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Preparation and Characterization of Natar Clay Treated with an Aluminum-Based Solution for Reducing Peroxide Value and Free Fatty Acid Content in Waste Cooking Oil

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Abstract: Repeated heating of cooking oil promotes hydrolytic and oxidative degradation, resulting in elevated levels of peroxide compounds and free fatty acids (FFAs) that compromise oil quality. In this study, Natar clay was treated with a hydrolyzed aluminum-based solution prepared from $AlCl_3$ and KOH, followed by thermal treatment, and evaluated as an adsorbent for reducing peroxide value and FFA content in waste cooking oil. The structural, morphological, and textural characteristics of the treated clay were analyzed using X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), and nitrogen adsorption-desorption analysis. The treated Natar clay exhibited reflections attributable to a kaolinite-related phase with aggregated pseudohexagonal plate-like particles. The specific surface area and pore volume of treated Natar clay were 60.994 m^2/g and 0.237 cm^3/g. Adsorption treatment reduced the peroxide value from 37.80 to 4.50 meq O_2/kg and decreased the FFA content from 0.40 ± 0.01% to 0.08 ± 0.02%, corresponding to reductions of 88% and 80%, respectively. These results demonstrate the potential of Natar clay treated with an aluminum-based solution as a locally sourced adsorbent for improving the quality of waste cooking oil.

Keywords: *Natar clay; adsorption; waste cooking oil; free fatty acids; peroxide value*

Introduction

Cooking oil plays an essential role in food preparation and is considered a staple commodity in many households in Indonesia [1]. Increasing global demand for cooking oil has contributed to supply constraints and considerable price fluctuations [2], [3]. Under these conditions, repeated reuse of cooking oil may be adopted as a cost-saving practice by some households and small-scale food vendors [4].

Repeated heating of cooking oil promotes chemical degradation through hydrolysis and oxidation processes, leading to the formation of free fatty acids (FFAs) and peroxides [5]. These oxidative by-products not only alter the physicochemical properties of the oil but also pose serious health risks when consumed, including increased likelihood of hypertension, obesity, hypercholesterolemia, and carcinogenic effects [6], [7]. Therefore, reducing peroxide compounds and FFAs is relevant for improving physicochemical quality in waste cooking oil.

Among the various treatment approaches, adsorption has attracted considerable attention due to its operational simplicity, relatively low cost, and effectiveness in removing degradation products from

waste cooking oil [8], [9]. Numerous studies have explored various low-cost adsorbents, including activated carbon, agricultural by-products, and clays [10] - [12]. Notably, clay minerals have shown promising performance in adsorbing degradation products from waste oil compared to several biomass-derived adsorbents [13], [14].

Clay minerals are naturally occurring aluminosilicates composed of alternating layers of tetrahedral silica and octahedral alumina sheets [15]. Although clay has been widely investigated as a low-cost and effective adsorbent, the adsorption performance of some natural clays may be constrained by limited specific surface area, pore accessibility, and availability of surface adsorption sites [16]. Chemical treatment is therefore commonly applied to improve their textural and surface characteristics [17] - [19].

One approach to improving the adsorption properties of clay involves treatment with hydrolyzed metal-containing solutions, followed by thermal treatment. In several clay systems, this approach can promote the development of porous structures with improved surface area and pore volume, thereby enhancing adsorption performance [20], [21]. Metal-treated clay materials based on bentonite- or montmorillonite-containing precursors have been investigated for waste cooking oil treatment. Permana et al. [22] reported maximum reductions of approximately 76.9% in FFA content and 80% in peroxide value using CuO-modified nanobentonite. In another study, Al/Cr-pillared clay reduced the acid value from 2.47 to 0.09 mg KOH/g and the peroxide value from 57.5 to 7.5 meq O_2/kg [11].

Building on these findings, the investigation of alternative clay precursors offers an opportunity to broaden the application of treated clay adsorbents for reducing peroxide and FFA. In this study, clay collected from Natar, South Lampung, was treated with a hydrolyzed aluminum-based solution followed by thermal treatment. The resulting material was characterized and evaluated for the simultaneous reduction of peroxide value and FFA content in waste cooking oil.

Method

Preparation of Natar Clay Treated with an Aluminum-Based Solution

A total of 200 g of raw clay from Natar, South Lampung, was dispersed in distilled water and stirred for 5 minutes. The suspension was decanted, and the sediment was collected, dried at 100 °C for 2 hours, ground, and sieved through a 200-mesh screen. For acid activation, 250 mL of 0.2 M H_2SO_4 was added to the dried clay and stirred for 10 minutes. The suspension was left to stand for 24 hours at room temperature, then filtered. The sample was thoroughly washed with distilled water to remove sulfate ions, dried at 100°C for 2 hours, ground, and then sieved through a 100-mesh screen.

The activated clay was subsequently treated with an aluminum-based solution using a clay-to-solution ratio of 5 g:70 mL. The treatment solution was prepared by dissolving $AlCl_3 \cdot 6H_2O$ in deionized water to obtain a 0.2 M solution, followed by the dropwise addition of 0.4 M KOH until the pH reached 2. The resulting hydrolyzed aluminum-based solution was mixed with the activated clay and aged at room temperature for 24 h. The solid material was then washed with distilled water to remove residual ions, dried at 100 °C for 2 h, ground, and calcined at 400 °C for 2 h. The resulting material is hereafter referred to as aluminum-based solution-treated Natar clay.

Adsorption of Waste Cooking Oil

Waste cooking oil was obtained from a local fried chicken vendor. The adsorption conditions were adapted from a previously reported method for waste cooking oil purification with modifications. For adsorption, 5 g of treated Natar clay was mixed with 20 mL of oil (1:4 w/v ratio) and stirred at 40 °C for 15 minutes to limit prolonged thermal exposure [11]. The mixture was then centrifuged, and the supernatant was collected for further analysis.

Characterization

The crystalline structure of the samples was analyzed using X-ray diffraction (XRD, Rigaku Miniflex) with Cu Kα radiation (λ = 1.5406 Å). Functional groups were identified via Fourier Transform Infrared Spectroscopy (FTIR, Shimadzu Prestige 21). Surface morphology was observed using a scanning electron microscope (SEM, Thermo Scientific Quanta 650). Surface area and pore structure were determined by nitrogen adsorption–desorption isotherms (BELSORP MINI X). The BET method was used to calculate surface area, while the BJH method was applied for pore volume and diameter.

Determination of Peroxide Value

Approximately 5.00 ± 0.01 g of oil was mixed with 50 mL of glacial acetic acid-chloroform (3:2 v/v). The solution was stirred until homogeneous, followed by the addition

of 0.5 mL saturated KI and shaking for 1 minute. Then, 30 mL of distilled water was added. The released I_2 was titrated with standardized $Na_2S_2O_3$ until the yellow color faded. After adding 0.5 mL of 1% starch solution, the titration continued until the blue color disappeared. Each sample was analyzed in duplicate.

$$PV, meq\ peroxide/kg = \frac{1000 \times N \times (V_1 - V_0)}{W}$$

Where:
N = normality of sodium thiosulfate standard
V_0 = volume of sodium thiosulfate used to titrate the sample (mL)
V_1 = volume of sodium thiosulfate used to titrate the blank (mL)
W = mass of sample (g)

Determination of Free Fatty Acid (FFA) Calculated as Palmitic Acid

FFA was measured by dissolving 5.00 ± 0.01 g of oil in 50 mL of warm ethanol, followed by the addition of five drops of 1% phenolphthalein. The solution was titrated with standardized 0.1 N KOH until a persistent pale pink color appeared. All samples were analyzed in duplicate.

$$\%\ Free\ fatty\ acid, as\ palmitic\ acid = \frac{25{,}6 \times V \times N}{W}$$

Where:
V = volume of potassium hydroxide used to titrate the sample (mL)
N = normality of potassium hydroxide
W = mass of sample (g)

Results and Discussion

The phase composition of the Natar clay-based adsorbent was analyzed using X-ray diffraction (XRD), as presented in **Figure 1**. The diffraction pattern exhibits characteristic peaks of kaolinite at the (2 theta) positions of 12.39°, 25.05°, and 38.50° [23]. These reflections indicate the presence of kaolinite-related minerals in the treated clay. Additional reflections, observed at 20.9° and 26.8°, are attributed to quartz, confirming the presence of quartz as a companion mineral phase. No distinct reflections attributable to a separate crystalline alumina phase were detected. Similar observations have been reported for clay materials treated with aluminum-containing solutions [19].

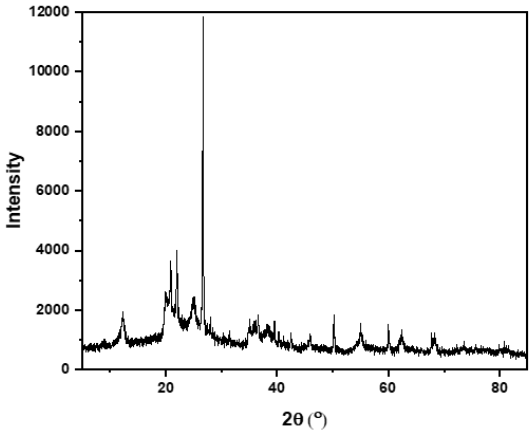

Figure 1. XRD pattern of treated Natar Clay

The FTIR spectrum of the prepared material is shown in **Figure 2**. The absorption band observed in the range around 3600 cm^{-1} is attributed to the O-H stretching of inner hydroxyl groups in the clay layers [24]. Additional bands at 3450.45 and 1631 cm^{-1} are associated with water molecule vibrations, indicating residual hydration of the treated material. The band at 912.33 cm^{-1} corresponds to Al-OH bending, typical of kaolinite group minerals, while the Al-O stretching appears at 430.13 cm^{-1} [25]. A band at around 536.21 cm^{-1} originates from the Si-O-Al vibration. Strong Si-O stretching vibrations are observed at 1035.77 cm^{-1} and 692.44 cm^{-1}, corresponding to in-plane and out-of-plane modes of the SiO_4 tetrahedra. Additionally, Si-O-Si bending vibrations are evident at 468.71 cm^{-1} [24], [26]. The presence of hydroxyl-containing surface groups may facilitate interactions with polar degradation products during adsorption.

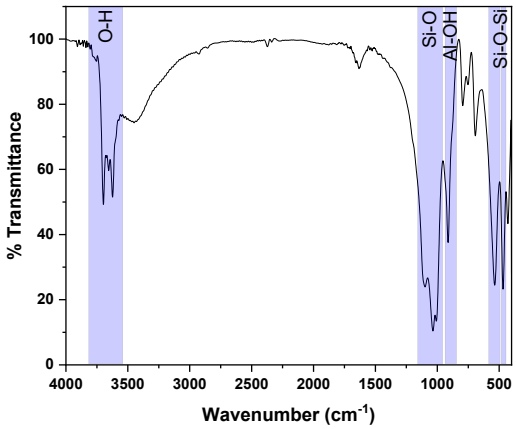

Figure 2. FT-IR spectrum of treated Natar Clay

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The treated Natar clay consists of aggregated pseudohexagonal plate-like particles, as shown in **Figure 3,** which is consistent with the morphology commonly associated with kaolinite-containing clay materials [27]. The textural properties were further evaluated using nitrogen adsorption-desorption analysis. As shown in **Figure 4**, the isotherm exhibits a Type II profile with an H3-type hysteresis loop. This type of hysteresis is commonly associated with plate-like particles [28]. This observation is consistent with the SEM morphology. The relatively limited adsorption at low relative pressures suggests a limited contribution from micropores, while the pronounced increase in adsorption at higher relative pressures may be associated with larger pores and interparticle voids.

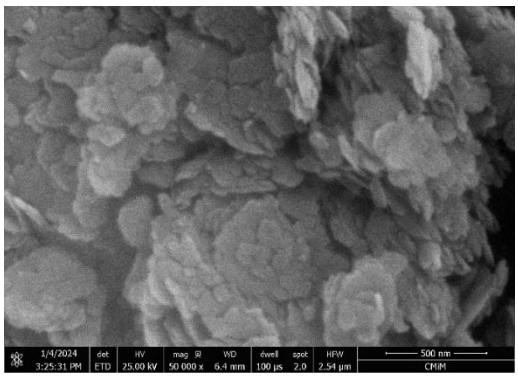

Figure 3. SEM image of treated Natar clay

The treated Natar clay exhibited a specific surface area of 60.994 m^2/g and a pore volume of 0.237 cm^3/g, indicating a porous structure suitable for adsorption applications. The pore size distribution curve (**inset Fig. 4**) exhibits multiple peaks, indicating a heterogeneous pore architecture. With an average pore radius of 1.704 nm, the material falls within the mesoporous range.

The adsorption performance of the treated Natar clay was evaluated based on its ability to reduce the peroxide value (PV) and free fatty acid (FFA) content of waste cooking oil. The PV was determined by iodometric titration, in which peroxide compounds oxidize iodide ions (I^-) to iodine (I_2), followed by titration with sodium thiosulfate ($Na_2S_2O_3$). According to SNI 7709:2012, edible cooking oil should have a PV below 10 meq O_2/kg [29]. The untreated waste cooking oil exhibited a PV of 37.80 meq O_2/kg, which exceeded the specified reference limit. After adsorption treatment with the treated Natar clay, the PV decreased to 4.50 meq O_2/kg, corresponding to an 88% reduction.

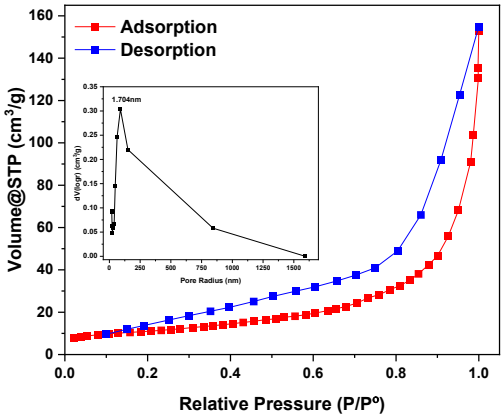

Figure 4. The N_2 adsorption-desorption isotherm (inset figure: pore size distribution of treated Natar clay)

The FFA content was determined using an alkalimetric titration method, in which free fatty acids react with potassium hydroxide (KOH). According to SNI 7709:2012, the maximum allowable FFA content in edible palm cooking oil is 0.3% [29]. The untreated waste cooking oil exhibited an FFA content of 0.40 ± 0.01%, which exceeded the specified reference limit. After adsorption treatment with the treated Natar clay, the FFA content decreased to 0.08 ± 0.02%, corresponding to an 80% reduction.

The observed reduction in peroxide value and FFA content may be associated with the porous architecture and hydroxyl-containing surface groups of the treated clay. The measured surface area and pore volume provide accessible regions for interactions with degradation products, while surface hydroxyl groups may facilitate interactions with polar compounds [30].

Table 1. Comparison of PV and FFA removal performance of clay-based adsorbents for waste cooking oil purification

Adsorbent	Adsorbent to oil ratio	Contact time (min)	PV reduction (%)	FFA reduction (%)	Ref.
Activated Ranong Kaolinite	15 g/ 85 g	30	75.7	26	[13]
Al/Cr Pillared Clay	0.2 g/ 10 mL	60	91.30	96.35	[11]
Nano bentonite-CuO	2 g/ 100 g	75	80	76.69	[22]
Activated Marauke Clay	5 g/ 100 mL	300	n.r	81.66	[14]
Fuller Earth	4.5 g/ 95.5 g	30	74	58.77	[31]

Fly ash-modified bentonite	5 g/ 50 g	90	n.r	70	[32]
Treated Natar Clay	5 g/ 20 mL	15	88	80	This work

n.r = not reported

As shown in **Table 1**, the treated Natar clay achieved reductions of 88% in peroxide value and 80% in FFA content within a contact time of 15 min. These values fall within the range reported for other clay-based adsorbents. However, direct comparison should be made cautiously because the studies employed different adsorbent loadings, contact times, temperatures, initial oil qualities, and analytical conditions.

Conclusions

The treated Natar clay exhibited textural and surface characteristics relevant to reducing the peroxide value and free fatty acid content of waste cooking oil. The peroxide value decreased to 4.50 meq O_2/kg, while the FFA content decreased to 0.08 ± 0.02%, corresponding to reductions of 88% and 80%, respectively. XRD analysis indicated the presence of kaolinite-related crystalline features and quartz as an accompanying mineral phase, while SEM analysis revealed aggregated pseudohexagonal plate-like particles. The treated material exhibited a specific surface area of 60.994 m^2/g, a pore volume of 0.237 cm^3/g, and a heterogeneous pore architecture. These textural and surface characteristics may contribute to the removal of oxidative and acidic degradation products from waste cooking oil. The results demonstrate the potential of treated Natar clay as a locally sourced adsorbent for reducing peroxide value and FFA content in waste cooking oil. Further surface-interaction studies would be required to establish the dominant adsorption mechanism.

Conflicts of interest

"There are no conflicts to declare".

References

[1] R. Rosmeika et al., "Environmental impact of palm cooking oil: a case study in Sumatra, Indonesia," Environmental Science and Pollution Research, vol. 32, no. 43, pp. 24839–24857, Sep. 2025, doi: 10.1007/s11356-025-37056-1.

[2] R. R. Febrinda, "Kebijakan Pemerintah Dalam Mengatasi Kenaikan Harga Minyak Goreng," Trade Policy Journal, vol. 1, no. 1, pp. 25–32, Dec. 2022.

[3] Y. Purbawa, I. G. M. Y. Bakti, H. J. Purba, N. J. Astrini, R. P. Putra, and S. Sumaedi, "Acceptable price of packaged palm cooking oil amid scarcity in Indonesia," Journal of Revenue and Pricing Management, vol. 22, no. 6, pp. 446–454, Dec. 2023, doi: 10.1057/s41272-023-00428-8.

[4] H. N. Muhammad, F. Nikmah, N. U. Hidayah, and A. K. Haqiqi, "Arang Aktif Kayu Leucaena Leucocephala sebagai Adsorben Minyak Goreng Bekas Pakai (Minyak Jelantah)," Physics Education Research Journal, vol. 2, no. 2, p. 123, Aug. 2020, doi: 10.21580/perj.2020.2.2.6176.

[5] P. S. Dewi and M. Ulfah, "Quality Test of Palm Cooking Oil Used Repeatedly Based on Free Fatty Acid Content, Moisture Content, Peroxide Number," Journal of Science and Technology Research for Pharmacy, vol. 1, no. 1, pp. 34–41, Mar. 2021, doi: 10.15294/jstrp.v1i1.44461.

[6] K. Ganesan, K. Sukalingam, and B. Xu, "Impact of consumption of repeatedly heated cooking oils on the incidence of various cancers-A critical review," Crit. Rev. Food Sci. Nutr., vol. 59, no. 3, pp. 488–505, 2019.

[7] C. Sayon-Orea, S. Carlos, and M. A. Martínez-Gonzalez, "Does cooking with vegetable oils increase the risk of chronic diseases?: A systematic review," Jul. 07, 2015, Cambridge University Press. doi: 10.1017/S0007114514002931.

[8] M. L. T. Ayu Putranti, S. K. Wirawan, and I. M. Bendiyasa, "Adsorption of Free Fatty Acid (FFA) in Low-Grade Cooking Oil Used Activated Natural Zeolite as Adsorbent," in IOP Conference Series: Materials Science and Engineering, Institute of Physics Publishing, Feb. 2018. doi: 10.1088/1757-899X/299/1/012085.

[9] S. A. E. A. Ismail, A. M. El-Anany, and R. F. M. Ali, "Regeneration of used frying palm oil with coffee silverskin (CS), CS Ash (CSA) and nanoparticles of CS (NCS)," J. Oleo Sci., vol. 66, no. 8, pp. 897–905, 2017, doi: 10.5650/jos.ess17015.

[10] A. Phetrungnapha, N. Wiengnak, and K. Maikrang, "Removal of free fatty acid from waste cooking oil using an adsorbent derived from cassava peels," Korean Journal of Chemical Engineering, vol. 40, no. 9, pp. 2253–2262, 2023, doi: 10.1007/s11814-023-1413-3.

[11] T. E. Triandhani, T. Taslimah, and S. Sriyanti, "Pilarisasi Lempung Dengan Al/Cr sebagai Adsorben Minyak Sisa Pakai," Greensphere: Journal of Environmental Chemistry, vol. 1, no. 1, pp. 13–18, 2021.

[12] W. D. P. Rengga, A. Seubsai, S. Roddecha, A. Yudistira, and A. D. Wiharto, "Isotherm adsorption of free fatty acid in waste cooking oil used activated carbon of banana peel as bio-adsorbent," in Journal of Physics: Conference Series, IOP Publishing Ltd, Jun. 2021. doi: 10.1088/1742-6596/1918/3/032008.

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[13] N. Worasith and B. A. Goodman, "Activated Kaolin Minerals as Bleaching Clays for Prolonging the Useful Life of Palm Oil in Industrial Frying Operations," JAOCS, Journal of the American Oil Chemists' Society, vol. 97, no. 4, pp. 389–396, Apr. 2020, doi: 10.1002/aocs.12327.

[14] M. Rasyiid Maulana, J. Y. Parlindungan, A. L. Rettob, L. Ferawaty Siregar, and H. Hitijahubessy, "Characterization of Clay from Merauke Regency and Its Utilization as an Adsorbent of Free Fatty Acids in the Purification of Waste Cooking Oil," Fullerene Journ.Of Chem, vol. 10, no. 2, pp. 128–135, 2025, doi: 10.37033/fjc.v10i2.747.

[15] N. Kumari and C. Mohan, "Basics of clay minerals and their characteristic properties," Clay Clay Miner, vol. 24, no. 1, pp. 1–29, 2021.

[16] M. E. Roca Jalil, R. S. Vieira, D. Azevedo, M. Baschini, and K. Sapag, "Improvement in the adsorption of thiabendazole by using aluminum pillared clays," Appl. Clay Sci., vol. 71, pp. 55–63, Jan. 2013, doi: 10.1016/j.clay.2012.11.005.

[17] Q. Zhang et al., "Adsorption of deoxynivalenol by pillared montmorillonite," Food Chem., vol. 343, May 2021, doi: 10.1016/j.foodchem.2020.128391.

[18] Y. Utubira, F. R. Lesbatta, J. B. Manuhutu, and V. Kayadoe, "Adsorption of tartrazine dye using Al2O3-pillared clay," in AIP Conference Proceedings, AIP Publishing LLC, 2021, p. 050022.

[19] P. Falaras, F. Lezou, G. Seiragakis, and D. Petrakis, "Bleaching Properties of Alumina-Pillared Acid-Activated Montmorillonite," Clays and Clay Minerals, vol. 48, no. 5, p. 0, 2000, doi: 10.1346/CCMN.2000.0480507.

[20] A. Parodia, J. A. Prasniski, F. Bertella, and S. B. C. Pergher, "Keggin-al13 polycations: Influence of synthesis and intercalation parameters on the structural properties of al-pillared clays," Minerals, vol. 11, no. 11, Nov. 2021, doi: 10.3390/min11111211.

[21] S. Ts. Khankhasaeva, S. V. Badmaeva, and M. V. Ukhinova, "Adsorption of diclofenac onto Fe2O3-pillared montmorillonite: Equilibrium, kinetics and thermodynamic studies," J. Mol. Liq., vol. 380, Jun. 2023, doi: 10.1016/j.molliq.2023.121725.

[22] E. Permana et al., "Optimization of Nanobentonite-CuO Adsorption for Reducing 3-MCPDE, Free Fatty Acids, and Peroxide Values in Bulk Cooking Oil: A Study of Adsorption Efficacy and Isotherm Modeling," Indonesian Food Science and Technology Journal, vol. 8, no. 1, pp. 108–116, 2024, doi: 10.22437/ifstj.v8i1.36390.

[23] N. Nabbou et al., "Removal of fluoride from groundwater using natural clay (kaolinite): Optimization of adsorption conditions," Comptes Rendus Chimie, vol. 22, no. 2–3, pp. 105–112, Feb. 2019, doi: 10.1016/j.crci.2018.09.010.

[24] T. Nazdracheva, A. Morozov, V. Yavna, and A. Kochur, "Study of hydration of kaolinite and montmorillonite mixture by IR spectroscopy," J. Mol. Struct., vol. 1250, Feb. 2022, doi: 10.1016/j.molstruc.2021.131871.

[25] R. E. Nugraha et al., "The effect of structure directing agents on micro/mesopore structures of aluminosilicates from Indonesian kaolin as deoxygenation catalysts," Microporous and Mesoporous Materials, vol. 315, Feb. 2021, doi: 10.1016/j.micromeso.2021.110917.

[26] A. Kumar and P. Lingfa, "Sodium bentonite and kaolin clays: Comparative study on their FT-IR, XRF, and XRD," in Materials Today: Proceedings, Elsevier Ltd, 2020, pp. 737–742. doi: 10.1016/j.matpr.2019.10.037.

[27] A. M. Georgescu, G. Brabie, I. D. Nistor, C. Penot, and F. Nardou, "Synthesis and characterization of Cr-pillared clays: modelling using factorial design methodology," Journal of Porous Materials, vol. 22, no. 4, pp. 1009–1019, Aug. 2015, doi: 10.1007/s10934-015-9975-z.

[28] M. Thommes et al., "Physisorption of gases, with special reference to the evaluation of surface area and pore size distribution (IUPAC Technical Report)," Pure and Applied Chemistry, vol. 87, no. 9–10, pp. 1051–1069, Oct. 2015, doi: 10.1515/pac-2014-1117.

[29] Badan Standardisasi Nasional, SNI 7709:2012 Minyak Goreng Sawit. 2012.

[30] P. Kanwal et al., "Analysis and removal of free fatty acid and peroxides from waste cooking oil using Fuller's earth-China clay adsorbent by titration methods," Analytical Methods in Environmental Chemistry Journal, vol. 8, no. 4, pp. 67–84, Sep. 2025, doi: 10.24200/amecj.v8.i04.1062.

[31] A. O. Etim, P. Musonge, and J. K. Bwapwa, "Used Frying Oil Decolorization Study Using Eco-Friendly Nano-Clay Adsorbent: Process Optimization by RSM and ANFIS Approaches," ChemistrySelect, vol. 11, no. 2, Jan. 2026, doi: 10.1002/slct.202505218.

[32] D. M. Widjonarko, W. M. Naufal, A. M. Fadhilah, Y. Hidayat, and S. Wahyuningsih, "Adsorption kinetics and surface interaction of fly ash-modified bentonite for free fatty acid removal from waste cooking oil," Next Materials, vol. 12, Jul. 2026, doi: 10.1016/j.nxmate.2026.102140.