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Transforming Adversity into Opportunity: Leveraging Sidoarjo's Volcanic Mud for Civil and Environmental Engineering

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ABSTRACT
The Sidoarjo volcanic mudflow disaster in East Java, which began in 2006, has caused ongoing environmental and socio-economic challenges. However, the volcanic mud's unique composition, rich in silica (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3), presents significant potential for resource recovery. This review utilizes a *Systematic Literature Review* (*SLR*) approach, following the *PRISMA* 2020 guidelines, to analyze 49 relevant publications from 2013 to 2024. The findings indicate that treated Sidoarjo mud can be effectively utilized in various civil engineering applications, including ceramic tiles, concrete bricks, geopolymer binders, and road base stabilizers, fulfilling national performance standards while contributing to reduced carbon emissions and construction costs. Moreover, Sidoarjo mud demonstrates its value in environmental engineering, showing effectiveness as an adsorbent for heavy metals, dyes, and organic pollutants in water treatment, as well as serving as a catalyst support in biodiesel production. This review underscores the multidisciplinary value of Sidoarjo mud, positioning it as a key material in advancing circular economy practices and promoting environmentally sustainable innovations within the built environment.

Keyword: Sidoarjo mud; Construction materials; Wastewater treatment; Adsorbent; Catalyst; Waste to Materials

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INTRODUCTION

The Sidoarjo volcanic mudflow disaster is a volcanic mud eruption triggered by hydrocarbon exploration, which occurred in Sidoarjo, East Java, in 2006. Commonly referred to as the *Lapindo mudflow* or *Sidoarjo mud*, this industrial catastrophe flooded approximately 64 hectares of fertile farmland, residential areas, industrial zones, schools, and critical infrastructure. Despite containment efforts, the mudflow proved uncontrollable. To alleviate the pressure on the retaining embankments surrounding the submerged areas, authorities diverted the mud into nearby rivers, ultimately forming a new delta at their estuary. At its peak, the eruption discharged approximately 150,000 m^3 of mud per day. To this day, mud disposal and management remain significant environmental and economic challenges. The massive volume of untreated mud raises concerns about land use conflicts, environmental degradation (groundwater contamination, land subsidence, and airborne particulate pollution), and socioeconomic displacement of affected communities. Sustainable utilization of *Sidoarjo mud* presents a viable solution to mitigate environmental impacts while generating economic value and reducing the vast stockpiled volume.

Sidoarjo mud represents a rich natural resource containing valuable mineral components. Its primary chemical composition consists of SiO_2 (53.40%), Al_2O_3 (23.80%), and

Fe_2O_3 (5.47%), collectively accounting for over 80% of its content (Jalil et al., 2010). While other oxides are present, they occur in significantly smaller quantities. From a physical standpoint, the mud contains 58.47% clay, 22.13% silt, and 19.40% sand (Mochni & Budhyantoro, 2021). Toxicology testing confirms that *Sidoarjo mud* does not qualify as hazardous waste (*B3*), as it contains no dangerous levels of inorganic substances (arsenic, barium, boron, lead, mercury, free cyanide) nor organic compounds (trichlorophenol, chlordane, chlorobenzene, chloroform). Research classifies *Sidoarjo mud* as clay-type soil with distinct plastic properties. Its unique composition, particularly the high silica and alumina content, gives it characteristics similar to natural clay while maintaining excellent plasticity, making it particularly suitable for construction applications. The high silica-alumina content of the mud creates a porous structure, enhancing its suitability as a natural adsorbent. Studies have demonstrated its potential in wastewater treatment and pollution control (Golomeova & Zendelska, 2016), offering sustainable solutions for environmental remediation.

Given its physical and chemical properties, along with its non-hazardous nature, *Sidoarjo mud* presents exciting opportunities for sustainable resource utilization. Rather than being treated as mere waste, this material can be transformed into valuable products that align perfectly with waste minimization and circular economy principles. Researchers have been actively exploring multiple applications across civil and environmental engineering fields. In construction, the mud shows particular promise as a raw material or additive for construction building products, for soil stabilization due to its favorable geotechnical properties, in embankment construction where it enhances soil strength, and as a solution to mitigate land subsidence risks. On the environmental engineering side, innovative uses include a low-cost adsorbent for pollutants (heavy metals, dyes, and crude palm oil spills), a base material for synthesizing novel compounds like magnetic silica, and catalyst applications in oil waste transesterification.

Previous review papers have primarily focused on the environmental risks of *Sidoarjo volcanic mud*, such as its impact on ecosystems (Alfina et al., 2024) or its role in construction materials (Hardjito & Antoni, 2013). However, this paper provides a more comprehensive and up-to-date synthesis by integrating recent research advancements in environmental remediation, sustainable material development, and the circular economy approach. Unlike previous reviews that focused on specific sectors, this review paper evaluates multidisciplinary applications—from civil engineering applications such as ceramics, concrete bricks, cement, paving blocks, soil stabilization, and clay stabilization, to environmental engineering such as adsorbents and catalysts, and even alternative energy—while addressing gaps in scalability and commercialization. By systematically comparing existing methods and proposing future research directions, this review offers a novel perspective on optimizing *Sidoarjo volcanic mud* utilization, contributing to both scientific and practical discourse on transforming the mud from a waste challenge into a resource opportunity.

METHOD

This paper employs a systematic literature review (SLR) approach, following the PRISMA (Preffered Reporting Items for Systematic Reviews and Meta-Analyses) 2020 guidelines, to ensure a rigorous and transparent methodology for collecting, summarizing, and synthesizing credible scientific resources (Roberts et al., 2006). The review process consists of

keyword identification, document screening and final paper selection conducted through Science Direct and Google Scholar. The search strategy using specific keywords which is "Lapindo mud", "Sidoarjo Mud", and "Sidoarjo Volcanic Mud". The inclusion criteria for this review comprise studies focusing Sidoarjo volcanic mud applications in Civil Engineering (construction materials, road materials) and Environmental engineering (adsorbent and catalysts) The selected literature was limited to English and Bahasa Indonesia publications from 2013-2024, with full-text availability for analysis. After applying this filters, 49 eligible papers were selected for in-depth analysis. The PRISM flow diagram (Fig. 1) illustrates the search strategy and screening process.

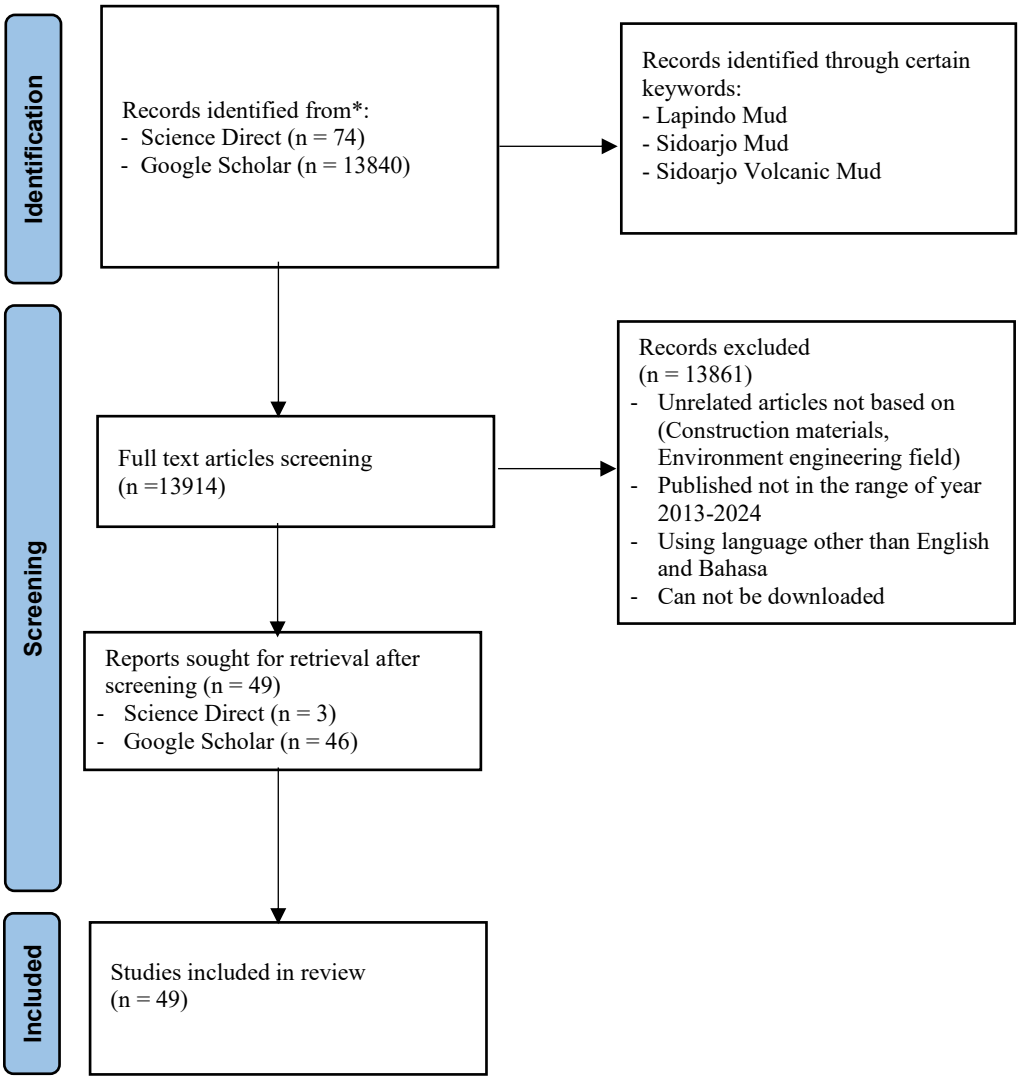

Figure 1. Flow Diagram for Systematic Literature Review

RESULTS AND DISCUSSION

Sidoarjo Mud Characteristics

The Sidoarjo Volcanic Mud has physical characteristics of dark grey color, fine-grained, highly plasticity and has a high dry shrinkage value (Lasino & Sugiarto, 2018). The main components of this mud are SiO_2, Al_2O_3 and Fe_2O_3, which has total more than 80% with SiO_2 content at 53,40%, Al_2O_3 at 23,80% dan Fe_2O_3 at 5,47%. Although other oxides are present, they are in smaller amounts. This composition remains nearly consistent over time and

at different radius of 500, 1000, 1500 meters from the eruption center that are shown in Table 1 (Ciptawati et al., 2022).

Tabel 1. Analysis of Oxide Content in Sidoarjo Mud using XRF

Oxides	Percentage (%) (500 m radius)	Percentage (%) (1000 m radius)	Percentage (%) (1500 m radius)
Al_2O_3	14 %	14 %	13 %
SiO_2	45,0 %	45,3 %	43,3%
K_2O	2,76 %	2,64%	2,64 %
CaO	6,05 %	6,34 %	6,30 %
TiO_2	1,91 %	1,88 %	2,01 %
V_2O_5	0,076 %	0,081 %	0,083 %
Cr_2O_3	0,077 %	0,076 %	0,085 %
MnO	0,29 %	0,30 %	0,35 %
Fe_2O_3	24,1%	23,7%	25,9 %
NiO	0,02 %	-	-
CuO	0,084 %	0,079 %	0,092 %
ZnO	0,04 %	0,04%	0,04 %
SrO	0,60 %	0,56 %	0,46 %
MoO_3	4,6%	4,5 %	4,8%
Eu_2O_3	0,35%	0,35 %	0,40 %
Yb_2O_3	0,05 %	-	-
Re_2O_7	0,1 %	0,1 %	0,2 %
P_2O_5	-	-	0.62 %

Source: (Ciptawati et al., 2022)

The composition of Sidoarjo mud has high silica and alumina contents that are give similar properties to natural clay, with proportions of 58.47% clay, 22.13% silt and 19.40% sand. The clay type in Sidoarjo mud contributes to the soil's plastic properties (Mochni & Budhyantoro, 2021). Table 2 presents the results of physical and mechanical properties related to the plasicity of Sidoarjo mud.

Table 2. Test Results for Physical and Mechanical Properties of Sidoarjo Mud

No	Description	Results	Limits	Information
	Plasticity			
1	Liquid Limit (LL).....%	65,50	-	-
	Plasticity Limit (PL).....%	28,10		
	Plasticity Index (PI) .....%	37,40	<30,00	highly plastic
2	Classification	CH	-	plastic silt
3	Wet Weight (g/cm3)	1,79	-	-

Source: (Masbuhin, 2020)

The morphology of Sidoarjo mud was observed using Scanning Electron Microscopy (SEM). The Sidoarjo mud's morphology appears as interconected sheets forming large particles in the micrometer size range (A'yuni et al., 2023). In the SEM analysis, Sidoarjo mud particles resemble soft clumps composed of irregular and porous particles (Jalil et al., 2010).

X-ray Diffraction (XRD) analysis can help to further investigate Sidoarjo mud's composition, which is particularly effective in identifying crystalline phases within the material. The XRD results indicate that Sidoarjo mud has a predominantly amorphous structure, with quartz (SiO_2) being the primary crystalline component. Additionally, several other minerals were identified, including mullite ($3Al_2O_3 \cdot 2SiO_2$ or $2Al_2O_3 \cdot SiO_2$), Magnetite (Fe_3O_4), Hematite (Fe_2O_3), Rutile (TiO_2) (Yolanda Putri & Fauzi, 2019). The XRD diffractogram based on Rafiza et al. (2014), it displays distinct peaks corresponding to these mineral phases, which notably: Fe2O3 exhibits prominent peak at 2θ = 28.86°; SiO2 shows strong reflections at 2θ = 26.64° dan 29.52°; Al2O3 peaks are observed at 2θ = 21.82°; 35.53°; and 53.11° (Tsaqif et al., 2024). Interestingly, the analysis also detected the presence of sulfur compounds, evidenced by two intense diffraction peaks at 2θ: 35.6° and 70.4°. This finding suggests that sulfur-bearing minerals or secondary sulfate phases may contribute to the mud's geological properties.

The Fourier Transform Infrared Spectroscopy (FTIR) analysis of Sidoarjo mud identified characteristic functional groups based on absorption peaks at the following wavenumbers: 3200, 1623, 1376 and 983 cm^{-1} corresponding to hydroxyl groups (OH-K and OH-Ca); 455 cm^{-1} associated to Si–O–Si bending vibrations; 880 cm^{-1} associated with Si-O or Si-OH bonds, 1410 cm^{-1} indicate of O-C-O stretching (carbonate groups); and 1600-3500 cm^{-1} indicate a broad reflecting H-O-H stretching vibrations of water molecules (Mustafa Al Bakri et al., 2012; Talib et al., 2016).

Toxicological testing confirms that Sidoarjo mud does not qualify as hazardous waste (B3) for inorganic substances such as arsenic, barium, boron, lead, mercury, free cyanide, and similar contaminants, nor for organic compounds including trichlorophenol, chlordane, chlorobenzene, chloroform, and others (Masbuhin, 2020; Pertiwi & Theresia Maria, 2012). Additonally, radiochemical analysis detected naturally occurring radionuclides specifically ^{226}Ra (radium-226), ^{232}Th (thorium-232), ^{40}K (potassium-40) and 238 U (uranium-238). All within acceptable concentration limits for construction material applications. Furthermore, measured gamma (γ) radiation exposure and radium equivalent activity levels also fall within internationally recognized safety thresholds (Razak et al., 2013).

Construction Material Applications

Several studies have explored the characterization of Sidoarjo volcanic mud and its potential as a construction material. Although its chemical composition appeared promising, early attempts were largely unsuccessful likely due to its unreactive crystalline microstructure. However, more recent findings show that treatments such as calcination at high temperature could substantially improve its reactivity which holds significant promise for construction applications (Ekaputri, 2007). Supporting this, Lasino & Sugiarto (2018) reported that Sidoarjo Volcanic Mud possesses physical and mechanical properties suitable for building materials, including a high plasticity index of 37.40%, indicating it is highly plastic. The high plasticity index of Sidoarjo Volcanic Mud makes it a promising construction material due to its moldability, cohesion, and adaptability to stabilization methods. When combined with proper treatment (e.g., thermal activation or cement blending), it can achieve both workability and strength, supporting sustainable construction applications (Jalil et al., 2010).

The use of Sidoarjo Volcanic Mud in construction materials has gained attention because of its high silica and alumina content, which makes it chemically suitable for pozzolanic reactions. Various applications have been tested, including ceramic roof tiles, lightweight bricks, concrete blocks, and cement mixtures. Studies from Nuri & Retno (2015) and Sriatun et al. (2013) showed that treated Sidoarjo Volcanic Mud could meet or exceed the Standar Nasional Indonesia (SNI) for strength and durability in roof tiles, particularly when fired between 800-900°C, achieved compressive strengths up to 142 kg/m² and fracture modulus of 126.7 kg/cm² (Nuri & Retno, 2015). The research from Sriatun et al. (2013) further demonstrated that additives such as dolomite (15%) and phosphate (10%) optimized tile density to 1.62 g/cm³ and hardness 3343.95 kg/cm², outperforming the market standards material by 20%.

Meanwhile, other research from Rosanti & Winanti (2016) and Dibiantara et al. (2015) explore Sidoarjo volcanic mud's potential in lightweight concrete bricks which results in its enhanced performance using calcined mud (800°C) combined with additives such as fly ash and kenaf fiber (0.2-0.5%) yielded the compressive strengths of 2.16-4.28 MPa, complying with the SNI class III standard. Adding excessive fiber more than 0.2% compromised the strength and using foaming agents reduced the density. Lightweight geopolymer aggregates achieved density below 1.2 g/cm³, with microstructural analysis revealing uniform pore distribution (2.5-6.9 μm) and the formation of stable mineral phases like sodalite and albite that contribute to long-term durability (Andrean Subroto et al., 2015).

In geopolymer applications, (Andrean Subroto et al., 2015) found that pre-foamed mixtures with 60% sodium silicate content could reach compressive strengths of 37.33 MPa. The geopolymerization process transforms the mud's silica-alumina content into a durable binder through dissolution and polycondensation reactions, creating materials with unique properties ranging from ultra-lightweight aggregates (0.82 g/cm³ density) to high-strength construction elements. Research by Razak et al. (2015) have achieved promising results by optimizing alkaline activation process using 12M NaOH concentration combined with a Na_2SiO_3/NaOH ratio of 0.4 to produce porous yet stable ALGA (Artificial Lightweight Geopolymer Aggregates) with 15.42% AIV (Aggregate Impact Value).

Beyond structural applications, Sidoarjo volcanic mud offers environmental advantages. Research by (Lestari & Razif (2019) confirmed that heavy metals such as lead (Pb) in the mud could be safely immobilized through stabilization/solidification using Portland cement and rice husk ash, reducing leaching by 96% (to 0.34 mg/l) while maintaining compressive strength up to 155.5 MPa at 10% mud content. Caroline & Propika (2021) also validated its use in batako (concrete bricks), showing that 5% mud substitution retained acceptable strength (20.94 kg/cm²) and low water absorption (3.21%), meeting SNI 03-0349-1989 standard. Additionally, studies by Amiruddin et al. (2022) demonstrated its viability as a silica source in GRC (Glass Fiber Reinforced Cement) boards, though excessive silica (>20%) reduced compressive strength (10.7–18.67 N/mm²). Citrasari et al. (2019) and Junaidi et al. (2019)highlighted its role in eco-cement, where 10% calcined Lusi (700°C) blended with Portland cement achieved 101.97 kg_f/cm^2 strength at 7 days, reducing CO_2 emissions by cutting clinker use.

Together, these findings indicate that with proper treatment such as calcination, activation optimization, additive incorporation, and compliance with SNI testing, Sidoarjo

volcanic mud can serve as sustainable and versatile alternative in construction, offering functional performance (strength and durability) alongside ecological benefits such as waste repurposing and lowering carbon footprint.

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Table 3. Summary of studies of Sidoarjo Volcanic Mud's utilization for construction materials

Item	Utilizations													
	Ceramic Roof Tiles		Lightweight Concrete		Bricks			Cement			Geopolymer Mortar		Geopolymer Aggregates	
	(Nuri & Retno, 2015)	(Sriatun et al., 2013)	(Rosanti & Winanti, 2016)	(Dibiantara et al., 2015)	(Lestari & Razif, 2019)	(Caroline & Propika, 2021)	(Mochni & Budhyantoro, 2021)	(Amiruddin et al., 2022)	(Citrasari et al., 2019)	(Junaidi et al., 2019)	(Tsaqif et al., 2024)	(Yolanda Putri & Fauzi, 2019)	(Andrean Subroto et al., 2015)	(Razak et al., 2015)
Sidoarjo Volcanic Mud (SVM)	100%	75%	30%	Not explicitly stated	10%	5% (C:S:SVM = 1:2:10)	SVM: PS (2:1)	120 gram (SVM:Silica Sand = 80:20)	1.8%	10%	10%	10%	SVM:FA = 1:1	SVM:AA = 1.7
Dolomite		15%												
Phosphate		10%												
Fly Ash (FA)			10%	Part of binder (exact % not specified)							75%		SVM:FA = 1:1	
Cement (C)			10% Type I	20%	75%	C:S: SVM = 1:2:10		480 gram (SVM:Silica Sand = 80:20)		90% Baturaja Type I Cement)				
Lime			10%											
Sand (S)			40%			C:S: SVM = 1:2:10								

Foam Agent			30%										3L Foam (Foam Agent:Water= 1:50)	
Kenaf Binders				0,20%										
Rice Husk					25%									
Paper Sludge (PS)							SVM: PS (2:1)							
Lloyd's type 300 glass fiber								150 gram						
Shell ashes									49.1%					
Organic Waste Ashes									49.1%					
Activated Carbon											5%			
Alkali Activator (AA) (Na_2SiO_3/NaOH)												Na_2SiO_3:NaOH= 4.0	NaOH 5M	0.4 (NaOH 12 M)
Sodium Silicate													60%	
Compressive strength	900°C: 142 kg/cm² (~13.93 MPa)		7 days: 2.16 Mpa 28 days: 4.28 Mpa	28 days: 2.05 MPa	10% mud content: 155.5 Mpa	20.94 kg/cm² ≈ 2.05 MPa *non-structural use, B4 grade)	37.78 kg/cm² ≈ 3.7 Mpa		2.77 Mpa	10.0 Mpa	17.43 Mpa	19.1 Mpa	2.31 Mpa	AIV = 15.42%
Density		1.35 g/cm³	Reduced by 30% with foam agent	691 kg/m³ (57–68% reduction)					2.20 g/mL					
Hardness		2688.37 kg/cm³												
Porosity		8.21%												

Fracture Modulus	800°C: 10.12 MPa (103.18 kg/cm²)													
Water Absorption	0,08 g/cm²		0.159% (SNI 03-0349-1949)			3.21% (met SNI 03-0349-1989)	17.17% (Compliant with SNI 15-2094-2000)	18.67 Mpa			39.6 g/cm²		17.78%	4.7%
Workability												Decreased with increased %mud content		
Setting Time												Prolonged with increased % mud content		
Specific Gravity														1.10 g/cm³
Environmental Safety					Pb leaching reduced by 96%									
Standard	Type I roof tiles according SII.0027 UDC-81. 666.74	SNI Type I for roof tiles	SNI Class III standards: >2 Mpa	ASTM C1693-11)	B1 grade, suitable for load-bearing walls	SNI 03-0349-1989			SNI 15-2049-2004 (Type IV Portland Cement standards,)				SNI 03-2461-2002	

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Road Construction Material Applications

Recent research demonstrates that Sidoarjo volcanic mud presents significant potential as a sustainable component in road construction materials, offering both geotechnical improvements and environmental benefits. Table 4 contains comprehensive meta-analyses reveal the Sidoarjo volcanic mud's effectiveness is particularly notable when used in combination with various stabilizing agents. Research from Sri Utami & Choiriyah (2018) reveal when Sidoarjo volcanic mud mixed with sand at 40% ratio, Sidoarjo volcanic mud achieves remarkable geotechnical enhancements, including 41.9% reduction in Liquid Limit (LL) and 46% decrease in Plasticity Index (PI), effectively transforming the high plasticity soil into medium plasticity material. This optimal mixture also doubles the California Bearing Ratio (CBR) from 3.65% to 7.59%, while increasing dry density by 19.7% (1.32 to 1.58 g/cm^3) and improving shear strength (φ from 13.22° to 22.9°) for enhanced slope stability.

The stabilizing potential of Sidoarjo volcanic mud extends to other mixture as well. A combination of 15% Sidoarjo Volcanic Mud with 30% steel slag produces exceptional results produce exceptional result, reducing swelling by an impressive 92.37% (from 3.54% to 0.27%) while boosting unconfined compressive strength (qu) by 158.7% (0.778 to 2.013 kg/cm^3 (Utami & Usada, 2018). These substantial improvements effectively convert weak clay soils into stable subgrade materials suitable for construction applications.

In asphalt applications, Sidoarjo volcanic mud demonstrated promising as a filler material. Research indicate that substituting up to 26.5% of conventional filler with the mud in asphalt concrete (AC-WC) maintain optimal Marshall stability (1025.57 kg compared to 993.48 kg control) while reducing voids (VIM:4,05% versus 5.48% control). However, exceeding 30% substitutions may compromise material performance by increasing plasticity and reducing workability (Jaelani & Prajitno, 2019).

The Sidoarjo Volcanic Mud silica content is 55% and pozzolanic properties contribute significantly to its binding capacity and strength development. These characteristics are particularly evident in geopolymers systems, where a mixture of 30% mud with 35% fly ash and 35% lime achieve compressive strength of 12.669 MPa, meeting SNI class c standard. While these results are promising, challenges remain regarding permeability (9.977%) and 55.46% higher cost compared to conventional mixes (Alfiansyah, 2017).

Environmental and economic considerations further support Sidoarjo volcanic mud's viability. As a cement substitute in paving blocks at 30% replacement, the mud maintains Quality A standard (408 kg/cm^2) while offering 18.67% cost savings. Importantly, the mud effectively mobilized heavy metals, with Pb/Cu leaching rates below 0.03 ppm, complying with hazardous waste regulations (Aji et al., 2014).

These findings position Sidoarjo volcanic mud as technically viable and environmentally responsible alternative for road construction applications. Successful implementation requires careful formulation to balance performance characteristics with economic considerations, but the demonstrated improvements in soil stabilization, material

strength, and environmental safety makes the mud a compelling option for sustainable infrastructure development.

The successful utilization of Sidoarjo Volcanic Mud in civil engineering, such as in construction materials and road construction materials not only demonstrates its structural viability but also highlights its role in supporting environmentally responsible development. This intersection of material performance and environmental benefit forms a critical link between Civil and Environmental engineering. As such, recent research has expanded into exploring Sidoarjo mud's potential in environmental applications, particularly in areas like pollutant adsorption, wastewater treatment, and the synthesis of eco-functional materials that contribute to broader sustainability and circular economy goals.

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Table 4. Summary of studies of Sidoarjo Volcanic Mud's utilization for road construction materials

Item	Utilization									
	Soil Stabilizer					Paving Block			Filler in AC-WC Asphalt Mixtures	
	(Sri Utami & Choiriyah, 2018)	(Meysita Pramaesti, 2021)	(Sudjianto et al., 2023)	(Utami & Usada, 2018)	(Sri Utami, 2015)	(Masbuhin, 2020)	(Aji et al., 2014)	(Alfiansyah, 2017)	(Jaelani & Prajitno, 2019)	(Novendra et al., 2024)
Sidoarjo Volcanic Mud (SVM)	60%	9%	20%	15%	30%, 40%, 50%	2,89 kg (40%)	30%	30%	26.5%	4%, 6%,8%
Sand (PS)	40%					4,33 kg 1Pc:2Ps + SVM	30%			
Steel Slag				30%						
Clay Soil					70%, 60%, 50%					
Cemen (PC)						5,02 kg 1Pc:2Ps + SVM				
Asphalt		8%								
Expansive Soil			80%							
Stone Ash									6.5%	
Fly Ash								35%		
Lime								35%		

Compression Strength						1Pc:2Ps + SVM (23,67 Mpa) Mutu B	Cemen Subt: 408 kg/cm² (Quality A) Sand Subt: > 408 kg/cm²	12.669 Mpa (Class C)		
Stability										4%SVM (835.40 kg), 6% SVM (839.14 kg), 8% SVM (1200.6 kg)
Liquid Limit (LL)	33.33%			35%	30% (50% SVM)					
Plasticity Index (PI)	13.33%	9.5%	15.3% low-plasticity (PI < 20%)	19.49%	8.14% (50% SVM)					
Dry Density (γ_a)	1.58 g/cm³			1.6 g/cm³	1.56 g/cm³ (40% SVM)					
California Bearing Ratio (CBR)	7.59% Suitable for landfill liners (fair subgrade CBR)	8.1%		8.21% Ideal for pavement subgrades (CBR ≥ 8%)	9.02% (30% SVM)					
Shear Angle (φ)	22.9°									

Unconfined Compression (qu).	1.02 kg/cm² (hard) with 20% sand	6.559 kg/cm² (7 days) Balanced strength	0.90 kg/cm² suitable for subgrades	2.013 kg/cm²	2.03 kg/cm² (40% SVM) Best for load-bearing (embankments/foundations) due to high qu					
Swelling	1.29% (50% sand)	0.08% (after 14 days	6.8%	0.27%	4% (50% SVM) Ideal for subgrades (low swelling)					
Water Absorption							Cemen Subt: 10.17% Sand subt: <10.17%	9.977%		
Abrasion Resistance								0.133 mm/min (Class B)		
Marshall Stability									1025.57 kg	

Flow									4.18 mm	4%SVM (2.73 mm), 6% SVM (2.67 mm), 8% SVM (<3 mm)
Voids in Mineral Aggregate (VIM)									4.05%	4% SVM (1.11–1.79%)
Voids Filled with Asphalt (VFA)									77.0%	
Environmental Safety							Pb/Cu <0.03 ppm (safe)			
Standard						SNI 03-0691-1996.		SNI 03-0691-1996		SNI 03-1737-1989

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Adsorbents

The Sidoarjo volcanic mud, a volcanic byproduct, has emerged as a promising low-cost adsorbent for wastewater treatment due to its high silica content, porosity, and modifiable surface properties. The research studies demonstrated its effectiveness in removing diverse pollutants, including heavy metals (e.g., Ni^{2+}, Hg^{2+}), dyes (e.g., naphtol, methyl orange) and organic compounds (e.g., crude palm oil), through various activation methods. For example, chemical activation with NaOH achieved 98.3% nickel removal (Sa'diyah et al., 2017). While HCl treatment optimized mercury adsorption (96.06% efficiency) by creating mesopores and silanol groups for Hg^{2+} binding (Trimayanto et al., 2019). The mud's rich in silica composition (up to 53.4% SiO_2) further enables functionalization, such as sulfonate group grafting (Ikhsan et al., 2017), enhancing cation exchange capacity (4.15 meq/g) for heavy metal recovery.

Physical and chemical activation methods significantly influence adsorption performance. Acid (H_2SO_4) and base (NaOH) treatments increase surface area (e.g., from 31.217 to 171.539 m2/g) and pore volume, critical for dye removal (Zahro & Adityosulindro, 2024). However, base activation often outperforms acid due hydroxide ion (OH^-) interactions with pollutants, as seen in Ni^{2+} adsorption. Composite adsorbents, like Sidoarjo Volcanic Mud blended with blood clam shell (Permatasari et al., 2023), synergize chemical adsorption (SiO_2) and physical filtration ($CaCO_3$), achieving 89.13% COD reduction.

Advanced modification such as magnetic silica Fe_2O_4 hybrids (Zuhara et al., 2024) and amino functionalized silica gels (Agipa & Muarif, 2022), expand applications. Magnetic adsorbents enable easy separation after crude palm oil adsorption with 1.76 mg/g capacity. While amino silica hybrids show potential as slow-release fertilizers (SRF), retaining phosphate effectively with 0.333 M/g. Mesoporous silica xerogels (A'yuni et al., 2023) derived from Sidoarjo volcanic mud exhibit exceptional humidity adsorption about 22.14% g/g, surpassing commercial silica gels.

The challenges with utilizing Sidoarjo volcanic mud mud include low yield in functionalized materials (e.g., 0.0075 sulfonated silica/g mud in cation exchange adsorbent) a consequence of multi-step processes involving silica extraction, thiol grafting, and oxidative sulfonation, each step introducing material losses through incomplete reactions, purification washes, and byproduct formation (Ikhsan et al., 2017). Additionally, residual impurities like Al^{3+} and Fe^{3+} (originating from the mud's natural composition) compete with target pollutants for adsorption sites and may leach into treated water, risking secondary contamination. These limitations underscore the need for optimized synthesis protocols to improve yield and purity. Nonetheless, Lapindo mud's versatility, cost-effectiveness, and high adsorption efficiency up to 98.3% position it as sustainable alternative for wastewater treatment, aligning with circular economy goals by reproposing hazardous waste into valuable resources.

Table 5. Summary of studies of Sidoarjo Volcanic Mud's utilization as adsorbents

No	Refference	Objective	Method	Material Characteristics	Application Result
1	(Alfiansyah, 2017)	- To investigate the effectiveness of Lapindo mud as an adsorbent for nickel (Ni) removal from nickel sulfate ($NiSO_4$) solutions. - The study aimed to compare different activation methods (physical, chemical, and chemico-physical) to determine the most effective approach for enhancing adsorption capacity.	- Pretreatment: Lapindo mud was washed, dried (105°C for 2 hours), and sieved (136 mesh). - Activation Methods: - Physical: Calcination at 500°C for 3 hours - Chemical: Reflux with 6 N HCl or 6 NNaOH for 6 hours - Chemico-physical: Combined acid/base activation followed by calcination. - Adsorption Test: 100 g adsorbent in 100 mL $NiSO_4$ solution, agitated at 100 rpm (50°C, 60 minutes). Analysis: XRF (composition), BET (surface area/pore size), UV-VIS spectrophotometry (Ni concentration).	- Si/Al Ratio: Increased from 3.01 (raw) to 7.85 (HCl chemico-physical activation), indicating enhanced silica content. - Surface Area (BET): Highest for acid activation (98.099 m^2/g) and base activation (53.419 m^2/g). - Pore Volume: Acid chemico-physical activation yielded the highest pore volume (0.136 cc/g). - Chemical reactions: - Acid activation dissolved Fe/Al oxides and increased Si/Al ratio and surface area but underperformed in adsorption compared to base activation. - Base activation dissolved silica/alumina, optimized Ni removal despite lower Si/Al ratios, likely due to surface OH^- groups.	- Lapindo mud's high porosity (46.75%) and metal oxide content (e.g., 29.8% Si, 11% Al) make it a viable, low-cost adsorbent for heavy metal remediation. - Adsorption Efficiency: Base (NaOH) activation achieved the highest Ni removal (98.3%). - Isotherm Models: - Freundlich: n = -2.94, k = 0.000149 (R^2 = 0.9576). - Langmuir: Maximum capacity = 0.000151 mg Ni/mg adsorbent (R^2 = 0.9855). - Optimal Method: Base activation (NaOH) was most effective for Ni adsorption due to hydroxide ion (OH^-) interactions with Ni^{2+}.
2	(Trimayanto et al., 2019)	- To evaluate the effectiveness of HCl-activated Lapindo mud as an adsorbent for mercury (Hg) removal from gold mining wastewater. - The study aimed to determine the optimal HCl concentration for activation and assess the adsorption capacity of the modified mud for Hg ions.	- Activation: Lapindo mud was soaked in HCl solutions (0.05 M, 0.1 M, 0.2 M, 0.4 M) for 24 hours, dried at 100°C, and sieved. - Characterization: SEM analyzed pore morphology; AAS measured residual Hg concentration. - Adsorption Test: Activated mud was mixed with $HgNO_3$ solution (25 g/L), filtered, and analyzed for Hg removal efficiency. Qualitative/Quantitative Tests: White precipitate (HgCl) formation and mass measurement.	- HCl activation removed non-adsorptive impurities (e.g., Ca^{2+}, Fe^{3+}) and created mesopores, increasing surface area for Hg binding. - Silanol groups ($[=Si(-O-H)_2]_n$) formed covalent bonds with Hg ions, ensuring stable adsorption. - Pore Structure: HCl activation increased pore number but reduced diameter (0.201–0.671 µm for 0.4 M HCl, classified as mesopores). - Surface Chemistry: HCl removed impurity ions (Ca^{2+}, Mg^{2+}, Fe^{3+}, Al^{3+}) and activated silanol groups ($[=Si(-O-H)_2]_n$), which bind Hg ions. - Chemical Reactions: - Impurity removal: $Ca^{2+} + 2HCl \rightarrow CaCl_2 + 2H^+$. - Hg binding: $[=Si(-O-H)_2]_n + Hg^{2+} \rightarrow [=Si-O-Hg-O-Si=]_n + 2H^+$.	- Adsorption Efficiency: 0.4 M HCl activation achieved 96.06% Hg removal (residual Hg: 0.5 ppm). - SEM Confirmation: 0.4 M HCl-treated mud HCl yielded the smallest pores (mesopores) but had the highest pore density, enhancing Hg trapping. - Isotherm Data: Quantitative tests showed a linear decrease in Hg concentration with increasing HCl activation strength (R^2 = 0.9639). - Optimal Condition: 0.4 M HCl activation was most improved Hg adsorption by optimizing pore structure and silanol availability.
3	(Zahro & Adityosulindro, 2024)	- To evaluate the potential of Sidoarjo volcanic mud (Lapindo mud) as an adsorbent for removing naphthol dye from real batik wastewater.	- Activation: - Physical: Calcination at 550°C for 3 hours. - Chemical: Treatment with 5N H_2SO_4 (2.5 hours, 100°C). - Adsorption Test: Batch experiments	- Pore Structure: Chemical activation with H_2SO_4 increased surface area (literature: 31.217 → 171.539 m^2/g) by removing impurities (Ca, Al, Fe). - Composition: SEM-EDS revealed 35.46% silica (SiO_2) and 14.23% alumina (Al_2O_3) in H_2SO_4-activated mud, vs. 17.4% SiO_2 and 1.38% Al_2O_3 in raw mud.	- Raw Wastewater: High apparent color removal (~90%) but unreliable due to suspended solids interference. - Chemical activation (H_2SO_4) was most effective, doubling silica content and creating

		- The study compared physical and chemical activation methods to optimize adsorption efficiency and addressed challenges in measuring true vs. apparent color in complex wastewater matrices.	with 100 mL wastewater (pH 9.5–10.5), 1–8 g/L adsorbent, 300 rpm agitation for 120 minutes. Analysis: UV-Vis spectrophotometry (SNI 6989.80:2011) for dye concentration; SEM-EDS for adsorbent characterization.	Morphology: Irregular, flaky particles with enhanced porosity after chemical activation.	mesopores for dye adsorption. - Physical activation (calcination) showed limited improvement (~23% removal), likely due to insufficient pore modification. - Pre-Treated Wastewater: Chemical activation achieved 50% true color removal (880 → 440 Pt-Co), outperforming physical activation (23.3%) and non-activated mud (18.75%). - Chemical Mechanism: Silanol groups (Si-OH) from silica bonded with anionic naphthol dye via ion exchange. Supported by high silica content (35.46%).
4	(Ikhsan et al., 2017)	- To transform silica extracted from Lapindo mud into a high-capacity cation exchange adsorbent by functionalizing its surface with sulfonate groups ($-SO_3H$). - The study aimed to enhance the material's ability to bind cations (e.g., Na^+, Zn^{2+}) for potential applications in wastewater treatment or slow-release fertilizers	- Silica Extraction: Washed mud reacted with NaOH to form Na_2SiO_3, then acidified to produce gel silica (SG). - Surface Modification: - Step 1: SG reacted with 3-(trimethoxysilyl)-1-propanethiol to attach mercapto (-SH) groups (SMM). - Step 2: SMM oxidized with HNO_3 to convert -SH to sulfonate ($-SO_3H$) groups (SCE). Analysis: FTIR, XRD, SEM-EDX for characterization; titration for cation exchange capacity (CEC)	- Composition: SCE contained 6.9% Si, 5.05% S (from $-SO_3H$), and elevated oxygen content (Si:O ratio 1:6). - Sulfonate functionalization ($-SO_3H$) drastically increased CEC, making SCE effective for cation binding. - Morphology: SEM revealed increased porosity in SCE compared to SG/SMM. - Functional Groups: FTIR confirmed $-SO_3H$ formation (disappearance of -SH peaks at 2553 cm^{-1}, new S=O peaks at 1028–1254 cm^{-1}). Crystallinity: XRD showed amorphous silica structure	- Cation Exchange Capacity (CEC): SCE achieved 4.15 meq/g, 13× higher than raw gel silica (0.32 meq/g) and 5× higher than mercapto-modified silica (0.84 meq/g). - Mechanism: $-SO_3H$ groups enabled reversible H^+/cation exchange (e.g., Na^+), suitable for heavy metal removal or nutrient delivery. - Yield: Low SCE yield (0.0075 g/g mud) due to multi-step synthesis.
5	(Ulfindray ani Fitri et al., 2019)	- To evaluate the effectiveness of SiO_2 extracted from Lapindo mud as an adsorbent for methyl orange (MO) dye removal from textile wastewater. - The study aimed to compare the adsorption performance of raw Lapindo mud with SiO_2-enriched material obtained via coprecipitation.	- SiO_2 Extraction: Lapindo mud was treated with NaOH to form Na_2SiO_3, then neutralized with HCl to precipitate purified SiO_2 (78.6% purity). - Characterization: XRF analyzed composition; UV-Vis spectrophotometry measured MO concentration. Adsorption Test: Batch experiments with 20 ppm MO solution, 1:10 adsorbent-to-solution ratio, and agitation at room temperature.	- Composition: SiO_2 content increased from 50% (raw mud) to 78.6% after extraction; impurities (Al_2O_3, Fe_2O_3) reduced. - Removal of Al_2O_3/Fe_2O_3 impurities reduced competitive adsorption, improving MO uptake. - Silanol groups (-Si-OH) facilitated dye binding via electrostatic inter - Surface Properties: Higher SiO_2 purity enhanced active sites for dye adsorption. Chemical Reaction: NaOH + SiO_2 → Na_2SiO_3 → HCl → purified SiO_2.	- Coprecipitation method significantly increased SiO_2 purity (50% → 78.6%), enhancing adsorption sites. - Adsorption Efficiency: Extracted SiO_2 achieved 81.39% MO removal (0.081 mg/g capacity), outperforming raw mud (64.89%, 0.065 mg/g) but the capacity remained low. - Mechanism: Electrostatic attraction between anionic MO dye and SiO_2 surface silanol groups (-Si-OH). - Low adsorption capacity (0.081 mg/g)

					compared to commercial adsorbents.
6	(Zuhara et al., 2024)	To synthesize a magnetic silica adsorbent from Lapindo Mud silica and magnetite (Fe_3O_4) using CTAB as a template, evaluate its adsorption capacity for Crude Palm Oil (CPO) in water.	- Silica Extraction: Acid leaching of Lapindo Mud with HCl, followed by NaOH treatment. - Magnetite Synthesis: Coprecipitation of $FeCl_3$ and $FeCl_2$ with NH_4OH. - Adsorbent Synthesis: Microemulsion method using CTAB and 1-butanol. Adsorption Tests: Batch experiments with varying contact times (10–90 min) and CPO concentrations (0.2–1 g).	- Magnetic Modification: Fe_3O_4 enhanced adsorbent recoverability and surface reactivity. - CTAB Template Role: Improved mesoporosity and hydrophobicity, critical for oil adsorption - Morphology: Irregular, heterogeneous particles (~5 µm) with rough texture (SEM). - Composition: 48.47% Fe, 33.5% O, 1.26% Si, 5.74% C (EDX) - Functional Groups: Si-OH, Fe-O, and Si-O-Fe bonds (FTIR). - Porosity: Mesoporous structure with 37.048 m^2/g surface area, 0.321 cm^3/g pore volume, 33.907 nm pore diameter (GSA). Crystallinity: Confirmed Fe_3O_4 peaks (XRD).	- Optimal Adsorption: Achieved at 60 min contact time, with 1.76 mg/g capacity. - Kinetics: Followed pseudo-second-order model ($R^2 = 0.9831$), indicating chemisorption. - Isotherm: Best fit with Langmuir model ($R^2 = 0.9781$), suggesting monolayer adsorption. - Efficiency: Effective CPO removal due to hydrophobic interactions and Fe_3O_4 magnetic properties for easy separation.
7	(Agipa & Muarif, 2022)	To synthesize Silica Gel (SG) and Amino Silica Hybrid (ASH) from Lapindo mud, compare their phosphate adsorption/desorption kinetics, and evaluate their potential as slow-release fertilizer (SRF) materials.	- Silica Extraction: Calcination of Lapindo mud (900°C, 1h), NaOH leaching (3M, 98°C), acidification to pH 7 for SG. - ASH Synthesis: SG modified with APTES (3-aminopropyltriethoxysilane) via sol-gel method. - Adsorption/Desorption: Phosphate binding (0.01 M KH_2PO_4, 30 min), desorption in water (pH 3) over 2–9 days. Kinetic Modeling: Lagergren pseudo-first and pseudo-second order kinetics.	- Lapindo Mud as Silica Source: High silica content (50%) enables efficient extraction for SG/ASH synthesis. - SG: Composed of Si-OH and Si-O-Si groups (FTIR peaks at 3448 cm^{-1}, 1095 cm^{-1}, 794 cm^{-1}). - ASH: Additional -NH_2 and -CH_2 groups (FTIR peaks at 1635 cm^{-1}, 1473 cm^{-1}) confirming APTES modification. - Porosity/Surface: High surface area with active silanol sites (SG) and enhanced covalent bonding (ASH). Composition: Lapindo mud-derived silica (50% SiO_2, Table 1).	- Phosphate Adsorption: ASH adsorbed more phosphate (0.00325 M) than SG (0.0021 M) due to amino groups. - Desorption: ASH released less phosphate (7.04% after 9 days) vs. SG (10.14%), indicating stronger binding. It also highlights its potential to mitigate eutrophication by controlled phosphate release. - Kinetics: Phosphate release followed pseudo-second order ($R^2 > 0.99$), suggesting chemisorption mechanisms which critical for designing SRF materials. - QE Values: 0.22089 M/g (SG) and 0.33333 M/g (ASH), confirming ASH's superior capacity for slow release fertilizer (SRF) applications.

8	(Permatasari et al., 2023)	To evaluate the effectiveness of Lapindo mud and blood clam shell adsorbents in reducing BOD, COD, TSS, and TDS levels in textile wastewater from Jetis Batik Village, Sidoarjo.	- Adsorbent Preparation:
			  - Lapindo Mud: Washed, dried (110°C, 24h), activated with H_2SO_4 (5M), calcined (800°C, 2h), sieved (120 mesh).
			  - Blood Clam Shells: Washed, dried, crushed, sieved (50-100 mesh), calcined (550°C, 2h), activated with H_2SO_4 (5M).
				- Lapindo Mud: High SiO_2 content (44.8–53.4%), Fe_2O_3, and Al_2O_3; mesoporous structure (pore size ~5.68 nm).
				- Blood Clam Shells: Rich in $CaCO_3$, providing active sites for adsorption.
				- Composite Adsorbents: Enhanced surface area and porosity due to acid activation and calcination.
				- Acid treatment (H_2SO_4) and calcination critically enhanced adsorbent porosity and reactivity.
					- Optimal Ratio: 1:1 (Lapindo mud:clam shells) achieved highest COD (89.13%) and BOD (98.99%) removal.
					- The 1:1 composite of Lapindo mud and clam shells showed superior performance, leveraging SiO_2's chemical adsorption (Lapindo) and $CaCO_3$'s physical porosity (clam shells).
					- TDS Reduction: Best with 2:1 ratio (86.07% removal).

			- Adsorption Tests: Batch experiments with varying adsorbent mass ratios (1:0, 0:1, 1:1, 1:2, 2:1) in textile wastewater, stirred for 3h, followed by filtration. Analysis: BOD, COD, TSS, and TDS measured before and after treatment.		- TSS Removal: Consistent across all ratios (~77.8%) due to filtration step. - Treated effluent still exceeded regulatory standards for BOD (45 ppm vs. 13 ppm achieved) and COD (125 ppm vs. 800 ppm achieved).
9	(A'yuni et al., 2023)	To synthesize mesoporous silica xerogel (SX) from hazardous volcanic mud (Lapindo mud) via sol-gel methods for efficient humidity adsorption and compare its performance with commercial silica gels.	- Silica Extraction: Acid leaching (5M HCl, 60°C) and thermal treatment (680°C) of Lapindo mud to concentrate SiO_2. - Sol-Gel Synthesis: Sodium silicate derived from treated mud was titrated to pH 6–10 to form SX. - Characterization: XRF, XRD, FTIR, SEM-EDX, BET surface area analysis. Humidity Adsorption: Tested at 70–90% RH using conventional gravimetric methods and TGA.	- Composition: Lapindo mud contained ~53.4% SiO_2, reduced to ~38.93% Si after synthesis (EDX). - Morphology: Amorphous, mesoporous structure (type IV isotherm) with aggregated particles (SEM). - Surface Area: Highest for SX8 (576.527 m^2/g) due to optimal pH 8 during synthesis. Functional Groups: Si–OH and Si–O–Si confirmed by FTIR (peaks at 950 cm^{-1} and 1200–1000 cm^{-1}).	- Lapindo mud, a hazardous waste, was successfully transformed into high-value silica xerogel with exceptional humidity adsorption properties. - Optimal Adsorbent: SX8 (pH 8) showed highest humidity adsorption (18.19% g/g via conventional method; 22.14% g/g via TGA). - Performance: Outperformed commercial silica gels (0.9–7% g/g). - Mechanism: Adsorption driven by Si–OH groups and mesoporous structure. - Challenges: Residual Al impurities (~3.33%) affected purity.

Catalysts

The Sidoarjo volcanic mud has shown significant potential as catalyst or catalyst support in energy and environmental applications based on meta-analysis of the recent studies that were put together on Table 6. One notable example is its use in hydrotreating waste cooking oil (WCO) to produce biofuels. Research from (Trisunaryanti et al., 2024) found that mesoporous silica extracted from Sidoarjo Volcanic Mud (Lp-MS) exhibited high surface areas (521-620 m2/g) and well-defined pore structures, making it an excellent support for noble metal catalysts. Mesoporous silica extracted from Sidoarjo volcanic mud when loaded with Pd (Pd/Lp-MS2) achieved a 60.9% liquid yield with minimal aromatic content (<4%), highlighting its efficiency in deoxygenation and hydrocracking reactions. The study also noted that smaller pore sizes whch is 4.78 nm improved hydrocarbon selectivity, while external Pd deposition enhanced hydrogen accessibility, ensuring stability over multiple reaction cycles.

Beyond noble metals, Sidoarjo Volcanic Mud's natural compositions that are rich in SiO_2, Al_2O_3, and Fe_2O_3 make it suitable for transition metal catalysts. For instance, research by (Kusumastuti et al., 2018) developed a biometallic Ni-Pd catalyst supported on amine-functionalized Sidoarjo volcanic mud, which outperformed monometallic versions by achieving a 71.5 wt% liquid yield and significantly reducing free fatty acids (FFAs) from 101.2 to 3.2 wt.%. The amine groups ($-NH_2$) played a dual role: adsorbing FFAs to prevent coke formation and promoting selective hydrocracking into gasoline-range hydrocarbons (C5-C12).

Similarly with study from (Swasdika et al., 2021) reported that Cu-Zn supported on Sidoarjo Volcanic Mud derived silica alumina (MSA) achieved a 90.49 wt.% liquid yield in cellulose derived bio-oil upgrading, attributed to synergistic metal interactions and optimized acidity (24.86 mmol/g).

In environmental applications, Sidoarjo Volcanic Mud has been adapted for wastewater treatment. (Parningotan et al., 2024) demonstrated that calcined Sidoarjo Volcanic Mud (CVM) removed 90% of Congo red dye via sequential adsorption Fenton oxidation, outperforming iron impregnated (ICVM) and unmodified (UVM) variants. The study also attributed CVM's success to its mesoporous structure and balanced iron content, which minimized leaching while maintaining catalytic activity.

Sidoarjo Volcanic Mud's utilization as catalyst for biodiesel production, (Talib et al., 2016) showed that raw Mud when calcined at 330 °C acted as an efficient heterogeneous catalyst achieving 96.6 % FAME (Fatty Acid Methyl Ester) yield in WCO (Waste Cooking Oil) transesterification. However, challenges like metal leaching and pore blockage were noted, particularly in reused catalysts (e.g., K_2O/MCM-41) which the yield dropped to 56.84% after three cycles (Wijaya et al., 2018). Collectively, these studies underscore Sidoarjo volcanic mud's potential as a sustainable, low-cost catalysts.

Table 6. Summary of studies of Sidoarjo Volcanic Mud's utilization as catalysts.

No	Refference	Objective	Method	Material Characteristics	Application Result
1	(Trisunaryanti et al., 2024)	- To produce liquid biogasoline with low aromatic content via catalytic hydrotreatment of waste cooking oil (WCO). - To utilize low-cost Lapindo mud-derived mesoporous silica (Lp-MS) as a catalyst support for noble metals (Pd, Pt). - To evaluate the deoxygenation and hydrogenation performance of Pd/Lp-MS2 and Pt/Lp-MS1, focusing on hydrocarbon yield and aromatic suppression.	- Silica Extraction: Acid-base reflux of Lapindo mud to extract SiO2 (81.55% purity). - Mesoporous Silica Synthesis: Hydrothermal treatment with CTAB surfactant (SiO2 CTAB ratios: 1.82 for Lp-MS1, 1.53 for Lp-MS2). - Catalyst Preparation: Wet impregnation of Pd/Pt (2% loading) on Lp-MS, followed by calcination and reduction. - Hydrotreatment: Semi-batch reactor at 525°C, H2 flow (20 mL/min), catalyst: feed ratios (1:100–1:200). - Analysis: XRD, BET, TEM, GC-MS.	- Lp-MS1: Surface area = 620.24 m2/g, pore diameter = 5.08 nm. - Lp-MS2: Surface area = 521.51 m2/g, pore diameter = 4.78 nm. - Catalyst Design: Smaller pore size (Lp-MS2) enhanced hydrocarbon selectivity; Pd external deposition improved H2 accessibility - Metal Dispersion: Pt particles (15.32 nm) occupied internal/external pores; Pd (20.15 nm) mainly on external surfaces - Acidity: Low Brønsted/Lewis acidity due to pure SiO2 structure, suppressing aromatic formation.	- Lapindo Mud Valorization: Demonstrated as a viable SiO2 source for mesoporous silica synthesis, offering cost-effective catalyst support. - Pd/Lp-MS2: Superior performance—60.9% liquid yield, 86.75% gasoline-range hydrocarbons, <4% aromatics. - Reusability: Stable for 4 cycles with consistent hydrocarbon selectivity (>80%). High stability and reusability of Pd/Lp-MS2 support scalability for WCO-to-fuel processes. - Optimal Conditions: 1:100 catalyst:feed ratio, 525°C. - Comparison: Outperformed Pt/Lp-MS1 and other mesoporous silica catalysts (e.g., Cr-SS1, Pt/MS) in selectivity and aromatic suppression.
2	(Trisunaryanti, Azizah, et al., 2022)	- To optimize hydrocracking conditions for converting waste	- Preparation: Physical treatment (washing, drying, grinding, calcination at 500°C).	- LM Composition: 41.16% SiO2, 18.24% Fe2O3, 12.84% Al2O3 (XRF). - Surface Area: 22.2 m2/g (LM), reduced to 2.3 m2/g after calcination (CLM).	- Lapindo Mud Valorization: Demonstrated as a viable, low-cost catalyst support without chemical

		palm cooking oil (WPCO) into bio-hydrocarbons using a cost-effective Ni-NH2/Lapindo mud (LM) catalyst. - To evaluate the impact of Ni loading (1–10 wt.%) and amine functionalization (3-APTMS) on catalyst performance. - To explore LM as a natural, chemically untreated catalyst support for sustainable biofuel production.	- Catalyst Synthesis: Wet impregnation of Ni (1, 5, 10 wt.%) on LM, followed by NH2 grafting via 3-APTMS. - Characterization: XRF (composition), XRD (crystallinity), FTIR (functional groups), BET/TEM (surface/pore properties). - Hydrocracking: Semi-batch reactor at 470–550°C, H2 flow (20 mL/min), feed/catalyst ratios (50–100). - Analysis: GC-MS for hydrocarbon selectivity.	- Ni Nanoparticles: Crystallite sizes: 57.17 nm (1 wt.%), 18.15 nm (5 wt.%), 33.65 nm (10 wt.%) (XRD). - NH2 grafting enhanced WPCO adsorption and deoxygenation, while Ni provided hydrogenation sites. - NH2 Functionalization: Confirmed by FTIR peak at 1566 cm-1; reduced acidity (0.229 mmol/g vs. 0.409 mmol/g for Ni(A)/LM). - Pore Structure: Mesoporous (3.2–3.9 nm diameter, Type IV isotherm).	extraction, leveraging its natural SiO2/Al2O3 /Fe2O3 content. - Optimal Catalyst: Ni(A)/LM (1 wt.% Ni) yielded 46.65 wt.% liquid product (41.7 wt.% hydrocarbons) at 470°C. - NH2 Enhancement: Ni(A)-NH2/LM increased liquid yield to 68.17 wt.% (550°C, feed ratio 75). - Higher temperatures (550°C) and moderate feed ratios (75) maximized liquid yields (63–68 wt.%) with controlled coke formation. - Selectivity: Gasoline-range (C_5–C_{12}) hydrocarbons dominated (30–40 wt.%), with <20 wt.% alcohols. - Reusability: Stable for 3 runs (~80 wt.% liquid yield; hydrocarbon selectivity dropped from 50.2 to 38.4 wt.%). - Low Coke Formation: <5 wt.% in all tests.
3	(Trisunaryanti, Alethiana, et al., 2022)	- To develop a cost-effective Ni–Pd bimetallic catalyst supported on amine-functionalized Lapindo Mud (LM) for hydrocracking waste cooking oil (WCO) into biofuels. - To evaluate the synergistic effects of Ni (hydrogenation) and Pd (deoxygenation) with amine groups (FFA sequestration) on catalytic performance. - To optimize reaction conditions (temperature, catalyst-to-feed ratio) for maximizing hydrocarbon yield and minimizing free fatty acid (FFA) content.	- Catalyst Preparation: LM was washed, dried, and calcined (500°C); Ni (3 wt.%) and Pd (0.1 wt.%) were co-impregnated via wet impregnation, followed by amine grafting using 3-APTMS. - Characterization: XRF (composition), XRD (crystallinity), FTIR (functional groups), BET/TEM (surface/pore properties), acidity measurement (gravimetric pyridine adsorption). - Hydrotreatment: Semi-batch reactor at 550–600°C, H2 flow (20 mL/min), catalyst-to-feed ratios (1:50 to 1:200). Analysis: GC-MS for hydrocarbon selectivity and FFA reduction.	- LM Composition: 45.49% SiO2, 13.82% Al2O3, 21.63% Fe2O3 (XRF). - Ni–Pd–NH2/LL: Surface area = 1.83 m2/g (BET), pore diameter = 141.18 nm (BJH), acidity = 0.07 mmol/g (pyridine adsorption). - Amine Grafting: Confirmed by FTIR (1566 cm-1 for NH2), reduced acidity 0.31 → 0.07 mmol/g (basic sites) and increased macropore diameter (130–140 nm), balancing active site accessibility and FFA adsorption. Metal Dispersion: XRD confirmed amorphous silica-alumina structure; TEM showed uniform metal distribution pre-reaction and coke deposition post-reaction.	- Bimetallic Ni–Pd enhanced hydrogenation (Ni) and deoxygenation (Pd), while amine groups sequestered FFA, improving hydrocarbon yield and purity - Optimal Catalyst: Ni–Pd–NH2 /LL achieved 71.5 wt.% liquid yield (48.9 wt.% hydrocarbons) at 550°C, reducing FFA from 10.1 to 3.2 wt.% versus unmodified Ni–Pd/LL. - Outperformed monometallic catalysts (Ni/LL: 71.0 wt.% liquid; Pd/LL: 71.3 wt.%) in FFA reduction and hydrocarbon selectivity. - Temperature Effect: 550°C maximized liquid yield (71.5 wt.%) and hydrocarbon selectivity (48.9 wt.%), while 600°C favored gas formation. - Feed Ratio: 1:100 catalyst-to-feed ratio yielded 78.9 wt.% liquid product (66.1 wt.% hydrocarbons). - Lower temperatures (550°C) and moderate feed ratios (1:100) minimized gas/coke formation and maximized diesel-range hydrocarbons (C13–C16). - Reusability: Stable for 3 runs with consistent liquid

					yield (~80 wt.%), though hydrocarbon selectivity declined due to coke accumulation (TEM).
4	(Trisunaryanti, Triyono, et al., 2022)	- To produce a hydrocracking catalyst based on Lapindo mud (LM) for converting waste palm cooking oil (WPO) into bio-hydrocarbons. - To enhance catalytic activity and selectivity by impregnating Ni and Pt metals and grafting amine groups onto LM. - To evaluate the effects of temperature, catalyst-to-feed ratio, and catalyst reusability on hydrocracking performance.	- Catalyst Preparation: - LM was crushed, sieved (100 mesh), and calcined to remove impurities. - Ni and Pt metals were impregnated via wet impregnation (monometallic: Ni/LM, Pt/LM; bimetallic: NiPt/LM). - Amine functionalization was performed using 3-aminopropyl trimethoxysilane (3-APTMS) via grafting. - Characterization: FTIR, XRD, XRF, BET/BJH surface area analysis, TEM. - Catalytic Testing: Hydrocracking of WPO in a semi-batch reactor at 500–600°C, H_2 flow (20 mL/min), and catalyst-to-feed ratios (1:50–1:200 w/w). Reusability was tested for 3 cycles.	- Raw LM Composition (XRF): SiO_2 (45.33%), Fe_2O_3 (24.24%), Al_2O_3 (18.83%), and minor oxides (K_2O, CaO, TiO_2, etc.). - LM's high SiO_2/Al_2O_3 content makes it a viable catalyst support, while amine functionalization addresses FFA challenges in WPO. - Modified Catalysts: - NiPt-NH_2/LM: 1.68 wt.% Ni, 0.4 wt.% Pt, surface area = 6.59 m^2/g, pore diameter = 15.51 nm. - Amine grafting confirmed by FTIR peaks (1558 cm^{-1} for N–H, 2931 cm^{-1} for $–CH_2$). - XRD confirmed NiO/PtO_x phases and amorphous silica-alumina structure. TEM showed uniform metal dispersion; pore blockage observed after reuse due to coke formation.	- Optimal Conditions: 550°C, catalyst-to-feed ratio = 1:50. - Product Yields: - Fresh NiPt-NH_2/LM: 79.4 wt.% liquid product (55.9 wt.% hydrocarbons, 6.8 wt.% oxygenates) under mild conditions (550°C) - Reused Catalyst (3rd cycle): 28.4 wt.% liquid product (23.6 wt.% hydrocarbons). - Key Findings: - Bimetallic NiPt-NH_2/LM outperformed monometallic catalysts in hydrocarbon yield (55.9 wt.%) and reduced oxygenates. - Amine groups enhanced FFA adsorption, favoring decarboxylation. - Catalyst deactivation occurred due to coke deposition (observed via TEM).
5	(Trimayanto et al., 2019)	- To develop an environmentally friendly adsorbent from HCl-activated Lapindo mud for removing mercury (Hg) from gold mining waste. - The study aimed to optimize the activation process to enhance Hg adsorption capacity by increasing the porosity and silanol group availability in the mud.	- Raw Lapindo Mud Composition: Contains Ca^{2+}, Mg^{2+}, Fe^{3+}, Al^{3+} as pore-filling impurities. - After HCl Activation: - Impurity removal: HCl dissolves Ca^{2+}, Mg^{2+}, Fe^{3+}, and Al^{3+}, increasing porosity. - Silanol group formation: HCl activates polysilanol $[=Si(-O-H)_2]_n$, which binds Hg ions. - Pore Structure (SEM): - 0.4 M HCl: Highest pore density (mesopores, 0.201–0.671 µm). - Control (no HCl): Larger but fewer pores (macropores, 3.015–7.527 µm). - Surface Area: Higher HCl concentration → smaller pores but greater number → increased adsorption sites.	- Optimal HCl Concentration: 0.4 M showed the highest Hg adsorption (96.06%).which ideal for gold mining wastewater treatment - Qualitative Test: 0.4 M HCl-treated mud produced no white precipitate, confirming complete Hg adsorption. - Quantitative Test: Precipitate mass decreased with increasing HCl concentration (0.0126 g for control vs. 0.0007 g for 0.4 M). - AAS Results: Residual Hg decreased from 12.7 ppm (control) to 0.5 ppm (0.4 M HCl). - Mechanism: - Polysilanol groups form stable complexes with Hg^+ and Hg^{2+} via covalent bonds. - Smaller mesopores (0.4 M HCl) enhance Hg trapping efficiency.	- Activation Process: - Lapindo mud was soaked in HCl solutions (0.05 M, 0.1 M, 0.2 M, 0.4 M, and 2 M) for 24 hours, followed by drying at 100°C. - Control treatment: Soaked in distilled water (no HCl). - Characterization: - SEM to analyze pore morphology. - Qualitative test (white precipitate formation with HCl addition). - Quantitative test (precipitate mass measurement). - AAS (Atomic Absorption Spectrophotometry) to measure residual Hg concentration. - Adsorption Testing: $HgNO_3$ solution (25 g/L) was treated with activated mud, and residual Hg was analyzed

6	(Trisunaryanti et al., 2020)	- To synthesize and characterize Ni-NH_2/mesoporous silica (MS) catalysts derived from Lapindo mud for hydrocracking waste cooking oil (WCO) into biofuels. - To evaluate the catalytic activity, selectivity, and efficiency of MS, NH_2/MS, and Ni-NH_2/MS in converting WCO into gasoline (C_5–C_{12}) and diesel (C_{13}–C_{17}) fractions. - To explore the role of amine functionalization (-NH_2) and Ni metal impregnation in enhancing hydrocracking performance. - To provide an eco-friendly alternative for biofuel production using waste-derived catalysts.	- Synthesis of Mesoporous Silica (MS): - Hydrothermal method using CTAB as a template and Lapindo mud-derived silica (96.86% SiO_2). - Calcination at 450°C to remove CTAB. - Functionalization: - Amine grafting via reflux with 3-APTMS to produce NH_2/MS. - Ni impregnation via wet impregnation ($Ni(NO_3)_2 \cdot 6H_2O$) to produce Ni-NH_2/MS. - Characterization: - FTIR (functional groups), SAA/BET (surface area, pore size), TEM (morphology). - Catalytic Testing: - Hydrocracking of WCO at 450°C, H_2 flow (15 mL/min), catalyst:feed = 1:50 (w/w). - Product analysis via GC-MS (hydrocarbon fractions).	- Raw Lapindo Mud: High silica content (>47% SiO_2), extracted for MS synthesis. - After Modification: - MS (Calcined): Surface area: 874.28 m^2/g, pore diameter: 3.59 nm, pore volume: 0.814 cc/g. Type IV isotherm (mesoporous), H1 hysteresis (uniform pores). - NH_2/MS: Reduced surface area (6.25 m^2/g) due to pore blocking by -NH_2 groups. -NH_2 grafting significantly improves gasoline selectivity by adsorbing FFAs, while Ni addition enhances hydrocracking activity. - FTIR confirmed -NH_2 peaks (2931 cm^{-1}, 1527 cm^{-1}). - Ni-NH_2/MS: Surface area increased to 13.65 m^2/g (Ni dispersion). - Wormhole-like pore structure (TEM). - Ni nanoparticles enhanced Lewis acid sites for cracking.	- Lapindo mud-derived mesoporous silica is a low-cost, sustainable catalyst support for biofuel production. - Catalytic Performance: - NH_2/MS: Highest liquid yield (70.32 wt.%), highest gasoline selectivity (34.98 wt.%). - MS: Highest diesel selectivity (1.52 wt.%). - Ni-NH_2/MS: Balanced activity (66.44 wt.% liquid yield). - Optimal Catalyst: NH_2/MS outperformed Ni-NH_2/MS in liquid yield (70.32 wt.%) and gasoline production (34.98 wt.%), suggesting amine groups are critical for selectivity - Mechanism: - NH_2 groups captured free fatty acids (FFAs), preventing coke formation. - Ni nanoparticles promoted hydrogenation/deoxygenation, converting FFAs to hydrocarbons. - Byproducts: - Coke formation: Lowest for NH_2/MS (1.94 wt.%). - Gas yield: ~27–30 wt.% (mainly light hydrocarbons).
7	(Trisunaryanti et al., 2021)	- To synthesize cobalt-supported mesoporous silica (Co/MS) catalysts derived from Lapindo mud for hydrocracking waste coconut oil (WCO) into gasoline (C_5–C_{12}) and diesel (C_{13}–C_{17}) fractions. - To investigate the effect of cobalt concentration (1–5 wt.%) on catalyst acidity, pore structure, and hydrocracking performance. - To optimize catalyst selectivity for hydrocarbon production while minimizing coke formation.	- Silica Extraction: Lapindo mud was treated with 6 M HCl and 6 M NaOH to extract high-purity silica (96.9% SiO_2). - Mesoporous Silica (MS) Synthesis: Hydrothermal method using CTAB as a template, followed by calcination at 550°C. - Catalyst Preparation: Wet impregnation of cobalt ($Co(NO_3)_2 \cdot 6H_2O$) at varying concentrations (1, 3, 5 wt.%) to produce Co(1)/MS, Co(2)/MS, Co(3)/MS. - Reduction under H_2 gas at 500°C. - Characterization: - XRF (silica purity), XRD (crystallinity), BET/SAA (surface area, pore volume), SEM/TEM	- Raw Lapindo Mud: Contained 45.49% SiO_2, 17.24% Al_2O_3, 8.19% Fe_2O_3. - After Modification: - MS (Calcined): Surface area: 291 m^2/g, pore volume: 0.93 cc/g, pore diameter: 3.28 nm (BET). - Type IV isotherm (mesoporous), H4 hysteresis (slit-like pores, SEM). - Co/MS Catalysts: - Co(1)/MS: Highest acidity (17.94 mmol/g) despite lowest Co loading (0.95 wt.%) and also achieved the best hydrocarbon selectivity demonstrating the importance of acid sites for cracking. - Pore blockage observed with increasing Co concentration (TEM). - Wormhole-like pore structure (TEM) retained after Co impregnation. - Acidity trend: Co(1)/MS > Co(3)/MS > Co(2)/MS > MS.	- Lapindo mud-derived mesoporous silica serves as a low-cost, high-purity support for Co-based hydrocracking catalysts. - Catalytic Performance: - Liquid Yield: Co(2)/MS (79.17 wt.%) > Co(3)/MS (77.20 wt.%) > Co(1)/MS (75.97 wt.%). - Hydrocarbon Selectivity: Co(1)/MS showed highest total hydrocarbons (64.85 wt.%: 43.11 wt.% gasoline, 21.74 wt.% diesel). - Gas/Coke Byproducts: Low coke formation (<0.5 wt.%) for all catalysts. - Key Findings: - Acidity-driven selectivity: Co(1)/MS's high acidity correlated with superior hydrocarbon production.

		- To provide a sustainable alternative for biofuel production using waste-derived materials.	(morphology), NH_3 adsorption (acidity). - Catalytic Testing: Hydrocracking at 450°C, H_2 flow (15 mL/min), catalyst:feed = 1:50 (w/w). Product analysis via GC-MS (hydrocarbon fractions).		- Optimal Co loading: Co(2)/MS (1.39 wt.% Co) balanced metal dispersion and pore accessibility, achieving highest liquid yield. - Low Co (0.95 wt.%): Maximized acidity and selectivity but lower liquid yield - Pore blockage: Excessive Co (Co(3)/MS, 5.26 wt.%) reduced efficiency due to agglomeration.
8	(Dewi et al., 2017)	- To synthesize MCM-41 from silica extracted from Lapindo mud using a sonochemical method. - To modify MCM-41 with (3-aminopropyl)trimethoxysilane (3-APTMS) to create MCM-41-NH_2, a base catalyst. - To evaluate the catalytic performance of MCM-41-NH_2 in the transesterification of waste palm oil into biodiesel.	- Silica Extraction: Lapindo mud was refluxed with HCl and NaOH solutions to extract silica (97.5% purity). - MCM-41 Synthesis: Sonochemical method with CTAB as a template, varying sonication times (30–150 min). - Modification: Grafting 3-APTMS onto MCM-41 via reflux in toluene. - Transesterification: Waste palm oil, methanol, and MCM-41-NH_2 catalyst under reflux.	- MCM-41 (150 min sonication): - Specific surface area: 1603 m^2/g - Pore diameter: 2.57 nm (mesoporous) - Ordered hexagonal pore structure (confirmed by XRD, TEM, and Type IV adsorption isotherm). - MCM-41-NH_2: - Reduced surface area (1037 m^2/g) and pore diameter (2.39 nm) due to 3-APTMS grafting. Confirmed amine functionalization via FT-IR.	- Lapindo Mud Valorization: High-purity silica (97.5%) extracted from Lapindo mud offers a sustainable resource for advanced materials. - Process Efficiency: Sonochemical synthesis (150 min) produced high-quality MCM-41, avoiding prolonged hydrothermal treatments. - Catalytic Performance: - MCM-41-NH_2's mesoporous structure and amine groups facilitated effective transesterification achieved 76.55% conversion of waste palm oil to methyl esters (biodiesel). - Demonstrated the viability of Lapindo mud-derived silica for eco-friendly base catalysts. - Advantages: - Sonochemical synthesis reduced time compared to hydrothermal methods. - High surface area and ordered pores enhanced catalytic activity.
9	(Parningotan et al., 2024)	- To evaluate Sidoarjo volcanic mud (VM) as a heterogeneous Fenton catalyst for Congo Red (CR) dye removal from wastewater. - To compare the performance of three modification methods: unmodified (UVM), calcination (CVM), and impregnation-	- Catalyst Preparation: - UVM: Dried at 60°C for 3 h. - CVM: Calcined at 550°C for 3 h. - ICVM: Impregnated with $Fe(NO_3)_3 \cdot 9H_2O$, calcined at 300°C for 2 h. - Fenton Oxidation: Batch experiments with CR (50 mg/L), pH=2, catalyst dosage=0.5 g/L, H_2O_2=485 mg/L.	- UVM: Natural VM with 19 mg/g Fe content; minimal iron leaching (0.3 mg/L). - CVM: Increased surface area (calcination-enhanced); 6 mg/g Fe content; higher adsorption capacity (70% CR removal). - ICVM: High Fe content (81 mg/g) due to impregnation; moderate iron leaching (1.15 mg/L); no significant improvement in catalytic performance. - Common Traits: Mesoporous structure (confirmed by adsorption isotherms), Fe-rich composition (40.56% Fe in raw VM).	- Lapindo Mud Valorization: High Fe content (40.56%) in raw VM makes it suitable for Fenton-based wastewater treatment. - CR Removal Efficiency: - Adsorption Only: CVM (70%) > ICVM (37%) ≈ UVM (35%). - Fenton Oxidation (smt): CVM (73%, adsorption-dominated) > ICVM (50%) > UVM (44%). - Sequential (sqt) Adsorption-Fenton: CVM (90%), ICVM (55%), UVM (52%).

		calcination (ICVM). - To assess the synergistic effects of adsorption-Fenton oxidation for CR removal	- Process Variations: Simultaneous (smt) vs. sequential (sqt) H_2O_2 addition. Analysis: UV-Vis spectrophotometry (CR removal), iron leaching, COD.		- Key Findings: - UVM is the most stable Fenton catalyst (lowest Fe leaching) meets the environmental standards, making it sustainable options. - CVM is better suited as an adsorbent but limits Fenton activity. - ICVM's high Fe content did not enhance catalytic performance due to potential hydroxyl radical scavenging but reduces cost-effectiveness.
10	(Faza Nisrina et al., 2024)	- To evaluate Sidoarjo volcanic mud (VM) as a heterogeneous catalyst for persulfate (PS) activation in Advanced Oxidation Processes (AOP) for Congo Red (CR) dye removal. - To compare three modification methods: unmodified (UVM), iron-impregnated (Fe-IVM), and calcined (CVM) VM. - To assess the efficiency of sequential vs. simultaneous PS activation methods.	- Catalyst Preparation: - UVM: Dried at 60°C for 3 h. - Fe-IVM: Impregnated with $Fe(NO_3)_3 \cdot 9H_2O$, dried at 105°C for 24 h, and calcined at 300°C for 2 h. - CVM: Calcined at 550°C for 3 h. - Experimental Setup: Batch reactions with CR (50 mg/L), pH=2, catalyst dosage=0.5 g/L, PS:COD=1:1. - Process Variations: Sequential (PS added at t=30 min) vs. simultaneous (PS added at t=0 min) methods - Analysis: UV-Vis spectrophotometry (CR removal), iron leaching, residual PS titration	- UVM: Natural VM with 19 mg/g Fe content; minimal iron leaching (1.95 mg/L). - Fe-IVM: High Fe content (81 mg/g) due to impregnation; moderate iron leaching (3.45 mg/L). - CVM: Enhanced surface area (calcination at 550°C); low Fe content (6 mg/g); highest adsorption capacity (73.05% CR removal). Common Traits: Mesoporous structure, Fe-rich composition (34–36% Fe in raw VM).	- Lapindo Mud Valorization: High Fe content (34–36%) in raw VM enables effective PS activation for CR degradation - CR Removal Efficiency: - Sequential Method: UVM (84.75%), Fe-IVM (81.72%), CVM (87.69%). - Simultaneous Method: UVM (83.15%), Fe-IVM (81.79%), CVM (77.90%). - Sequential PS injection (after 30 min adsorption) improved CR removal by 1–10% compared to simultaneous methods. - Key Findings: - UVM: Highest catalytic performance (83.73% oxidation contribution) with lowest Fe leaching (1.95 mg/L). - CVM: Dominated by adsorption (73.05%); limited PS activation. - Fe-IVM: No significant improvement over UVM despite higher Fe content. Homogeneous Comparison: UVM matched $FeCl_3$/$FeSO_4$ performance (~84% CR removal), proving feasibility as a low-cost alternative.
11	(Kusumastuti et al., 2018)	- To synthesize mesoporous silica-alumina (MSA) from Lapindo mud using catfish bone gelatin as a template for catalytic support.	- MSA Synthesis: - Extraction of SiO_2 and Al_2O_3 from Lapindo mud using NaOH/HCl. - Gelatin template from catfish bone (SDS-PAGE confirmed 10–291	- MSA: - Si/Al ratio: 5.65; BET surface area: 212.29 m^2/g. - Pore diameter: 20.05 nm; pore volume: 1.29 cm^3/g. - Acidity: 13.56 mmol/g (pyridine adsorption). - Amorphous structure (XRD) with mesopores (Type IV isotherm, H1 hysteresis).	- Lapindo Mud Valorization: High silica (49.24 wt.%) and alumina (19.30 wt.%) content in Lapindo mud enabled MSA synthesis with optimal acidity and porosity for catalysis - Catfish bone gelatin (13.87% yield) served as an effective, low-cost

		- To evaluate MSA-supported Ni, Mo, NiMo, and MoNi catalysts for hydrocracking pyrolyzed α-cellulose into bio-oil. - To compare the performance of mono- (Ni, Mo) and bimetallic (NiMo, MoNi) catalysts.	kDa molecular weight). - Hydrothermal treatment (100°C, 24 h) and calcination (550°C, 4 h). - Catalyst Preparation: Wet impregnation of Ni/Mo salts onto MSA, calcination (500°C, 3 h), and H_2 reduction (450°C, 3 h). - Hydrocracswaking: Pyrolyzed α-cellulose (600°C, 4 h) reacted at 450°C for 2 h with catalysts (1:30 catalyst/oil ratio).	- Catalysts: - Ni/MSA: 0.93 wt.% Ni, 22.08 mmol/g acidity. - NiMo/MSA: 0.88 wt.% Ni, 1.09 wt.% Mo, 19.60 mmol/g acidity. MoNi/MSA: 0.72 wt.% Ni, 0.95 wt.% Mo, 22.22 mmol/g acidity.	biopolymer template for mesopore formation. - Hydrocracking Performance: - Liquid Yield: NiMo/MSA (85.51 wt.%) > MoNi/MSA (85.29 wt.%) > Ni/MSA (77.33 wt.%) > Mo/MSA (76.67 wt.%). - NiMo/MSA achieved the highest liquid yield due to balanced metal dispersion and acidity. - MoNi/MSA showed superior acidity (22.22 mmol/g) despite lower metal loading - Product Selectivity: Bimetallic catalysts favored aldehydes (15.85–13.68 wt.%), ketones (33.40–52.22 wt.%), and carboxylic acids (42.05–27.17 wt.%). - Key Findings: - Bimetallic catalysts (NiMo, MoNi) outperformed monometallic due to synergistic effects (Ni enhances Mo reactivity). - MSA's high acidity and mesoporosity critical for catalytic activity. Hydrocracking via carbonium ion mechanism (catalytic) reduced gas formation compared to radical-based thermal cracking.
12	(Talib et al., 2016)	To investigate the potential of Lapindo mud (LM), a volcanic eruption waste, as a cost-effective and recyclable heterogeneous catalyst for the transesterification of waste oils (waste cooking oil (WCO) and palm oil mill effluent (POME)) into biodiesel (FAME).	- Catalyst Preparation: LM was calcined at 550°C for 3 h to remove impurities. - Characterization: XRD, FESEM-EDX, BET surface area analysis, Hammett indicator titration, FTIR, and ESR spectroscopy. - Transesterification: Optimized via Response Surface Methodology (RSM) using Central Composite Design (CCD). - Kinetic Study: Langmuir-Hinshelwood first-order reaction model and Arrhenius	- Composition: Major components include SiO_2, K_2O, and CaO (confirmed by XRD and EDX). - Basicity: Total basicity increased from 0.4926 to 0.9858 mmol/g after thermal activation (350°C). - Surface Area: Increased from 7.478 to 14.291 m^2/g after activation. - Active Sites: Formation of non-bridging oxygen holes (NBOH) centers, enhancing catalytic activity (ESR analysis). Morphology: Irregular particle aggregates (FESEM).	- LM repurposes volcanic waste into a viable catalyst, reducing biodiesel production costs. - WCO Transesterification: Achieved 96.6% FAME yield under optimized conditions (85.6°C, LM:methanol:oil = 0.0295:0.44:1, 330°C activation). - POME Transesterification: 91.69% FAME yield (LM:methanol:POME = 0.03:0.225:1, 350°C activation). - Reusability: Stable performance with <10% decline in FAME yield after 7 cycles (95% catalyst recovery). - Kinetics: Activation energies of 55.7 kJ/mol (WCO) and 59.75 kJ/mol

			equation for activation energy calculation. - Reusability Test: Catalyst recovery and performance over multiple cycles.		(POME), indicating efficient catalysis. - Biodiesel Quality: Met international standards (ASTM D6751, EN 14214) for viscosity, acid value, and flash point.
13	(Wijaya et al., 2018)	- To synthesize and characterize K_2O/MCM-41 catalysts derived from Lapindo mud (LM) silica via a sonochemical method for the transesterification of used cooking oil (UCO) into biodiesel. - The study aimed to optimize catalyst performance by varying K^+ loading and reaction temperature.	- Silica Extraction: LM was washed, refluxed with HCl/NaOH, and precipitated to extract silica (96.7% purity). - MCM-41 Synthesis: Sonochemical method using CTAB template, followed by calcination (540°C, 5 h). - Catalyst Preparation: K_2O/MCM-41 was prepared by impregnating MCM-41 with K^+ (0.80–2.49 wt.%) and calcining (550°C, 6 h). - Characterization: XRD, FTIR, TEM, BET surface area analysis, ICP. - Transesterification: UCO reacted with methanol (15:1 molar ratio) at 50–70°C for 2 h using 10 wt.% catalyst. - Reusability: Catalyst tested over 3 cycles (2 h each).	- MCM-41: Hexagonal mesopores (30.49 Å diameter), high surface area (1282.33 m^2/g), confirmed by XRD/TEM. - K_2O/MCM-41: Reduced surface area (225.81 m^2/g) and pore volume due to K^+ impregnation. - K^+ Loading: Varied from 0.80 to 2.49 wt.% (ICP-verified). Basicity: Enhanced nucleophilicity from K_2O, promoting methoxide formation.	- Optimal Conditions: 70°C, 2.49 wt.% K^+ (K_2O_4/MCM-41), yielding 79.80 wt.% biodiesel. - Temperature Effect: Higher temperatures (70°C) improved yield due to better reactant miscibility. - Catalyst Lifetime: Linear regression predicted 15.41 hours of activity before deactivation. - Reusability: Yield dropped to 56.84 wt.% by the 3rd cycle, indicating gradual K^+ leaching. - Biodiesel Quality: Met basic ester content standards (GC-MS analysis). - Sonochemical synthesis of MCM-41 from LM silica is faster than hydrothermal methods. - K_2O_4/MCM-41 (2.49 wt.% K^+) outperformed lower-loading variants, achieving near-80% yield.
14	(Swasdika et al., 2021)	- To synthesize mesoporous silica-alumina (MSA) from Lapindo mud and catfish bone gelatin, then impregnate it with Cu/Zn metals for hydrotreatment of cellulose-derived bio-oil. - The study aimed to develop a cost-effective, bifunctional catalyst to upgrade bio-oil by reducing oxygen content and improving fuel quality.	- Silica/Alumina Extraction: LM was acid/alkali-treated to extract SiO_2 (96.3% purity) and Al_2O_3 (84.5% purity). - MSA Synthesis: Gelatin template (from catfish bone) was used to create MSA via hydrothermal treatment (100°C, 24 h) and calcination (550°C, 5 h). - Catalyst Preparation: Cu/Zn was loaded onto MSA via wet impregnation, followed by calcination (500°C) and reduction (H_2, 450°C). - Characterization: XRD, FTIR, BET, TEM, ICP-AES, and acidity measurement (NH_3 adsorption). - Hydrotreatment: Bio-oil (from cellulose	- MSA: High Si/Al ratio (115.34), mesoporous (8.19 nm pore diameter), surface area = 200.52 m^2/g. - CuZn/MSA: Cu (5.23 wt.%) and Zn (3.15 wt.%) loading reduced surface area to 170.77 m^2/g but increased acidity (24.86 mmol/g). - Structure: XRD confirmed amorphous MSA; TEM showed uniform metal dispersion. - Acidity: Enhanced by Cu/Zn's Lewis acid sites, critical for hydrodeoxygenation (HDO).	- Optimal Catalyst: CuZn/MSA achieved 90.49 wt.% liquid yield, outperforming monometallic (Cu/MSA: 19.95 mmol/g acidity) and other bimetallic variants. - Reaction Mechanism: Synergy between Cu (hydrogenation) and Zn (H_2 activation) enhanced oxygen removal. - Product Quality: Reduced ketones/acids (e.g., 2,3-butanedione, methanoic acid) and produced hydrocarbons (e.g., n-hexane). - Comparison: CuZn/MSA surpassed previous Ni/Mo-MSA catalysts (85.29 wt.% yield) in bio-oil upgrading.

			pyrolysis) was upgraded at 450°C under H_2 using CuZn/MSA (catalyst:feed = 1:30).		
15	(Paramesti et al., 2021)	- To synthesize Ni-loaded mesoporous silica (Ni/MS) catalysts from Lapindo mud for hydrocracking waste cooking oil (WCO) into biofuels (gasoline and diesel fractions). - The study evaluated the effect of Ni loading (4–8 wt.%) on catalyst performance	- Silica Extraction: LM was treated with HCl/NaOH to extract silica (96.86% purity). - MS Synthesis: Hydrothermal method using CTAB template, followed by calcination (540°C, 5 h). - Catalyst Preparation: Ni (4, 6, 8 wt.%) was loaded via wet impregnation, calcined (500°C, N_2), and reduced (H_2, 450°C). - Characterization: XRD, FTIR, SEM, BET, AAS. - Hydrocracking: WCO was processed at 450°C with H_2 flow (catalyst:feed = 1:50) for 2.5 h. Products analyzed by GC-MS.	- MS Support: High surface area (874.28 m^2/g), mesoporous (3.59 nm pore diameter). - Mechanism: Ni sites facilitated hydrogenation and cracking of WCO's free fatty acids (FFAs) into shorter hydrocarbons. - Ni/MS Catalysts: - Ni(4)/MS: 63.08 m^2/g surface area, 3.26 nm pores, 4.40 wt.% Ni. - Ni(6)/MS: 91.45 m^2/g, 3.22 nm pores, 6.97 wt.% Ni. - Ni(8)/MS: 120.45 m^2/g, 3.59 nm pores, 9.57 wt.% Ni. - Acidity: Increased with Ni loading, enhancing cracking activity. Structure: XRD confirmed NiO/Ni phases; SEM showed irregular mesopores.	- Optimal Ni Loading: 4 wt.% Ni balanced surface area and acidity, maximizing liquid yield and gasoline selectivity - Liquid Yield: Ni(4)/MS achieved the highest yield (80.57 wt.%), outperforming Ni(6)/MS (74.63 wt.%) and Ni(8)/MS (75.77 wt.%). - Biofuel Selectivity: - Gasoline (C_5–C_{12}): Ni(4)/MS produced 54.22 wt.%. - Diesel (C_{13}–C_{17}): Ni(8)/MS produced 8.37 wt.%. - Catalyst Stability: Ni(4)/MS showed minimal coking (2.68 wt.%) compared to higher Ni loadings. - Comparison: Ni(4)/MS surpassed non-catalytic thermal cracking (76.67 wt.% liquid yield) and pure MS (63.95 wt.%).
16	(Mahardika et al., 2017)	- To synthesize CaO/MCM-41 catalyst from Lapindo mud silica via sonochemical method for transesterification of used cooking oil into biodiesel, optimizing reaction conditions and evaluating catalyst lifetime.	- Silica extraction: Refluxed Lapindo mud with 6 M HCl and 6 M NaOH. - MCM-41 synthesis: Sonochemical method (150 min) using CTAB template. - CaO loading: Wet impregnation with Ca(CH₃COO)₂. - Transesterification: Reflux at 55–75°C, methanol/oil ratio 15:1, catalyst/oil ratio 5–15 wt.%.	- MCM-41: Hexagonal pore structure (TEM), surface area = 1290 m^2/g, pore diameter = 3.4 nm (SAA). CaO/MCM-41: Ca^{2+} content 1.15–3.25 wt.% (ICP), reduced surface area (203.84 m^2/g), retained mesoporosity (3.41 nm).	- Lapindo mud (44.24% SiO) served as a low-cost silica source, with sonochemical synthesis reducing time vs. hydrothermal methods. - Highest methyl ester conversion: 78.17% at 65°C, catalyst/oil ratio 15/100. - Catalyst lifetime: 9.8 h (3 reuse cycles; deactivation due to glycerol blockage). - CaO(4)/MCM-41 (3.25 wt.% Ca^{2+}) achieved optimal activity, balancing pore accessibility and active sites - Key advantage: Utilization of waste (Lapindo mud) for sustainable biodiesel production.

CONCLUSION

The Sidoarjo Volcanic Mud, long regarded as a disaster byproduct, presents substantial potential as a valuable material in civil and environmental engineering. Its high silica and alumina content, favorable physical properties, and non-hazardous classification make it suitable for diverse applications, including construction materials (e.g., ceramics, geopolymers, and lightweight bricks), road stabilizers, adsorbents for wastewater treatment, and catalysts for biofuel production. With proper treatment, such as calcination, chemical activation, and

composition optimization, Sidoarjo mud can achieve mechanical strength, durability, and environmental performance that meet or exceed national standards. Despite these advancements, challenges remain in scalability, commercialization, and optimizing material performance. Future research should focus on refining treatment methods, improving activation processes, and addressing economic and technical barriers to large-scale implementation. By transforming Sidoarjo mud into sustainable products, this approach not only mitigates environmental degradation but also creates economic opportunities, turning a disaster into a resource for sustainable development.

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