneous Catalysts. *Equilibrium Journal of Chemical Engineering*, *7*(1), 87. https://doi.org/10.20961/equilibrium.v7i1.74484

Ecker, J., Scherer, M., Schmitz, G., & Liebisch, G. (2012). A rapid GC-MS method for quantification of positional and geometric isomers of fatty acid methyl esters. *Journal of Chromatography B: Analytical Technologies in the Biomedical and Life Sciences*, *897*, 98–104. https://doi.org/10.1016/j.jchromb.2012.04.015

Iman, N., Rahman, A., & Nurhaeni, D. (2016). Synthesis of Methyl Ester Sulfonic (MES) from Methyl Laurate. *KOVALEN*, *2*(2), 54–66.

Lim, Y. S., Baharudin, N. B., & Ung, Y. W. (2019). Methyl Ester Sulfonate: A High-Performance Surfactant Capable of Reducing Builders Dosage in Detergents. *Journal of Surfactants and Detergents*, *22*(3), 549–558. https://doi.org/10.1002/jsde.12230

Makalalag, A., Riset, B., Standardisasi, D., & Manado, I. (2018*).* Production Of Methyl Ester From Coconut Oil. In *Jurnal Penelitian Teknologi Industri* (Vol. 10, Issue Desember).

Morrow, D., & Piwoni, M. D. (1993). *LAS: Aquatic Toxicity and Biodegradation Electronic Version*. www.wmrc.uiuc.edu

Oko, S., & Feri, M. (2019). *Pengembangan Katalis CaO dari Cangkang Telur Ayam dengan Impregnasi KOH dan Aplikasinya terhadap Pembuatan Biodiesel dari Minyak Jarak*. *11*(2). https://doi.org/10.24853/jurtek.11.2.103-110

Pasawan, M., Chen, S.-S., Das, B., Chang, H.-M., Chang, C.-T., Nguyen, T. X. Q., Ku, H.-M., & Chen, Y.-F. (2022). Ultrasonication Assisted Catalytic Transesterification of Ceiba Pentandra (Kapok) Oil Derived Biodiesel Using Immobilized Iron Nanoparticles. *Fuels*, *3*(1), 113–131. https://doi.org/10.3390/fuels3010008

Penteado, F., Monti, B., Sancineto, L., Perin, G., Jacob, R. G., Santi, C., & Lenardão, E. J. (2018). Ultrasound-Assisted Multicomponent Reactions, Organometallic and Organochalcogen Chemistry. In *Asian Journal of Organic Chemistry* (Vol. 7, Issue 12, pp. 2368–2385). Wiley-VCH Verlag. https://doi.org/10.1002/ajoc.201800477

Qadariyah, L., Sahila, S., & Mahfud, M. (2021). The effect of reaction time and temperature on the synthesis of methyl ester sulfonate surfactant from palm oil as a feedstock using microwave-assisted heating. *ASEAN Journal of Chemical Engineering*, *21*(1), 104–112. https://doi.org/10.22146/ajche.63786

Suryani, S., Sariani, S., Earnestly, F., Marganof, M., Rahmawati, R., Sevindrajuta, S., Indra Mahlia, T. M., & Fudholi, A. (2020). A comparative study of virgin coconut oil,

coconut oil and palm oil in terms of their active ingredients. *Processes*, *8*(4). https://doi.org/10.3390/PR8040402

Syarif, A., Hasan, A., Taqwa, A., & Behzod, Z. (2025). *Preparation Of Cao Catalyst From Eggshell With Koh Impregnation And Its Application In The Production Of Biodiesel From Used Cooking Oil* (pp. 357–363). https://doi.org/10.2991/978-94-6463-678-9_34

Tooy, D., Langi, T. M., & Lomo, C. (2025). *Potential of Non-Standard Coconut as a Raw Material for Bioenergy Production*. *15*(1).

Yohanes Setyawan, E., Kusuma Rastini, E., Studi Teknik Kimia, P., & Teknologi Nasional Malang Jln Raya Karanglo Km, I. (n.d.). *Transesterifikasi Minyak Kelapa Sawit Berkatalis Basa Pada Temperatur Kamar : Pengaruh Waktu Pengadukan Dan Waktu Reaksi (Alkali-Catalyzed Palm Oil Transesterification at Room Temperature : Effect of Stirring Time and Reaction Time) ARTICLE INFO ABSTRAK*. *7*(1), 63–73. https://doi.org/10.33366/rekabua

Yusuff, A. S., Ishola, N. B., & Gbadamosi, A. O. (2023). Artificial Intelligence Techniques and Response Surface Methodology for the Optimization of Methyl Ester Sulfonate Synthesis from Used Cooking Oil by Sulfonation. *ACS Omega*, *8*(22), 19287–19301. https://doi.org/10.1021/acsomega.2c08117