JIMESE
Journal of Innovation Materials, Energy, and Sustainable Engineering
JIMESE 4(1): 55–73
ISSN 3025-0307

Institute for Advanced Science, Social and Sustainable Future
MORALITY BEFORE KNOWLEDGE

Refining the future: A serpentine-based reactive adsorbent for carbon dioxide valorization

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Received Date: April 1, 2026 Revised Date: June 8, 2026 Accepted Date: July 27, 2026

ABSTRACT

Background: The rising global carbon dioxide (CO_2) emissions necessitate efficient and sustainable carbon capture solutions, particularly for Indonesia's industrial sector. This study explores the potential of Aceh serpentinite, a local mineral resource, as a raw material to produce magnesium oxide (MgO) for use as a reactive adsorbent in carbon capture, utilization, and storage (CCUS) technology. Unlike other methods that use expensive imported materials, this research utilizes domestic natural resources through an economical chemical and thermal activation process. **Methods:** The research methodology involved the preparation of serpentinite samples, which were thermally activated at 700 °C for 2 hours to remove hydroxyl groups and enhance mineral reactivity. This was followed by acid leaching using 1M hydrochloric acid (HCl) and precipitation with sodium hydroxide (NaOH) to extract the MgO. **Findings:** The findings demonstrated that thermal activation led to a mass loss of 9.63% (Loss on Ignition), indicating successful dehydroxylation of the mineral structure. Mass balance calculations estimate that approximately 3.54 grams of MgO could be produced from 13.19 grams of raw rock, representing a process efficiency of 72.8%. **Conclusion:** The findings confirm that Aceh serpentinite contains sufficient reactive magnesium to be a viable and cost-effective material for CCUS applications, offering a sustainable alternative for industrial emission reduction. **Novelty/Originality of this article:** The novelty of "REFINE" lies in the strategic use of common local minerals through a simplified and economical chemical path to replace expensive imported carbon capture materials, turning natural resources into high-value environmental products.

KEYWORDS: Aceh serpentinite; carbon capture; magnesium oxide; reactive adsorbent; sustainability.

1. Introduction

The continuous and unabated escalation of global climate change driven predominantly by the exponential accumulation of anthropogenic greenhouse gases within the atmosphere has emerged as the most formidable environmental and socioeconomic challenge of the twenty first century (Bullock et al., 2022). Carbon dioxide acting as the primary greenhouse gas emitted through the extensive combustion of fossil fuels intensive industrial manufacturing processes and large-scale land use alterations has seen its atmospheric concentration escalate to unprecedented and alarming levels in recent decades (Zhang et al.,

Cite This Article:
Heztio, M. F., Syihab, N. A., & Liem, C. S. (2026). Refining the future: A serpentine-based reactive adsorbent for carbon dioxide valorization. *Journal of Innovation Materials, Energy, and Sustainable Engineering, 4* (1), 55-73. https://doi.org/10.61511/jimese.v4i1.2026.3662

2020). In response to this accelerating ecological crisis conventional mitigation strategies which primarily focus on gradually reducing the rate of new emissions or transitioning to renewable energy sources are fundamentally insufficient to halt global temperature increases and restore atmospheric balance (Kelemen et al., 2020). Achieving stringent global climate targets particularly the ambition to limit global warming to safe thresholds now mandates the aggressive and immediate deployment of negative emission technologies capable of actively extracting carbon dioxide directly from high emission point sources (International Energy Agency Greenhouse Gas R&D Programme [IEAGHG], 2022). The implementation of Carbon Capture Utilization and Storage technologies is universally recognized by the scientific community and policymakers as one of the most essential technological pillars for the deep decarbonization of the global energy and industrial infrastructure (Stokreef et al., 2022).

Within the diverse portfolio of alternative carbon capture methodologies mineral carbonation also referred to as mineral sequestration presents an exceptionally stable and thermodynamically favorable pathway for permanent carbon fixation (Stokreef et al., 2022). Mineral carbonation is fundamentally engineered to emulate and significantly accelerate the natural geological process of silicate weathering where basic minerals naturally absorb atmospheric gases over geological timescales (Bullock et al., 2022). In this controlled engineering process gaseous carbon dioxide is chemically reacted with alkaline earth metal oxides predominantly magnesium oxide and calcium oxide to form geologically stable and environmentally benign carbonate minerals such as magnesite and calcite (Saleem et al., 2025). Unlike direct geological storage in depleted oil and gas reservoirs or deep saline aquifers which carries a persistent risk of gas leakage over centuries mineral carbonation provides a permanent nontoxic and leak proof storage solution because the carbon dioxide is chemically bound within a solid rock crystalline framework (IEAGHG, 2022). This solid-state sequestration guarantees permanent storage without the need for extensive post injection monitoring thereby eliminating long term environmental liabilities and ensuring absolute ecological safety (Galina et al., 2023). Furthermore, the industrial integration of mineral carbonation networks provides an opportunity to utilize alkaline industrial wastes and mining tailings turning massive stockpiles of hazardous materials into valuable environmental remediation tools (IEAGHG, 2022).

However, the successful large-scale deployment of this technology requires an intricate understanding of the fundamental reaction kinetics thermodynamics and specific geochemical properties of the host rocks targeted for carbonation (Woodall et al., 2019). Among the diverse array of natural silicate minerals currently being investigated for global carbonation initiatives minerals from the serpentinite group have garnered profound academic and industrial interest due to their ubiquitous distribution in the Earth crust and their theoretically massive carbon sequestration capacity (Stankovic et al., 2025). Magnesium silicates such as olivine and serpentine are abundant, offering a colossal potential to store carbon dioxide, but they naturally react extremely slowly with carbon dioxide under ambient atmospheric conditions (Makikouri et al., 2026). Therefore, extensive scientific interventions are strictly necessary to engineer these raw minerals into highly porous reactive chemisorbents capable of capturing industrial carbon dioxide emissions at realistic operational timeframes (Vieira et al., 2022).

In the context of developing nations, the utilization of domestic mineral resources for carbon capture applications is of paramount strategic importance to establish national mineral sovereignty in climate mitigation (IEAGHG, 2022). Serpentinite is a magnesium rich metamorphic rock predominantly composed of serpentine group minerals naturally exhibiting a high chemical affinity for carbonation (Stankovic et al., 2025). Comprehensive morphological and chemical characterizations have delineated that global serpentinite possesses a remarkably high magnesium oxide content often reaching up to forty three percent by weight alongside a substantial silica matrix (Auyeshov et al., 2025). This exceptionally high intrinsic magnesium concentration serves as a fundamental prerequisite

for its viability as a precursor for reactive carbon capture adsorbents considering that magnesium cations act as the primary active binding sites for carbon dioxide chemisorption and subsequent carbonate precipitation (Abu Fara et al., 2024).

Despite this tremendous theoretical potential, the direct utilization of raw serpentinite for carbon capture is severely impeded by its innate crystallographic constraints (Makikouri et al., 2026). In its natural geological state, the magnesium ions within the serpentinite matrix are tightly sequestered within a complex octahedral sheet (Auyeshov et al., 2024). This specific structural configuration is heavily stabilized by an extensive network of strong hydroxyl bonds which effectively lock the magnesium cations inside the lattice and shield them from external chemical interactions (Makikouri et al., 2026). Consequently, the chemical reactivity of raw serpentinite under ambient conditions is virtually negligible, making it an ineffective medium for direct gas capture (Stankovic et al., 2025). The dense and highly ordered crystalline lattice acts as a formidable kinetic barrier completely preventing both aqueous acidic leaching agents and gaseous carbon dioxide molecules from accessing the active magnesium sites (Dufourny et al., 2022). To unlock the true sequestration potential of these magnesium rich minerals and bridge the colossal gap between theoretical capacity and practical industrial application advanced interventions are specifically designed to fundamentally alter the crystalline phase of the mineral (Auyeshov et al., 2025).

The crystallographic transformation of serpentinite through thermal activation commonly referred to as calcination represents the most critical preprocessing stage in unlocking its carbon sequestration potential (Makikouri et al., 2026). This high temperature intervention is fundamentally designed to drive the endothermic dehydroxylation reaction a complex physical process that forcibly expels the structurally bound water molecules from the mineral lattice (Auyeshov et al., 2024). The expulsion of these hydroxyl groups induces a profound structural collapse converting the ordered chemically inert crystalline structure of raw serpentinite into the desired disordered amorphous phase (Makikouri et al., 2026). The formation of this amorphous meta serpentine is accompanied by a substantial expansion in the material specific surface area and intra particle porosity which dramatically enhances the exposure of magnesium cations to subsequent chemical reagents (Abu Fara et al., 2024). The dynamics of this phase transition are governed by complex non isothermal kinetics where the applied thermal window dictates the ultimate reactivity of the end product (Makikouri et al., 2026).

Recent thermogravimetric and crystallographic studies unequivocally indicate that the optimal temperature for maximizing the yield of the reactive amorphous phase lies precisely within the range of six hundred to seven hundred and fifty degrees Celsius (Makikouri et al., 2026). If the calcination temperature is maintained below this critical threshold the thermal energy remains insufficient to overcome the activation energy required for complete hydroxyl bond cleavage leaving the inert silicate matrix largely intact (Makikouri et al., 2026). Conversely elevating the temperature beyond this optimal window or extending the duration excessively triggers a detrimental secondary phase transition wherein the amorphous meta serpentine undergoes rapid recrystallization to form highly stable ordered orthosilicate minerals such as forsterite (Auyeshov et al., 2024). Because these recrystallized forsterite phases possess exceptionally low chemical affinity for both acidic solvents and carbon dioxide precise thermal regulation is absolutely imperative to prevent the permanent passivation of the mineral precursor (Makikouri et al., 2026). Recent innovations emphasize the utilization of electrically heated fluidized bed reactors to achieve extremely rapid and uniform heat distribution drastically reducing the required thermal activation duration from hours down to just a few minutes thereby preserving the amorphous structure while maximizing energy efficiency (Makikouri et al., 2026). Implementing an online fourier transform infrared analyzer provides real time data on the dehydroxylation degree ensuring precise control over the thermal activation process (Makikouri et al., 2026).

Following the successful generation of the meta serpentine phase, the liberation of magnesium from the residual silicate framework is achieved through hydrometallurgical

acid leaching (Saleem et al., 2025). In the context of producing high purity magnesium precursors for carbon capture utilization and storage the selection of the solvent is of paramount importance (Saleem et al., 2025). Hydrochloric acid and sulfuric acid have been extensively proven to be highly efficient for serpentinite dissolution primarily due to their high selectivity and the high aqueous solubility of the resulting metal salts (Galina et al., 2023). The dissolution kinetics of magnesium in acidic media are governed by a combination of chemical reaction rates at the mineral liquid interface and diffusion through the porous solid product layer (Abu Fara et al., 2024). Studies regarding the specific dissolution behaviors of different serpentine group minerals including antigorite chrysotile and lizardite show varying degrees of vulnerability to acid attack based on their distinct crystallographic layers (Abu Fara et al., 2024). During the initial stages of dissolution there is an exceptionally rapid rate of magnesium extraction driven by the low potential of hydrogen and the high concentration of reactive protons in the solvent (Abu Fara et al., 2024).

However, as the chemical reaction progresses the potential of hydrogen naturally increases, and an amorphous silica precipitate inevitably forms surrounding the unreacted mineral core (Abu Fara et al., 2024). This dense silica rich layer acts as a formidable diffusion barrier that physically blocks the continuous transport of protons to the active reaction sites, ultimately decelerating the mineral dissolution rate dramatically (Abu Fara et al., 2024). Overcoming this passivation layer without resorting to extreme acid concentrations demands intelligent process design such as carefully optimizing the solid to liquid ratio and extending the reaction retention time to ensure maximum penetration of the solvent into the porous silica network (Abu Fara et al., 2024). Under aggressive leaching conditions typically characterized by the utilization of highly concentrated acids such as five molar hydrochloric acid at temperatures approaching the boiling point magnesium extraction efficiencies exceeding ninety percent can be achieved within a matter of hours (Galina et al., 2023). Furthermore, leaching with nitric acid has also been evaluated demonstrating substantial magnesium recovery under controlled elevated temperatures (Chen et al., 2022). However, translating such aggressive hydrometallurgical protocols to an industrial scale presents prohibitive economic and severe environmental challenges (Galina et al., 2023). The continuous handling of hot concentrated acid accelerates the corrosion of industrial reactors significantly increases operational hazards demands excessive energy inputs and generates massive volumes of highly acidic effluent that require costly downstream neutralization (Saleem et al., 2025).

In response to these constraints, contemporary research paradigms are increasingly shifting towards the optimization of mild leaching conditions and exploring biological alternatives (Stankovic et al., 2025). The strategic utilization of dilute acidic solutions coupled with moderate operating temperatures and extended retention times offers a highly pragmatic compromise (Galina et al., 2023). This low intensity approach substantially mitigates reagent costs and infrastructure degradation while still achieving competitive extraction yields, making it an exceptionally viable strategy for processing regional ores (Galina et al., 2023). Furthermore, the application of bioleaching utilizing specialized sulfur oxidizing bacteria such as *Acidithiobacillus thiooxidans* has emerged as a groundbreaking and highly sustainable alternative to conventional chemical leaching (Stankovic et al., 2025). Bioleaching in stirred tank bioreactors has been demonstrated to achieve magnesium recoveries exceeding ninety percent providing a low cost biologically driven process that operates at ambient temperatures (Stankovic et al., 2025). In contrast to the bioleaching of copper sulfide ores which generates excess sulfuric acid and leads to severe environmental hazards such as acid mine drainage the bioleaching of serpentine minerals naturally consumes the biogenically produced acid preventing toxic accumulation (Stankovic et al., 2025). The solid residues remaining after biological magnesium extraction are chemically inert posing absolutely no risk to surrounding ecosystems (Stankovic et al., 2025). The integration of simulated heap leaching techniques using coarse rock particles further avoids the high energy costs associated with the fine grinding necessary for chemical reactors

(Stankovic et al., 2024). Although larger particle sizes generally reduce the overall leaching efficiency the significant reduction in both capital expenditure and continuous operational costs makes heap leaching a highly attractive proposition for large scale environmental remediation (Stankovic et al., 2024). The successful coupling of these low energy biological and mild chemical extraction methods with downstream carbonation networks could eventually enable scalable and cost-effective carbon dioxide removal perfectly aligned with global sustainability mandates (Petersen, 2023).

When serpentinite is dissolved in acidic media alongside the desired magnesium several unwanted impurity metals such as iron aluminum and calcium are inevitably co extracted into the solution (Auyeshov et al., 2025). The presence of these heavy elements severely complicates the downstream precipitation of pure magnesium compounds because they tend to precipitate simultaneously thereby reducing the quality and carbon dioxide binding capacity of the final adsorbent (Auyeshov et al., 2025). Therefore, a highly selective purification phase utilizing the potential of hydrogen swing mineral carbonation method is mandatory within the integrated framework (Galina et al., 2023). Conventionally purification is achieved by incrementally adding basic solutions such as aqueous sodium hydroxide to raise the potential of hydrogen to specific levels for instance a value of five to precipitate ferric iron and nine for ferrous iron (Galina et al., 2023). However, this conventional approach introduces massive amounts of extraneous sodium ions into the system and consumes large volumes of expensive reagents which diminishes the overall economic viability of the entire process (Galina et al., 2023). While aqueous sodium hydroxide remains the industry standard its large-scale application introduces a severe environmental penalty in the form of massive fresh water consumption (Galina et al., 2023). In eco industrial implementations where water conservation is paramount the utilization of solid phase sodium hydroxide has emerged as a groundbreaking alternative (Galina et al., 2023). Experimental validations unequivocally indicate that substituting aqueous sodium hydroxide solutions with solid sodium hydroxide particles not only drastically reduces the total water footprint of the carbonation process from over one hundred cubic meters down to eighty cubic meters per ton of carbon dioxide but also improves the selectivity and crystallization of the final magnesium precipitates avoiding the unintended formation of highly hydrated secondary phases (Galina et al., 2023). Furthermore, a central composite rotatable design reveals that precise adjustment of the alkaline reagent concentrations is crucial to maximize the ultimate carbon dioxide sequestration efficiency (Galina et al., 2023).

To further overcome these economic and chemical limitations recent process innovations have demonstrated the exceptional efficacy of utilizing thermally activated serpentinite itself as a primary neutralizing agent during the critical purification stage (Auyeshov et al., 2025). Due to its extremely high surface area and the vast abundance of basic active sites generated during thermal dehydroxylation the activated rock can effectively neutralize the acidic suspension without the need for external bases (Auyeshov et al., 2025). This intrinsic acid base interaction selectively precipitates the majority of iron and aluminum contaminants while simultaneously enriching the remaining solution with additional dissolved magnesium (Auyeshov et al., 2025). This auto neutralization strategy drastically reduces the dependency on external alkaline chemicals and ensures that the resulting sulfate or chloride solution maintains an exceptionally high purity which is an absolute prerequisite for synthesizing premium grade magnesium hydroxide (Auyeshov et al., 2025). Following the successful isolation of the purified magnesium rich solution the subsequent technological hurdle involves the final precipitation of the target reactive precursor (Auyeshov et al., 2025). The controlled addition of alkaline reagents triggers the precipitation reaction yielding magnesium hydroxide which is subsequently recovered washed thoroughly to remove residual salts and dried (Auyeshov et al., 2025). This intermediate serves as a highly reactive compound that can either be directly utilized for atmospheric carbon capture or further calcined at moderate temperatures to yield a final highly porous magnesium oxide adsorbent (Auyeshov et al., 2025). Magnesium oxide

possesses superior carbon dioxide binding kinetics compared to naturally occurring silicates making it the ultimate target material for engineered carbon capture and storage operations (Stokreef et al., 2022). High pressure carbonation environments reaching up to one hundred and fifty bar have also been explored revealing that elevated pressures fundamentally shift the thermodynamic equilibrium toward the rapid formation of dense crystalline magnesite and hydromagnesite phases (Galina et al., 2023).

The integration of mineral carbonation into the circular economy paradigm offers unprecedented opportunities for industrial symbiosis where multiple high value products are generated simultaneously (IEAGHG, 2022). When serpentinite is processed sequentially through acid and alkali treatments the resulting by products extend far beyond the primary magnesium oxide adsorbent (Auyeshov et al., 2025). The amorphous silica rich residue generated during the initial acid leaching phase possesses a unique and highly porous structure making it an exceptionally valuable secondary resource (Auyeshov et al., 2025). Recent characterizations utilizing nitrogen adsorption measurements reveal that this specifically synthesized silica gel belongs to the category of mesoporous materials exhibiting a massive specific surface area often reaching four hundred square meters per gram (Auyeshov et al., 2025). The presence of a bimodal pore distribution featuring both narrow micropores and larger mesopores confirms the structural uniformity and advanced functional applicability of the synthesized silica (Auyeshov et al., 2025). This residual mesoporous silica can be directly repurposed as a high-performance catalyst support an advanced industrial desiccant or an active mineral additive for high strength concrete thereby actively displacing the continuous need for virgin construction materials (Auyeshov et al., 2025). Furthermore, alkaline treatment of this acid insoluble residue using sodium hydroxide allows for the highly selective precipitation of pure amorphous silica yielding a recovery rate exceeding sixty percent of the original silicon content present in the host rock (Auyeshov et al., 2025). The simultaneous production of a premium reactive carbon capture medium and a high value industrial silica product perfectly exemplifies the core principles of a circular industrial economy (IEAGHG, 2022). This dual product stream not only maximizes the comprehensive utility of the extracted geological resource but also significantly enhances the overall economic viability of the carbon capture facility by creating diverse and robust revenue channels (IEAGHG, 2022).

Scaling up this localized carbon capture technology requires a thorough understanding of the entire process from a comprehensive life cycle perspective (IEAGHG, 2022). In recent years life cycle assessment has become an indispensable and mature scientific tool for rigorously quantifying the comprehensive environmental footprint of carbon dioxide mineralization processes (IEAGHG, 2022). Traditional evaluations often focused solely on the global warming potential or the total mass of carbon dioxide permanently sequestered (IEAGHG, 2022). However modern life cycle assessments emphasize that the true environmental cost must holistically account for continuous reagent consumption massive water usage land degradation and the highly energy intensive thermal activation stages required to process the rock (IEAGHG, 2022). By utilizing mild dilute acid solutions substituting aqueous neutralizing agents with solid phase particles and implementing cutting edge energy integration systems such as storing hot thermally activated minerals in insulated thermal energy silos the proposed methodologies proactively minimize the secondary environmental impacts typically associated with large scale hydrometallurgical operations (Makikouri et al., 2026). This strategic reduction in water chemical usage and electrical power demand is absolutely essential to ensure that the carbon footprint of the extraction process itself does not inadvertently negate the profound climate benefits achieved by the captured carbon dioxide (Galina et al., 2023). Furthermore, understanding the exact thermodynamics and kinetic limitations of each specific reaction step allows engineers to design incredibly efficient closed loop systems where waste heat is continuously recycled back into the endothermic calcination phase (Makikouri et al., 2026).

To directly address this critical scientific void this research designated under the Refining the Future initiative presents a comprehensive evaluation of reactive magnesium oxide synthesis utilizing raw Aceh serpentinite. The primary objective of this overarching manuscript is to deeply investigate the synergistic efficacy of a low intensity localized processing route integrating optimized thermal activation at seven hundred degrees Celsius with a prolonged mild acid leaching protocol and subsequent alkaline precipitation. It is strongly hypothesized that extending the leaching duration in a mild hydrochloric acid environment will effectively overcome the formidable kinetic barriers imposed by the amorphous silica layer yielding a highly concentrated magnesium solution without the severe infrastructural degradation universally associated with hot concentrated acids. Furthermore, it is postulated that this highly localized and meticulously optimized processing methodology will successfully produce a high purity magnesium oxide adsorbent with a commercially competitive mass balance efficiency that directly rivals expensive synthetic alternatives. The empirical data generated from this comprehensive investigation will serve as a foundational operational blueprint for optimizing the extraction of magnesium from endemic Indonesian serpentinite. Proving the viability of this low intensity approach will unequivocally validate the hypothesis that maximum operational efficiency and high carbon capture capacity can be successfully achieved without resorting to extreme corrosive and environmentally damaging processing environments. Ultimately the successful domestication and large-scale deployment of this technology will strategically empower the national industrial sector to actively combat atmospheric carbon accumulation decisively propelling the nation closer to fulfilling its international Net Zero Emissions commitments while simultaneously fostering the rapid growth of a new green and highly sustainable mineral processing economy.

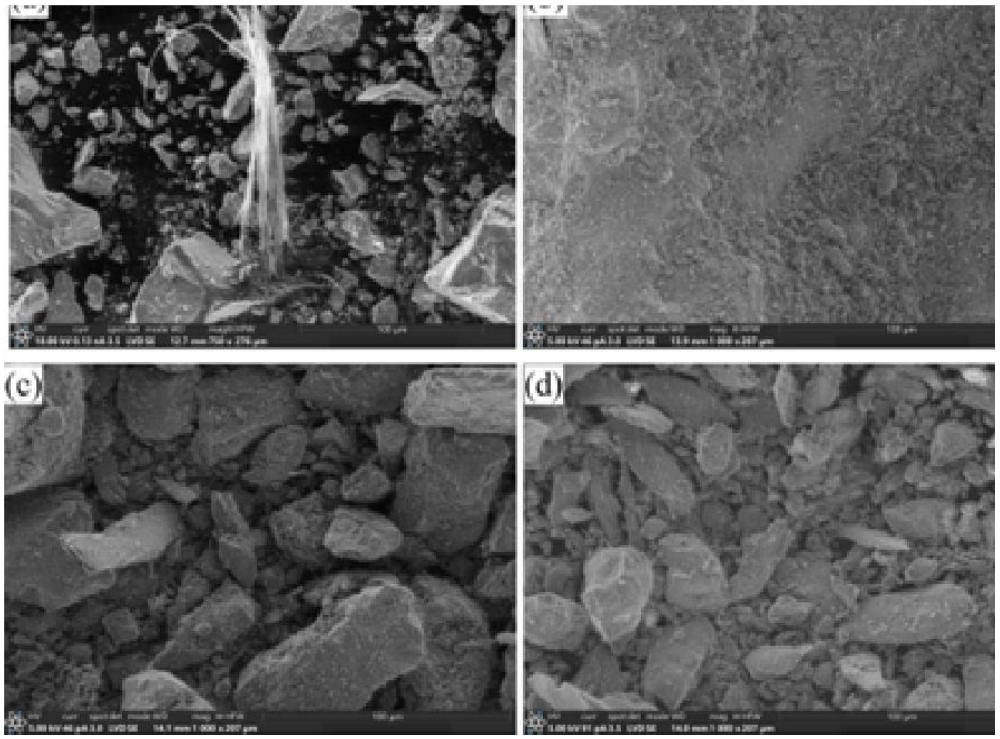

Fig. 2. SEM micrographs showing the morphological characterization of serpentine adsorbents: (a) raw serpentine at 750× magnification (scale bar = 100 μm); thermally activated serpentine: (b) 50 mesh at 1000× magnification (scale bar = 100 μm); (c) 100 mesh at 1000× magnification (scale bar = 100 μm); and (d) 150 mesh at 1000× magnification (scale bar = 100 μm)
(Reza et al., 2024).

Globally, the widespread implementation of Carbon Capture, Utilization, and Storage (CCUS) technologies is often hindered by the prohibitive costs of commercial synthetic

adsorbents and the long-term environmental liabilities associated with direct geological storage in depleted reservoirs. Therefore, material innovation that strategically utilizes abundant domestic mineral resources, such as serpentinite, is of paramount strategic importance to establish national mineral sovereignty in climate mitigation efforts, particularly for developing nations. Mineral carbonation presents an exceptionally stable, thermodynamically favorable, and leak-proof pathway for permanent carbon fixation, securely binding carbon dioxide within a solid rock crystalline framework and eliminating the need for extensive post-injection monitoring. However, because raw magnesium silicates react extremely slowly under ambient conditions, advanced scientific interventions are strictly necessary to engineer these natural minerals into highly porous, reactive chemisorbents capable of capturing industrial emissions at realistic operational timeframes. By focusing on a low-intensity, localized processing route that mitigates severe infrastructural degradation, this approach offers a highly economical and scalable carbon capture solution. Ultimately, the successful domestication of this technology will empower national industrial sectors to actively combat atmospheric carbon accumulation, decisively propelling the nation closer to fulfilling its international Net Zero Emissions commitments while simultaneously fostering the rapid growth of a new, highly sustainable green mineral processing economy. The morphological characterization of the serpentine adsorbents is mentioned in Figure 2.

2. Methods

Serpentinite rock obtained from Aceh, Indonesia, was selected as the raw material for this study due to its relatively high magnesium content and abundance in the region. Hydrochloric acid (HCl, 37%, analytical grade), sodium hydroxide (NaOH, analytical grade), and deionized water were used throughout the experiments. All reagents were commercially available laboratory-grade chemicals and were used without further purification. The rock sample was first mechanically crushed using a standard laboratory hammer to reduce its size into smaller fragments, which facilitated subsequent grinding and ensured more uniform chemical reactivity. Following mechanical crushing, the fragments were ground into fine powder using a mortar and pestle. This step was performed gradually to avoid overheating or partial alteration of the mineral structure, which could inadvertently affect the reactivity of magnesium-containing phases. The powder was then sieved using a standard mesh to obtain a uniform particle size of less than 150 μm. Homogenization of particle size is a critical parameter as it directly influences surface area, heat transfer during thermal treatment, and contact efficiency during acid leaching. Previous studies have indicated that variations in particle size can lead to inconsistent leaching rates, resulting in lower reproducibility across experimental batches (Ruan et al., 2019).

The sieved serpentinite powder was calcined at 700 °C for 2 h using a laboratory muffle furnace with a heating rate of 10 °C min^{-1}. This initial calcination step was performed to remove physically adsorbed water, structurally bound water, and carbonate components naturally present in the mineral. The dehydroxylation reaction can be represented as:

$$Mg_3Si_2O_5(OH)_4 \rightarrow Mg_3Si_2O_7 + + 2H_2O \quad \text{(Eq. 1)}$$

The removal of moisture and carbonate species is necessary to prevent interference during acid leaching and to improve the stability and reproducibility of subsequent chemical reactions (Raschman et al., 2013). Calcination at elevated temperatures partially breaks down the crystal structure of serpentine, creating an amorphous phase with higher surface area and rendering magnesium more accessible for dissolution (Du Breuil et al., 2019). After calcination, the sample was cooled naturally inside the closed furnace to room temperature and stored in a desiccator over silica gel to prevent moisture re-adsorption.

Acid leaching was performed to transform magnesium-containing components from the calcined serpentine into the aqueous phase. Hydrochloric acid (1M) was selected as the leaching agent for three reasons, it efficiently dissolves magnesium while leaching silicate components in the solid residue, it avoids the formation of sulfate or nitrate complexes that could interfere with subsequent precipitation, and chloride systems are well-established for magnesium recovery with high selectivity (El-Sayed et al., 2023). For the leaching experiment, 10 g of serpentine powder was added to 50 mL of 1M HCl, corresponding to a solid-to-liquid ratio of 1:5 g/mL. The mixture was heated to 80–90°C and continuously stirred for 24 hours to maintain effective contact between solid particles and acid solution, enhancing mass transfer during the leaching process (Fedoročková et al., 2012). The 24-hour duration was chosen as conservative measure to ensure near-complete extraction, compensating for potential mass transfer limitations in the experimental setup. After leaching, the solid residue was separated via gravity filtration using Whatman Grade 1 filter paper (11 μm pore size, 125 mm diameter). The residue was washed with deionized water to remove entrained acid and subsequently dried in an oven at 80 °C for 24 h. During the filtration process, part of the leachate was accidentally lost, preventing direct determination of magnesium concentration using Atomic Absorption Spectroscopy (AAS) or Inductively Coupled Plasma (ICP) analysis. Consequently, magnesium extraction efficiency could not be experimentally verified and was instead estimated using literature-reported leaching efficiencies under comparable conditions.

The recovered leachate (MgCl2 solution) was intended for precipitation of magnesium hydroxide. Under controlled pH conditions, dissolved magnesium species are converted to Mg (OH)2 by gradual addition of 4 M NaOH solution to the leachate until pH 10.5 is reached. This pH value represents an optimal balance between magnesium recovery and impurity rejection: below pH 10, precipitation is incomplete, while above pH 11, impurities such as Fe, Ca, and Si may co-precipitate (Li & Hitch, 2018). The precipitation reaction proceeds as:

$$MgCl_2 + 2NaOH + \rightarrow Mg(OH)_2 + 2NaCl \quad \text{(Eq. 2)}$$

The resulting $Mg(OH)_2$ precipitate is then calcined at 500 °C for 2 h to produce MgO (Chen et al., 2023). Although the precipitation and final calcination steps were not experimentally performed in this study due to laboratory limitations, literature indicates that gradual addition of NaOH to achieve pH 10–10.5 can yield magnesium recovery above 95% while minimizing impurity co-precipitation (Senevirathna et al., 2023). Therefore, these stages were included only as theoretical estimations for mass-balance evaluation and remain important for complete process validation in future work.

Previous studies have reported magnesium extraction efficiencies from thermally activated serpentine ranging from approximately 75% to above 90%, depending on leaching temperature, acid concentration, and reaction time (Saleem et al., 2025). Under conditions comparable to the present study, magnesium recovery values around 80–90% have been reported for 1 M HCl leaching at elevated temperatures (El-Sayed et al., 2023). Similar efficiency ranges were also observed in other investigations involving thermally activated serpentinite systems (Beglaryan et al., 2023). Based on these reported values, a conservative magnesium extraction efficiency of 85% was adopted for the mass-balance estimation in this study (Baigenzhenov et al., 2015). The mass balance was calculated as follows:
The theoretical magnesium content in the calcined sample is calculated as:

$$Theoretical\ Mg\ in\ calcined\ sample = sample\ mass \times Mg\ content\ (22.2\%) \quad \text{(Eq. 3)}$$

This represents the total Mg available in the sample. Assuming 85% extraction efficiency, the amount of magnesium actually extracted is:

$$Extracted\ Mg = theoretical\ Mg \times 0.85 \quad \text{(Eq. 4)}$$

The theoretical magnesium hydroxide yield is calculated based on the extracted Mg and the assumed precipitation efficiency:

$$Theoretical\ Mg(OH)_2 = extracted\ Mg \times (\frac{58.3}{24.3}) \times 0.95 \quad \text{(Eq. 5)}$$

The final theoretical MgO is obtained by converting $Mg(OH)_2$ to MgO:

$$Theoretical\ MgO = Mg(OH)_2 \times (\frac{40.3}{58.3}) \quad \text{(Eq. 6)}$$

Overall MgO recovery efficiency is determined by comparing the final MgO mass with the theoretical maximum MgO available in the raw serpentinite:

$$Overall\ efficiency\ (\%) = (\frac{Final\ MgO}{Theoretical\ Maximum\ MgO\ from\ raw\ rock}) \times 100\% \quad \text{(Eq. 7)}$$

After the leaching step, the mixture was filtered to separate the solid residue from the leachate. The collected residue was then dried in an oven at 80 °C for 24 h to remove residual moisture and remaining acid. During the leaching process, magnesium contained in the calcined serpentinite dissolves into the aqueous phase primarily as Mg^{2+} ions in the form of $MgCl_2$. In conventional magnesium recovery processes, dissolved magnesium species are converted into magnesium hydroxide through alkaline precipitation using sodium hydroxide, followed by calcination to produce magnesium oxide (Chen et al., 2023). Magnesium oxide derived from serpentine has been widely reported as a suitable material for CO_2 capture applications due to its high reactivity toward carbon dioxide (Senevirathna et al., 2023).

Although the precipitation and final calcination steps were not experimentally conducted in this study due to laboratory and time limitations, this process was included in the theoretical mass-balance evaluation. Previous studies on hydrochloric acid leaching of thermally activated serpentine have reported magnesium extraction efficiencies typically ranging from about 75% to above 90%, depending on temperature and reaction time (Saleem et al., 2025). Similar investigations have reported extraction efficiencies generally between 80% and 90% under comparable leaching conditions (Li & Hitch., 2018). Based on these reported ranges, a conservative magnesium extraction efficiency of 85% was adopted for mass-balance estimation in this study (Baigenzhenov et al., 2015).

3. Results and Discussion

3.1 Result

A total of 13.1902 grams of Aceh serpentine was subjected to thermal activation at 700°C for 2 hours. The mass after calcination was 11.92 grams, corresponding to a mass loss of 1.2702 grams. The Loss on Ignition (LOI) was calculated at 9.63% using equation 8.

$$LOI\ (\%) = [(initial\ mass - final\ mass)\ /\ initial\ mass] \times 100\% = 9.63\% \quad \text{(Eq. 8)}$$

This value is lower than the theoretical 13.1% mass loss for pure serpentine [$Mg_3Si_2O_5(OH)_4$], most likely due to the presence of non-hydroxyl-bearing impurities ($2SiO_2$, Fe_2O_2, and carbonates) in the natural Aceh serpentine. Similar LOI values in the 10-12% range are reported for impure serpentine ores in industrial processing studies (Bai et al., 2025).

HCl leaching (1M, 80°C, 24 hours) was performed on the calcined material (11.92 grams). Due to an accidental loss of leachate filtrate during filtration, direct measurement of magnesium concentration via AAS or ICP was not possible. Therefore, the extraction yield

was estimated based on literature kinetic models for serpentinite dissolution in HCl. Under similar conditions (1M HCl, 80°C), leaching for 24 hours is expected to approach near-complete extraction because the dissolution kinetics are known to plateau after 3-4 hours under more aggressive conditions (El-Sayed et al., 2023). A conservative extraction efficiency of 85% was adopted for mass-balance calculations, in line with reported values for extended leaching durations (Li & Hitch, 2018).

The MgO content of the calcined Aceh serpentine was taken as 36.83% (Reza et al., 2024), equivalent to 22.2% Mg. Thus, the theoretical Mg mass in the 11.92 grams calcined sample was calculated as:

$$M_{Mg,\ theoritical} = 11.92 \times 0.222 = 2.646 \text{ grams Mg} \quad \text{(Eq. 9)}$$

Assuming 85% extraction efficiency,

$$M_{Mg,\ extracted} = 2.646 \times 0.85 = 2.249 \text{ grams Mg} \quad \text{(Eq. 10)}$$

The leaching efficiency was determined by comparing the magnesium content in solution with the theoretical magnesium content in the original serpentine. Thus, the magnesium extraction yield was calculated based on the MgO recovery equation used in serpentinite leaching studies (El-Sayed et al., 2023):

$$\eta MgO(\%) = \frac{C_{Mg}\, x\, V}{M_{sample}\, x\, \omega_{MgO}} x\ 100 \quad \text{(Eq. 11)}$$

Where C_{Mg} is the Mg concentration in the leachate (g/L), V is the leachate volume (L), m_{sample} is the mass of calcined serpentinite (g), and MgO is the MgO content in the sample (0.3683 g/g, based on XRF data. (Reza et al. ,2024)). In the present study, due to the loss of leachate, CMg could not be determined experimentally. Based on the adopted extraction efficiency of 85%, the MgO recovery under the applied leaching conditions is estimated to be 8%.

The leachate was precipitated with 4M NaOH at pH 10.5, yielding a white crystalline $Mg(OH)_2$ powder. The recovery efficiency from chloride solutions is typically >95% under controlled pH conditions, as reported in mineral carbonation process reviews (Li & Hitch., 2018). Assuming a precipitation efficiency of 95%, the mass of $Mg(OH)_2$ obtained is estimated as,

$$M_{Mg(OH)2} = 2.249 \text{ g Mg}\ x\ \frac{M_{Mg(OH)_2}}{M_{Mg}}\ x\ 0.95 \quad \text{(Eq. 12)}$$
$$= 2.249\ x\ \frac{58.3}{24.3}\ x\ 0.95\ \approx\ 5.12\ grams\ Mg(OH)_2$$

Subsequently, calcination of $Mg(OH)_2$ at 500°C produces MgO. The stoichiometric conversion yields,

$$M_{MgO}\ =\ 5.12\ x\ \frac{40.3}{58.3}\ \approx\ 3.54 \quad \text{(Eq. 13)}$$

The estimated mass of MgO assuming 95% precipitation and 100% conversion efficiency.The theoretical maximum MgO from the original serpentinite sample,

$$M_{MgO,original} = 13.1902 \text{ x } 0.3683 \approx 4.86 \text{ grams} \quad \text{(Eq. 14)}$$

Therefore, overall yield representing the MgO production,

$$\eta_{overall} = \frac{3.54}{4.86} \times 100\% \approx 72.8\% \quad \text{(Eq. 15)}$$

Thus, 3.54 g of MgO is the estimated yield, representing a 72.8% overall yield from the original serpentine. The MgO content of activated Aceh serpentinite is 36.83% (Reza et al., 2024). From the estimated 3.54 g MgO, the theoretical CO_2 capture capacity via carbonation,

$$MgO_{(s)} + CO_{2(g)} \rightarrow MgCO_{3(s)} \quad \text{(Eq. 16)}$$

So, the capture capacity using the molar masses of MgO and CO_2,

$$CO_2\ capacity = 3.54\ g\ MgO\ x\ \frac{44.01\ g/mol\ CO_2}{40.30\ g/mol\ MgO} = 3.68\ g\ CO_2 \quad \text{(Eq. 17)}$$

Table 1. Summary of experimental result

Process Stage	Input Mass (g)	Output Mass (g)	Yield/Recovery	Remarks
Initial Serpentine	13.1902	-	-	Raw Aceh serpentine
After Calcination	-	11.92	LOI: 9.63 %	Thermal activation
Mg in Leachate (est.)	-	2.249 grams Mg	85%	Based on El-Sayed et al., 2023; Li&Hitch, 2018
$Mg(OH)_2$ Precipitate (est.)	-	5.12	95%	pH 10,5, 4M NaOH; Li & Hitch.,2018
Final MgO	-	3.54	72.8%	Calcined at 500°C

This corresponds to 1.09 g CO_2 per gram of MgO or 292 g CO_2 per kilogram of raw Aceh serpentinite. Magnesium oxide (MgO) has demonstrated tremendous potential in carbon capture and utilization (CCU) technology (Huang et al.,2025). The summary of the overall experimental results is mentioned in Table 1. The mass-balance efficiency at each processing stage is mentioned in Table 2. The summary of the theoretical carbon capture capacity is mentioned in Table 3.

Table 2. Mass-balance efficiency at each stage

Parameter	Efficiency (%)	Calculation Basis	Supporting reference
Calcination (LOI)	9.63 (LOI)	Experimental measurement	Bai et al. (2025)
Leaching efficiency	85	Literature kinetics	El-Sayed et al. (2023); Li & Hitch, (2018)
Precipitation efficiency	95	Literature	Li & Hitch (2018)
Conversion efficiency	100	Stoichiometric calculation	
Overall process efficiency	72.8	Mass balance	This work

Table 3. Summary of capture capacity

Parameter	Value
MgO produced per kg raw rock	268 g
Theoretical CO_2 captured per kg MgO	1.09 kg
Theoretical CO_2 captured per kg raw rock	0.292 kg

3.2 Discussion

The theoretical maximum MgO yield from 13.1902 grams of serpentine from Aceh is approximately 4.86 grams, based on the reported MgO content of 36.83% for thermally activated serpentine (Reza et al., 2024). Our estimated experimental yield of 3.54 grams MgO represents 72.8% of this theoretical maximum. This discrepancy can be attributed to several

factors, including incomplete leaching, losses during filtration and transfer operations, impurities in the original serpentine reducing available magnesium content, and incomplete precipitation or co-precipitation of impurities. The mass balance revealed the following efficiencies at each stage.

Table 4. Efficiency from each stage

Parameter	Efficiency (%)
Calcination efficiency	9.63
Leaching efficiency	85
Precipitation efficiency	95
Conversion efficiency	100
Overall process efficiency	72.8

The overall process efficiency of 72.8% is particularly notable given that it was achieved using mild conditions (1M HCl) and local Aceh serpentinite containing significant impurities. Literature values of 85–92% (Bai et al., 2025) and 97.6% (El-Sayed et al., 2023) were obtained using either higher acid concentrations (5M HCl) or optimized temperature protocols and higher-grade ores. Our result demonstrates that Aceh serpentinite is viable for MgO production without aggressive processing, which has positive implications for cost, safety, and environmental impact in the Indonesian context. Literature suggests that thermal pretreatment enhances subsequent leaching kinetics (González et al., 2021). The calcination at 700°C for 2 hours proved effective, as evidenced by the LOI of 9.63%, which aligns with values reported for implore serpentine ores (Bai et al.,2025).

The use of 1M HCl with extended leaching time (24 hours) at 80°C represents a compromise between extraction efficiency and practical considerations. The extended leaching time is expected to have achieved high extraction due to the prolonged contact, although the lack of agitation beyond the initial 5 minutes may have slightly reduced the rate. While higher acid concentrations can achieve >95% extraction in shorter times (El-Sayed et al., 2023), our approach minimizes acid consumption and equipment corrosion while maintaining acceptable yields. The 95% precipitation efficiency assumed for $Mg(OH)_2$ from chloride solution is supported by mineral carbonation review (Li at al., 2018). However, actual purity may vary due to co-precipitation of Ca, Fe, or Si impurities. The comparison of our processing conditions with previous studies is mentioned in Table 4.

Table 5. Comparison with Previous Studies

Study	Serpentine Source	Process Conditions	Final MgO Yield	Key Findings
This Work	Aceh, Indonesia	700°C calcination, 1M HCl, 24 h, NaOH precipitation	72.8%	First demonstration for Aceh serpentinite mild conditions
Bai et al. (2025)	Various	650-700°C Calcination optimization	85-92% leaching efficiency	Temperature optimization critical for maximum yield
El-Sayed et al. (2023)	Egyptian	5M HCl, 95°C, 3h	97.6% recovery	Concentrated acid enables near-complete extraction

From 13.1902 grams of serpentine, we obtained 3.54 grams MgO, corresponding to 268 grams MgO per kilogram of raw material. This yield suggests that serpentine from Aceh could be a viable magnesium source, though economic viability would depend on scaling factors and local infrastructure. The process consumes HCl and NaOH for producing per gram of MgO, while dilute acid reduces costs and environmental impact, the extended processing time increases energy requirements. Optimization should consider both reagent consumption and processing time.

For Indonesia, where serpentinite is abundant and carbon capture is urgently needed, this work provides the first experimental evidence that local resources can be processed into functional materials under technically accessible conditions. THe ability to use 1M HCl rather than concentrated acids is particularly relevant for technology transfer to Indonesian industries, where handling and disposal of aggressive chemicals pose greater challenges.

3.2.1 Limitations and future works

The present study has several limitations that should be addressed in future research. First, product purity was not assessed. The purity of the $Mg(OH)_2$ and final MgO products was not quantitatively evaluated via techniques such as XRF or XRD, leaving uncertainty regarding co-precipitated impurities (Fe,Ca,Si). Iron contamination may affect CO_2 adsorption performance, while calcium dilutes the active MgO content. Second, all experiments were conducted at laboratory scale and thus the result may not directly translate to industrial performance in terms of yield, energy efficiency, or operational stability. Third, no detailed energy analysis was performed for the calcination and leaching stages. Which is critical for evaluating the overall sustainability of the process. Finally, the silica-rich residue generated after leaching was neither characterized nor utilized, representing a missed opportunity for valorization.

3.2.2 Recommendations for future research

To address these limitations, several improvements are recommended. Real-time pH monitoring during precipitation could optimize $Mg(OH)_2$ purity and yield. Microwave-assisted leaching may reduce processing time and potentially enhance extraction efficiency. Characterization of the silica residue could open pathways for applications such as adsorbents, cement additives, or construction materials. A full life-cycle assessment (LCA) is needed to evaluate the environmental footprint of the entire process. Finally, pilot-scale demonstration is essential to assess economic feasibility and process robustness under continuous operations.

3.2.3 Implications for CO_2 capture performance and CCUS applications

Magnesium oxide has demonstrated tremendous potential in carbon capture and utilization technology (Huang et al., 2025), and our estimated value of 1.09 g CO_2/g MgO suggests that Aceh serpentinite, derived MgO is competitive with other MgO, based adsorbents. From a practical CCUS perspective, processing 1 ton of raw Aceh serpentinite would yield approximately 268 kg of MgO, capable of sequestering 292 kg of CO_2 as stable magnesium carbonate. For a small industrial source emitting 1.000 tons CO_2/year, approximately 3.400 tons of local serpentinite would be required annually, a realistic scale given Aceh's abundant serpentinite deposits.

4. Conclusions

This study demonstrates that Aceh serpentinite can be utilized as a viable raw material for producing magnesium oxide (MgO) for carbon capture applications. Thermal activation at 700°C for 2 hours resulted in loss on ignition of 9.63%, confirming successful dehydroxylation of the mineral structure. This value aligns with reported LOI ranges for natural serpentinite containing impurities. Acid leaching using 1M HCl at 80°C was estimated to extract about 85% of the magnesium from the calcined material based on literature-supported kinetics. From an initial mass of 13.19 g of raw serpentine, mass-balance calculations yielded an estimated 3.54 g of MgO, corresponding to an overall process efficiency of 72.8% of the theoretical maximum. This yield is particularly

noteworthy given that it was achieved using mild leaching conditions, 1M HCl, and local Aceh serpentinite containing significant impurities. Although direct magnesium measurements were not obtained due to experimental limitations, the estimated yields are consistent with the previous studies on serpentinite processing.

The trade-off inherent in this approach, accepting longer processing time in exchange for milder, safer, and more cost-effective conditions, aligns with the goal of developing technologies suitable for the Indonesian context, where capital costs, operational safety, and local resource utilization are critical considerations. The results highlight the potential of locally available Indonesian serpentinite as a low-cost and sustainable source of MgO for CO_2 mineralization, supporting carbon capture efforts while aligning with circular economy principles by converting CO_2 into a stable solid product. Future work should focus on direct validation of magnesium extraction via AAS or ICP analysis, optimization of leaching parameters, characterization of final MgO purity, quantitative assessment of CO_2 capture capacity, valorization of the silica-rich residue, and pilot-scale demonstrations to evaluate techno-economic.

Acknowledgement

The authors would like to express their gratitude to the Department of Chemistry and the Department of Industrial Engineering, Institut Teknologi Sepuluh Nopember (ITS), for providing the laboratory facilities and technical support necessary for this research. We also acknowledge the providers of the Aceh serpentinite samples used in this study, which allowed us to evaluate the potential of Indonesia's local mineral resources for carbon capture applications.

Author Contribution

M.F.H. conceptualized the "REFINE" project, developed the research framework, and drafted the manuscript; N.A.S. and C.S.S.L. designed and performed the laboratory experiments, including thermal activation and chemical leaching processes; M.F.H. and N.A.S. conducted the data analysis and calculated the extraction efficiency. All authors participated in the final review, editing, and approval of the manuscript for submission.

Funding

This research received no external funding.

Ethical Review Board Statement

Not available.

Informed Consent Statement

Not available.

Data Availability Statement

The data presented in this study are available on request from the corresponding author. The data are not publicly available due to ongoing further research in the "REFINE" project.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the research, authorship, and/or publication of this manuscript. The results presented are objective and were not influenced by any third-party interests.

Declaration of Generative AI Use

During the preparation of this work the authors used NotebookLM to assist in improving grammar clarity and ensuring the manuscript aligns with the required academic template format. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

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