

Thermal Conversion of Coral Waste and its Utilization as Low-Cost Catalyst for Biodiesel Production

Suci Widianingsih^{1,2}, Ika Yanti^{1,2}, Azlan Kamari³, Is Fatimah^{1,2*}

¹Department of Chemistry, Faculty of Mathematics and Natural Sciences, Universitas Islam Indonesia, Sleman, Daerah Istimewa Yogyakarta, 55584, Indonesia

²Nanomaterials and Sustainable Chemistry Research Centre, Universitas Islam Indonesia, Chemistry Research Building, Sleman, Daerah Istimewa Yogyakarta, 55584, Indonesia

³Department of Chemistry, Universiti Pendidikan Sultan Idris, Tanjong Malim, Perak, 35900, Malaysia

*Corresponding author: isfatimah@uii.ac.id

Abstract

This study investigates the thermal conversion of waste coral and its utilization as a heterogeneous catalyst for biodiesel production from soybean oil. In this work, waste coral is calcined at varied temperatures of 800, 900, and 1000°C, and the effect of the calcination temperature on the physicochemical character of the solid is evaluated through Fourier-transform infrared spectroscopy, X-ray diffraction, scanning electron microscopy, and basicity measurement. The results show that the higher temperature facilitates the conversion of CaCO₃ of the aragonite and calcite phases in raw waste coral into CaO, achieving a complete conversion at the temperature of 1000°C. Thermal conversion influences the increased surface basicity of the solid, which is associated with the higher activity for biodiesel production. Further studies on the obtained CaO as a catalyst demonstrate the catalyst dosage and the methanol-to-oil ratio as significant factors for fatty acid methyl ester production. The highest yield of 98.7% is achieved after a 3 hours reaction with 8 wt.% catalyst dosage and 9:1 methanol-to-oil ratio. The catalyst exhibits stability with an insignificantly decreased yield until the fifth usage cycle. The optimum conditions and reusability features of the calcined waste coral suggest that waste coral is a favorable CaO catalyst source for biodiesel production.

Keywords

Biodiesel, CaO, Heterogeneous Catalyst, Waste Coral

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1. INTRODUCTION

Energy is one of the world's main problems in the 21st century. Until now, fuel oil remains as the main consumption of countries worldwide. The world's population increase and industrial development have resulted in an increase in the need for energy. The fuel that is currently being used is obtained from fossil fuels, which are a non-renewable natural resource. As a result, fossil fuel sources are increasingly being depleted in line with the increasing energy demands. The exploration and development of renewable energy are the strategies for overcoming the global fuel need. One of the feasible alternatives is biodiesel. Biodiesel has been chosen as an attractive alternative fuel because it is renewable, biodegradable, non-toxic, environmentally friendly, and affordable (Mathew et al., 2021). Biodiesel has a high flash point, better lubricity, and high cetane number and is quite similar in terms of physical and chemical characteristics to conventional diesel fuel. Vegetable oils and animal fats are the best sources for biodiesel. These sources can be subjected to transesterification reactions to experience

changes in viscosity and volatility. Transesterification is performed with simple alcohols in the presence of a catalyst, which can be a homogeneous or heterogeneous catalyst (Farouk et al., 2024).

Conventional biodiesel production occurs through the transesterification of vegetable oil catalyzed by a homogeneous base or an acid catalyst, such as NaOH, KOH, or H₂SO₄, by dissolving it in methanol. However, the use of a homogeneous catalyst has weaknesses, that is, it is difficult to separate from the reaction mixture; hence, this catalyst is only used once per reaction. In addition, in the process of separating and washing catalyst residues, a large amount of the liquid waste is produced, which can cause environmental problems (Jamil et al., 2018). To overcome the problem of using homogeneous catalysts, researchers are interested in developing solid heterogeneous system catalysts, called heterogeneous catalysts. Heterogeneous catalysts are more stable, have a lower chance of causing corrosion to equipment, and are environmentally friendly compared to homogeneous catalysts. Because it is a solid phase, this catalyst is easily separated from the reaction mixture by filtration.

Apart from that, solid catalysts are considered more economical because they have the potential to be used many times.

Various types of heterogeneous catalysts have been used for the transesterification process, including alkaline earth metal oxides and various alkali metal compounds supported on alumina or zeolite. In the green chemistry perspective, the use of animal wastes and natural rocks is an interesting alternative. The utilization of animal waste and rock for biodiesel production is multifaceted, encompassing waste management, economic stability, reduced greenhouse emissions, energy resource diversification, and climate change mitigation (Colombo and Ender, 2017; Fatimah et al., 2018a,b). Previous studies revealed the effectiveness and the eco-friendly potential of CaO derived from animal shell, such as from bones and sea animal's shells (Minaria and Mohadi, 2016). The available surface porosity for conducting adsorption of reactants along with sufficient surface basicity is an important reaction parameter. In this case, waste coral is another potential environmental waste. Theoretically, the thermal conversion of waste coral will produce calcium salt and oxide potential for catalyzing transesterification. The study on thermal conversion for obtaining a highly active heterogeneous catalyst based on calcium is important for intensive biodiesel production (Sulaiman et al., 2020). Even though previous work on the use of coral waste for biodiesel production has been reported (Moradi and Mohammadi (2014), studies related to the effect of thermal treatment on the activity have not yet been recorded. Based on these considerations, this study aims to evaluate surface basicity of raw waste coral (RWC) as a function of thermal conversion for biodiesel production applications. The novelty of this work is related to the study on the thermal conversion effect of RWC on the transesterification mechanism for producing biodiesel and the evaluation on its reusability for production.

2. EXPERIMENTAL SECTION

2.1 Materials

The waste coral was obtained from Krakal Beach, Gunung Kidul, Yogyakarta, Indonesia. The solid was washed, dried, crushed, and sifted into a particle size of 200 mesh. Soybean oil (SBO) was obtained from a traditional market in Yogyakarta, as well. Some of the chemicals used in this work were methanol (CH_3OH) (99.8%, Merck), NaOH, hydrochloric acid (HCl) (97%, Merck), phosphoric acid (H_3PO_4) (96.5%, Sigma-Aldrich, UK), and ethanol ($\text{CH}_3\text{CH}_2\text{OH}$) (96%, Merck).

2.2 Methods

The RWC powder was treated by calcination at varied temperatures of 800, 900, and 1000°C for 2 hours. The obtained samples from different temperatures are denoted herein as C800, C900, and C1000, respectively.

Some of the equipment used for the physicochemical characterization in this research work included a Fourier-transform infrared (FTIR) spectrometer (Perkin-Elmer, USA), the X-ray diffraction Bruker D2 Phaser, the scanning electron microscope, Phenom-X, and a gas chromatography mass spec-

trimeter (GCMS) (Agilent Technologies, USA). The X-ray diffraction patterns were recorded using $\text{CuK}\alpha$ radiation with a scan speed of $4^\circ/\text{min}$.

The surface basicity of the solids was determined based on the back titration method using H_3PO_4 as the acid and NaOH as the base. Approximately 1 g of solid was mixed with excess 0.5 M of H_3PO_4 , followed by stirring overnight. The unreacted H_3PO_4 was then determined by titration using the NaOH standard solution. The basicity was measured as mg of H_3PO_4 adsorbed per gram of solid.

The catalytic activity examination of the samples on biodiesel production was performed by using SBO and methanol as the reactants. The reactions were conducted at the temperature of 60°C at varied methanol-to-oil (MTO) ratios and catalyst dosages. The result of the reaction was transferred into a separating funnel, and the organic phase of the result was analyzed by using the GCMS. The percentage of fatty acid methyl ester (FAME) was calculated based on the weight of biodiesel and the FAME content analyzed by the GCMS.

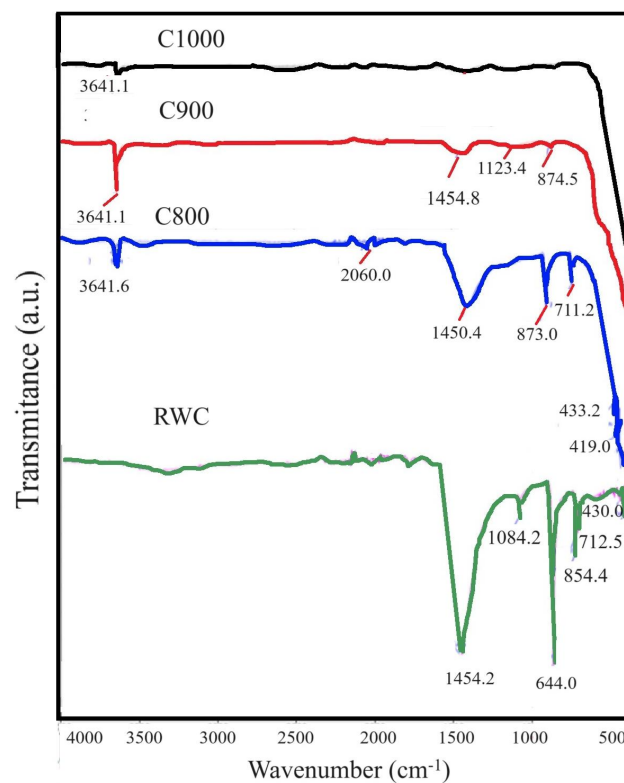


Figure 1. FTIR Spectra of the RWC and the Thermally Converted Materials

3. RESULTS AND DISCUSSION

3.1 Thermal Conversion of the RWC

The FTIR analysis was used to determine the functional groups of both organic and inorganic compounds in the materials to

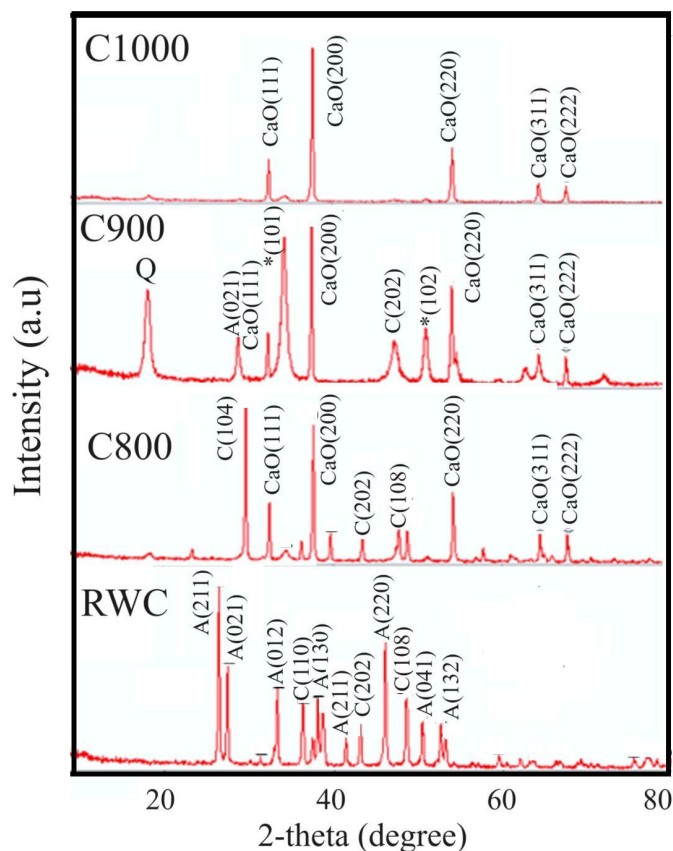


Figure 2. XRD Patterns of the RWC and the Thermally Converted Materials

Table 1. Basicity of the Samples

Sample	Basicity (meq/mg)
RWC	1.02
C800	2.10
C900	5.10
C1000	8.10

identify the mineral change by thermal treatment. The spectra are provided in Figure 1.

The FTIR spectrum of the RWC exhibited the band at 1454.2 cm^{-1} , indicating the presence of asymmetric stretching of the -C=O vibrations of CO_3^{2-} . The two other absorption bands at 854.4 and 712.5 cm^{-1} indicated asymmetric and symmetric vibrations of -C-O from CO_3^{2-} , confirming the presence of CaCO_3 in the RWC that was not calcined. In the present case, the peak at 1084.2 cm^{-1} indicated the observed aragonite phase calcium carbonate, whose CO_3^{2-} ions were inactive in the infrared region. The additional peak at 430 cm^{-1} indicated orthoclase feldspar usually present as impurities (Ramasamy et al., 2017). After calcination, the correlated peak was shifted as an indication of the disappearance of CO_3^{2-} . At a calcination temperature of 800°C , there were shifts of the

correlated peaks at 1450.4 , 873.0 , and 711.2 cm^{-1} . Apart from that, a new absorption band also appeared at 3641.6 cm^{-1} , confirming the presence of OH from the indication of the formed Ca(OH)_2 . By increasing the calcination temperature of 900°C , the shifts were at 1454.8 and 874.5 cm^{-1} . In addition, the presence of OH was assigned to the bands at 3641.1 cm^{-1} along with the peak at 1123 cm^{-1} .

At the calcination temperature of 1000°C (C1000), the bands associated with the presence of CO_3^{2-} and -OH were presented with an insignificant intensity. These changes of the spectra conclude that along with the calcination treatment until 900°C , CO_3^{2-} remained, but tended to shift to a lower wavenumber. On the other side, the band corresponding to the presence of -OH , which came from the Ca(OH)_2 formation, appeared, confirming that the thermal conversion led to the conversion of CaCO_3 into Ca(OH)_2 . The additional temperature increase to 1000°C confirmed the disappearances of either the peak of CO_3^{2-} or -OH , suggesting the thermal conversion of Ca(OH)_2 into CaO (Razali et al., 2022).

The thermal conversion of CaCO_3 into Ca(OH)_2 and CaO was confirmed by the XRD analysis results presented in Figure 2. The pattern of the aragonite and calcite phases appeared in the RWC sample, as indicated by some peaks at 36.0 , 43.2 , and 47.4° corresponding to the (110), (202), and (018) planes of calcite, respectively, according to JCPDS Card No. 24-0027. The remaining peaks confirmed the pattern of aragonite (JCPDS No. 05-0543). The domination of the aragonite phase compared to the calcite phase was concluded by the more intensive peaks and the intensity of aragonite compared to calcite. This is a characteristic of the calcium rock associated with the wastes of sea animals (Triunfo et al., 2022). The thermal conversion into the C800 sample demonstrated the CaO formation, as shown by the peaks at $2\theta = 32.5$, 37.7 , 42.4 , 64.4 , and 67.6° assigned to (111) (200), (220), (311), and (222), respectively.

The XRD pattern of the coral fragment samples calcined at a temperature of 900°C (C900) showed characteristic CaO peaks with an increasing intensity at $2\theta = 32.475$, 37.592 , 54.135 , 64.439 , and 67.623° . This XRD pattern still depicted a characteristic peak of CaCO_3 , which indicated the remaining CaCO_3 compound in the sample. The characteristic peak of aragonite that appeared can be due to the contact between the catalyst and air before characterization, resulting in the formation of the Ca(OH)_2 due to hygroscopic properties. Two peaks at 45.25 and 51.43° were also found to be associated with the (101) and (102) peaks of the identification of Ca(OH)_2 due to the hydroscopic property of CaO (Rahman and Oomori, 2008). Furthermore, a complete conversion of CaCO_3 into CaO was confirmed as the peaks at 32.4 , 37.5 , 54.1 , and 64.4° attributed to the growth alongside (111), (200), (220), and (311), respectively, and (222) referred to JCPDS: 77-2376 (Mohamed et al., 2021).

The surface morphology identification of the samples under the influence of thermal treatment was performed by a SEM analysis, with the images presented in Figure 3.

The SEM images provide a clear visual demonstration of

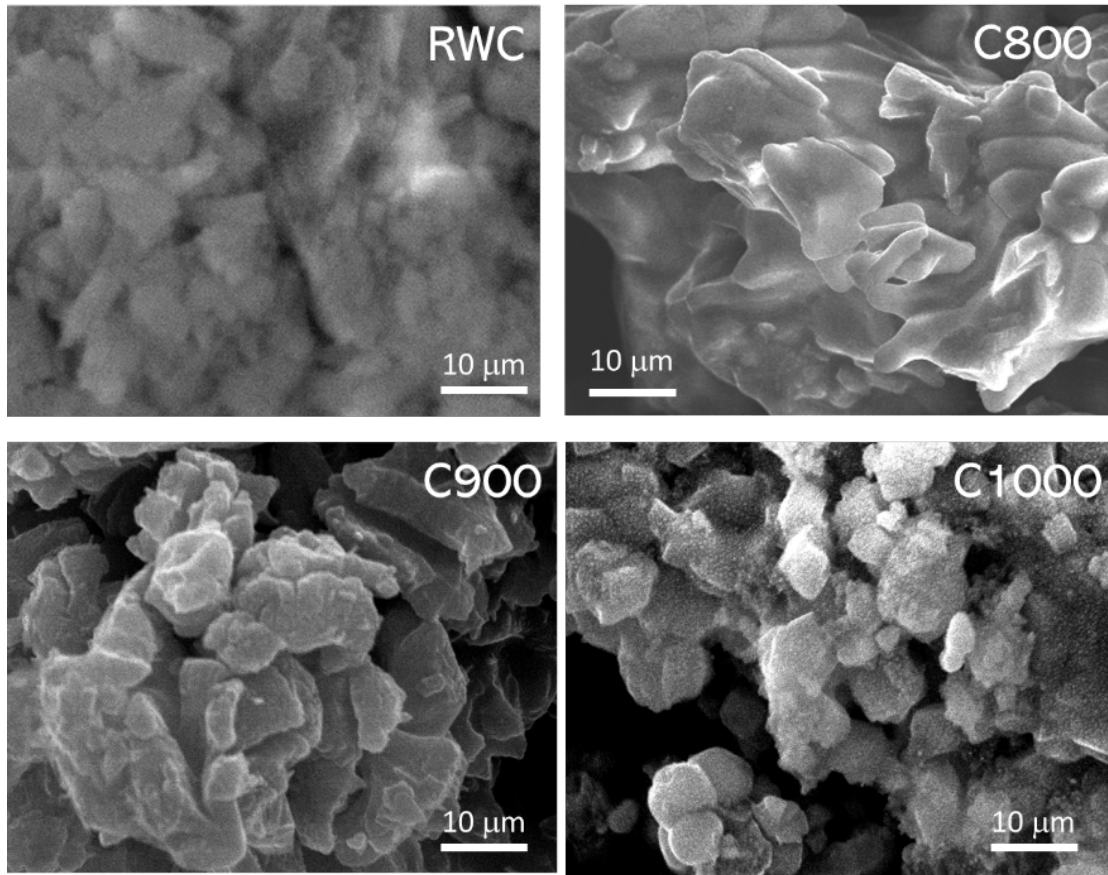


Figure 3. SEM Images of the Materials Used in This Work

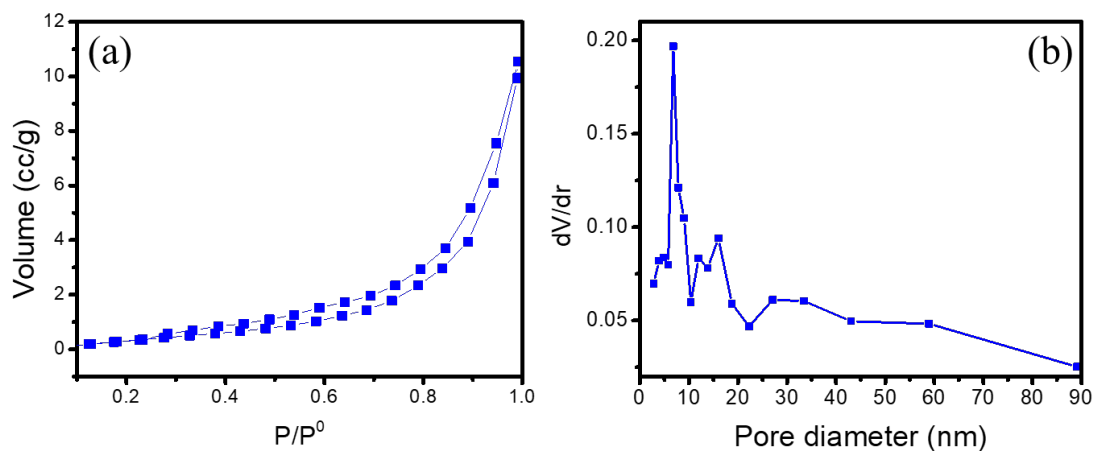


Figure 4. (a) Adsorption-Desorption Isotherm, (b) Pore Size Distribution of the C1000 Sample

the morphological changes of the observed thermal treatment effect to the RWC. The RWC sample expressed irregular rod-like morphology as a characteristic form of aragonite, which from the XRD analysis, was dominantly presence in the sample (Sevčík et al., 2018). The thermal treatment influence

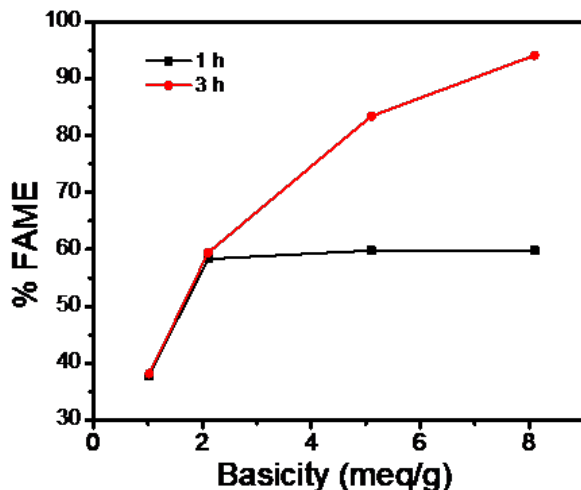
on the morphological alterations into spherical cubic forms was specific for CaO and clearly visible in the C1000 sample (Mahmood et al., 2021; Nassar and Alotaibi, 2021). These data implied that the temperature completely decomposed CaCO₃ into CaO. Even though from many literatures the

Table 2. Composition of the Produced FAME

Peak No.	Retention Time (min)	Compound	Percentage (%)
1	16.028	Methyl stearic	12.15
2	17.870	Methyl linoleic	80.88
3	18.055	Methyl palmitate	5.52
4	19.688	Methyl oleic	0.30
5	19.883	Methyl arachidic	0.43
6	21.586	Methyl behenic	0.52
7	23.251	Methyl lignoceric	0.20

Table 3. Physical and Fuel Properties of the Produced Biodiesel

Peak No.	Unit	ASTM Standards D6751	Measurement
Calorific value	MJ/kg	35	37.02
Acid value	Mg KOH/g	Maximum 0.50	0.372
Flash point	°C	> 150°C	230
Glycerin content	ppm	Maximum 200	32
Density (15°C)	kg/m ³	880	850

**Figure 5.** Effect of Surface Basicity on %FAME [Catalyst Weight: 4 g/100 mL, Temperature: 60°C, MTO = 10:1]

CaCO₃ decomposition could be completed at a certain temperature higher than 700°C, the phase composition of CaCO₃, the presence of impurities, and the crystallite size influenced the chemical and physical transformations.

Certain groups on the surface determine the acidity or basicity and the acid–base catalysis mechanism. In the biodiesel production over the basic catalyst, both the Lewis and Brønsted basicity played important roles to give direction to the transesterification mechanism. To measure the strength and the quantitative amount of base on the surface, a determination of the number of acids chemically adsorbed on the surface

can be performed. The back titration method utilizing H₃PO₄ was chosen as the method for basicity determination, with the results presented in Table 1.

Considering the surface mechanism that usually happens for heterogeneous catalysis, the surface profile of C1000 was evaluated by a gas sorption analyzer, providing the adsorption–desorption isotherm depicted in Figure 4a. Using the Brunauer–Emmett–Teller (BET) equation, the specific surface area (BET_{SAA}) of C1000 was determined as 14.29 m²/g. The pore size distribution plot was depicted in Figure 4b based on the Barrett–Joyner–Halenda equation. The isotherm reflected the dominant microporous structure in CaO, which was in line with the pore size distribution suggesting the trend of the pore size ranging from 5 to 20 nm. The BET_{SAA} of the C1000 sample was higher compared to that of CaO derived from calcined RWC with the value of 6.88 m²/g and the total basicity of 0.47 meq/g (Boro et al., 2014), which was also higher compared to that reported from Niju with the BET_{SAA} value of 8.64 m²/g. The BET_{SAA} of the CaO was subjected to the thermal conversion related to the hydration–dehydration treatment on the calcium carbonate conversion structure into CaO (Niju et al., 2014).

Effect of surface basicity on catalytic activity The influence of surface basicity on the biodiesel conversion is reflected in the graph presented in Figure 5. As can be seen in the plot, the increasing percentage of FAME was obtained at the increasing basicity for both varied times of reactions, that is, 1 and 3 hours. By the varied time of reaction, there was an insignificant percentage of FAME for the samples with a basicity of 1.02 and 2.10 meq/g associated with the RWC and C800 samples, respectively. These findings reflect that CaO provided sufficient basicity for catalyzing the reaction, and that during the 3 hours range, the reaction was kinetically controlled. The low activity

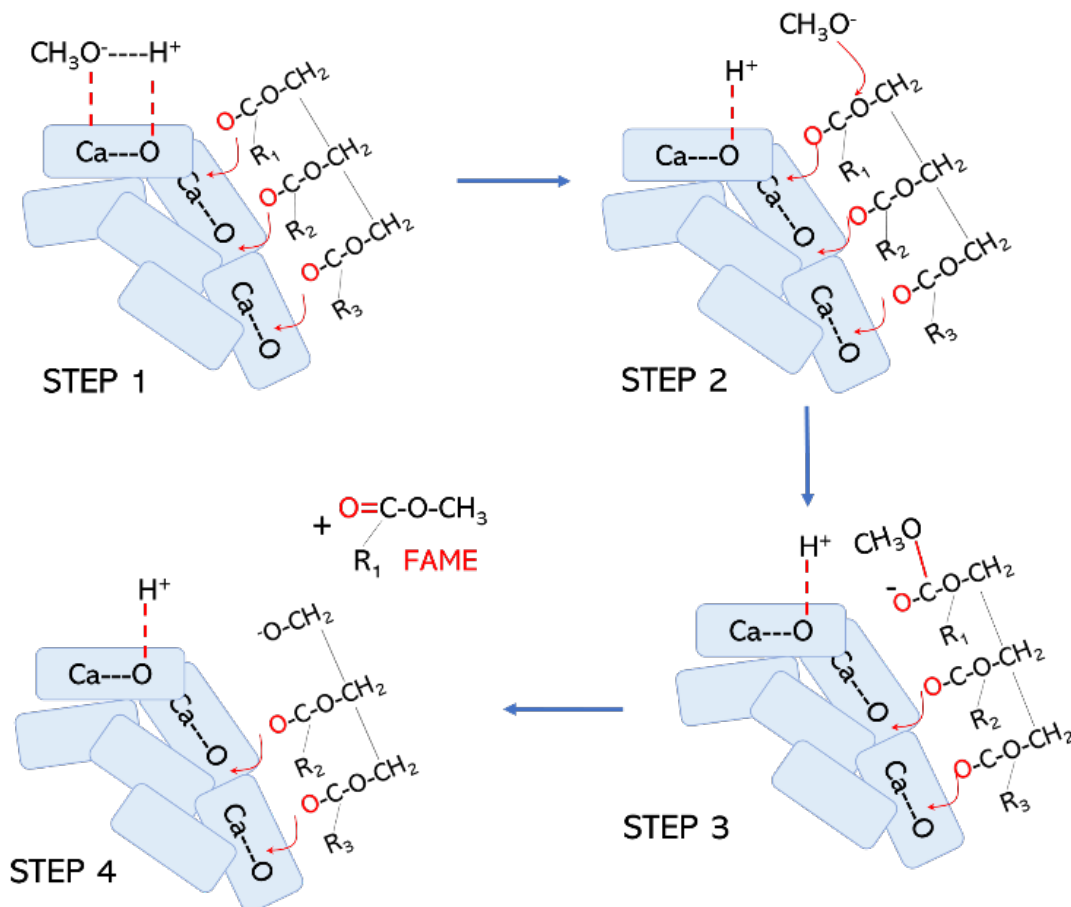


Figure 6. Schematic Representation of the CaO-Catalyzed Transesterification Reaction

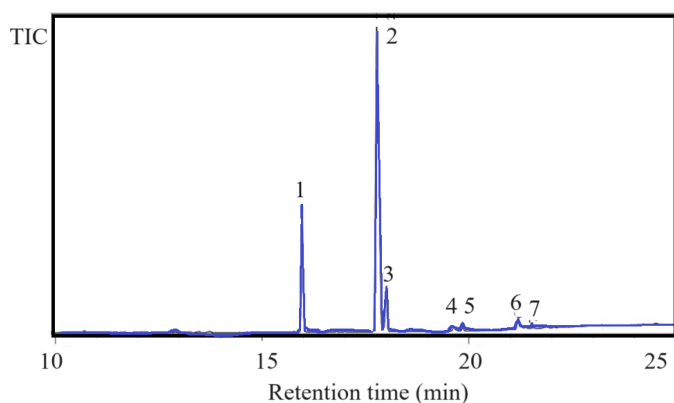


Figure 7. Chromatogram of the Produced FAME

of CaCO_3 in the RWC was also confirmed by the study on the effect of the calcination temperature of CaCO_3 from natural rock on palm kernel oil with a very low percentage of FAME ($\cong 0\%$). Meanwhile, the activity was expressed after calcination at 800°C (Ngamcharussrivichai et al., 2010).

The increasing surface basicity that leads to an increasing

activity is referred to as the availability of $-\text{OH}$ on the surface that plays the role of converting triglyceride into FAME from SBO by the mechanism depicted in Figure 6.

The mechanism includes methanol activation by the surface interaction of methanol and CaO as the first step. The methoxy ion can interact with sorbed triglyceride. Furthermore, the intermediate is formed by bonded methoxy, and the unstable intermediate will release FAME as a product. The mechanism will be continued until all triglycerides are converted, and glycerol is formed as a byproduct (Basumatary et al., 2023; Zhu et al., 2021). Referring to the basicity and the BET_{SAA} data compared to CaO in some previous studies, the higher percentage of the produced FAME is related to the higher values of both parameters. With similar reaction time and MTO of 3 h and 20:1, respectively, the greatest %FAME obtained by CaO from calcined eggshell with the BET_{SAA} of $8.64 \text{ m}^2/\text{g}$ and $6.88 \text{ m}^2/\text{g}$ were 94.52 and 94%, respectively (Niju et al., 2014; Zul et al., 2021). It is also higher than the yield of 64% produced by CaO derived from Staghorn coral having BET_{SAA} of $5.24 \text{ m}^2/\text{g}$ (Zul et al., 2020).

The composition of the produced FAME analyzed by using a GCMS is presented in the chromatogram depicted in Figure 7.

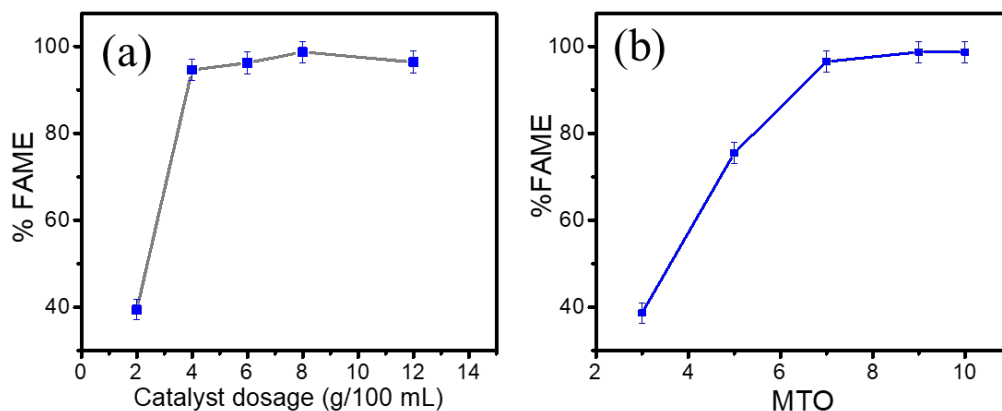


Figure 8. Effect of (a) Catalyst Dosage and (b) MTO on %FAME [Reaction Condition: Temperature = 60°C, Time of Reaction = 3 h)

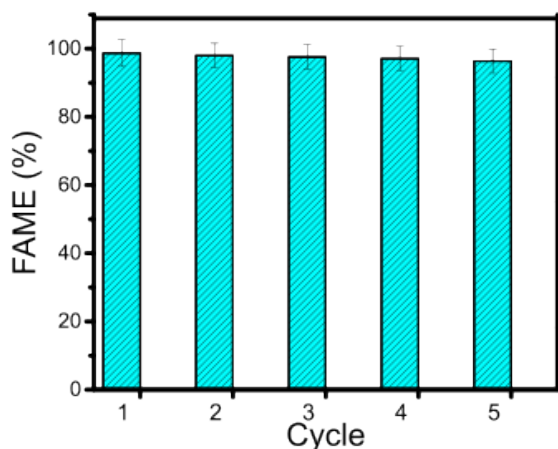


Figure 9. Reusability of the C1000 Catalyst in Biodiesel Production

The list of compounds is provided in Table 2. The composition of FAME is dominated by methyl linoleic, followed by methyl stearic and methyl palmitic, and it is similar with that in other works (Ayodeji et al., 2018a).

The fuel properties of the produced biodiesels were determined according to the American Society for Testing and Materials. The results are presented in Table 3, with the referred values for biodiesel (ASTM-D6751).

From the data in Table 3, the biodiesel produced was within the limit of ASTM D6751 for biodiesel.

3.2 Effect of the Catalyst Dosage

The effect of the C1000 catalyst dosage to the reaction efficiency was investigated. As the surface basicity contributes to the kinetics of reaction, it is important to evaluate the influ-

ence of the catalyst dosage. Theoretically, a higher amount of the catalyst provides more surfaces to adsorb both reactants of triglyceride and methanol and can produce more methoxy for the further step of methanolysis. However, the separation phase between hydrophilic methanol and hydrophobic oil is also one of the problems in the heterogeneous catalyst usage. As depicted in Figure 8a, the reaction yields higher FAME at a higher catalyst dosage and reaches the optimum catalyst dosage of 8 g/100 mL with %FAME of 98.7%. Adding the amount of 10 g/100 mL, the percentage is reduced. The reducing efficiency at a higher dosage is probably caused by the higher adsorption capability and lesser desorption of the product.

3.3 Effect of MTO

As the transesterification of triglyceride is a reversible reaction, the molar ratio of MTO is an important factor influencing the equilibrium to the right side. Even though stoichiometrically, three moles of FAME will be produced by reacting one mole of triglyceride with three moles of methanol, some optimizations revealed a feasible MTO higher than 6:1 (Basumatary et al., 2023; Roschat et al., 2012). From a previous study, transesterification was also insufficient at the MTO molar ratios below 5:1 (Karaosmanog and Cctinkaya, 2004). The effect of MTO on %FAME for biodiesel production from SBO by the C1000 catalyst is presented in Figure 8b. The plot illustrates that increasing MTO leads to an increasing %FAME. More specifically, MTO of 10 gives an insignificant difference of %FAME compared to MTO of 9, suggesting that a reversible condition is achieved at the ratio of 9. From the obtained maximum yield of 98.7% under the optimum condition of the catalyst dosage and MTO, the C1000 catalyst is favorable and comparable with other CaO-based catalysts from many sources. A comparison of the activities of the CaO-based catalyst for biodiesel production using SBO is presented in Table 4. By the compared %FAME and reaction condition, the CaO catalyst in this work (C1000) was efficient in terms of MTO (9:1),

Table 4. Comparison of the Catalytic Activities of CaO in This Work with Those in the Other Previous Works on Biodiesel Production Using SBO

Catalyst/Catalyst Source	Remark	Optimum Yield (% FAME)	Reference
Waste coral	The catalyst was obtained by calcination at 900°C. The raw oil was SBO. Reaction condition: MTO = 12:1:1 catalyst dosage of 6 wt.%; and reaction time = 3 h. The maximum yield was obtained at MTO = 14.79:1, reaction temperature of 62.63°C, catalyst concentration of 3.32 wt.%, and reaction time of 79.07 min.	100	(Moradi and Mohammadi, 2014)
Waste phosphate rock	The maximum yield was obtained at MTO = 14.1:1, reaction temperature of 60°C, catalyst concentration of 4 wt.%, and reaction time of 3 h.	96.07	(Kiprono et al., 2022)
CaO from eggshell	The optimal conditions established for the production of biodiesel were MTO of 7.1, catalyst concentration of 5.9 wt/wt.% oil, and reaction time of 2.1 h.	91	(Ayodeji et al., 2018b)
CaO from eggshell	The maximized biodiesel yield was produced on MTO of 13, catalyst dosage of 5 wt.%, reaction time of 90 min, and reaction temperature of 72°C.	92.6	(Ayoola et al., 2019)
Ag/CaO	The optimal reaction parameters were MTO of 20:1, catalyst dosage of 8 wt.%, reaction time of 2.5 h, and temperature of 65°C.	90.95	(Zhu et al., 2021)
Green synthesized CaO	The optimal reaction parameters were MTO of 12:1, catalyst dosage of 20 wt.%, reaction time of 2.5 h, and temperature of 55°C.	81.3	(Sahu et al., 2023)
CaO from cow bone	The maximum yield was obtained by catalyst loading of 3 wt.%, reaction time of 2 h, and MTO of 6:1. The reaction utilized acetone as a co-solvent. The catalyst can be reused up to 11 cycles.	92.2	(Ayodeji et al., 2018a)
CaO	The maximum yield was obtained by catalyst loading of 8 wt.%, reaction time of 3 h, and MTO of 9:1. The catalyst can be reused up to five cycles.	98	(Laskar et al., 2020)
CaO from waste coral		98.7	This work

which is less than that in the other reactions and does not need a co-solvent to improve the yield.

3.4 Reusability

The study on the reusability of the catalyst is an important step for further development in the industrial scale. The waste cata-

lyst was recycled by washing in methanol, followed by drying at 90°C. The percentages of FAME at the cycles are depicted in Figure 9. The C1000 catalyst demonstrated retained activity, as shown by the insignificantly decreasing %FAME until the fifth cycle, during which the decreasing %FAME was no more than 5%. This could be attributed to the stability of the catalyst to provide basicity and accommodate reactant adsorption and transfer resistance.

4. CONCLUSIONS

In this study, waste coral was thermally converted for use as a heterogeneous catalyst for biodiesel production from soybean oil. The investigation performed by using FTIR, XRD, SEM, and basicity measurement on the thermally converted coral demonstrated the conversion of CaCO_3 in aragonite and calcite phases into CaO at the temperature of 1000°C. The increasing calcination temperature affected the increasing basicity, which linearly influenced the activity of the coral as a catalyst for biodiesel production from soybean oil. The study on the effect of the MTO ratio and the catalyst dosage revealed the optimum ratio of 9:1 and the catalyst dosage of 8 g/100 mL for producing 98.7% of FAME. In conclusion, the calcined waste coral at 1000°C can be used as a low-cost catalyst for biodiesel production.

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REFERENCES

- Ayodeji, A., I. Blessing, and F. Sunday (2018a). Data on Calcium Oxide and Cow Bone Catalysts Used for Soybean Biodiesel Production. *Data in Brief*, **18**; 512–517
- Ayodeji, A., M. Ojewumi, B. Rasheed, and J. Ayodele (2018b). Data on CaO and Eggshell Catalysts Used for Biodiesel Production. *Data in Brief*, **19**; 1466–1473
- Ayoola, A., O. Fayomi, O. Adeyo, J. Omodara, and O. Adegbite (2019). Impact Assessment of Biodiesel Production Using CaO Catalyst Obtained from Two Different Sources. *Cogent Engineering*, **6**(1); 1615198
- Basumatary, S., S. Brahma, M. Hoque, B. Das, M. Selvaraj, S. Brahma, and S. Basumatary (2023). Advances in CaO -Based Catalysts for Sustainable Biodiesel Synthesis. *Green Energy & Resources*, **1**; 100032
- Boro, J., L. Konwar, and D. Deka (2014). Transesterification of Non Edible Feedstock with Lithium Incorporated Egg Shell Derived CaO for Biodiesel Production. *Fuel Processing Technology*, **122**; 72–78
- Colombo, K. and L. Ender (2017). The Study of Biodiesel Production Using CaO as a Heterogeneous Catalytic Reaction. *Egyptian Journal of Petroleum*, **26**; 341–349
- Farouk, S., A. Tayeb, S. Abdel-Hamid, and R. Osman (2024). Recent Advances in Transesterification for Sustainable Biodiesel Production, Challenges, and Prospects: A Comprehensive Review. *Environmental Science and Pollution Research*, **31**; 12722–12747
- Fatimah, I., G. Aulia, W. Puspitasari, R. Nurillahi, L. Sophia, and R. Herianto (2018a). Microwave-Synthesized Hydroxypapatite from Paddy Field Snail (*Pila ampullacea*) Shell for Adsorption of Bichromate Ion. *Sustainable Environment Research*, **28**; 462–471
- Fatimah, I., A. Taushiyah, F. Najah, and U. Azmi (2018b). ZrO_2 / Bamboo Leaves Ash (BLA) Catalyst in Biodiesel Conversion of Rice Bran Oil. In *IOP Conference Series: Materials Science and Engineering*, volume 349. page 012027
- Jamil, F., L. Al-Haj, A. Al-Muhtaseb, M. Al-Hinai, M. Baawain, U. Rashid, and M. Ahmad (2018). Current Scenario of Catalysts for Biodiesel Production: A Critical Review. *Reviews in Chemical Engineering*, **34**; 267–297
- Karaosmanog, F. and M. Cctinkaya (2004). Optimization of Base-Catalyzed Transesterification. *Energy & Fuels*, **18**; 1888–1895
- Kiprono, J., H. Rutto, and T. Seodigeng (2022). Production of Biodiesel Using Phosphate Rock as a Heterogeneous Catalyst: An Optimized Process Using Surface Response Methodology. *Environmental and Climate Technologies*, **26**; 822–835
- Laskar, I., T. Deshmukhya, P. Bhanja, B. Paul, R. Gupta, and S. Chatterjee (2020). Transesterification of Soybean Oil at Room Temperature Using Biowaste as Catalyst; An Experimental Investigation on the Effect of Co-Solvent on Biodiesel Yield. *Renewable Energy*, **162**; 98–111
- Mahmood, N., K. Marossy, and P. Baumli (2021). Effects of Nanocrystalline Calcium Oxide Particles on Mechanical, Thermal, and Electrical Properties of EPDM Rubber. *Colloid and Polymer Science*, **299**; 1669–1682
- Mathew, G., D. Raina, V. Narisetty, V. Kumar, S. Saran, A. Pugazhendhi, R. Sindhu, A. Pandey, and P. Binod (2021). Recent Advances in Biodiesel Production: Challenges and Solutions. *Science of the Total Environment*, **794**; 148751
- Minaria, M. and R. Mohadi (2016). Preparation and Characterization of Calcium Oxide from Crab Shells (*Portunus Pelagicus*) and Its Application in Biodiesel Synthesis of Waste Cooking Oil, Palm and Coconut Oil. *Scientific and Technological Innovations*, **1**; 1–7
- Mohamed, F., M. Shaban, G. Aljohani, and A. Ahmed (2021). Synthesis of Novel Eco-Friendly CaO/C Photocatalyst from Coffee and Eggshell Wastes for Dye Degradation. *Journal of Materials Research and Technology*, **14**; 3140–3149
- Moradi, G. and F. Mohammadi (2014). Utilization of Waste Coral for Biodiesel Production via Transesterification of Soybean Oil. *International Journal of Environmental Science and Technology*, **11**; 805–812
- Nassar, A. and N. Alotaibi (2021). Eggshell Recycling for Fabrication of Pd@CaO , Characterization and High-Performance Solar Photocatalytic Activity. *Environmental Science and Pol-*

- lution Research*, **28**; 3515–3523
- Ngamcharussrivichai, C., P. Nunthasanti, S. Tanachai, and K. Bunyakiat (2010). Biodiesel Production through Transesterification over Natural Calciums. *Fuel Processing Technology*, **91**; 1409–1415
- Niju, S., M. Begum, and N. Anantharaman (2014). Modification of Egg Shell and Its Application in Biodiesel Production. *Journal of Saudi Chemical Society*, **18**; 702–706
- Rahman, M. and T. Oomori (2008). Structure, Crystallization and Mineral Composition of Sclerites in the Alcyonarian Coral. *Journal of Crystal Growth*, **310**; 3528–3534
- Ramasamy, V., P. Anand, and G. Suresh (2017). Biomimetic Synthesis and Characterization of Precipitated CaCO_3 Nanoparticles Using Different Natural Carbonate Sources: A Novel Approach. *International Journal of Materials Science*, **12**; 499–511
- Razali, N., N. Jumadi, A. Jalani, N. Kamarulzaman, and K. Pa'ee (2022). Thermal Decomposition of Calcium Carbonate in Chicken Eggshells: Study on Temperature and Contact Time. *Malaysian Journal of Analytical Science*, **26**; 347–359
- Roschat, W., M. Kacha, B. Yoosuk, T. Sudyoadsuk, and V. Promarak (2012). Biodiesel Production Based on Heterogeneous Process Catalyzed by Solid Waste Coral Fragment. *Fuel*, **98**; 194–202
- Sahu, S., K. Saikia, B. Gurunathan, A. Dhakshinamoorthy, and S. Rokhum (2023). Green Synthesis of CaO Nanocatalyst Using Watermelon Peels for Biodiesel Production. *Molecular Catalysis*, **547**; 113342
- Sevčík, R., P. Sasek, and A. Viani (2018). Physical and Nanomechanical Properties of the Synthetic Anhydrous Crystalline CaCO_3 Polymorphs: Vaterite, Aragonite and Calcite. *Journal of Materials Science*, **53**; 4022–4033
- Sulaiman, N., A. Yacob, and S. Lee (2020). Transesterification Reaction from Rice Bran Oil to Biodiesel over Heterogeneous Base Calcium Oxide Nanoparticles Catalyst. *Scientific and Technological Innovations*, **5**; 62–69
- Triunfo, C., S. Gärtner, C. Marchini, S. Fermani, G. Maoloni, S. Goffredo, J. Gomez Morales, H. Cölfen, and G. Falini (2022). Recovering and Exploiting Aragonite and Calcite Single Crystals with Biologically Controlled Shapes from Mussel Shells. *ACS Omega*, **7**; 43992–43999
- Zhu, Z., Y. Liu, W. Cong, X. Zhao, J. Janaun, T. Wei, and Z. Fang (2021). Soybean Biodiesel Production Using Synergistic CaO/Ag Nano Catalyst: Process Optimization, Kinetic Study, and Economic Evaluation. *Industrial Crops and Products*, **166**; 113479
- Zul, N., S. Ganesan, T. Hamidon, W. D. Oh, and M. Hussin (2021). A Review on the Utilization of Calcium Oxide as a Base Catalyst in Biodiesel Production. *Journal of Environmental Chemical Engineering*, **9**; 105741
- Zul, N., S. Ganesan, and M. Hussin (2020). Biodiesel Synthesis through Methanolysis of Palm Olein Using Calcium Oxide Catalyst Derived from Staghorn Coral. *Journal of Physical Science*, **31**; 37–55