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High-Performance of Catalyst Synthesized from Waste Can Aluminum and Rice Husk Silica for Conversion Coconut Oil into Biodiesel

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Abstract: The development of biodiesel is one of the extensive research projects that have been undertaken in response to the diminishing fossil energy reserves, air pollution, and climate change. This work introduces catalysts synthesized from waste can aluminum and rice husk silica (AS) with Si/Al molar ratios of 10, 20, and 30. The catalysts were synthesized by the hydrothermal process in an autoclave at 100 ºC for 24 h, followed by calcined at 550 °C for 5 h, and evaluated as catalysts for biodiesel (fatty acid methyl esters, FAMEs) production from coconut oil. The AS-10 catalyst demonstrates highly performance, with 99.57% yield under operational conditions (10 wt.% catalyst, 1:2 oil-to-methanol ratio, 60 °C, 6 h). In addition, the catalyst has 99.69% FAME selective, with biodiesel that most closely matched the fatty acid composition of coconut oil. For the characteristic, this catalyst exhibits amorphous phase and a small average crystal size, as demonstrated by the XRD patterns and SEM images. The FTIR spectra after pyridine absorption qualitatively shows the presence of Brønsted (1546 cm^{-1}) and Lewis (1457 cm^{-1}) acid sites on this catalyst. High-performance catalytic activity is usually attributed to these characteristics, which may be able to enhance the adsorptivity towards triglycerides of coconut oil. Hence, these findings suggest the prospective use of the catalyst in the biodiesel production derived from coconut oil.

Keywords: Biodiesel, Coconut oil, Catalyst, Waste can aluminum (WCA), Rice husk silica (RHS)

Introduction

Indonesia's plentiful natural resources offer significant prospects for sustainable biodiesel development practices. The advancement of biodiesel is conducted in response to the depletion of fossil fuel reserves,

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climate change, and air pollution, as well as aims to diminish import reliance on fossil fuels, which are experiencing substantial price increases (Wirawan et al., 2024). Indonesia has around 40 varieties of oil-producing plants recognized as feedstocks for biodiesel synthesis, including coconut oil (*Cocos nucifera*) (Rachmaditasari et al., 2024). The potential of coconut oil for biodiesel production is substantial, providing extensive feedstock diversity to enhance energy security and safety, improve environmental quality, and achieve energy independence (Rahman et al., 2021). The use of this local natural resource also contributes to regional development and aligns with global sustainability goals (SDGs).

In practice, the production of biodiesel is inextricably linked to the utilization of catalysts to facilitate the transesterification and esterification of coconut oil into fatty acid methyl esters (FAMEs) (Sakti La Ore et al., 2020). Nevertheless, the development of heterogeneous catalysts is fraught with a challenge in the acquisition of active, selective (Mulyatun et al., 2022), and stable catalysts (Gardy et al., 2019). Furthermore, the dependence on synthetic compounds as precursors for the synthesis of heterogeneous catalysts remains substantial. For instance, certain researchers have reported that raw materials from sodium metasilicate, sodium silicate, sodium aluminate, and α- and γ-alumina are used to produce heterogeneous catalysts, including aluminosilicate (Simanjuntak et al., 2013), alumina, silica, and zeolite (Simanjuntak et al., 2021). Despite the fact that these synthetic heterogeneous catalysts exhibit high activity, selectivity, and stability in certain instances, it is imperative to investigate catalyst development by utilizing sustainable and environmentally friendly raw materials, such as waste can aluminum (WCA) and rice husk silica (RHS), while simultaneously addressing these limitations. Combining WCA with RHS processed using hydrothermal methods (Pratika et al., 2021) is an intriguing approach. The development of sustainable catalysts by utilizing refuse and waste has contributed to advancements in materials science and is a prominent initiative for the development of next-generation catalysts (Nayak et al., 2024). Thus, the synthesis of heterogeneous catalysts (e.g., alumina and silica (AS) from the combination of WCA and RHS) provides a customizable solution for specific catalyst requirements, such as those for the production of biodiesel from coconut oil.

In this current investigation, we synthesized catalysts from waste can aluminum (WCA) and rice husk silica (RHS) with varying Si/Al ratios of 10, 20, and 30 for one-step conversion of coconut oil to biodiesel. While RHS has been frequently employed as a matrix/support in a variety of applications, as far as our literature is concerned, the use of WCA as an alumina source is limited. These catalysts are currently in the early stages of development and has the potential to be further developed to achieve the desired characteristics for specific applications. Furthermore, a sustainable solution for the development of biodiesel and heterogeneous catalysts is appealing due to the fact that it employs natural resources, refuse, and waste as raw materials. Therefore, these catalysts were experimentally tested for their performance to produce biodiesel from coconut oil.

Materials and Methods

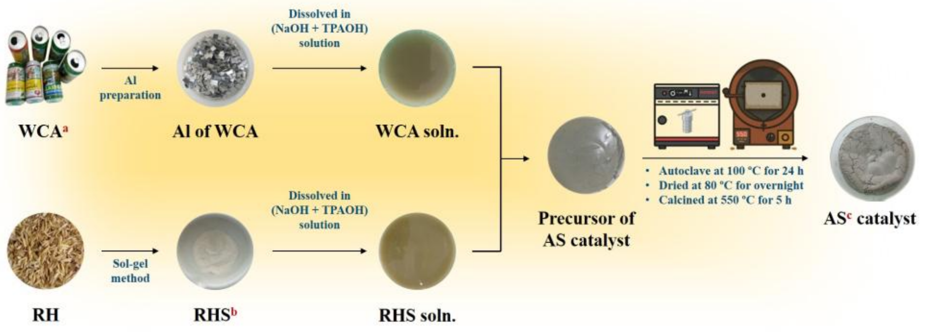
Materials

Waste can aluminum and rice husk were used as the primary catalyst materials, obtained from the adjacent environment of Bandar Lampung City and the local rice milling industry in Pringsewu Regency, Lampung, Indonesia, respectively. Coconut oil in this study was procured from PT Barco Indonesia. Methanol (CH_3OH, Merck) was used for transesterification-esterification reagent. Nitric acid (HNO_3, Merck) was utilized for the neutralization of rice husk silica sol-gel. Reagent-grade tetrapropylammonium hydroxide (TPAOH) and sodium hydroxide (NaOH 98%) were acquired from Sigma-Aldrich.

Catalyst Preparation

The fabrication process flow of catalysts synthesized from waste can aluminum (WCA) and rice husk silica (RHS), with Si/Al ratios of 10, 20, and 30 is illustrated in Figure 1. With some modification of procedure adopted from López-Juárez et al., (2018), the aluminum was prepared from WCA. The WCA were initially sanded to remove the paint, rinsed with detergent water until impurities free, dried, and randomly cut into small sizes (± 0.5 cm) for dissolution in the subsequent stage.

The sol-gel method was employed to extract RHS (Setyawan et al., 2021). The rice husk was cleansed, washed repeatedly with hot water, and filtered, then collected, immersed in a 10% HNO_3 solution overnight, rinsed with clean water, and dried. After that, 200 g of dried rice husk was immersed in 2000 mL of 1.5% NaOH solution, heated to simmering for 30 min, chilled overnight, and filtered to produce silica-containing filtrate (silica sol). The filtrate was progressively added with a 10% HNO_3 solution until the silica sol transformed into silica gel at a neutral pH (7.0), as determined by a universal indicator. The silica gel was aged at room temperature for 24 h before being rinsed with hot water until spotless and white. RHS was obtained by sieving it through a 200-micron sieve after 8 h of dehydrating in an oven at 80 ºC. This RHS was utilized in the subsequent procedure. After the precursor preparation process (aluminum and silica), the hydrothermal method was employed to synthesize the catalysts, namely AS-10, AS-20, and AS-30 catalysts. To prepare solution A, 11.2 g of NaOH was dissolved in 450 mL of distilled water, then 2.5 mL of TPAOH solution was added, and the mixture was stirred steadily until it was homogeneous. Solutions A were divided into two portions: 200 mL and 250 mL, respectively. After that, 2.7 g of WCA was dissolved in 200 mL of solution A (called solution B). Meanwhile, 60 g of RHS was dissolved in 250 mL of solution A (called solution C). Solutions B and C were combined until formed a homogeneous paste. The paste was then placed in an autoclave at 100 ºC for 24 h. Ultimately, the catalyst material was rinsed with distilled water, dried at 80 ºC for overnight, pulverized, and filtered through a 200-micron sieve, followed by calcination at 550 ºC for 5 h in a muffle furnace (Heraeus MR 260E).



Notes: [a]WCA: waste can aluminum [b]RHS: rice husk silica. [c]AS: aluminosilicate.

Figure 1. Fabrication of AS-10, AS-20, and AS-30 catalysts.

Catalyst Characterization

The crystal phase, crystallinity, and average crystal size (calculated by Debye Scherrer equation) of the catalysts were determined using X-ray diffraction (XRD, PANalytical type Empyrean) with Cu Kα radiation (1.54060 Å) in the 2θ range of 5 - 80º. The surface morphology and elemental composition of the catalysts were analyzed using scanning electron microscope-energy dispersive x-ray (SEM-EDX, Zeiss EVO MA 10). The acid sites before and after pyridine absorption, chemical bonds, and functional groups of the catalysts were characterized using Fourier Transform Infrared Spectroscopy (FTIR, Nicolet Avatar 360) with a wave number range of 400 - 4000 cm^{-1}.

Catalytic Performance of Catalysts in Biodiesel Production

The catalytic performance was evaluated for biodiesel production using coconut oil as the feedstock in one-pot conversion (Pandiangan et al., 2021). The experiment was conducted using reflux with 2.5 g catalyst (10 wt.% of the feed), 1:2 oil-to-methanol ratio at 60 ºC under a stirring speed of 600 rpm for 6 h. The reflux product was separated by separating the funnel. The biodiesel (FAMEs) was taken and washed with warm distilled water. The composition of biodiesel was analyzed using gas chromatography-mass spectrometry (GC-MS, QP2010 SE Shimadzu). The yield (%) and selectivity (%) were calculated to determine the catalytic performance according to the following equations (1) and (2):

$$\text{Yield (\%)} = \frac{W_{\text{biodiesel product}}}{W_{\text{feed}}} \text{ x \%FAME area} \tag{1}$$

$$\text{Selectivity (\%)} = \frac{\text{Peak area of each FAME}}{\text{Total area of GC}} \text{ x } 100 \tag{2}$$

where W_{feed} is the initial weight of feed (g), $W_{biodiesel\ product}$ is the weight of biodiesel (g), and %FAME area is GC-MS area of FAMEs.

Results and Discussion

XRD Analysis of the Catalysts

X-ray diffraction (XRD) patterns in the 2θ range between 5 and 80º, as illustrated in Figure 2, indicate that the AS-10, AS-20, and AS-30 catalysts have characteristic of kyanite (JCPDS PDF#83-1569), cristobalite (JCPDS PDF#82-1235), and aluminum oxide (JCPDS PDF#77-0396), which comprise the aluminosilicate framework. Sodium aluminum oxide (002) phase is presented in AS-10 catalyst, as indicate by the typical peak at 2θ = 7.84º (JCPDS PDF#72-1406). The typical peaks at 2θ = 31.93º (JCPDS PDF#87-1259) and 2θ = 7.84º (JCPDS PDF#72-1406) on AS-20 and AS-30 catalysts, respectively, indicate the presence of calcium silicate (020) and sodium aluminum oxide (002) phases. To ascertain the catalyst's crystallinity percentage, the area of the crystal peak is compared to the total area of the diffractogram. Overall, the crystallinity may be enhanced by an increase in the Si/Al ratio of the catalyst (Okada et al., 2025). The Debye-Scherrer equation can be employed to determine the average crystal size and the results are summarized in Table 1. Compared to AS-10 and AS-30 catalysts, the average crystal size of the AS-20 catalyst is elevated. These findings suggest that the AS-20 catalyst may have agglomerated crystalline particles. The average crystal size of the catalysts can be increased by increasing the Si/Al ratio, as explained by Wang et al. (2023).

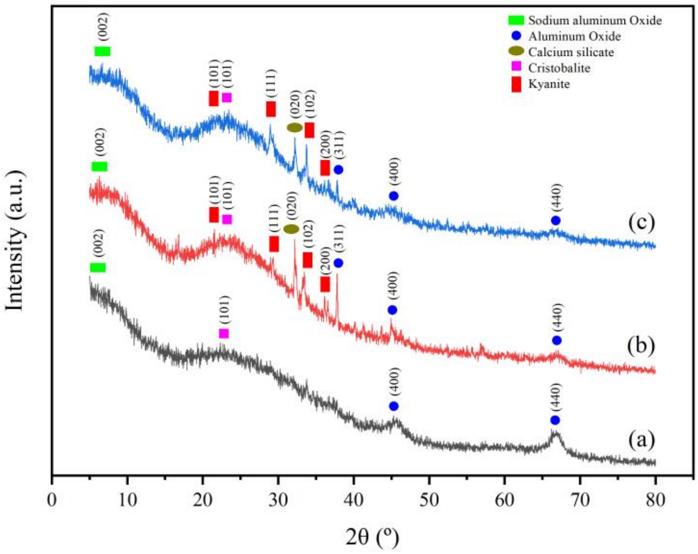


Figure 2. XRD patterns of (a) AS-10, (b) AS-20, and (c) AS-30 catalysts.

Morphological and Elemental Composition Analysis of the Catalysts

The scanning electron microscopy (SEM) was employed to characterize the morphology of AS-10, AS-20, and AS-30 catalysts at a magnification of 20,000 times. Figure 3, which displays the SEM images, demonstrates the distinct structural and surface shape differences between the AS-10 catalyst and the AS-20 and AS-30 catalysts. The AS-10 catalyst exhibits an irregular structure and a variety of particle morphologies, with an average particle diameter in the micrometer range. The AS-20 and AS-30 catalysts exhibit a porous structure and a smoother surface, with the particles' shapes dispersed randomly on the surface. In general, the XRD pattern (refer to Figure 2) confirmed that the particles of these catalysts exhibited amorphous dominance. The catalytic activity of the one-step conversion of coconut oil to biodiesel is significantly enhanced by the catalytic surface characteristics, as reported by Kwon et al. (2014).

Energy dispersive X-ray spectroscopy (EDS) provides the elemental composition for AS-10, AS-20, and AS-30 catalysts, as summarized in Table 1. Overall, these catalysts are composed of high concentrations of silicon (Si), aluminum (Al), and oxygen (O) atoms, which supports the existence of an aluminosilicate framework on the catalysts. The existence of active sites on the catalyst surface is further strengthened by the presence of other elements, including sodium (Na) and calcium (Ca). These components represent the catalyst's framework and active sites, which are crucial in the catalytic reactions of transesterification and esterification of coconut oil into biodiesel, as reported by Al-Ani et al. (2020). Furthermore, the XRD patterns confirm the existence of phases that are derived from these elements. The catalysts synthesized from WCA and RHS possess amorphous characteristics, with the aluminosilicate phase consisting of Si, Al, O, Na, and Ca.

Therefore, these characteristics are usually attributed to catalytic activity, which may be able to lead the adsorptivity towards triglycerides of coconut oil.

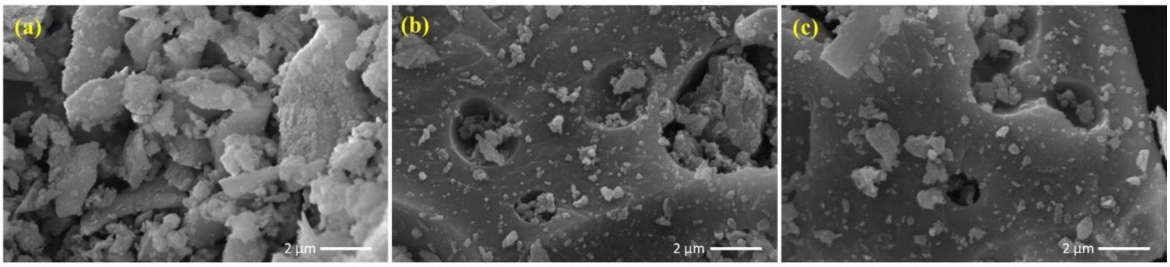


Figure 3. SEM images of (a) AS-10, (b) AS-20, and (c) AS-30 catalysts at 20,000 times magnifications.

Table 1. Elemental composition, crystallinity, and average crystal size of catalysts.

Catalysts	Elemental composition (wt.%)[a]						Crystallinity	Average crystal size[b]
	Si	Al	Na	O	Ca	C	(%)	(nm)
AS-10	29.65	16.05	9.72	39.12	nd	5.43	31.25	5.86
AS-20	30.32	14.73	4.97	28.76	16.90	4.29	36.33	17.18
AS-30	55.15	3.78	3.20	31.33	0.83	5.68	48.89	14.45

Notes: nd = not detected. [a]Analyzed by EDS. [b]Calculated by Debye Scherrer equation and XRD analysis.

FTIR and Active Sites Analysis of the Catalysts

Figure 4 illustrates the FTIR spectra of the catalysts before (1) and after (2) pyridine absorption. The characteristics of the aluminosilicate framework on the catalysts are confirmed by the Si-O-Al absorption bands of SiO_4^{4-} and AlO_4^- in the range of 466 - 599 cm^{-1}. The symmetrical stretching vibrations of the Si-O-Si bond are indicated by the absorption band at 788 cm^{-1}, whereas the asymmetrical stretching vibrations of the Si-O-Si bond are represented by the widened area at 1037 cm^{-1}. These patterns suggest the formation of Si-O-Si tetrahedral bonds in silica (Simanjuntak et al., 2013). The bending vibrations of the O-H bond of water, which is chemically bound in the silanol (Si-OH) structure of the catalyst, are indicated by the absorption band at 1654 cm^{-1}. The O-H stretch vibrations of water that are physically adsorbed on the catalyst surface are represented by the broad peaks in the 3301 - 3510 cm^{-1} areas. In addition to the identification of functional groups and bonds on the catalyst, the Brønsted and Lewis acid sites (BAS and LAS) were qualitatively determined through the FTIR spectra after the pyridine absorption (Gould & Xu, 2018). The interaction between the pyridine base and the BAS (N-H stretching vibration) of the catalyst is demonstrated by the absorption band at 1546 cm^{-1} (area 1515-1565 cm^{-1}). This band is formed by the proton contribution from the BAS. The pyridine base's N-H bending is indicated by a peak at 1457 cm^{-1} in the absorption area of 1435 - 1470 cm^{-1}, which is the result of a coordinate bond with the LAS on the catalyst (Emeis, 1993).

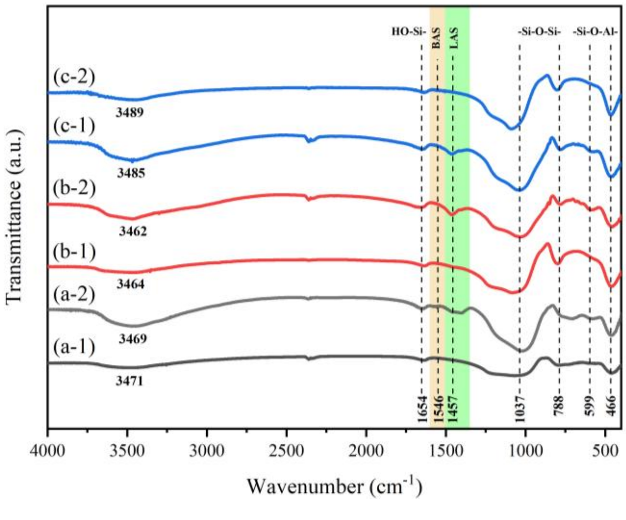


Figure 4. FTIR spectra of before (1) and after (2) pyridine absorption (a-1 and a-2) AS-10, (b-1 and b-2) AS-20, and (c-1 and c-2) AS-30 catalysts. BAS: Brønsted acid sites, LAS: Lewis acid sites.

The Brønsted acid sites on these catalysts are derived from silanol groups (Si-OH) that are present on the surface of the aluminosilicate framework. These groups provide H^+ ions that will be donated to other species. Meanwhile, Lewis acid sites are formed by the coordination of Al^{3+}, Na^+, or Ca^{2+} ions to the aluminosilicate on its surface. This process alters the electron distribution and creates empty orbitals on the Al and Si atoms of the catalyst, which facilitate the acceptance of electron pairs (Katada, 2018).

Catalytic Performance of the Catalysts in Biodiesel Production

After ensuring the characteristics of each catalyst, the catalyst's activity was systematically evaluated for the one-step transesterification and esterification reaction and compared with those of other catalysts. The GC-MS chromatogram presented in Figure 5 shows the relative quantity of FAMEs produced from coconut oil using various catalysts (AS-10, AS-20, and AS-30). The highest FAME yield can be observed by setting the operational condition of one-step conversion at 60 °C for 6 h with a stirring speed of 600 rpm, a 10 wt.% catalyst, and a 1:2 oil-to-methanol ratio. Temperature and reaction time generally influence reaction rates. The catalyst dosage, which is selective and possesses the number of active sites available, can accommodate to achieve an effective conversion. The oil-to-methanol ratio usually enhances the yield of FAME and reduces the deactivation of the catalyst due to an excess of methanol (Trisunaryanti et al., 2025). The correlation between these variables can determine the catalyst's performance and the conversion effectiveness. Thus, our investigation focuses on the catalytic performance and selectivity towards coconut oil rather than catalyst stability.

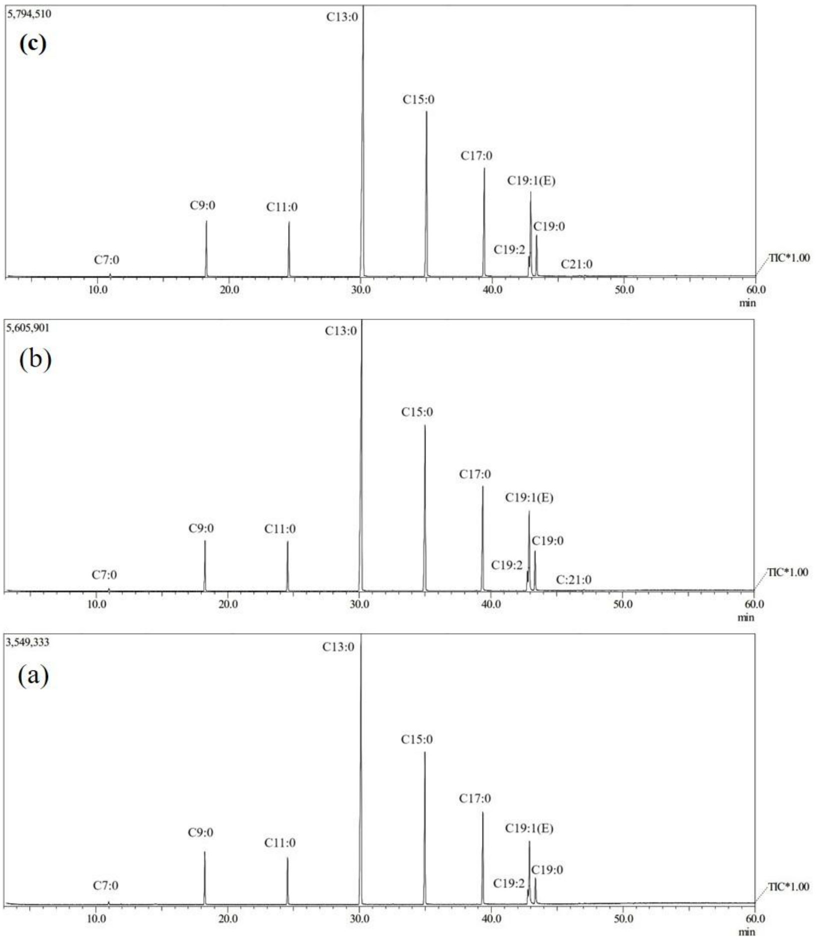


Figure 5. GC-MS chromatogram of FAMEs produced using catalysts of (a) AS-10, (b) AS-20, and (c) AS-30.

In Table 2, the biodiesel contains 100% FAMEs, with methyl palmitate, methyl myristate, and methyl laurate being the most prevalent components. The biodiesel also contains methyl caproate, which has a composition of less than 1%. This composition is consistent with the fatty acid content of coconut oil. These findings indicate that the one-step transesterification and esterification of coconut oil were entirely converted to FAMEs.

Table 2. Fatty acids of coconut oil and FAMEs in biodiesel.

Reference[a]		This work Catalyst	AS-10	AS-20	AS-30
FA of coconut oil	Area (%)	FAMEs	Area (%)		
-	-	Methyl Caproate (C7:0)	0.31	0.29	0.21
Caprylic acid (C8:0)	3.35	Methyl Caprylate (C9:0)	5.41	4.58	4.79
Capric acid (C10:0)	3.21	Methyl Caprate (C11:0)	4.97	4.62	4.67
Lauric acid (C12:0)	32.72	Methyl Laurate (C13:0)	43.97	43.77	43.81
Myristic acid (C14:0)	18.38	Methyl Myristate (C15:0)	20.14	20.67	20.48
Palmitic acid (C16:0)	13.13	Methyl Palmitate (C17:0)	11.21	11.61	11.36
Linoleic acid (C18:2)	3.60	Methyl Linoleic (C19:2)	1.80	2.02	1.98
Oleic acid (C18:1)	12.88	Methyl Elaidate (C19:1(E))	8.59	9.11	8.69
Stearic acid (C18:0)	4.35	Methyl Stearate (C19:0)	3.60	3.20	3.91
-	-	Methyl Eicosanoate (C21:0)	-	0.13	0.11

Notes: FA = fatty acids. FAMEs = fatty acid methyl esters. [a]Cited from Nakpong et al., (2010) and Lugo-Méndez et al., (2021).

The results of the biodiesel yield were determined by employing Equation (1), as shown in Figure 6a. Here, the AS-10 catalyst demonstrated the highest yield of 99.57%, suggesting that the catalyst is highly effective in the conversion of coconut oil into FAMEs. The biodiesel yields using AS-20 and AS-30 catalysts under the same conditions were slightly lower at 98.06 % and 94.70 %, respectively. This decrease in yield may be influenced by the large average crystal size of the catalyst, high crystallinity, and the availability of the number of Brønsted and Lewis acid sites (BAS and LAS). Consequently, the adsorption of triglycerides on the catalyst surface and the catalytic process are decreased.

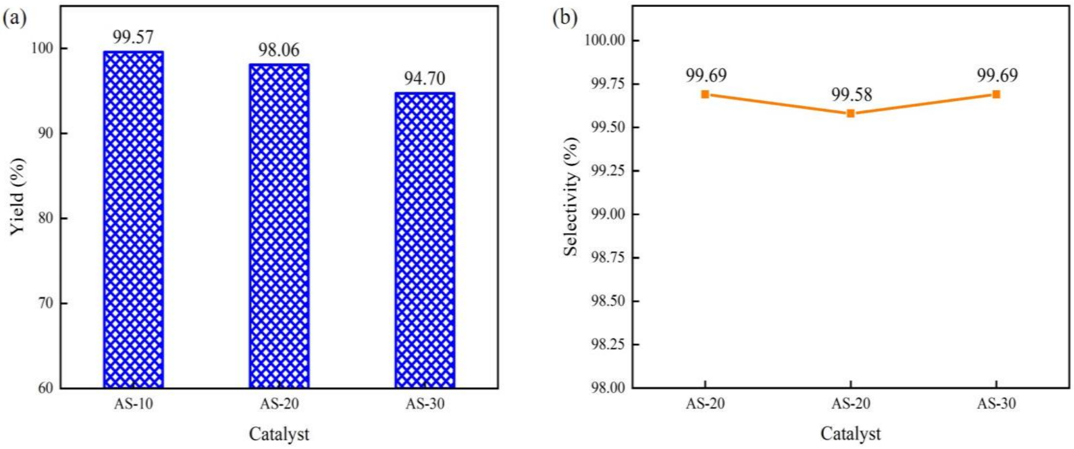


Figure 6. Graph of (a) biodiesel yield and (b) selectivity of various catalysts.

This phenomenon of yield reduction is crucial for comprehending the catalytic performance of the transesterification-esterification process, particularly in the context of the catalyst with a Si/Al ratio of 10 (AS-10), which exhibits superior performance in comparison to the catalysts with higher Si/Al ratios (AS-20 and AS-30). The catalyst surface that generates BAS and LAS may be capable of enhancing its interaction with carbonyl groups on triglycerides, thereby facilitating the adsorption and catalytic processes necessary to produce FAMEs, as explained by Cao et al. (2016).

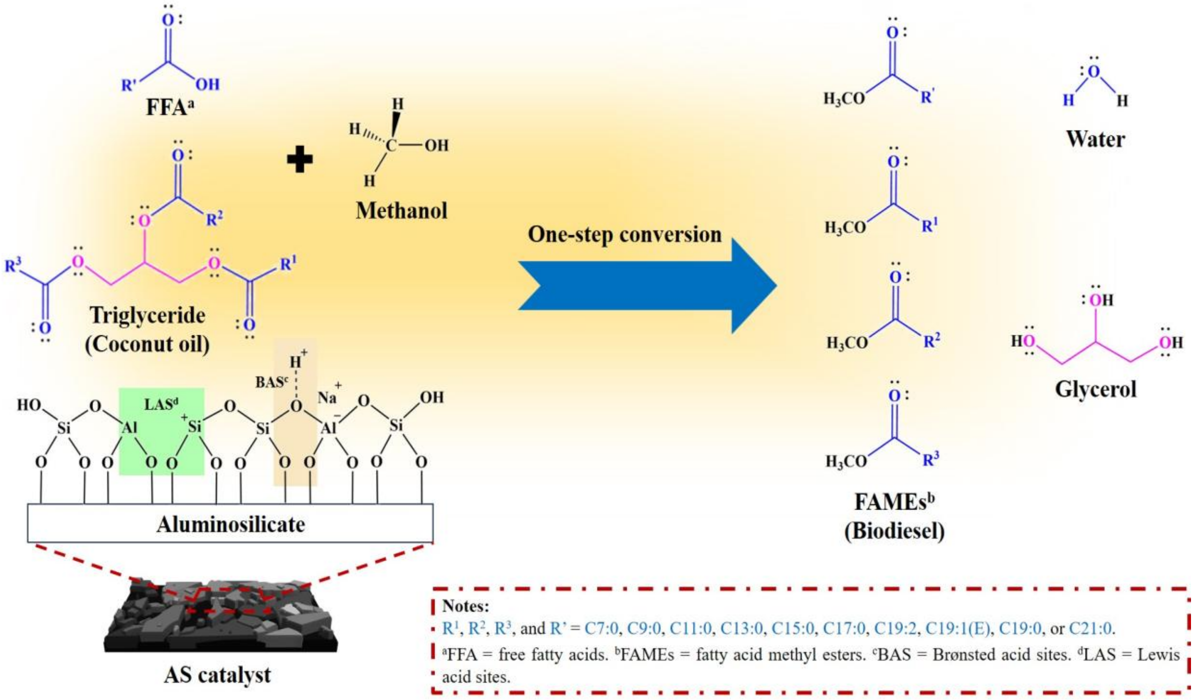
To evaluate their catalytic selectivity, the composition of FAMEs was also compared to the fatty acid composition of coconut oil based on the secondary data from Nakpong et al. (2010) and Lugo-Méndez et al. (2021). Coconut oil is primarily composed of Caprylic acid (C8:0), Capric acid (C10:0), Lauric acid (C12:0), Myristic acid (C14:0), Palmitic acid (C16:0), Linoleic acid (C18:2), Oleic acid (C18:1), and Stearic acid (C18:0). The fatty acids of coconut oil were consistent with the FAMEs that were produced through the catalytic process using AS-10, AS-20, and AS-30 catalysts. AS-10 and AS-30 catalysts were employed to achieve the highest selectivity, which was 99.69%, as presented in Figure 6b. Nevertheless, catalyst AS-20 exhibited a selectivity value of 99.58 %, which was slightly decreasing. Despite the fact that all catalysts exhibited impressive selectivity trends, the catalytic activity varied based on the specific catalyst used. The AS-10 catalyst, which exhibits high selectivity and yield, exhibited consistent results. Nevertheless, the AS-20 catalyst showed a relatively high yield and lower selectivity, whereas the AS-30 catalyst exhibited vice versa.

This distinctive phenomenon serves as confirmation that the yield and selectivity of the catalyst are influenced by the correlation between its average crystal size, crystallinity, and active site characteristics, as explained by Barkhuizen et al. (2006).

The catalyst employed in this study has an aluminosilicate framework, according to the results of XRD, EDS, and FTIR analyses. In general, aluminosilicate is an amorphous and porous material. This characteristic is due to the aluminosilicate framework, where the tetrahedral bonding of aluminum atoms with several silicon (silanol) atoms forms Brønsted and Lewis acid sites. These active sites are typically balanced by cations like Na^+ and Ca^{2+}, which can be exchanged within the porous structure (Muraoka et al., 2016). The high catalytic performance of the one-step conversion of coconut oil to biodiesel is usually attributed to these catalyst characteristics.

Evaluation of Proposed Catalytic Mechanisms

In Figure 7, adsorption of triglycerides (TGs) and coconut oil free fatty acids (FFAs) on catalyst active sites and their activation are the primary factors governing the catalytic process of the one-step transesterification-esterification reaction for biodiesel production. The aluminosilicate (AS) catalyst's integrated Brønsted and Lewis acid sites play a critical role in the adsorption and catalytic processes. The TGs adsorbed and activated on the active sites of these catalysts are progressively converted into diacylglycerol and monoacylglycerol through a nucleophilic reaction with methanol during the transesterification process. This process results in the production of FAMEs (biodiesel), with glycerol serving as a by-product. For the esterification process, the adsorbed and activated FFAs react with methanol, resulting in the production of FAMEs and water as a by-product. Thus, these two processes are the most likely plausible mechanisms for the production of biodiesel through adsorption and catalysis.



Notes:
- R^1, R^2, R^3, and R' = C7:0, C9:0, C11:0, C13:0, C15:0, C17:0, C19:2, C19:1(E), C19:0, or C21:0.

[a]FFA = free fatty acids. [b]FAMEs = fatty acid methyl esters. [c]BAS = Brønsted acid sites. [d]LAS = Lewis acid sites.

Figure 7. Proposed catalytic mechanism for biodiesel production derived from coconut oil.

In the transesterification reaction mechanism, three reversible reaction stages may occur sequentially. These phases involve the protonation (H^+) of the active site (BAS) on the AS catalyst towards one of the carbonyl groups on the coconut oil triglyceride. After the nucleophilic attack of methanol on the carbocation leading to the carbonyl group, a tetrahedral intermediate is generated. The first FAMEs and diacylglycerols are produced by the displacement of H^+ and the cleavage of these tetrahedral intermediates. The H^+ migration in each stage is bound back to the active site of the catalyst so that the catalytic process occurs continuously and repetitively (Savaliya et al., 2023). Therefore, the final products of this reaction, mixed FAMEs and glycerol, are obtained as a whole.Meanwhile, the FFA esterification reaction mechanism is purported to facilitate its interaction with the active site (LAS) on the catalyst. This reaction process involves the same stages as the transesterification reaction in one catalytic process FAMEs and water are obtained as the final products (Guo et al., 2022). In this process, there are by-products of glycerol and water that need to be separated through washing using heated distilled water to obtain pure biodiesel products. Hence, the catalyst's characteristics, including the average crystal size, which affects the catalyst's surface area, the crystallinity, which has the potential to enhance adsorptivity, and the catalyst active sites, play an important pathways of the one-step transesterification-esterification catalytic reaction for biodiesel production.

Although the reaction mechanisms of transesterification and esterification are distinct processes, these reactions are likely to occur simultaneously and be incorporated into a one-step process. These findings highlight the importance of studying molecular interactions and catalyst characteristics in designing these reaction mechanism systems. By comprehending these factors, it may be possible to enhance of the selectivity and performance of catalysts for biodiesel production, thereby providing a promising opportunity for technological advancement in the design of catalyst materials for energy independence. Again, the experimental results obtained indicate that this catalyst has the potential to be one of the sustainable solutions for the production of biodiesel from coconut oil by offering a number of important advantages.

First, this catalyst contributes to environmental management and making it more environmentally friendly by reducing the necessity for predominantly synthetic chemicals by utilizing waste can aluminum (WCA) and rice husk silica (RHS). Second, this catalyst is capable of operating at a high efficiency with a catalyst dosage of 10 wt.% and an oil-to-methanol ratio of 1:2, thereby reducing the overall consumption of excess methanol. Third, the utilization of locally sourced WCA, RHS, and coconut oil in Indonesia not only reduces material costs but also promotes the use of sustainable, eco-friendly feedstocks. This catalyst is a practicable and environmentally favourable option in biodiesel production technology due to the combination of these features.

Comparison of the Result in This Study with Others Research

The AS-10 catalyst that was developed in this study demonstrated the highest biodiesel yield of 99.57% and a selectivity of 99.69%, indicating high-performance catalytic activity under moderate operational conditions. The AS-10 catalyst was more efficient in both yield and selectivity when compared to NiO/CaO/MgO-P (Widiarti et al., 2021) and Fe-TiO_2 (Maulidiyah et al., 2024) catalysts, as shown in Table 3. Methanol consumption can be substantially diminished by a decrease in the oil-to-methanol ratio. In summary, this minimises the total material consumption necessary for biodiesel production.

Table 3. Comparison of biodiesel production from coconut oil using various catalysts.

Catalyst	Feed : MeOH ratio	Operational conditions	Yield (%)	Selectivity (%)	Reference
AS-10	1:2	60 ºC, 6 h	99.57	99.69	This work
NiO/CaO/MgO-P	1:9	125 ºC, 3 h	89.77	99.68	Widiarti et al., 2021
NaOH	1:1	60 ºC, 6 h	80.10	-	Lugo-Méndez et al., 2021
Fe-TiO_2	5:3	UV, 3 h	30.80	-	Maulidiyah et al., 2024

This catalyst's primary advantage is its utilization of environmentally favourable raw materials, which are derived from waste can aluminum (WCA) and rice husk silica (RHS). These materials have the potential to address environmental issues, while ensuring economic feasibility. In addition, the production of sustainable and environmentally beneficial biodiesel is becoming more feasible due to the availability of local feedstock, coconut oil. The feedstock can also foster the development of local resources, contribute to the diversification of feedstocks for energy security, and align with the objectives of the SDGs. Future research should focus on the optimisation of the biodiesel production process to meet the specifications set forth by ASTM standards and pertinent regulations. Furthermore, it is imperative to conduct additional techno-economic evaluations to examine the viability and efficiency of this biodiesel production method, biodiesel, and catalyst applications in the real-world industrial sector.

Conclusion

Aluminosilicate (AS) catalysts were synthesized from waste can aluminum (WCA) and rice husk silica (RHS) with Si/Al ratios of 10, 20, and 30 using the hydrothermal method, resulting in AS-10, AS-20, and AS-30 catalysts. These catalysts have proven to be highly effective in the production of biodiesel from coconut oil, showing outstanding performance. In particular, the performance of the AS-10 catalyst reached the highest of 99.57% with a selectivity of 99.69% compared to the other catalysts which slightly decreased in yield. This difference in catalytic performance can be attributed mainly to the catalyst characteristics. The AS-10 catalyst has an average crystal size of 5.86 nm, low crystallinity of 31.25%, and Brønsted and Lewis acid sites, all of which plausible contribute to the high catalytic performance and selectivity for biodiesel production. These characteristics are also likely to provide effectiveness in adsorption and activation towards coconut oil in the catalytic process. These findings highlight that the performance and selectivity of AS-10 catalyst for biodiesel production from coconut oil has the potential to be further developed.

Recommendations

Future research should focus on further characterization of AS catalysts synthesized from WCA and RHS in order to understand the catalyst characteristics and plausible catalytic mechanisms more comprehensively so that catalysts with good activity, selectivity, and stability can be obtained. In addition, testing this catalyst on non-edible oil is necessary to increase the diversification of feedstocks. Supporting biodiesel analysis (e.g. ^{13}C-NMR and ^{1}H-NMR analysis), as well as testing the physical and chemical properties of biodiesel according to ASTM standards and applicable regulations also need to be evaluated. Finally, studies on the scalability and environmental impact assessment of catalysts and biodiesel production processes can be conducted to ensure effectiveness, techno-economic feasibility, and sustainability for large-scale applications.

CRediT Authorship Contribution Statement

Ganjar Andhulangi: Writing – original manuscripts, Methodology, Investigation, Data curation, Software, Visualization, Project administration, Funding acquisition. *Wega Trisunaryanti:* Writing – review & editing, Supervision, Validation, Formal analysis. *Wasinton Simanjuntak & Kamisah Delilawati Pandiangan*: Supervision, Conceptualization, Methodology, Resources, Validation, Formal analysis. *I Ilim:* Supervision, Validation, Formal analysis. *H Herliana & K Khasandra:* Investigation, Methodology, Data curation.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM Journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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