



Serpentinite as a strategic Earth material: geological controls, mineral reactivity, carbon mineralization, geologic hydrogen, and sustainable resource pathways

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Abstract

Serpentinite, the hydrated ultramafic lithology formed during serpentinization of mantle peridotites, is increasingly recognized as a strategic yet heterogeneous geomaterial for construction, carbon-management, and energy-related pathways. This review synthesizes knowledge by linking geological origin, serpentine polymorph assemblage, accessory phases, alteration degree, and structure–property–reactivity relationships to application performance. Rather than cataloguing uses, it evaluates serpentinite pathways according to mineralogical control, processing intensity, evidence maturity, functional advantage, scalability, and environmental or occupational risk. Emphasis is placed on how lizardite, chrysotile, antigorite, brucite, magnetite, microstructural heterogeneity, and serpentinization degree govern surface reactivity, Mg accessibility, porosity evolution, mechanical competence, dissolution behavior, carbonation kinetics, and fiber-related constraints. These controls explain serpentinite’s established use as dimension stone, aggregate, and refractory or ceramic feedstock, while supporting process-sensitive pathways such as magnesium-silicate binders, low-carbon construction products, Mg recovery, adsorption media, radiation-shielding concretes, and engineered porous materials. The review assesses its relevance to climate and energy systems, particularly permanent CO₂ sequestration by mineral carbonation and abiotic hydrogen generation through serpentinization-driven redox reactions. Additional opportunities, including enhanced rock weathering, magnesium-chemical production, thermal-management materials, and quarry-residue valorization, are evaluated as lithotype-specific and risk-governed options. Practical deployment remains constrained by mineralogical heterogeneity, carbonation and Mg-extraction kinetics, activation-energy demand, water and reagent requirements, Ni–Cr mobility, and potential chrysotile or elongated mineral-particle occurrence. Future progress requires polymorph- and texture-resolved databases, pilot-scale validation, integrated techno-economic and life-cycle assessment, and risk-aware resource allocation. Overall, serpentinite is best understood as a fit-for-purpose geomaterial platform whose value depends on coupling mineralogical qualification with controlled processing and environmental governance.

Keywords Serpentinite geomaterials · Serpentinization · Mineral carbonation and CO₂ sequestration · Magnesium–silicate binders · Geologic hydrogen systems · Sustainable resource valorization

Introduction

Serpentinite has transitioned from a rock chiefly discussed within metamorphic petrology to a strategically important geomaterial for selected construction, environmental, carbon-management, and energy-related applications (Segal 2024, Carmignano et al. 2020). This relevance reflects an uncommon combination of attributes concentrated in a single natural resource: widespread occurrence in ophiolite belts, high magnesium-silicate content, structurally bound

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hydroxyl groups, and strong responsiveness to thermal and chemical activation. Together, these features support both conventional bulk uses and engineered reactivity in applications where serpentinite offers a clear mineralogical or functional advantage (Ivanova et al. 2022, Şaşmaz et al. 2024, Ahmad et al. 2025, Evans 2004, Evans et al. 2013). However, serpentinite should not be treated as a universally applicable raw material. Its value depends on the specific lithotype, serpentine polymorph assemblage (lizardite, chrysotile, and antigorite), degree of alteration, accessory phases, processing route, and environmental risk profile. In parallel with circular-economy strategies, serpentinite quarry fines and processing residues are increasingly being reconsidered as secondary resources rather than unavoidable wastes, but only where lithology-specific risks are identified and managed (Cavallo 2018).

From a mineralogical standpoint, serpentinite is inherently heterogeneous. It is typically dominated by serpentine-group phases, mainly lizardite, chrysotile, and antigorite, with variable contributions from brucite and magnetite, alongside remnants of olivine, pyroxenes, and spinel, and in some settings, secondary carbonates (Evans et al. 2013, Eberhard 2021, Pereira et al. 2025, Lu 2025). This variability is not a minor descriptive feature; it is a controlling factor for density–porosity structure, thermal stability and dehydroxylation behavior, magnesium release during activation or leaching, surface charging and hydroxyl availability, and ultimately adsorption and carbonation performance (Evans 2004, HUANG et al. 2026, Ray et al. 2025). Although serpentine polymorphs share broadly similar bulk chemistry, their structural differences strongly influence reaction pathways and extraction response. This has been demonstrated in magnesium-recovery and leaching studies where activation enhances Mg availability and where polymorph identity affects yields and process sensitivity (Fedoročková et al. 2012, Beglaryan et al. 2023). At an applied level, polymorph assemblage and the presence of brucite are particularly influential because they regulate both Mg accessibility and surface hydroxyl density, with measurable consequences for reactivity and sorption after processing (Fedoročková et al. 2012, Beglaryan et al. 2023). Recent characterization of serpentinites in the northern Semail Ophiolite, UAE, further highlights Mg-rich resources accompanied by elevated Ni–Cr signatures, underscoring both their potential value and the need for risk-informed deployment (Sami et al. 2026).

Within this mineralogical framework, the present review focuses on serpentinite applications for which the link between geological characteristics, processing response, and functional performance is especially important. In traditional geomaterials practice, serpentinite has a long record as dimension stone, aggregate, filler, and industrial feedstock for refractory and ceramic products. Ceramic

processing studies have demonstrated the conversion of serpentinite-derived wastes into forsterite-rich refractory materials (Cheng et al. 2002, Ramezani et al. 2018, Nemat et al. 2016, Cavallo et al. 2021). Broader utilization routes, including concrete-related products, agglomerated stone, ceramics, and fillers, have been reviewed with explicit attention to constraints associated with naturally occurring asbestos (Cavallo 2018). Importantly, serpentinite can also be positioned in higher-value ceramic systems. Cordieritic ceramics, for example, can be engineered from blends containing serpentinite/olivine combined with aluminosilicate and Mg-bearing additives, enabling useful trade-offs among porosity, mechanical strength, and thermal expansion (Ramezani et al. 2018, Thomaidis and Kostakis 2015). More recent work emphasizes that deliberate control of mineral transformation during firing, particularly the development of forsterite and enstatite, can improve sintering behavior and mechanical performance in magnesia–silicate ceramics (Vakalova et al. 2022). These examples show that serpentinite is already an established geomaterial, but also that successful value upgrading depends on controlled processing rather than on rock abundance alone.

A second major focus of this review is serpentinite's role in carbon mineralization and permanent CO₂ storage (Steinhorsdottir 2025, Al Kalbani et al. 2024). Magnesium-silicate-rich serpentinite can react with CO₂ to form stable carbonate phases; however, both laboratory and field evidence indicate that practical implementation depends on overcoming kinetic barriers, especially limited Mg liberation and the development of passivating silica-rich layers. Consequently, pretreatment and process intensification—such as mechanical comminution/grinding, thermal activation or calcination/dehydroxylation, and chemical activation through acid leaching, alkali/ammonium-salt treatment, intercalation, or exfoliation—are commonly required (Al Kalbani et al. 2024, Hamed et al. 2025, Krevor and Lackner 2011, Sanna et al. 2014). Direct aqueous mineralization under flue-gas-relevant conditions has been demonstrated using finely ground and heat-activated serpentinite residues, where CO₂ uptake increases with enhanced Mg availability (Hamed et al. 2025, Godard et al. 2022, Pasquier et al. 2014). Pilot-scale evaluation of serpentinite tailings exposed to cement-plant flue gas further supports feasibility of scale-up, while highlighting the operational importance of pretreatment strategy, dissolution management, and solids handling (Kemache et al. 2016). Indirect carbonation also remains an active innovation space; recyclable ammonium-salt approaches, for instance, have been proposed to couple Mg extraction with carbonate precipitation while improving reagent circularity (Wang et al. 2024). These studies position serpentinite as a promising platform for mineral-based decarbonization, but only where activation energy, water

demand, solids handling, and process integration are explicitly considered.

Closely linked to carbonation, serpentinite has relevance for magnesium recovery and chemical production, with downstream implications for MgO, Mg(OH)₂, related magnesium compounds, and intermediates used in indirect carbonation routes. Thermal activation and calcination can substantially enhance Mg dissolution during acid leaching (Fedoročková et al. 2012, Taheri and Larachi 2025, Chen et al. 2023), and polymorph-dependent structural contrasts can translate into meaningful differences in extraction performance (Beglaryan et al. 2023). In addition, waste-to-product approaches have been advanced for serpentinite-related residues. Construction ceramics incorporating high proportions of serpentine extraction wastes have been produced with immobilization of hazardous components and improved product performance, illustrating a practical circular pathway when appropriately engineered (Mymrin et al. 2020). Thus, Mg recovery and residue valorization are treated in this review not as isolated chemical processes, but as part of a broader structure–process–product framework in which impurity control, silica-residue management, and risk governance determine feasibility.

Beyond ceramics, carbonation, and Mg recovery, serpentinite is considered here only where a clear functional mechanism links its mineralogy to performance. Serpentinite-bearing aggregates are being explored for radiation-shielding concrete because they can combine adequate density with chemically bound water; experimental studies indicate promising shielding behavior while drawing attention to durability, microstructural evolution, and long-term stability (Dąbrowski et al. 2022, Wu et al. 2025), consistent with broader syntheses of serpentine-group minerals in concrete technologies (Jain et al. 2023). For environmental remediation, engineered processing, particularly activation and exfoliation, has been shown to generate mesoporous, hydroxyl-rich serpentinite surfaces capable of efficient binding of divalent heavy metals (Diab et al. 2025b). Serpentinite also shows potential in thermal management, where packed-bed thermal energy storage assessments report favorable thermophysical performance provided operating temperatures remain within stability windows that avoid irreversible deserpentinization (Alami 2025). These examples are included because they illustrate mineralogically controlled functionality; they are not presented as evidence that serpentinite is broadly suitable for all advanced-material applications.

Another focused dimension of the review is serpentinite's connection to geologic hydrogen systems. Serpentinization is widely recognized as a principal abiotic mechanism for H₂ generation in ultramafic rocks, driven by oxidation of Fe(II)-bearing phases coupled with magnetite formation,

particularly where fluid access sustains reaction progress (Isah et al. 2025, Kim 2025). Regional evaluations identify Arabian ophiolite serpentinites as prospective targets for hydrogen exploration (Saidy et al. 2024). Field observations from the northern Semail Ophiolite in Ras Al Khaimah, UAE, additionally report natural hydrogen anomalies linked to fault-controlled migration pathways and alkaline springs within active carbonation settings (Pasquet et al. 2024, Cherkose et al. 2026). In this review, geologic hydrogen is therefore treated as a serpentinite-hosted resource-system problem rather than simply another application category. The key issue is not merely whether serpentinite is present, but whether source rocks, fluid pathways, reaction conditions, migration routes, and potential trapping systems are sufficiently developed.

Serpentinite valorization must also be approached with explicit attention to environmental and occupational constraints, especially where fibrous serpentine varieties occur. Risk-focused analyses emphasize that reuse pathways should avoid chrysotile-bearing materials unless robust control measures and regulatory compliance can be assured (Cavallo 2018). Recent work further documents the generation of elongated mineral particles during mining and crushing, reinforcing the need for integrated petrographic screening, dust and exposure control, and long-term environmental monitoring as core elements of responsible practice (Obminski and Świątkowska 2026). In engineered pathways, risk reduction can also be supported through immobilization strategies such as high-temperature ceramic incorporation of serpentinite extraction residues (Mymrin et al. 2020). Therefore, environmental risk is not treated in this review as a separate concluding concern, but as a cross-cutting criterion that determines which serpentinite lithotypes are suitable for which end uses.

On this basis, the review develops a focused structure–property–function framework for serpentinite. Rather than presenting an exhaustive catalogue of all possible uses, it evaluates selected conventional and emerging pathways according to five linked criteria: mineralogical control, processing intensity, evidence maturity, functional advantage, and environmental or occupational risk. The central synthesis question is how geological origin, serpentine polymorph assemblage, accessory phases, degree of serpentinization, thermal evolution, surface activation, and environmental constraints govern performance across realistic deployment pathways. This approach is necessary because serpentinite exhibits strong mineralogical and textural variability, leading to markedly different behavior when used as construction aggregate, refractory or ceramic precursor, carbonation feedstock, magnesium source, environmental adsorbent, radiation-shielding component, thermal-energy-storage medium, or hydrogen-related host rock.

The novelty of this review lies in integrating previously fragmented research domains—petrology, industrial mineral processing, environmental materials science, carbon mineralization, and emerging energy-resource studies—into a unified but deliberately bounded geomaterials perspective. By linking mineralogical characteristics with processing routes, reactivity, durability, scalability, and environmental governance, the review identifies realistic technological pathways while clarifying the constraints that limit broad deployment. Although the synthesis is globally relevant, the United Arab Emirates is used as a focused geological case study. The northern Semail Ophiolite contains extensive Mg-rich serpentinite resources characterized by elevated Ni–Cr signatures relevant to both resource evaluation and environmental screening (Sami et al. 2026), while the same belt has recently attracted attention due to serpentinitization-related hydrogen anomalies and exploration interest (Pasquet et al. 2024, Cherkose et al. 2026). This combined perspective highlights serpentinite as a strategic but heterogeneous geomaterial platform whose future applications depend on coupled control of mineralogy, processability, evidence maturity, and risk-aware utilization.

Review methodology and synthesis framework

This review was designed as a structured critical narrative synthesis rather than a formal meta-analysis, because the literature on serpentinite is distributed across several fields with different experimental designs, terminology, performance metrics, and scales of validation. The reviewed studies span metamorphic petrology, mineralogy, geochemistry, industrial mineral processing, construction materials, carbon mineralization, magnesium recovery, environmental remediation, geologic hydrogen, thermal management, and sustainability assessment. Accordingly, the objective was not to provide a simple catalogue of serpentinite applications, but to critically evaluate how geological origin, serpentine polymorph assemblage, accessory phases, alteration state, texture, Mg accessibility, surface reactivity, and environmental constraints determine the suitability of serpentinite for different resource pathways.

The review was guided by three linked questions: (i) which mineralogical and textural characteristics control serpentinite properties and reactivity; (ii) how these characteristics are modified by processing routes such as comminution, thermal activation, acid leaching, exfoliation, carbonation, and sintering; and (iii) which applications are supported by mature evidence, which remain process-sensitive or pilot-scale, and which should be treated as emerging concepts requiring further validation. This structure was used to avoid treating serpentinite as a uniform material and

to emphasize that its technological value depends on lithotype-specific qualification.

Relevant literature was identified through searches in major scientific databases and publisher platforms, including Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley Online Library, MDPI, Taylor & Francis, and Google Scholar. Searches were conducted using combinations of the following keyword groups: “serpentinite,” “serpentine minerals,” “lizardite,” “chrysotile,” “antigorite,” “serpentinization,” “ultramafic rocks,” “magnesium extraction,” “mineral carbonation,” “CO₂ sequestration,” “enhanced weathering,” “low-carbon binders,” “magnesium silicate hydrate,” “M–S–H,” “refractory ceramics,” “radiation shielding concrete,” “adsorption,” “heavy metals,” “geologic hydrogen,” “natural hydrogen,” “thermal activation,” “asbestos,” “fibrous minerals,” “Ni–Cr mobility,” and “United Arab Emirates ophiolite.” Searches were complemented by backward and forward citation tracking of key papers. The literature search covered foundational publications and recent studies available up to June 2026.

Studies were included when they directly addressed serpentinite, serpentine-group minerals, serpentinite-bearing rocks, or serpentinite-derived products in relation to mineralogical controls, physicochemical properties, processing behavior, engineering performance, environmental risk, carbon mineralization, Mg recovery, geologic hydrogen, or sustainable utilization. Priority was given to studies that included mineralogical characterization, geochemical data, processing conditions, performance measurements, scale-up information, or environmental and occupational constraints. Studies were excluded when they focused on unrelated Mg-silicate materials without a clear serpentinite link, when serpentinite was only mentioned incidentally, or when application claims were not supported by mineralogical, experimental, or process-based evidence.

The selected literature was organized into thematic groups corresponding to the structure of the review: geological origin and serpentinitization; serpentine polymorphs and accessory phases; structure–property relationships; traditional geomaterial uses; construction materials and low-carbon binders; advanced functional applications; metallurgy and Mg chemistry; agriculture and land systems; carbon capture, utilization, and storage; geologic hydrogen; electrochemical and energy-material concepts; thermal management; techno-economic and sustainability assessment; and the UAE case study. Within each group, evidence was evaluated using the synthesis criteria summarized in Table S1. These criteria were used to distinguish established applications, such as dimension stone, aggregates, and refractory or ceramic systems, from process-sensitive pathways, such as Mg recovery, low-carbon binders, adsorption materials, and mineral carbonation, and from early-stage concepts,

such as serpentinite-derived electrochemical composites and osmotic-energy analogues.

This methodology allowed the review to move beyond descriptive reporting by comparing application pathways according to controlling mineralogical variables, processing intensity, evidence maturity, functional advantage, scalability, and risk. In particular, the synthesis emphasizes that serpentinite valorization is feasible only when the functional benefit of the material exceeds the additional burden of activation, impurity control, environmental management, and occupational safety. Therefore, the review adopts a fit-for-purpose framework in which serpentinite is assessed not simply as an abundant rock, but as a heterogeneous geo-material whose deployment must be guided by mineralogical screening, process-specific qualification, and risk-aware resource allocation.

Geological origin, mineralogy, and classification of serpentinite

Serpentinization of ultramafic rocks

Serpentinite is produced by hydration and metasomatic alteration of ultramafic protoliths—most commonly dunite,

harzburgite, lherzolite, and pyroxene-bearing peridotites—during interaction with aqueous fluids across a wide spectrum of geological settings (Fig. 1A). In mechanistic terms, serpentinization is a coupled fluid–rock reaction in which primary olivine and pyroxenes are progressively replaced by serpentine-group minerals (lizardite, chrysotile, and antigorite). The reaction commonly generates or co-precipitates brucite and magnetite, with the final assemblage controlled by silica activity, temperature, and the bulk composition of the reacting system (Klein et al. 2013, Klein et al. 2022, Katayama et al. 2010). A defining geochemical outcome is the formation of hyperalkaline, strongly reducing fluids. In Fe-bearing lithologies, oxidation of Fe(II) during secondary mineral growth can release H₂, and this hydrogen can subsequently drive abiotic reduction of dissolved carbon species to CH₄ where catalytic surfaces and thermodynamic conditions are favorable (Fig. 1A) (Sleep et al. 2004, McCollom and Bach 2009, McCollom et al. 2020, Preiner et al. 2018). These interlinked redox and mineralogical transformations are now widely recognized as among the most consequential alteration pathways for mantle-derived ultramafic rocks, exerting first-order control on evolving geochemistry, permeability development, and long-term reactivity (Klein et al. 2013, Klein et al. 2022, McCollom et al. 2020, McCollom and Donaldson 2016).

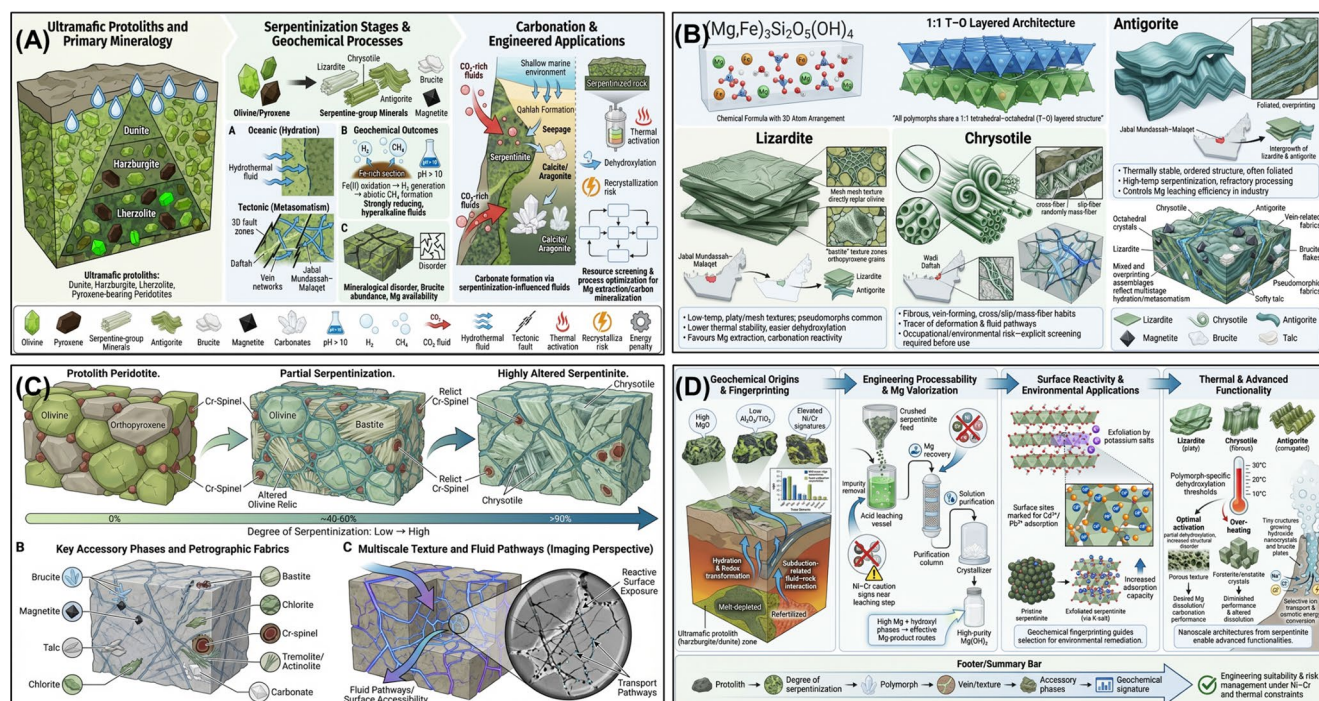


Fig. 1 Origin, mineralogy, textures, and functional significance of serpentinite. **A** Serpentinite formation through hydration of ultramafic protoliths, producing serpentine minerals with brucite and magnetite and generating alkaline reducing fluids. **B** Structural and morphological differences among serpentine polymorphs (lizardite, chrysotile, antigorite). **C** Progressive textural evolution during serpentinization,

including mesh and bastite fabrics, chrysotile veins, accessory minerals, and fracture-controlled fluid pathways. **D** Geochemical characteristics and processing routes linking Mg-rich serpentinite to applications such as Mg recovery, adsorption, carbonation, and advanced functional materials

In the UAE segment of the Semail Ophiolite, available evidence indicates that serpentinization was commonly polyphase, reflecting superposed oceanic and tectonic episodes rather than a single alteration event. In the Daftah area, chrysotile occurs both as disseminated material and as vein-hosted phases, consistent with late, low-grade alteration promoted by deformation and focused fluid flow during tectonic emplacement, overprinting earlier peridotite hydration (Heikal et al. 2024). Geochemical constraints from the Jabal Mundassah–Malaqet serpentinites likewise support derivation from mantle peridotites that experienced serpentinization under subduction/fore-arc fluid–rock interaction prior to Late Cretaceous obduction, implying tectono-metasomatic overprinting superimposed upon earlier ocean-floor alteration signatures (Sami et al. 2026). Considered together, these UAE studies support a two-level framework in which serpentinites archive both (i) ocean-floor hydration processes and (ii) later deformation-driven metasomatism during ophiolite emplacement (Sami et al. 2026, Heikal et al. 2024).

Serpentinization systems may further evolve toward carbonate precipitation when CO₂-bearing fluids infiltrate serpentinite, or when serpentinization-derived alkaline waters mix with seawater or meteoric fluids. This coupling is exemplified by the Upper Cretaceous Qahlah Formation (UAE), where shallow-marine seepage and carbonate precipitation have been linked to serpentinization-influenced fluids sourced from the underlying ophiolitic substrate (Eickmann et al. 2021). The same fluid–rock–carbon linkage underpins modern concepts of long-term carbon fixation in ultramafic terranes and provides a direct mechanistic connection between natural serpentinization and engineered mineral carbonation strategies (Pasquier et al. 2014, Eickmann et al. 2021). From an applied perspective, serpentinization history is not simply descriptive; it exerts a strong control on subsequent technological performance by regulating mineralogical disorder, brucite abundance, fracture and vein networks, and Mg accessibility (Fig. 1A). Across carbonation and Mg-extraction workflows, the activation state and structural disorder of serpentine minerals are repeatedly identified as primary determinants of Mg release and reaction kinetics. Thermal activation and dehydroxylation are therefore widely treated as enabling pretreatments, yet their energetic cost and the possibility of recrystallization into less reactive phases demand careful optimization of temperature windows, residence times, and downstream handling (Balucan et al. 2013, Balucan and Dlugogorski 2013, Dlugogorski and Balucan 2014). Consequently, a clear practical implication follows: the geological pathway of serpentinization and subsequent overprinting imposes measurable constraints on reactivity, and should be incorporated explicitly into resource screening and process design

for carbon mineralization and magnesium recovery technologies (Pasquier et al. 2014, Balucan et al. 2013, Balucan and Dlugogorski 2013, Dlugogorski and Balucan 2014).

Mineralogical classes: lizardite, chrysotile, and antigorite

Serpentinite is classified mineralogically by the dominant serpentine polymorphs—lizardite, chrysotile, and antigorite (Fig. 1B). Although these phases share a broadly similar ideal composition, (Mg, Fe)₃Si₂O₅(OH)₄, they differ fundamentally in crystal structure, habit and fabric, thermal stability, and the engineering/environmental constraints that accompany their use (Carmignano et al. 2020, Evans et al. 2013). All serpentine minerals exhibit a 1:1 (T–O) layer structure, comprising a tetrahedral silicate sheet bonded to an octahedral, brucite-like sheet. The key distinction among polymorphs lies in how lattice misfit between these sheets is accommodated—through curvature, modulation, and variations in stacking—resulting in contrasting crystallography and characteristic microtextures (Fig. 1B) (Evans 2004, Diab et al. 2025a, Diab et al. 2025b, Shemy et al. 2025). These differences are not merely descriptive: they influence dehydroxylation pathways, the tendency toward disorder or amorphization during activation, and the accessibility of Mg in leaching and carbonation processes (Beglaryan et al. 2023, Dlugogorski and Balucan 2014).

Lizardite is typically the predominant low-temperature serpentine polymorph in many massive serpentinites and commonly forms platy to cryptocrystalline aggregates (Fig. 1B). Petrographically, it is classically expressed as mesh textures replacing olivine and bastite textures replacing orthopyroxene—features widely used to interpret replacement mechanisms, reaction progress, and fluid pathways during serpentinization (Tarling et al. 2022, Wang 2026, Wicks and Whittaker 1977). In the UAE, geochemical–mineralogical constraints from the Jabal Mundassah–Malaqet serpentinites indicate intergrown lizardite and antigorite, supporting lizardite as a major framework component within the northern Semail Ophiolite serpentinites (Sami et al. 2026). From an applied standpoint, lizardite-rich serpentinite commonly exhibits lower thermal stability and comparatively easier dehydroxylation, which can affect calcination response and the reactivity achieved after activation—parameters that are central to designing Mg extraction and carbonation routes (Dlugogorski and Balucan 2014).

Chrysotile is distinguished by its fibrous habit, making it especially significant for two reasons: it often records deformation-assisted fluid flow, and it can impose occupational and environmental constraints on serpentinite valorization (Fig. 1B). Chrysotile commonly occurs in fracture- and

vein-controlled networks, including cross-fiber and slip-fiber forms, or as more massive fibrous aggregates, reflecting localized permeability creation and focused fluid access during late-stage serpentinization or tectonic overprinting (Evans 2004, Kim 2025, Wicks and Whittaker 1977, Zhao et al. 2024). In the UAE Wadi Daftah serpentinite, detailed characterization documented cross-fiber, slip-fiber, and mass-fiber chrysotile habits associated with distinct fracture and shear settings, reinforcing chrysotile as a mineralogical marker of fluid–deformation coupling and, simultaneously, as a phase requiring explicit screening where fibrous morphologies occur (Heikal et al. 2024). Practically, the presence of chrysotile—or more broadly, elongated mineral particles—requires systematic petrographic and mineralogical assessment as part of responsible resource appraisal prior to construction use or industrial processing (Cavallo 2018, Obminski and Świątkowska 2026).

Antigorite is generally the most structurally ordered and thermally stable serpentine polymorph, commonly associated with higher temperature serpentinization, recrystallized fabrics, and frequently foliated or tectonized serpentinites (Fig. 1B). Phase relations syntheses consistently place antigorite in a higher-temperature stability field than lizardite and chrysotile, which has direct implications for selecting thermal activation windows and for refractory-oriented processing where high-temperature behavior is critical (Dlugogorski and Balucan 2014, Cox et al. 2021, Viti et al. 2018). The industrial importance of polymorph identity is further supported by extraction studies demonstrating that the dominant serpentine phase can significantly influence magnesium dissolution efficiency and leaching response, confirming polymorphism as a process-relevant variable rather than a purely crystallographic distinction (Beglaryan et al. 2023).

In natural bodies, serpentinite rarely contains a single end-member polymorph. More commonly, lizardite–antigorite assemblages, localized chrysotile vein systems, and overprinting parageneses reflect multistage hydration followed by tectono-metasomatic modification. This pattern is well illustrated in the UAE through lizardite–antigorite coexistence in the Jabal Mundassah–Malaqet serpentinites and the chrysotile overprint described from Wadi Daftah (Sami et al. 2026, Heikal et al. 2024). Consequently, a robust mineralogical classification should be implemented as an integrated scheme that considers: (i) the dominant polymorph assemblage, (ii) accessory phases (e.g., brucite, talc), (iii) diagnostic textures and microstructures (pseudomorphic replacement versus vein-related fabrics), and (iv) paragenetic sequence. These factors jointly determine both reactivity (activation, dissolution, carbonation) and risk profile (fibrous phases and particle-release potential) (Cavallo 2018, Wicks and Whittaker 1977).

Textural evolution, alteration degree, and associated accessory phases

Serpentinite textures provide reliable petrographic evidence of protolith identity and alteration because serpentinization proceeds through pseudomorphic replacement and fracture- or vein-controlled precipitation (Fig. 1C). The principal fabrics are mesh texture, formed by olivine replacement while commonly preserving the original grain framework, and bastite texture, produced by orthopyroxene replacement. Since the work of Wicks and Whittaker, these fabrics and their transitional forms have been used to interpret serpentinization pathways, replacement mechanisms, and reaction progress in ultramafic rocks (Wicks and Whittaker 1977). Evidence from the UAE sector of the Semail Ophiolite supports this interpretation. Sami et al. (Sami et al. 2026) described massive and foliated serpentinites in the Jabal Mundassah–Malaqet area containing altered olivine relics, well-developed mesh fabrics, and preserved Cr-spinel. These features indicate a mantle-peridotite protolith affected by multistage alteration and variable deformation. More broadly, persistent chromite/spinel and incomplete replacement textures constrain serpentinization intensity, fluid access, and deformation-related modification of earlier fabrics (Sami et al. 2026, Wicks and Whittaker 1977).

Textural evolution is closely linked to serpentinization degree, ranging from partial replacement of peridotite to near-complete transformation into serpentinite (Fig. 1C). Increasing alteration generally produces more pervasive microfracturing and veining, higher structural-water contents, and greater serpentine±brucite abundance. These changes regulate permeability, fluid accessibility, reactive-surface exposure, and the availability of Mg-bearing phases for carbon mineralization and Mg extraction. Because matrix porosity is commonly limited, connected fractures, veins, and replacement fronts provide the main pathways for fluid circulation and localize dissolution and precipitation. Accordingly, engineered carbonation depends on rock volume, fracture connectivity, and dissolution–precipitation kinetics along accessible transport pathways (Steinthorsdottir 2025). Late-stage overprinting is particularly important where fibrous serpentine develops. At Wadi Daftah, Heikal et al. (Heikal et al. 2024) showed that chrysotile occurs in tension gashes, shear-related slip surfaces, and localized metasomatic replacement zones, demonstrating strong control by deformation and transient fluid conduits. Serpentinite fabric is therefore dynamic: early mesh and bastite textures may be obscured or reworked by repeated hydration, veining, deformation, and Mg–Fe–Si redistribution. Such overprinting creates heterogeneity that affects technological performance and risk screening where fibrous habits occur (Heikal et al. 2024).

Accessory minerals are also fundamental to characterization and performance assessment. Common phases include brucite, magnetite, Cr-spinel, talc, chlorite, sulfides, tremolite/actinolite, and secondary carbonates (Fig. 1C). In UAE serpentinites, magnetite and talc occur with chrysotile-bearing zones at Wadi Daftah, whereas Cr-spinel remains a key relict phase in the Jabal Mundassah–Malaqet rocks (Sami et al. 2026, Heikal et al. 2024). These minerals record fluid chemistry and alteration conditions and influence engineering and environmental behavior. Magnetite affects density and magnetic response; brucite contributes to alkalinity buffering and Mg availability; and amphiboles and other fibrous phases are important occupational and environmental considerations. Accessory assemblages may also influence trace-element behavior, especially Ni–Cr mobility, linking petrography to risk-aware resource evaluation.

The Cabo Ortegal ultramafic massif in northwestern Spain provides a complementary example of continued fluid–rock interaction. There, serpentinite progressively transforms into carbonated serpentinite, talcose serpentinite, and talc-rich rock through low-temperature hydrothermal alteration involving SiO₂- and CO₂-rich fluids. This evolution is accompanied by mineralogical and geochemical redistribution, including variations in potentially toxic Cr, Ni, and Co. Talc-rich domains, carbonate phases, and chrysotile-bearing zones increase within-outcrop heterogeneity, complicate predictions of physical and mechanical behavior, and constrain commercial utilization and environmental suitability. This example demonstrates that talc formation, carbonation, fibrous-mineral occurrence, and trace-element mobility should be treated as coupled criteria in lithotype-specific serpentinite evaluation (Pereira et al. 2025).

Modern analytical studies further show that serpentinite fabrics are intrinsically multiscale. Reactive interfaces and transport pathways are controlled by vein networks, microfractures, replacement fronts, magnetite distribution, and residual primary grains. Super-resolution analysis of X-ray CT datasets has reconstructed grain shapes and complex vein architectures, strengthening links between microstructure and transport–reactivity models (Omori et al. 2023). This complexity affects adsorption, dissolution, and carbonation because reaction progress depends on pathway continuity and accessible reactive surfaces. Engineered activation and exfoliation therefore target microstructural opening through surface-area generation and delamination to improve serpentinite-derived sorbents (Diab et al. 2025b). Thus, multiscale characterization directly links geological evolution, material heterogeneity, processing response, functional performance, and environmental risk.

Geochemical fingerprints and engineering significance

The geochemical signature of serpentinite integrates two coupled controls: (i) the primary composition and melt-depletion history of the ultramafic protolith and (ii) secondary modification during hydration, redox evolution, and fluid–rock interaction (Fig. 1D). Accordingly, whole-rock geochemistry is indispensable not only for tectonic discrimination (e.g., depleted versus refertilized mantle; mid-ocean-ridge versus supra-subduction environments), but also for engineering evaluation because it constrains Mg resource potential, impurity loads (notably Ni–Cr–Fe–Al), and the likely abundance of reactive phases such as serpentine and brucite (Fig. 1D). In the UAE segment of the Semail Ophiolite, Sami et al. (Sami et al. 2026) reported that the Jabal Mundassah–Malaqet serpentinites are characterized by high MgO, very low Al₂O₃ and TiO₂, and elevated Ni and Cr, consistent with a highly depleted dunite–harzburgite protolith and a supra-subduction-zone (fore-arc) affinity. From an applications perspective, the same signature is double-edged: it implies a strong Mg-bearing feedstock suitable for chemical valorization (Mg extraction and carbonation), while simultaneously highlighting the need for impurity-aware processing and risk-informed screening where Ni–Cr mobilization may become relevant under aggressive leaching or long-term weathering conditions (Sami et al. 2026).

Geochemical constraints translate directly into processability. High MgO contents combined with structurally bound hydroxyls make serpentinite attractive for magnesium recovery and for manufacturing Mg-based products (e.g., Mg(OH)₂ and Mg salts), provided that dissolution kinetics are sufficiently accelerated and dissolved impurities can be managed (Fig. 1D). Auyeshov et al. (2025) demonstrated an operationally relevant flowsheet for producing high-purity magnesium hydroxide from serpentinite via acid leaching followed by purification, explicitly addressing the recurring challenge of impurity carryover in serpentinite-derived Mg solutions. Similarly, El-Sayed et al. (El-Sayed et al. 2023) emphasized acid leaching as a foundational step in producing purified magnesium compounds from serpentinite and provided kinetic and process insights for hydrochloric-acid leaching applicable to chemical-process design. Together, these studies reinforce a practical conclusion: whole-rock and mineral chemistry should be treated as primary screening criteria when selecting serpentinite for Mg-chemical valorization, because they govern reagent choice, purification requirements, and the attainable product quality (Auyeshov et al. 2025, El-Sayed et al. 2023).

The same mineral–chemical framework also underpins serpentinite’s performance in adsorption and remediation (Fig. 1D). Diab et al. (2025b) showed that reagent-assisted

exfoliation of Mg-rich serpentinite using potassium salts can expose hydroxyl-bearing reactive surfaces, increase accessible porosity, and substantially improve Cd^{2+} and Pb^{2+} uptake relative to untreated serpentinite. This supports an applied interpretation in which “geochemical fingerprinting” is not merely a tectonic tool; it is a functional guide for identifying serpentinite as a reactive precursor, because Mg-rich compositions, hydroxylated layers, and brucite-like domains can be strategically leveraged through controlled modification to create effective sorbents for water-treatment applications (Diab et al. 2025b).

Thermal response adds another engineering dimension that is tightly linked to polymorph identity and composition. Dlugogorski and Balucan (2014) synthesized evidence that serpentine polymorphs differ substantially in dehydroxylation behavior and in the reactivity of the resulting activated solids, with antigorite generally decomposing at higher temperatures than lizardite and chrysotile. They further emphasized that activation is often optimized when partial dehydroxylation and structural disorder are achieved, whereas excessive heating that promotes recrystallization toward forsterite and enstatite may reduce carbonation performance and modify dissolution behavior. This aligns with experimental evidence that calcination can enhance Mg dissolution (Fedoročková et al. 2012) yet requires careful tuning to balance reactivity gains against energy cost and phase evolution (Fedoročková et al. 2012, Dlugogorski and Balucan 2014).

In more specialized contexts, serpentinite-derived alteration products can also yield functional microstructures with properties beyond conventional geomaterials use (Fig. 1D). Lee et al. (2024) reported that serpentinite-hosted deep-sea hydrothermal vent precipitates, dominated by aligned layered hydroxide nanocrystals, can support selective ion transport and osmotic energy conversion across concentration gradients. While distinct from aggregate or cement-related applications, this example demonstrates—under natural conditions—how serpentinite-associated brucite/layered hydroxides and their nanoscale architectures can generate emergent functionalities relevant to membrane-like selectivity and energy-harvesting concepts (Lee et al. 2024).

Overall, serpentinite is best assessed through an integrated descriptor set—protolith type, serpentinization degree, dominant polymorph assemblage, texture and vein architecture, accessory phases, and whole-rock geochemical signature—because these variables collectively determine suitability across aggregate applications, ceramic/refractory processing, Mg extraction and Mg-product manufacture, carbon mineralization, adsorption/remediation systems, and emerging advanced uses. In particular, Ni–Cr enrichment and polymorph-dependent thermal behavior should be treated as first-order constraints in engineering

decision-making, as they influence both processing efficiency (activation and leaching performance) and responsible deployment (impurity management and risk screening).

Structure–property relationships governing serpentinite performance

Mineralogical controls on density, porosity, and mechanical behavior

Serpentinite performance as an engineering material is controlled foremost by mineral assemblage and microstructural state, including the relative proportions of serpentine polymorphs, brucite, magnetite, residual olivine/pyroxenes, secondary carbonates, and vein-related phases (Fig. 2; Table 1). Because serpentinization converts dense, anhydrous mantle silicates into hydrous phyllosilicate minerals and is commonly accompanied by veining, microcracking, and strain localization, it typically produces systematic changes in bulk density, elastic properties, porosity, and failure mode. This is consistent with ultramafic rock datasets showing wide spreads in density, porosity, elastic modulus, and unconfined compressive strength across dunite–serpentinite suites, where more strongly serpentinized rocks commonly exhibit lower mechanical competence and greater internal disturbance than less altered counterparts (Fig. 2) (Al Kalbani et al. 2024). Comparable trends have been documented in serpentinite used as dimension/building stone. Reported variability in density, ultrasonic velocity, and compressive strength reflects differences in mineralogy (including accessory phases), fabric (massive versus foliated), and alteration intensity (Fig. 2). These outcomes underline a practical requirement: serpentinite intended for architectural use must be qualified by integrated petrographic and petrophysical testing rather than by lithologic name alone (Visalli et al. 2025).

Mineralogical controls remain decisive after processing into fired or bonded products. In serpentinite/olivinite-containing ceramic mixtures, changes in blend composition can strongly shift density, open porosity, shrinkage behavior, and compressive strength, indicating that the sintering pathway is highly sensitive to the Mg-silicate fraction and its transformation reactions (Fig. 2; Table 1) (Thomaidis and Kostakis 2015). Similarly, heat-treated serpentines enriched in chrysotile, lizardite, or antigorite can show contrasting hydration behavior and strength evolution in magnesium silicate binder systems, demonstrating that polymorph identity and activation response influence performance beyond bulk (Ivanova et al. 2022). In concrete technology, mineralogy also governs the interfacial transition zone: serpentinite aggregates may produce a wider and more porous

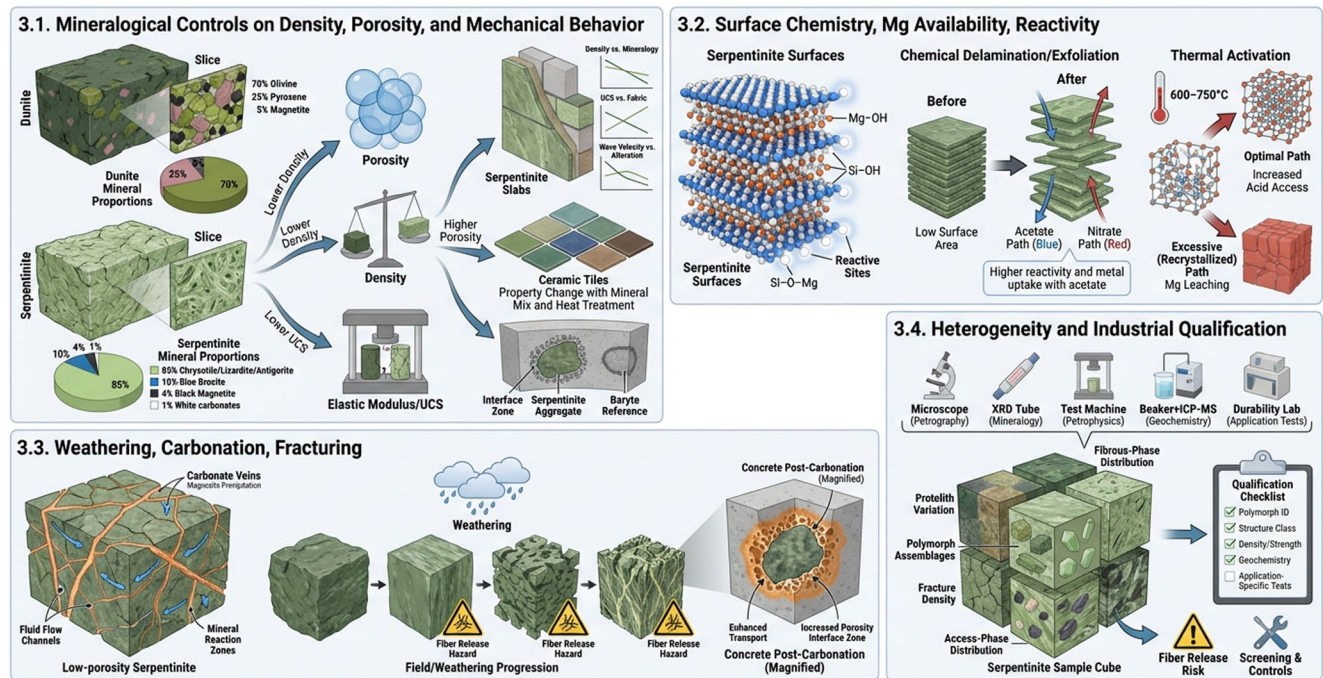


Fig. 2 Conceptual diagram of structure–property relationships in serpentinite, illustrating how mineralogy, surface chemistry, alteration, and heterogeneity control density, reactivity, mechanical behavior, and engineering performance

aggregate–paste contact region than baryte-bearing references, implying that shielding benefits can coexist with microstructural discontinuities that require mitigation through mix design and durability-oriented optimization (Dąbrowski et al. 2022).

3.2. Surface chemistry, Mg availability, and reactivity

In reactive applications—adsorption, dissolution-based processing, and carbonation—serpentinite behavior is controlled by surface chemistry and by the extent to which Mg becomes structurally accessible (Fig. 2; Table 1). Key reactive motifs include Mg–OH groups, Si–OH sites, edge hydroxyls, and Si–O–Mg linkages, which together determine acid–base response, surface charge development, adsorption affinity, dissolution kinetics, and carbonation rates (Fig. 2). In many natural serpentinites, reactivity is limited by low accessible surface area and restricted exposure of reactive sites; therefore, chemical activation and delamination are often used to open the lamellar structure, introduce mesoporosity, and increase the density of hydroxyl-bearing surface functionalities. Comparative modification routes indicate that acetate-assisted exfoliation can yield stronger textural development and higher divalent-metal uptake than nitrate-based approaches, consistent with a structure–function enhancement via improved site accessibility and transport through newly created pore networks (Diab et al. 2025b).

Mg accessibility is equally central to leaching and Mg-recovery workflows, where dissolution is frequently impeded by silica-rich residues and passivating layers (Fig. 2; Table 1). Thermal activation within moderate high-temperature windows has been shown to disrupt chrysotile-rich lattices, increase acid reactivity, and improve Mg extraction efficiency (Auyeshov et al. 2024a, 2024b). This aligns with broader interpretations that reactivity depends less on total MgO content than on the fraction of Mg rendered accessible through controlled disordering and partial dehydroxylation; conversely, excessive heating that drives recrystallization toward less reactive products can reduce the effective reactive fraction (Długogorski and Balucan 2014). Collectively, these findings support a structure–accessibility framework: performance is governed by the coupled accessibility of surface sites, pore architecture, and hydroxyl chemistry under the relevant operational conditions.

Effects of weathering, carbonation, and fracturing

Weathering, carbonation, and deformation modify serpentinite by reshaping surface area, permeability structure, mineral assemblage, porosity, and mechanical integrity (Fig. 2; Table 1). Because matrix porosity is often limited, reaction progress and fluid circulation are frequently controlled by fractures, veins, and cataclastic domains, which act as principal transport pathways and reaction loci (Fig. 2). Field-based characterization of fractured

Table 1 Quantitative structure–property controls governing serpentinite performance

Mineralogical controls on density, porosity, and mechanical behavior	Structure control	System	Quantitative value or range	Relevance to serpentinite performance	Ref.
Mineralogical controls on density, porosity, and mechanical behavior	Serpentinization degree versus bulk density	Ultramafic rocks with variable serpentinite content	Measured bulk density: 2540–3200 kg m ⁻³ ; model end-members: 3300 kg m ⁻³ for unserpentinized peridotite and 2500 kg m ⁻³ for fully serpentinized rock	Increasing serpentinite content generally lowers density and contributes to mechanical weakening; useful for linking mineralogical alteration to engineering performance	(Kalbani et al. 2024, Hamed et al. 2025)
	Porosity response to serpentinization	Slightly to extensively serpentinized ultramafic samples	Porosity: 2.1–8.4%	Porosity does not always scale linearly with serpentinite content because weathering, fracture history, and local deformation strongly modify pore structure	(Kalbani et al. 2024, Hamed et al. 2025)
	Elastic-property degradation	Ultramafic rocks with increasing serpentinite content	Shear modulus: 13.4–58.1 GPa; bulk modulus: 41.5–115 GPa; Young's modulus: 32.5–76.4 GPa; Poisson's ratio: 0.28–0.35	Quantifies how serpentinization weakens the rock framework and changes stiffness, which affects construction, geomechanics, fracture propagation, and in situ carbonation behavior	(Kalbani et al. 2024, Hamed et al. 2025)
	Building-stone density and water absorption	Serpentinite used as dimension/building stone	Bulk density: 2597–2838 kg m ⁻³ , average 2747 kg m ⁻³ ; water absorption: 0.1–0.7%, average 0.4%	Demonstrates that serpentinite can meet density requirements but may exceed water-absorption limits depending on lithotype, fabric, and alteration degree	(Visalli et al. 2025)
	Mechanical strength and ultrasonic velocity	Serpentinite building-stone samples	UCS: 24.2–119.6 MPa, average 57.1 MPa; P-wave velocity: 1859–5914 m s ⁻¹ ; S-wave velocity: 1264–3342 m s ⁻¹	Shows high variability in strength and wave velocity; supports the need for sample-specific testing rather than lithological classification alone	(Visalli et al. 2025)
	Static and dynamic elastic modulus	Serpentinite building-stone samples	Dynamic Young's modulus: 9–78 GPa; static Young's modulus: 12–66 GPa	Confirms that fabric, foliation, carbonate/talc content, and discontinuities strongly influence mechanical response	(Visalli et al. 2025)
	Natural-stone qualification thresholds	ASTM C1526-type serpentinite stone criteria	Minimum bulk density: 2560 kg m ⁻³ ; minimum UCS: 69 MPa; water absorption limit: 0.2% for exterior and 0.6% for interior use	Provides quantitative screening thresholds for architectural and ornamental use	(Visalli et al. 2025)
	Ceramic and binder activation response	Heat-treated antigorite, chrysotile, and lizardite	Firing interval: 550–800 °C; optimal activation: antigorite 700 °C, chrysotile/lizardite 650 °C	Demonstrates that polymorph identity controls activation response and strength development	(Ivanova et al. 2022, Dlugogorski and Balucan 2014)
	Binder reactivity and strength	Heat-treated serpentinite-group minerals	ANC: antigorite 7.7 meq g ⁻¹ ; chrysotile and lizardite 19.6–19.7 meq g ⁻¹ ; 7-day strength: antigorite/chrysotile 2.2 MPa, lizardite 0.5 MPa; 1-year strength: chrysotile ~8 MPa, antigorite ~3 MPa	Quantifies polymorph-dependent reactivity and confirms that serpentinite-derived binders are feasible but slower and weaker than conventional Portland cement systems	(Ivanova et al. 2022, Bernard 2022, Sreenivasan et al. 2024)
	Ideal serpentinite composition	Serpentine-group minerals, Mg ₃ Si ₂ O ₅ (OH) ₄	MgO 43.6 wt%; SiO ₂ 43.4 wt%; structural H ₂ O 13.0 wt%	Defines theoretical Mg, silica, and hydroxyl inventories controlling Mg recovery, carbonation, activation, and neutron-shielding behavior	(Carmignano et al. 2020, Evans et al. 2013, Dlugogorski and Balucan 2014)
Surface chemistry, Mg availability, and reactivity					

Table 1 (continued)

Structure control	System	Quantitative value or range	Relevance to serpentinite performance	Ref.
Theoretical carbonation capacity	Ideal serpentinite	0.476 g CO ₂ g ⁻¹ serpentinite, equivalent to 476 kg CO ₂ t ⁻¹	Provides an upper theoretical benchmark; practical CO ₂ uptake is lower because of kinetic barriers, Mg accessibility, passivation, and process limitations	(Steinhilber et al. 2025, Kalbani et al. 2024, Pasquier et al. 2014, Dlugogorski and Balucan 2014)
Brucite composition and carbonation capacity	Brucite, Mg(OH) ₂	MgO 69.1 wt%; H ₂ O 30.9 wt%; theoretical CO ₂ capacity 0.755 g CO ₂ g ⁻¹ brucite	Explains why brucite-bearing serpentinites may show higher alkalinity, Mg accessibility, and carbonation potential than serpentinite-only rocks	(Evans et al. 2013, Lu 2025, Steinhilber et al. 2025, Kalbani et al. 2024, Dlugogorski and Balucan 2014)
Brucite decomposition	Brucite-bearing serpentinite	Approximately 350–450 °C	Early thermal event affecting MgO formation, alkalinity, structural-water loss, and activation behavior	(Dlugogorski and Balucan 2014, Auyeshov et al. 2024a, 2024b)
Main serpentinite dehydroxylation/lattice disruption	Lizardite-/chrysotile-rich serpentinite	Approximately 600–725 °C, commonly with maximum near ~660 °C	Main window for increasing Mg accessibility through structural disordering and dehydroxylation	(Dlugogorski and Balucan 2014, Auyeshov et al. 2024a, 2024b)
Practical thermal-activation window	Thermally activated serpentinite	Commonly 600–750 °C; strongest reactivity often near 725–750 °C	Supports the manuscript's argument that reactivity depends on accessible Mg rather than total MgO alone	(Fedorchuková et al. 2012, Dlugogorski and Balucan 2014, Auyeshov et al. 2024a, 2024b)
Over-firing/recrystallization threshold	Strongly heated serpentinite	Forsterite-related crystallization commonly develops around 750–850 °C, depending on feedstock and firing regime	Beneficial for ceramic/refractory products but may reduce Mg leaching or carbonation reactivity if the objective is chemical extraction	(Cheng et al. 2002, Ramezani et al. 2018, Nemat et al. 2016, Cavallo et al. 2021, Thomaidis and Kostakis 2015, Vakalova et al. 2022, Dlugogorski and Balucan 2014, Auyeshov et al. 2024a, 2024b, Kalaitzidou et al. 2022)
Antigorite dehydroxylation kinetics	Antigorite-rich serpentinite	Activation energy 290–515 kJ mol ⁻¹ ; only ~49% dehydroxylation before a steep kinetic increase above 650 °C	Shows that antigorite-rich serpentinites are more energy-intensive to activate and may be less favorable for low-energy Mg extraction or carbonation	(Balucan et al. 2013, Balucan and Dlugogorski 2013, Dlugogorski and Balucan 2014)
Polymorph-dependent Mg dissolution	Chrysotile-, lizardite-, and antigorite-rich serpentinites	Up to ~97% Mg recovery reported for chrysotile- and lizardite-rich serpentinites within 30 min under tested extraction conditions	Confirms that polymorph identity is a process variable, not only a crystallographic descriptor	(Beglarov et al. 2023)

Table 1 (continued)

	Structure control	System	Quantitative value or range	Relevance to serpentinite performance	Ref.
Effects of weathering, carbonation, and fracturing	Surface opening by exfoliation	Chemically modified serpentinite	Quantitative parameters should include BET surface area, pore volume, average pore diameter, and adsorption capacity	Supports the structure–function link between delamination, mesoporosity, hydroxyl-site exposure, and metal uptake	(Diab et al. 2025a)
	Reactive cation inventory	Dunite and serpentinite samples for in situ mineralization	Divalent cations: dunite ~30%, serpentinite ~26%	Quantifies the reactive cation pool available for mineral carbonation and explains why composition must be included in site screening	(Kalbani et al. 2024)
	Stimulated rock mass to CO ₂ sequestered ratio	Dunite and serpentinite in geomechanical CO ₂ mineralization assessment	Average RCO ₂ : dunite ~2.20, serpentinite ~2.53	Provides a quantitative measure of mineralization scalability and rock-volume demand	(Kalbani et al. 2024)
	Fracture width in stimulated systems	Fractured dunite–serpentinite systems	Average predicted fracture width: ~6.0 mm	Links mechanical properties to reactive surface generation, injectivity, and in situ carbonation feasibility	(Kalbani et al. 2024)
	Rock volume and theoretical CO ₂ storage	Example stimulated-volume calculation	~600 kg exposed rock capable of sequestering ~300 kg CO ₂ for 10 m ³ CO ₂ -bearing fluid in one model case	Shows how fracture geometry and exposed rock mass control mineral-trapping scale	(Kalbani et al. 2024)
	Experimental serpentinite carbonation	Lizardite-dominated serpentinite core experiment	Approximately 30 kg CO ₂ t ⁻¹ rock, equivalent to ~3% carbonation over about half a year; corrected estimate ~2% if recycled vein carbonate is considered	Demonstrates that carbonation occurs but is concentrated along fractures and exposed surfaces; bulk-rock conversion remains slow	(Lacinska et al. 2017)
	Fracture-controlled reaction localization	Carbonated serpentinite	Carbonate precipitation concentrated along fractures, grain boundaries, veins, and exposed surfaces	Supports the statement that permeability architecture and fluid access are primary controls on carbonation progress	(Steinthorsdottir 2025, Klein et al. 2013, Klein et al. 2022, Lacinska et al. 2017)
	Carbonation effect on rock mechanics	Carbonated fault-zone serpentinite	Quantitative values are site-specific; diagnostic assemblages include talc–magnesite and silica–carbonate products	Carbonation is not only a CO ₂ -storage process; it can alter friction, strength, and rock mechanical behavior	(Klein et al. 2013, Klein et al. 2022)
	Fiber-release tendency	Massive, foliated, and cataclastic serpentinite	Ordinal risk trend: massive pseudomorphic < foliated < cataclastic/fibrous-veined serpentinite	Converts qualitative petrography into a practical risk-ranking framework for industrial screening	(Obminski and Świątkowska 2026, Marzini et al. 2024, Punturo et al. 2023)
	Mineralogical heterogeneity	Serpentinite dimension-stone samples	Serpentine 48–100%; magnesite 0–41%; talc 0–25%; dolomite 0–11%	Quantifies phase variability and explains why density, strength, durability, and failure mode vary strongly among samples	(Visalli et al. 2025)
Implications of heterogeneity for industrial qualification	Strength variability/anisotropy	Foliated and nodular serpentinite	Maximum UCS 119.6 MPa at favorable fabric; minimum UCS 24.2 MPa in foliated/talc-rich material; anisotropy ratio ~4–6 in high-anisotropy case	Demonstrates that fabric and weak mineral bands can dominate strength even when bulk lithology is similar	(Visalli et al. 2025)

Table 1 (continued)

Structure control	System	Quantitative value or range	Relevance to serpentinite performance	Ref.,
Qualification parameters for industrial use	Serpentinite feed-stock for construction, carbonation, Mg adsorption, Mg recovery, or thermal processing	Required measured variables: polymorph %, density, porosity, water absorption, UCS, ultrasonic velocity, MgO wt%, Ni-Cr concentration, fiber/asbestiform occurrence, carbonation rate, adsorption capacity, activation temperature	Provides a decision pathway for fit-for-purpose allocation of serpentinite lithotypes	(Cavallo 2018, Sami et al. 2026, Diab et al. 2025b, Obminski and Świątkowska 2026, Visalli et al. 2025, Marzini et al. 2024, Yin et al. 2024, Sideridis et al. 2025, Punturo et al. 2023) (Yin et al. 2024)
Beneficial versus problematic Mg-silicate behavior	Serpentine-rich gangue in processing systems	Quantitative response is process-specific; key variables include particle-size distribution, ultrafine fraction, surface charge, and flotation recovery	Shows that properties useful for activation and sorption can be detrimental in mineral separation because of ultrafine hydrophilic particle generation	(Sideridis et al. 2025)
Provenance and deposit selection	Serpentinite and ophicalcitic stone	No single universal numerical index; recommended approach is multi-parameter petrographic–mineralogical–geochemical fingerprinting	Supports the conclusion that serpentinite should be qualified through combined descriptors rather than by rock name or bulk chemistry alone	

serpentinite systems shows that deformation architecture can co-vary with mineralogical reactivity (notably serpentinite±brucite abundance), thereby governing both fluid access and carbonation potential at the scale relevant to feasibility assessment (Steinthorsdottir 2025). Natural and experimental carbonation analogues reinforce the primacy of structural openness. Lizardite-dominated serpentinite, for example, can show substantial carbonation capacity, with magnesite precipitation focused on exposed surfaces and within fractures where reactive transport is sustained (Fig. 2) (Lacinska et al. 2017). In tectonically active environments, carbonation can also alter mechanical behavior: modeling and field-constrained interpretations indicate that carbonation in creeping faults promotes talc and magnesite formation, with consequences for frictional properties and rheological evolution (Klein et al. 2013, Klein et al. 2022). Carbonation therefore has a dual engineering implication—it can increase CO₂ fixation while simultaneously modifying rock mechanics.

Weathering and deformation also intersect directly with environmental safety and industrial handling. Fiber-release potential is strongly dependent on microstructural class and deformation style; grinding and release experiments indicate increasing hazard potential from massive pseudomorphic serpentinite to foliated serpentinite, and further to cataclastic serpentinite where fibrous veins are pervasive and more readily liberated (Fig. 2; Table 1) (Marzini et al. 2024). In cementitious systems, carbonation and interfacial porosity carry additional implications for transport properties and durability: serpentinite aggregates may widen the porous contact zone and increase vulnerability unless matrix design is specifically optimized (Dąbrowski et al. 2022).

Implications of heterogeneity for industrial qualification

A defining characteristic of serpentinite is multiscale heterogeneity, and this heterogeneity is the principal reason why industrial qualification must be rigorous (Fig. 2; Table 1). Variations in protolith, polymorph assemblage, alteration degree, fracture density, carbonatization, accessory phases, and the distribution of fibrous minerals mean that serpentinite is seldom a uniform raw material. Consequently, integrated workflows combining petrography, mineralogy, geochemistry, and petrophysical testing are widely recommended for evaluating serpentinite suitability as building/ornamental stone and for anticipating durability and safety constraints (Fig. 2) (Visalli et al. 2025). The same issue arises in processing and extractive contexts, where serpentinite can be either beneficial or problematic depending on the target application. In nickel sulfide beneficiation,

serpentine-rich Mg-silicate gangue may hinder flotation because of its softness and tendency to generate ultrafine hydrophilic particles, illustrating how a property advantageous for some engineered uses can be detrimental to separation efficiency (Yin et al. 2024). For traceability and deposit selection, provenance-oriented frameworks likewise emphasize that reliable “fingerprinting” requires combined petrographic, mineralogical, and geochemical evidence rather than reliance on a single index or bulk parameter (Sideridis et al. 2025).

Environmental qualification must be treated as a core component, not an afterthought. Because fiber-release potential is deformation-dependent (Marzini et al. 2024), and because serpentine used as stone may host chrysotile and/or amphiboles in veins or mixed fabrics, screening and handling controls must be tailored to the intended application and the material’s microstructural class (Visalli et al. 2025, Marzini et al. 2024). At minimum, industrial qualification should therefore include: (i) serpentine polymorph identification, (ii) petrographic/structural classification, (iii) density–porosity–strength testing, (iv) geochemical screening for Mg, Ni, Cr and associated elements, and (v) application-specific tests (e.g., carbonation kinetics, adsorption performance, durability metrics, or thermal response). In serpentine systems, heterogeneity is not a secondary complication—it is the controlling factor that determines both value and risk (Fig. 2).

Traditional applications of serpentine as a geomaterial

Dimension stone, ornamental stone, and architectural uses

Serpentine has long been valued as an ornamental and dimension stone, largely because of its characteristic green to dark-green coloration, attractive veining, and excellent polishability—properties that have supported its widespread commercial marketing under the broader “green marble” category (Fig. 3; Table 2) (Punturo et al. 2023). Its cultural and archaeological significance is well established, yet recent syntheses stress that successful use in monuments, conservation, façade cladding, and interior architectural elements depends on rigorous material qualification. This is because serpentine performance is highly sensitive to lithotype, fabric (massive versus foliated), alteration degree, and weathering response; therefore, petrographic, mineralogical, geochemical, and petrophysical datasets must be integrated to predict durability and compatibility in service environments (Fig. 3) (Punturo et al. 2023). Provenance-oriented studies further indicate that serpentine and ophealcitic equivalents were historically employed across a spectrum of uses, from practical stone implements and low-grade architectural components to higher-status architectural contexts where carbonate-cemented or otherwise

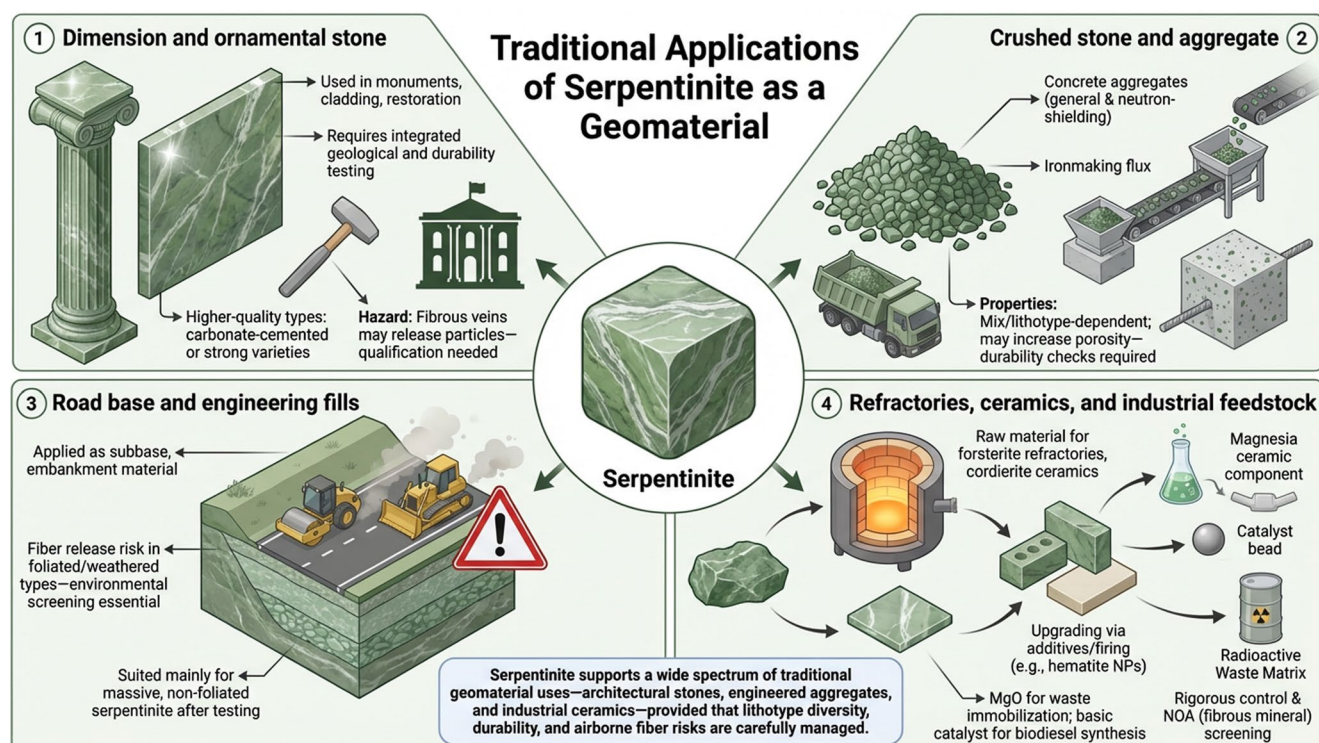


Fig. 3 Traditional applications of serpentine as a geomaterial, including dimension stone, aggregates, road-base materials, and refractory/ceramic feedstock

Table 2 Representative quantitative performance indicators for serpentinite in geomaterial, construction, binder, ceramic, shielding, and catalytic applications

Application domain	Representative system	Quantitative indicators	Performance meaning	Ref.,
Dimension stone and architectural use	Serpentinite used as natural stone	Bulk density: 2597–2838 kg m ⁻³ ; water absorption: 0.1–0.7%; UCS: 24.2–119.6 MPa; natural-stone thresholds: density ≥ 2560 kg m ⁻³ , UCS ≥ 69 MPa, water absorption ≤ 0.2% for exterior and ≤ 0.6% for interior use	Shows that serpentinite can meet stone-use requirements, but performance varies strongly with lithotype, fabric, alteration, and veining.	(Visalli et al. 2025, Punturo et al. 2023)
Crushed stone, aggregate, and fill	Serpentinite aggregate and geotechnical fill	Quantitative qualification should include density, water absorption, UCS/crushing resistance, abrasion resistance, particle-size distribution, and NOA/fiber screening	Supports use only after material testing; massive low-fiber lithotypes are preferable for open aggregate and fill uses.	(Chenget al. 2002, Jain et al. 2023, Obminkia and Świątkowska 2026, Marzini et al. 2024, Punturo et al. 2023)
Serpentinite-bearing concrete	Serpentinite aggregate in concrete, including shielding concrete	Key variables include aggregate water absorption, porosity, ITZ width, chloride migration, carbonation depth/rate, and strength retention	Serpentinite aggregate can provide functional value, especially for shielding, but may increase ITZ porosity and transport sensitivity unless mix design is optimized.	(Dąbrowskiet al. 2022, Jain et al. 2023, Scrivener et al. 2004, Stroeven 2022)
Thermally activated Mg–silicate binder precursor	Heat-treated antigorite, chrysotile, and lizardite	Heating range: 550–800 °C; optimum activation reported near 700 °C for antigorite and 650 °C for chrysotile/lizardite; ANC: 7.7 meq g ⁻¹ for antigorite and 19.6–19.7 meq g ⁻¹ for chrysotile/lizardite	Confirms that binder reactivity is polymorph-dependent and controlled by activation temperature.	(Ivanova et al. 2022, Dlugogorski and Balucan 2014, Bernard 2022, Sreenivasan et al. 2024)
Serpentinite-derived M–S–H binders	Hydrated heat-treated serpentine-group minerals	7-day compressive strength: 0.5–2.2 MPa; longer-term strength reported up to ~8 MPa depending on precursor and curing	Supports M–S–H as a feasible but slower-strength, application-specific binder, not a universal Portland cement replacement.	(Ivanova et al. 2022, Bernard 2022, Sreenivasan et al. 2024, Marsiske et al. 2023)
CO ₂ -aware construction products	Activated serpentinite residues used as reactive Mg–silicate solids	Carbonation performance depends on activation temperature, particle size, Mg accessibility, fluid chemistry, and CO ₂ exposure conditions	Supports carbonation-linked construction concepts, but performance must be evaluated with carbonation kinetics and activation-energy demand.	(Pasquier et al. 2014, Kemache et al. 2016, Lacinska et al. 2017)
Forsterite/enstatite ceramic and proppant products	Serpentinite + silica additives	Silica additives: 20–30 wt%; firing temperature reduced by 50–70 °C from 1300–1350 °C to 1250–1280 °C; pressed-specimen strength up to 440 MPa; proppant bulk density 1.58–1.62 g cm ⁻³ ; breaking pressure up to 52 MPa	Strong quantitative support for controlled ceramic valorization through phase engineering, especially for forsterite–enstatite systems.	(Thomaidis and Kostakis 2015, Vakalova et al. 2022, Kalaitzidou et al. 2022)
Construction ceramics from serpentinite waste	Serpentine extraction waste + glass waste + clay–sand mix	Serpentinite waste up to 70 wt%; flexural strength up to ~57 MPa; water absorption 0.28–17.61%; As and Pb leaching reduced by 19× and 102×, respectively	Demonstrates waste immobilization and circular construction potential, but only under controlled firing and leachability verification.	(Mymrin et al. 2020)
Magnetite–serpentine radiation-proof concrete	Composite shielding concrete	Room temperature: compressive strength 42.0 MPa, LAC 0.236 cm ⁻¹ ; at 800 °C: compressive strength 12.2 MPa, LAC 0.189 cm ⁻¹ ; LAC at 800 °C retained 80.9% of room-temperature value	Confirms shielding functionality but also shows high-temperature strength loss and the need for service-condition testing.	(Wu et al. 2025)
Serpentine/magnetite-doped shielding ceramics	Ceramic bodies with serpentine or magnetite additives	Additive levels: 0, 10, 20, and 30 wt%; tested γ-ray energies: 81–383 keV	Shows that serpentinite-derived phases can improve radiation attenuation in fired ceramics, especially when combined with high-density additives.	(Oto et al. 2024)
Catalytic precursor/solid-base catalyst	K ₂ MgSiO ₄ -bearing catalyst from serpentinite	KOH impregnation: 5, 10, and 20 wt%; thermal treatment: 500, 700, and 900 °C	Demonstrates serpentinite as a process-dependent catalytic precursor, not an intrinsically active catalyst.	(Ballotin et al. 2016)

mechanically reinforced varieties were available (Sideridis et al. 2025).

Industrial case evidence confirms that serpentinite occupies a mature commercial niche rather than being confined to “heritage stone” usage. For instance, in Taiwan, serpentinite exploitation included an established dimension-stone stream directed to building-decoration markets alongside crushed-rock production (Cheng et al. 2002). However, the same body of evidence supports a qualified approach to selection: mechanical durability may vary markedly among serpentinite lithotypes (Punturo et al. 2023), and deformation-related fabrics—especially where fibrous veins are abundant—can increase the likelihood of releasing hazardous elongated mineral particles during quarrying, cutting, and finishing (Marzini et al. 2024). Consequently, safe and durable architectural deployment requires application-specific testing and risk screening, rather than reliance on appearance-based grading alone (Marzini et al. 2024, Punturo et al. 2023).

Crushed stone and aggregate in civil construction

Serpentinite also has a long-standing role as crushed stone in regions where ultramafic rocks are abundant and quarry economics are favorable (Fig. 3; Table 2). A representative industrial example is the large-scale crushed serpentine/serpentinite production documented in Taiwan, where material was supplied predominantly as a flux for iron-making while dimension-stone production proceeded in parallel (Cheng et al. 2002). Although flux use is not a structural application, it demonstrates serpentinite’s sustained position as a commercially relevant crushed-rock commodity. Within civil construction, serpentinite aggregates have been investigated for concrete. A recent synthesis of serpentine/serpentinite in concrete highlights both performance opportunities and durability limitations that depend strongly on lithotype, processing, and mix design (Fig. 3) (Jain et al. 2023). In radiation-shielding concretes, serpentinite can be attractive because structurally bound hydroxyls contribute to neutron attenuation; yet microstructural evidence shows that serpentinite aggregates may generate a wider and more porous aggregate–paste contact zone than baryte-bearing references, potentially increasing transport sensitivity (e.g., chloride ingress, carbonation progression) if the paste system is not optimized (Dąbrowski et al. 2022). Thus, serpentinite can be beneficial in specialized concretes, but it demands durability-focused qualification that explicitly accounts for its intrinsic mineralogical and textural variability (Dąbrowski et al. 2022, Punturo et al. 2023).

Road base, embankment, and geotechnical fill applications

Serpentinite-derived crushed rock has also been used or considered for road base layers, embankment fills, subbases, and other geotechnical earthworks, particularly where local availability reduces cost. However, the most defensible position is conditional rather than universal (Fig. 3; Table 2). Recent assessments emphasize that earthworks in serpentinite-bearing terrains can disturb fibrous phases and elevate exposure potential during excavation, crushing, grading, transport, and compaction (Marzini et al. 2024, Punturo et al. 2023). This concern becomes more pronounced where serpentinite is foliated or cataclastic and hosts abundant fibrous veins, because deformation fabrics increase fiber accessibility and facilitate liberation during comminution (Marzini et al. 2024). Additional occupational and environmental evidence indicates that mining and crushing operations can generate respirable elongated mineral particles and associated contaminants, supporting the need for integrated exposure assessment and monitoring in crushed-rock and fill scenarios (Obminski and Świątkowska 2026).

Accordingly, serpentinite may be suitable for subbase, embankment, and engineered fill applications—especially where quarry logistics are favorable—only after systematic mineralogical identification, geotechnical characterization, weathering-performance evaluation, and explicit NOA/fiber-risk screening (Fig. 3). In general, massive and weakly deformed serpentinite is typically less problematic than foliated, cataclastic, or strongly weathered serpentinite, which may combine reduced engineering competence with higher airborne-fiber potential (Marzini et al. 2024, Punturo et al. 2023).

Industrial stone in refractory and ceramic systems

Among serpentinite’s most technically established traditional applications is its use as a raw material for refractory and ceramic production, particularly for forsterite-rich and other Mg-silicate products (Fig. 3; Table 2). A clear demonstration is the conversion of waste serpentine cutting into synthetic forsterite refractories, showing that serpentinite residues can be upgraded into refractory feedstocks rather than disposed ((Cheng et al. 2002). This interpretation is consistent with work on chromite-mine wastes, where serpentine-rich residues were processed into refractory and ceramic products with refractoriness appropriate for iron- and steel-industry environments (Nemat et al. 2016). More recent studies focused on upgrading serpentinitized by-products from magnesite beneficiation confirm that refractory

performance depends strongly on initial mineralogy and on controlled phase evolution toward forsterite; optimization of firing protocols and targeted additives (including nanoscale modifiers) can substantially improve strength and refractory behavior (Fig. 3) (Kalaitzidou et al. 2022). Serpentine utility also extends beyond classical refractories. Serpentine-bearing formulations have been applied to cordierite ceramics (Thomaidis and Kostakis 2015), and natural serpentine can serve as a precursor for magnesia–silicate ceramics and ceramic proppants when sintering is guided through phase-control strategies (notably forsterite–enstatite transformation routes) (Vakalova et al. 2022). Broader resource-valorization reviews similarly identify forsterite and high-MgO ceramics, cordierite systems, and vitroceraamics as principal targets for serpentine-derived ceramic, while reiterating that NOA screening is essential where fibrous phases may be present (Cavallo 2018).

Beyond refractories and structural ceramics, serpentine-derived Mg phases have supported additional industrial products. MgO sourced from serpentine has been employed as a precursor in magnesium potassium phosphate matrices designed for radioactive waste immobilization, illustrating that serpentine can underpin higher-value Mg-based materials under controlled processing (Kulikova et al. 2020). Serpentine has also been upgraded into catalytic solids: alkali impregnation followed by thermal treatment can generate K_2MgSiO_4 -bearing basic catalysts used in biodiesel synthesis, reflecting the same industrial logic of transforming abundant Mg-silicates into value-added thermal products (Ballotin et al. 2016). Overall, the validated literature supports serpentine as a long-established—and still relevant—industrial geomaterial for architectural stone markets, crushed-rock supply chains, and, most robustly, refractory and ceramic systems. Across all traditional uses, however, applicability must be governed by lithotype variability, durability response, and explicit risk-aware handling where fibrous phases may occur (Fig. 3) (Cavallo 2018, Cheng et al. 2002, Nemat et al. 2016, Obminski and Świątkowska 2026, Marzini et al. 2024, Punturo et al. 2023, Kalaitzidou et al. 2022).

Serpentine in construction materials and low-carbon binders

Serpentine as mineral filler and aggregate in concrete systems

Research on serpentine in cementitious materials has focused mainly on two implementation routes: (i) use as coarse and/or fine aggregate, and (ii) more selective incorporation as a mineral filler or as a solid constituent derived

from quarrying/mining residues (Fig. 4A; Table 2). Collectively, the literature indicates that serpentine can be used in concrete when local resource availability, radiation-shielding requirements, or circular-economy drivers provide a clear rationale; however, outcomes are strongly governed by lithotype variability, alteration degree, and mixture design (Fig. 4A) (Dąbrowski et al. 2022, Jain et al. 2023).

Shielding concretes provide one of the most application-specific demonstrations. Serpentine aggregate can enhance neutron attenuation because of its hydrogen-bearing mineralogy, yet microstructural observations indicate that durability may be sensitive to how serpentine interacts with the cement paste at the aggregate surface (Dąbrowski et al. 2022). This behavior aligns with established interfacial transition zone (ITZ) concepts: local packing density, bleeding/water redistribution, and porosity gradients near the aggregate can produce a more porous contact zone unless countered through mixture optimization (Scrivener et al. 2004, Stroeve 2022). Consequently, serpentine aggregate is best framed as a candidate for specialized concretes (e.g., shielding and potentially certain high-temperature service scenarios) where its mineralogical functionality is valuable, provided that durability-oriented qualification and targeted mix-design measures (grading control, paste quality, and transport-property management) are implemented to limit ITZ-related permeability vulnerabilities (Fig. 4A) (Dąbrowski et al. 2022, Jain et al. 2023).

For filler-type or waste-derived incorporation, the evidence base is smaller than for aggregate use, but it remains technically promising within a waste-valorization logic. Serpentine/serpentine residues are repeatedly discussed within broader substitution strategies for construction materials, contingent on mineralogical screening and safety constraints (Fig. 4A; Table 2) (Jain et al. 2023). In parallel, immobilization-oriented construction studies illustrate that serpentine-rich extraction wastes can be converted into stable ceramic construction products rather than remaining long-term disposal burdens, supporting the general feasibility of serpentine-bearing residues as construction feedstocks when properly engineered (Mymrin et al. 2020).

Thermal activation and production of reactive magnesium–silicate phases

Thermal activation is the step that most clearly shifts serpentine from a largely inert geological material to a reactive precursor suitable for Mg-based construction chemistries (Fig. 4A; Table 2). Controlled heating removes structurally bound hydroxyls, destabilizes the layered structure, and generates disordered or metastable Mg–Si phases (often grouped under “metaserpentine”), which typically show much higher chemical reactivity

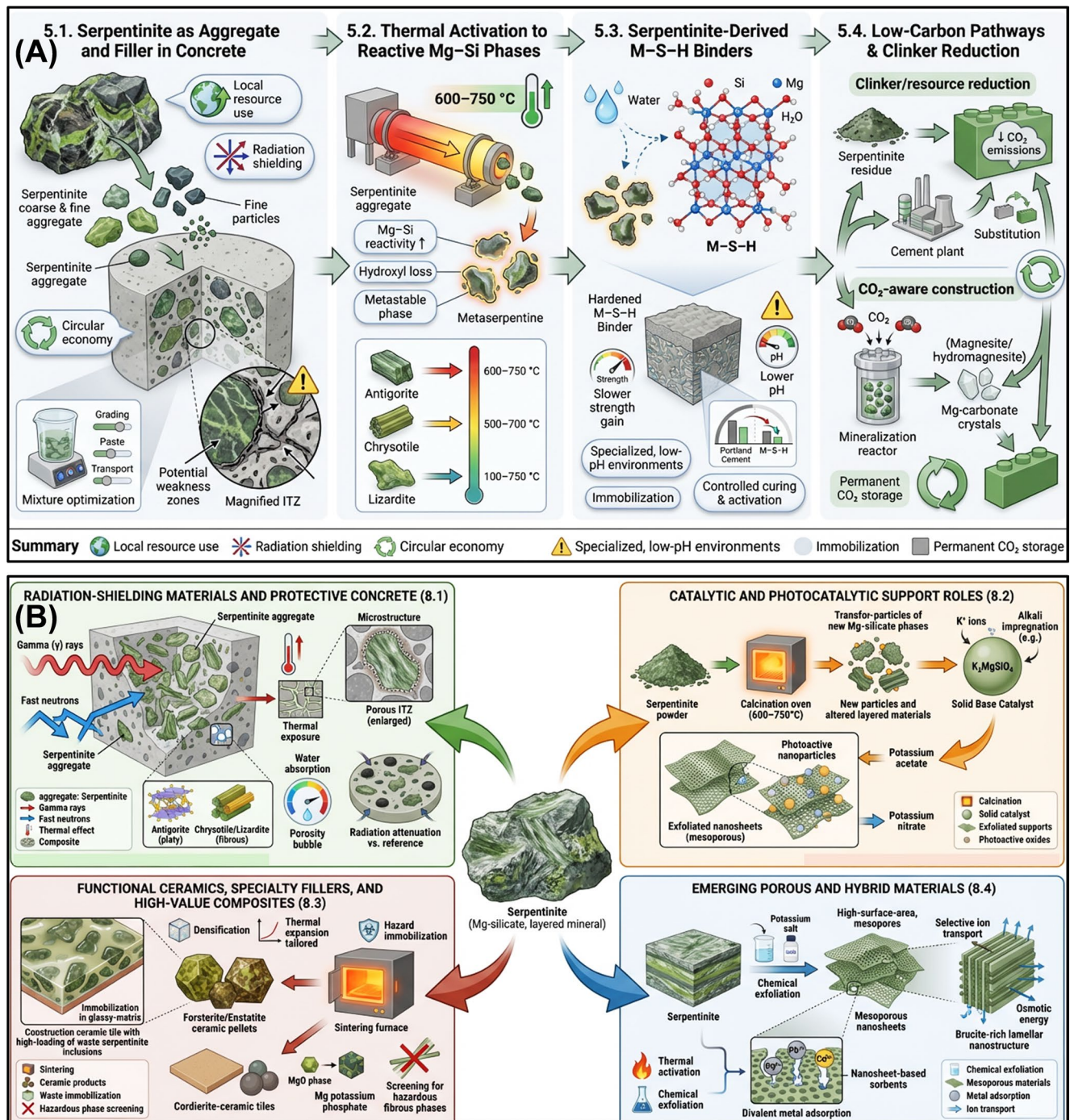


Fig. 4 Applications and valorization pathways of serpentine. **A** Use in construction and low-carbon binder systems, including aggregates and fillers in concrete, thermally activated Mg-Si phases, M-S-H binders, and carbonation-based CO₂-aware construction. **B** Advanced

functional applications, including radiation-shielding materials, catalytic and photocatalytic supports, functional ceramics and composites, and engineered porous or hybrid materials

than the parent serpentine minerals (Fig. 4A) (Ivanova et al. 2022, Długogorski and Balucan 2014). Activation responses are highly dependent on the temperature window and the downstream chemical route. Thermo-acid studies report pronounced increases in Mg extraction efficiency and acid reactivity after heating within

approximately 600–750 °C, with strong enhancement commonly observed toward the upper end of this range. Complementary activation studies likewise identify temperature conditions around ~700–750 °C as particularly effective for improving performance prior to acid-based extraction workflows (Auyeshov et al. 2024a, 2024b).

Polymorph identity introduces an additional control. Binder-oriented experiments indicate that antigorite-, chrysotile-, and lizardite-rich serpentines do not reach maximal “chemical activity” at the same temperature, reinforcing the need to tailor activation protocols to mineralogy and to avoid over-firing that promotes extensive recrystallization toward forsterite/enstatite, which may reduce reactive accessibility depending on the intended application (Fig. 4A) (Ivanova et al. 2022, Dlugogorski and Balucan 2014). For low-carbon construction concepts, this implies that calcined serpentinite should not be treated merely as an inert filler: under optimized activation, it can supply reactive Mg–Si species that participate in hydration/neutralization reactions and can further harden through carbonation under CO₂ exposure.

Serpentinite-derived binders and M–S–H cement systems

A direct binder pathway from activated serpentinite involves formation of magnesium–silicate hydrate (M–S–H), a member of low-pH Mg-based binder families (Fig. 4A; Table 2). Controlled hydration of thermally treated serpentine-group minerals has been shown to yield magnesium silicate binding phases, with performance governed strongly by precursor structure, degree of activation, and the resulting balance between reactive Mg and silicate species (Fig. 4A) (Ivanova et al. 2022). Broader syntheses of M–S–H binders emphasize that mechanical development, microstructural densification, and durability are controlled by variables including Mg/Si ratio, precursor reactivity, alkalinity and carbonate chemistry, and curing regime (Fig. 4A). These reviews position M–S–H as a credible low-carbon binder family, while also noting that kinetics and strength evolution can differ substantially from Portland cement systems (Bernard 2022, Sreenivasan et al. 2024). Low-pH M–S–H formulations are also discussed for chemically demanding or immobilization-related contexts where low alkalinity and chemical stability are advantageous, supporting niche adoption rather than direct one-to-one replacement of ordinary Portland cement in all structural settings (Marsiske et al. 2023). Accordingly, serpentinite-derived M–S–H systems are best presented as feasible but application-specific binders: they offer value in Mg-rich and low-pH environments and in specialized construction/immobilization uses, but generally require careful control of activation level, water demand, and curing conditions to achieve robust performance (Ivanova et al. 2022, Sreenivasan et al. 2024).

Opportunities for clinker reduction and CO₂-aware construction

Serpentinite’s low-carbon relevance in construction can be framed through two complementary strategies (Fig. 4A).

- (i) Clinker and virgin-resource reduction via substitution and residue valorization. Where quality and safety constraints are satisfied, serpentinite and serpentine-rich residues can contribute to circular construction schemes by partially substituting conventional aggregates and/or supporting alternative construction solids, thereby reducing demand for virgin raw materials and, in some cases, lowering embodied impacts associated with primary extraction (Fig. 4A) (Mymrin et al. 2020, Jain et al. 2023).
- (ii) CO₂-aware construction via Mg-silicate carbonation. Independent of conventional concrete mixing, activated serpentinite residues can mineralize CO₂ under aqueous, flue-gas-relevant conditions to form Mg-carbonate products, demonstrating a route in which serpentinite-derived solids act as reactive CO₂ sinks and potential precursors for carbonation-cured or mineralized construction products (Fig. 4A) (Pasquier et al. 2014). Carbonation analogues further show that serpentinite can display substantial reactivity under controlled conditions, with reaction progress commonly localized on exposed surfaces and along fracture networks—features that are conceptually aligned with carbonation-cured material design (Lacinska et al. 2017).

Overall, the validated evidence supports a balanced interpretation: serpentinite offers credible opportunities for substitution-driven clinker reduction, Mg–Si binder development, waste valorization, and carbonation-linked construction concepts (Fig. 4A). At the same time, constraints remain—such as ITZ porosity and transport sensitivity in concretes, activation-window dependence, and typically slower strength evolution in Mg–Si systems relative to Portland cement. For these reasons, serpentinite is best positioned as a strategic geomaterial for targeted low-carbon binders, clinker-reduction schemes, CO₂-reactive products, and circular construction routes, rather than as a universal replacement for Portland cement (Ivanova et al. 2022, Dąbrowski et al. 2022, Jain et al. 2023, Sreenivasan et al. 2024).

Serpentinite in advanced functional applications

Radiation-shielding materials and protective concrete

One of the most mature “functional” uses of serpentinite is in radiation-shielding materials, particularly protective concretes and shielding blocks, and more recently in radiation-attenuation ceramic bodies (Fig. 4B; Table 2). The continued

interest stems from a useful combination of properties: moderate bulk density, the presence of structurally/chemically bound water (as hydroxyls), and Mg-silicate mineralogy. Together, these attributes can improve fast-neutron attenuation and, when coupled with high-Z constituents, support photon shielding performance as well (Fig. 4B) (Dąbrowski et al. 2022, Wu et al. 2025, Jain et al. 2023).

Performance is strongly controlled by the mineralogical class and fabric of the serpentinite aggregate. Dąbrowski et al. (Dąbrowski et al. 2022) emphasized that serpentinite-based concretes exhibit wide variability in both attenuation and mechanical behavior, reflecting differences in polymorph assemblage (e.g., antigorite-rich versus lizardite/chrysotile-rich) and in aggregate quality metrics such as water absorption, porosity, and crushing/impact indices (Fig. 4B). Their work also highlighted a recurring durability challenge: serpentinite aggregates may produce a wider and more porous aggregate–paste contact zone, increasing transport sensitivity (including chloride migration and carbonation) unless mixture design is deliberately optimized (Dąbrowski et al. 2022).

Thermal performance further reinforces the need for service-condition qualification. In magnetite–serpentine radiation-proof concretes, elevated-temperature exposure can affect mass loss, ultrasonic pulse velocity, mechanical properties, and shielding performance, indicating that both hydrous-phase stability and temperature-driven changes in the cementitious matrix may influence long-term functionality (Fig. 4B) (Wu et al. 2025). Consistent with this, the broader synthesis by Jain et al. (Jain et al. 2023) frames serpentinite/serpentine as a frequent candidate aggregate group for biological shielding, while underscoring that outcomes depend on replacement level, curing/exposure regime, and durability-critical transport properties (Jain et al. 2023).

Beyond cementitious systems, serpentinite-containing ceramics also show potential. Oto et al. (2024) reported that magnetite- and serpentine-doped ceramic bodies can exhibit enhanced gamma and fast-neutron attenuation relative to undoped references, supporting the view that serpentinite-derived phases can contribute to shielding in fired materials where microstructure and additive synergy are engineered (Fig. 4B) (Oto et al. 2024). Overall, the literature supports serpentinite as a credible functional component in protective construction, provided that aggregate mineralogy, porosity/ITZ development, and temperature-dependent stability are treated as first-order design constraints (Dąbrowski et al. 2022, Wu et al. 2025, Jain et al. 2023, Oto et al. 2024).

Catalytic and photocatalytic support roles

Serpentinite is being explored as a low-cost precursor or support for selected catalytic systems because it is abundant,

Mg-rich, and can be substantially modified by heat treatment and chemical activation (Fig. 4B; Table 2). In its natural state, however, serpentinite should not be regarded as a high-activity catalyst. Its catalytic relevance depends mainly on processing steps that alter phase assemblage, surface hydroxyl chemistry, defect density, and acid–base character. A representative example is the preparation of a K_2MgSiO_4 -bearing solid-base catalyst from serpentinite through calcination followed by alkali impregnation, which was successfully applied in transesterification reactions relevant to biodiesel production (Fig. 4B) (Ballotin et al. 2016). This demonstrates that serpentinite can serve as a precursor for engineered catalytic solids when its Mg–silicate framework is chemically transformed and functionalized.

The mechanistic basis for this behavior is consistent with activation studies showing that calcination in the approximately 600–750 °C range disrupts the layered serpentine structure, modifies defect chemistry and surface functionality, and promotes formation of more reactive Mg–silicate phases. At higher temperatures, recrystallization toward forsterite-related products may also occur, meaning that the activation window must be selected according to the intended catalytic or support function (Auyeshov et al. 2024a, 2024b). These transformations can increase basicity, expose reactive surface sites, and provide a stable mineral-derived host for catalytically active species. Therefore, serpentinite is most appropriately described as a process-dependent catalytic precursor rather than as an intrinsically active catalyst.

For photocatalytic applications, the evidence base remains more limited than for adsorption, ceramics, or mineral carbonation. The available serpentinite-specific evidence mainly supports its role as a surface-engineered support material rather than as a standalone photocatalyst. Intercalation and exfoliation can transform serpentinite into mesoporous nanosheets with increased surface area, accessible hydroxylated sites, and improved surface reactivity—properties that are potentially useful for dispersing, anchoring, or stabilizing photoactive oxides and hybrid catalytic components (Fig. 4B) (Diab et al. 2025b). Comparative modification routes further show that potassium acetate produces stronger mesoporosity and higher accessible site density than potassium nitrate, confirming that surface development is highly processing-sensitive (Diab et al. 2025b).

Accordingly, serpentinite-derived catalytic and photocatalytic materials should be classified as an emerging, activation-dependent pathway. The strongest evidence currently supports serpentinite as a precursor for solid-base catalysts and as a mineral support or scaffold for hybrid catalytic systems after appropriate thermal or chemical modification. Further studies are still needed to verify photocatalytic

performance, long-term stability, regeneration behavior, and scalability under realistic operating conditions. Thus, serpentinite is best positioned as an emerging support/precursor platform for catalytic and photocatalytic composites, rather than as an established standalone catalyst family.

Functional ceramics, specialty fillers, and high-value composites

A well-established route for upgrading serpentinite into higher-value products is its conversion into functional ceramics and composites, particularly through forsterite–enstatite and cordierite-related processing strategies (Fig. 4B; Table 2). For magnesia–silicate ceramics and ceramic proppants, sintering challenges are often linked to difficult-to-densify forsterite; however, silica additions can promote enstatite formation and improve densification and strength, enabling more advanced products from serpentinite-based feedstocks (Vakalova et al. 2022). Serpentinite also participates effectively in cordieritic and specialty ceramic bodies. Mixtures incorporating serpentinite/olivine can be formulated to tailor density, porosity, mechanical performance, and thermal expansion behavior, supporting diversified ceramic design beyond classical refractories (Thomaidis and Kostakis 2015). Resource-valorization syntheses further identify serpentinite wastes as promising ceramic precursors and specialty fillers where phase evolution is carefully controlled through firing protocols and additives, while simultaneously emphasizing the necessity of strict screening where fibrous phases could occur (Cavallo 2018, Kalaitzidou et al. 2022).

Serpentinite-derived magnesium phases additionally support chemically specialized composite systems. MgO produced from serpentinite has been used as a component in magnesium potassium phosphate matrices for immobilization applications, demonstrating a pathway from Mg-silicate rock to functional Mg-based composite chemistries (Fig. 4B) (Kulikova et al. 2020). High-loading incorporation of serpentine extraction wastes into construction ceramics also illustrates a circular route in which potentially hazardous residues are converted into engineered solids through high-temperature immobilization and glassy-matrix development (Mymrin et al. 2020).

Emerging roles in engineered porous and hybrid materials

An emerging direction is the use of serpentinite as a precursor for engineered porous and hybrid materials after exfoliation, nanoscale restructuring, and surface functionalization (Fig. 4B). In this context, serpentinite is not treated as a ready-made advanced material, but as

a layered Mg-silicate starting material whose porosity, accessible surface area, and reactive-site density can be improved through controlled processing. The strongest direct evidence for this concept comes from intercalation-assisted exfoliation using potassium salts, which produces mesoporous nanosheets with increased surface accessibility and greater exposure of hydroxyl-bearing functional sites. This microstructural opening significantly enhances adsorption performance toward divalent heavy metals, demonstrating that porosity engineering can convert serpentinite into a more reactive sorbent platform under laboratory conditions (Diab et al. 2025b). However, the extension of serpentinite-derived porous materials beyond adsorption into broader hybrid or multifunctional systems should be considered at an early stage. The available evidence supports the feasibility of producing reactive, high-surface-area Mg-silicate nanosheets, but additional studies are still required to verify their long-term stability, regeneration behavior, scalability, and performance in continuous-flow or real wastewater systems (Diab et al. 2025b). Therefore, serpentinite-derived porous materials are best described as laboratory-promising engineered sorbents and precursor platforms, rather than mature multifunctional materials.

The broader relevance of serpentinite-associated Mg systems to porous functionality is also supported by observations from serpentinite-hosted hydrothermal environments. Lee et al. (Lee et al. 2024) reported brucite-rich lamellar precipitates with aligned nanocrystals and porous architectures capable of selective ion transport and osmotic energy conversion. These findings show that serpentinitization-related Mg hydroxide systems can naturally generate ordered, transport-active nanostructures (Fig. 4B) (Lee et al. 2024). Nevertheless, this example should be interpreted as a geomimetic analogue rather than direct evidence that bulk serpentinite itself functions as an osmotic-energy or membrane material. Its main value is conceptual: it demonstrates that Mg-hydroxide architectures associated with serpentinitization can inspire the design of synthetic ion-selective or membrane-like materials. Taken together, chemical exfoliation and thermal activation demonstrate that serpentinite can be transformed into porous, reactive, and potentially hybridizable Mg-silicate materials when appropriately processed (Diab et al. 2025b, Auyeshov et al. 2024a, 2024b). At present, the most defensible application pathway is the development of nanosheet-based sorbents and mineral-derived supports for hybrid composites. Broader roles in membrane-like, ion-selective, or energy-relevant materials remain emerging and require targeted synthesis, performance validation, durability testing, and scale-up assessment before they can be considered technologically mature.

Metallurgy and industrial chemistry

Serpentine has a long-standing industrial role that extends well beyond construction and remediation, particularly in high-temperature metallurgy and the production of magnesium chemicals (Fig. 5; Table 3). The industrial rationale is clear: serpentinite is an abundant Mg–Si lithology that can enter high-temperature value chains as a bulk crushed-rock commodity (including flux-related uses) and can also be chemically upgraded—typically after activation and leaching—into MgO, Mg(OH)₂, and dissolved Mg salts, while generating silica-rich co-products (Fig. 5). Whether these pathways are technically and economically viable depends strongly on mineralogical state (polymorph assemblage and brucite abundance), activation conditions, and the effectiveness of impurity management across the process chain (Fedoročková et al. 2012, Cheng et al. 2002, Dlugogorski and Balucan 2014, Auyeshov et al. 2025, Auyeshov et al. 2024a, 2024b).

7.1. Flux in ironmaking/steelmaking and related high-temperature processes

A traditional metallurgical entry point for serpentinite is its use as a flux or flux-related crushed-rock input in high-temperature processing (Fig. 5; Table 3). Cheng et al. (Cheng et al. 2002) provided a clear industrial example, documenting large-scale production of crushed serpentinite rock supplied mainly as a flux material for ironmaking, operating alongside a separate dimension-stone stream that targeted building-decoration markets (Cheng et al. 2002). This demonstrates that serpentinite can serve as a commercial crushed-rock commodity in metallurgical value chains

where local availability and process compatibility justify its use. From a process perspective, flux suitability is controlled by bulk composition and by thermal behavior during heating (Fig. 5). Hydrous Mg-silicate phases dehydroxylate and undergo phase transformation, so variability in serpentine polymorph assemblage, brucite content, and accessory minerals can influence devolatilization, dusting tendency, and phase evolution during furnace feeding. For this reason, thermochemical and phase-evolution insights developed in serpentine activation research remain directly relevant even when Mg extraction is not the objective, because they inform how serpentinite behaves during rapid heating and high-temperature handling (Dlugogorski and Balucan 2014, Auyeshov et al. 2024a, 2024b).

Magnesium chemicals production via thermal activation and leaching

A major industrial-chemistry route treats serpentinite as a feedstock for magnesium chemicals, including Mg(OH)₂ and MgO, as well as soluble Mg salts such as MgCl₂ and MgSO₄ (Fig. 5; Table 3). In practice, these flowsheets commonly combine thermal activation—used to destabilize the serpentine structure and increase Mg accessibility—with acid leaching and downstream precipitation and purification steps (Fig. 5). The mechanistic basis is well established: activation increases defect density, disrupts the layered lattice, and enhances Mg dissolution kinetics during acid attack (Fedoročková et al. 2012, Dlugogorski and Balucan 2014, Auyeshov et al. 2024a, 2024b).

Thermal activation must be treated as a windowed process rather than a generic “calcination” step. Synthesis and

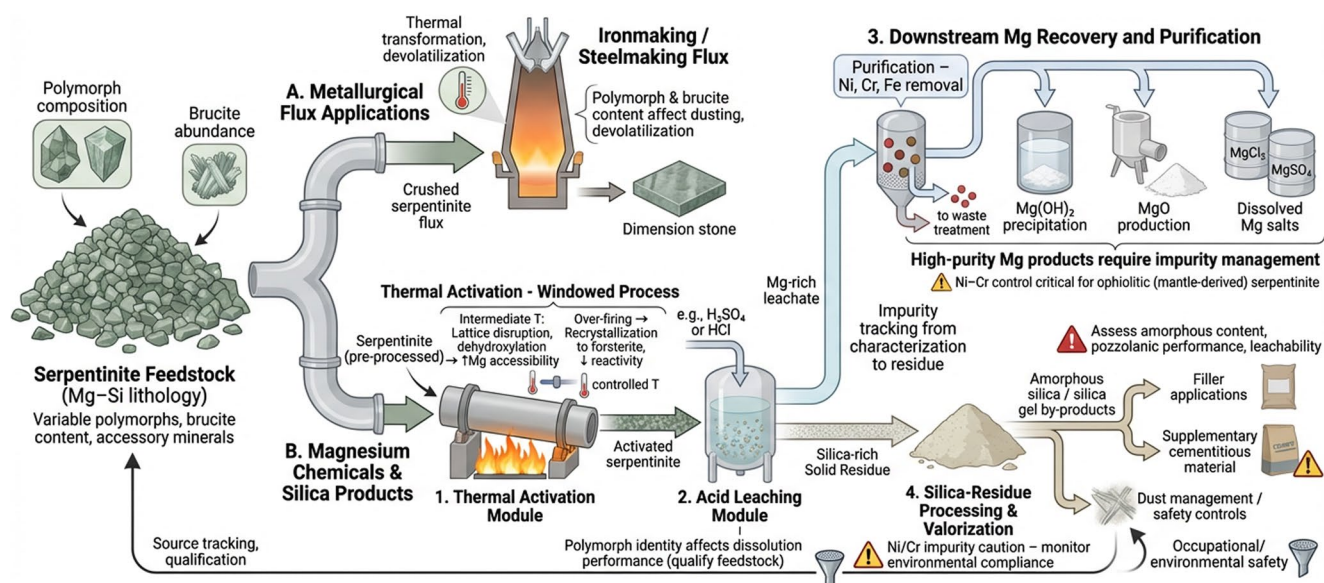


Fig. 5 Industrial processing pathways of serpentinite, illustrating its use as a metallurgical flux and as a feedstock for magnesium chemicals through thermal activation, acid leaching, downstream purification, and valorization of silica-rich residues into industrial by-products

Table 3 Representative quantitative indicators for serpentinite in metallurgy, Mg-chemical production, enhanced weathering, and agricultural land systems

Application domain	Process/system	Representative quantitative values	Performance meaning	Ref.,
High-temperature metallurgical use	Serpentinite as flux-related crushed rock and furnace feedstock	Brucite decomposition: 350–450 °C; serpentine dehydroxylation/lattice destruction: 600–725 °C; structural transformation completed around 750–800 °C; mass loss at 750–800 °C: 13.34–13.92 wt%	Quantifies why serpentinite behavior in high-temperature systems depends on volatile release, polymorph assemblage, and phase transformation.	(Cheng et al. 2002, Dlugogorski and Balucan 2014, Auyeshov et al. 2024a, 2024b)
Thermal activation before Mg extraction	Zhitikarinsky serpentinite activated at 105–800 °C and dissolved in 1.0 M H ₂ SO ₄ at 80 °C	Mg conversion to sulfate solution: 40.0% at 105 °C, 46.6% at 600 °C, 72.9% at 660 °C, 82.3% at 725 °C, 86.3% at 750 °C, and 81.16% at 800 °C	Demonstrates that Mg accessibility increases strongly after activation, with optimal performance near 725–750 °C, while over-heating can reduce reactivity.	(Fedoročková et al. 2012, Dlugogorski and Balucan 2014, Auyeshov et al. 2024a, 2024b)
Polymorph-controlled Mg leaching	Serpentinities dominated by chrysotile/lizardite or antigorite; 100–200 µm particles; 8–10% HCl at 95 °C	Mg extraction up to ~97% for chrysotile–lizardite serpentinites after 30 min quiescence; antigorite-rich samples generally < 70%	Confirms that Mg recovery depends on serpentine polymorph identity and not only on bulk MgO content.	(Beglaryan et al. 2023)
MgSO ₄ production from serpentinite waste	Sulfuric-acid leaching of powdered serpentinite processing waste	168.65 g MgSO ₄ from 100 g waste after 30 min, approximately 70% of theoretical yield; little increase between 30 and 180 min	Supports Mg-salt recovery, while showing that prolonged leaching may not always improve yield significantly.	(Auyeshov et al. 2025)
High-purity Mg(OH) ₂ production	H ₂ SO ₄ leaching, purification with thermally activated serpentinite at 750 °C for 1 h, followed by NaOH precipitation	Mg(OH) ₂ purity ≥ 99.5%; preliminary production estimate about USD 495 t ⁻¹ Mg(OH) ₂	Demonstrates a technically promising Mg-chemical route, but still requiring scale-up, impurity control, and full techno-economic validation.	(Auyeshov et al. 2025)
Silica-rich residue valorization	Residues after serpentinite acid leaching and Mg recovery	Insoluble residue after leaching contains approximately 34.53–36.45 wt% Si and residual Mg decreasing from 3.31 to 2.39 wt% across 30–180 min tests	Shows potential for silica-rich co-products, but qualification must include amorphous content, fineness, pozzolanic behavior, and trace-metal leachability.	(Auyeshov et al. 2025, El-Sayed et al. 2023, Auyeshov et al. 2024a, 2024b)
ERW temperature sensitivity	Olivine soil-column analogue for Mg-silicate weathering	Weathering rate higher at 32 °C than at 19 °C and 4 °C; estimated CO ₂ capture at 32 °C about 115 t CO ₂ km ⁻² yr ⁻¹ at an amendment rate of 12.7 kg m ⁻²	Supports cautious extrapolation to serpentinite: soil temperature, hydrology, and cation retention strongly control real ERW performance.	(Hartmann et al. 2013, Beerling et al. 2020, Renforth et al. 2015, Iff et al. 2024)
ERW comminution-energy constraint	Fine grinding of olivine for soil weathering analogue	Grinding to ≤ 1 µm may require approximately 1.5 GJ t ⁻¹ electrical energy to enable dissolution over 1–5 years	Highlights why serpentinite ERW must include particle-size optimization and life-cycle energy accounting.	(Beerling et al. 2020, Renforth et al. 2015)
Mg-silicate amendment and trace-metal risk	Olivine pot experiment as cautionary analogue for ultramafic amendments	Olivine doses: 1,630–204,000 kg ha ⁻¹ ; highest dose increased plant growth by 15.6% and plant K by 16.5%; Mg and Ni bioavailability and plant uptake increased at all doses	Demonstrates the dual benefit–risk pattern relevant to serpentinite: Mg release and plant response may occur together with Ni mobilization.	(Levy et al. 2024, Dupla et al. 2023, Suhrhoff 2022, Ten et al. 2012)
Direct serpentinite agronomic testing	Greenhouse evaluation of serpentinite as soil remineralizer/Mg fertilizer	Experimental design: 7 treatments, 4 replications, 2 crops — corn and common bean — and 2 contrasting soils	Provides direct controlled evidence for serpentinite as a Mg source, but not universal proof of field-scale agronomic suitability.	(Viana et al. 2021, Viana et al. 2024)
Oil palm Mg fertilization	Ground serpentinite/serpentinite rock compared with ground magnesium limestone	Reported MgO content: ground serpentinite 29.20 wt%, ground magnesium limestone 18.2 wt%; digestion tests used 5 mL HNO ₃ + 10 mL HCl for 1–16 h	Supports serpentinite as a Mg-rich amendment source, while emphasizing dissolution-rate and management dependence.	(Mathews et al. 2022)

Table 3 (continued)

Application domain	Process/system	Representative quantitative values	Performance meaning	Ref.,
Deployment qualification for land use	Serpentinite ERW/Mg-fertilizer screening	Required monitored variables: particle size, Mg release, soil pH, alkalinity, crop Mg uptake, soil/plant Ni–Cr, leachate chemistry, and fibrous-mineral occurrence	Confirms that agricultural use should remain lithotype-specific, monitored, and risk-governed rather than broadly generalized.	(Swoboda et al. 2022, Levy et al. 2024, Dupla et al. 2023, Viana et al. 2021, Viana et al. 2024, Mathews et al. 2022, Dietzen et al. 2018, Suhrhoff 2022, Ten et al. 2012)

experimental evidence show that Mg extraction benefits from lattice disordering and dehydroxylation at intermediate temperatures, whereas excessive heating that drives extensive recrystallization toward stable high-temperature Mg-silicates such as forsterite-rich assemblages can reduce chemical reactivity for certain downstream extraction schemes (Fig. 5; Table 3) (Dlugogorski and Balucan 2014, Auyeshov et al. 2024a, 2024b). This yields a practical design rule for Mg-chemical production: the activation protocol should be selected to maximize Mg accessibility while avoiding over-firing unless the target product is itself a fired Mg-silicate ceramic.

Leaching response is also mineralogically sensitive. Fedoročková et al. (Fedoročková et al. 2012) demonstrated that calcination substantially increases Mg dissolution compared with untreated serpentine, confirming thermal activation as a core enabling step in Mg recovery routes (Fig. 5; Table 3) (Fedoročková et al. 2012). In addition, polymorph identity can significantly affect extraction performance; different dominant serpentine minerals can yield different dissolution behavior under comparable leaching conditions, indicating that feedstock qualification should be polymorph-resolved rather than treating serpentinite as a uniform source (Beglaryan et al. 2023).

In industrial settings, purification is often the decisive constraint for product-grade outputs, because dissolved liquors may carry Ni, Cr, Fe, and other impurities that must be controlled (Fig. 5). Auyeshov et al. (2025) demonstrated a route for producing high-purity Mg(OH)₂ from serpentinite that explicitly highlights impurity removal as a key step in achieving specification-compliant magnesium chemicals (Auyeshov et al. 2025). This constraint is particularly relevant for ophiolitic serpentinites that may exhibit elevated Ni–Cr signatures. For example, Sami et al. (Sami et al. 2026) reported Ni–Cr enrichment in depleted mantle-derived serpentinites from the UAE sector of the Semail Ophiolite, implying that impurity tracking must extend

from early characterization to leach-liquor purification and residue management (Sami et al. 2026). In parallel, stone-focused syntheses emphasize that serpentinite variability and trace-element burdens require careful screening when valorization pathways involve processing fines and residues (Punturo et al. 2023).

Silica products as by-products of serpentinite leaching

A characteristic feature of serpentinite leaching is that Mg extraction is coupled to the generation of silica-rich residues, commonly involving amorphous silica or silica gel-like products (Fig. 5; Table 3). This silica formation is not only a waste-management issue; if purity, particle size, and surface chemistry are controlled, silica-rich solids may become valuable co-products (Fig. 5). At the same time, silica precipitation can hinder Mg recovery by forming passivating layers or gel phases that restrict mass transfer and slow dissolution. Mechanistic studies indicate that silica formation is inherent to serpentine dissolution chemistry and therefore must be managed deliberately. Acid–structure interaction investigations describe transformation of silicate fragments toward amorphous silica during leaching and highlight diffusion and product-layer constraints consistent with passivation-controlled kinetics (Fig. 5) (Auyeshov et al. 2024a, 2024b). Thermal activation further modifies this behavior by disrupting the original lattice and altering dissolution–precipitation pathways during subsequent acid treatment, which can improve Mg liberation but also reshape silica-residue characteristics (Fedoročková et al. 2012, Auyeshov et al. 2024a, 2024b).

From a valorization standpoint, silica-rich residues may be evaluated as fillers and, only after rigorous testing, as potential supplementary cementitious candidates (Fig. 5; Table 3). Appropriate qualification should include assessment of amorphous content, fineness, pozzolanic

performance, and trace-element leachability. Because serpentinite commonly contains elevated Ni and Cr—particularly in depleted mantle-derived lithotypes—residue and silica-product qualification must include impurity accounting and environmental compliance as part of responsible deployment (Sami et al. 2026, Punturo et al. 2023). In addition, occupational and environmental safety considerations remain critical: where fibrous phases may be present, grinding and handling of serpentinite fines can increase elongated-particle release potential, requiring strict screening and dust-control measures across comminution and solids management (Marzini et al. 2024). Overall, serpentinite upgrading is most appropriately treated as a coupled Mg–Si process system. Routes with the strongest industrial logic are those that maximize recovery of Mg into high-value chemical products, convert silica-rich residues into saleable co-products or demonstrably inert solids, and maintain strict control of Ni–Cr burdens and fibrous-phase risks throughout the full process chain (Auyeshov et al. 2025, Marzini et al. 2024, Punturo et al. 2023).

Serpentinite in agriculture and land systems

Serpentinite, together with other ultramafic Mg-silicates, has potential relevance to agroecosystems through two linked but evidence-dependent functions: enhanced rock

weathering (ERW) as a pathway for alkalinity generation and possible CO₂ removal, and soil remineralization as a slow-release source of magnesium that may partially substitute conventional Mg fertilizers and, in acidic soils, provide a liming-like alkalinity benefit (Fig. 6; Table 3). However, these applications should be considered emerging and risk-sensitive rather than broadly established. Compared with many basaltic ERW feedstocks, serpentinite requires more stringent feedstock qualification because ultramafic lithologies can contain elevated Ni–Cr inventories and, depending on lithotype and deformation fabric, may include fibrous phases that impose handling, exposure, and regulatory constraints (Hartmann et al. 2013, Beerling et al. 2020, Swoboda et al. 2022, Levy et al. 2024, Dupla et al. 2023).

8.1. Enhanced rock weathering and soil alkalinity management

Enhanced rock weathering accelerates natural silicate dissolution by applying finely ground reactive rocks to soils. As dissolution proceeds, base cations such as Mg²⁺ are released and alkalinity is generated, which can be transported as dissolved inorganic carbon, predominantly bicarbonate, and/or stored in solid carbonate phases (Fig. 6; Table 3). When implemented with acceptable life-cycle emissions, this process can contribute to net atmospheric CO₂ removal (Hartmann et al. 2013, Beerling et al. 2020). For serpentinite,

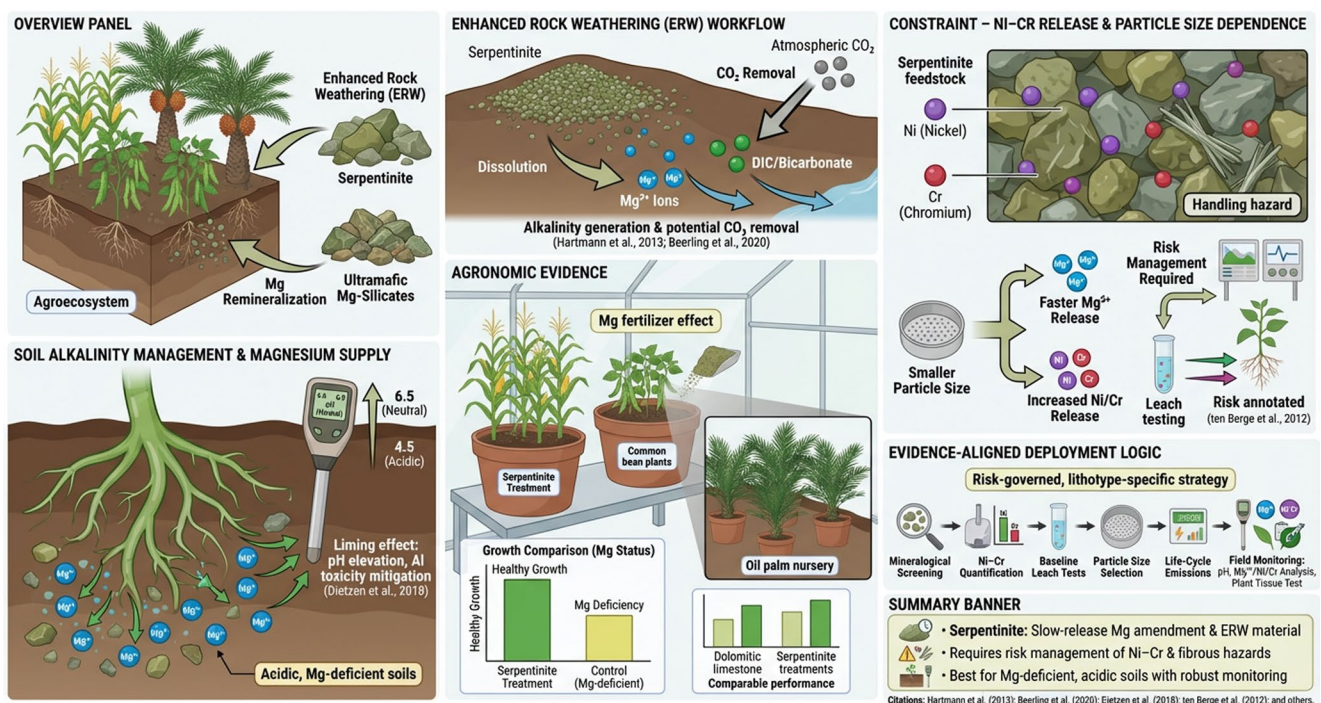


Fig. 6 Conceptual framework for serpentinite use in agriculture and land systems, illustrating enhanced rock weathering for CO₂ removal, soil alkalinity management and slow-release Mg fertilization, agro-

nomic performance evidence, and key constraints related to Ni–Cr release and particle-size-dependent risk requiring controlled, lithotype-specific deployment

however, ERW should be framed as a conditional opportunity rather than a mature field-scale technology. Much of the current ERW evidence base is derived from basalt, olivine, or broader silicate-rock systems, and these findings provide useful analogues but not direct proof of large-scale serpentinite performance. A recurring observation across ERW studies is that weathering rates under soil and field conditions are often substantially lower than laboratory kinetic estimates and are sensitive to temperature, hydrology, soil pH, soil–water chemistry, and biological activity (Fig. 6; Table 3). A soil-column study using olivine quantified dissolution behavior and demonstrated that grinding energy can, under certain assumptions, dominate net CO₂ removal accounting, emphasizing the need for integrated life-cycle evaluation alongside geochemical performance (Renforth et al. 2015). More recent soil-column work confirmed a strong temperature dependence of silicate dissolution, with higher dissolution rates at 32 °C than at 19 °C and 4 °C, while reiterating that field trials are essential for defining realistic performance bounds (Iff et al. 2024).

Although the same Mg-silicate weathering logic applies to serpentinite, its deployment requires additional environmental and occupational screening. Serpentinite powders may increase Ni and Cr fluxes during weathering, and certain lithotypes may host chrysotile or other elongated mineral particles that influence safe handling, dust management, and acceptable deployment design (Levy et al. 2024, Dupla et al. 2023). Therefore, serpentinite should not be treated as a generic ERW material. It is more appropriately considered a lithotype-specific Mg-silicate amendment whose CO₂-removal potential must be evaluated together with dissolution kinetics, comminution energy, trace-metal mobility, and exposure risk (Hartmann et al. 2013, Beerling et al. 2020, Swoboda et al. 2022, Levy et al. 2024, Dupla et al. 2023, Renforth et al. 2015, Iff et al. 2024).

Serpentinite as a slow-release Mg fertilizer and liming-substitute component

Magnesium is an essential plant macronutrient, central to chlorophyll formation and multiple enzymatic functions, and Mg deficiency is common in acidic, sandy, or highly weathered soils (Fig. 6; Table 3). In this context, silicate rock powders have been discussed as remineralizing amendments that can replenish base cations and support broader soil-function benefits (Swoboda et al. 2022). Within this framework, serpentinite has direct but still limited agronomic evidence as a Mg source. A greenhouse study reported that serpentinite met relevant legal compositional requirements in the tested context and supplied Mg adequate to support the growth of corn and common bean, with several performance indicators comparable to those of

dolomitic limestone treatments (Fig. 6) (Viana et al. 2021, Viana et al. 2024). In plantation nursery conditions, ground serpentinite has also been evaluated as a magnesium source for oil palm seedlings, where results indicated improved plant Mg status relative to no-Mg controls and responses comparable to alternative Mg amendments under the tested management regime (MATHEWS and KAWADING 2022).

These studies support the potential of serpentinite as a slow-release Mg amendment under controlled conditions, but they do not by themselves establish universal agronomic suitability. Agronomic performance depends on particle size and surface area, which control dissolution rate; soil pH and soil CO₂, which influence carbonate-system buffering and mineral dissolution; and hydrology, which determines whether alkalinity is retained in soil solution or exported (Fig. 6; Table 3). In acidic soils, Mg-silicate dissolution can provide a liming-like pH benefit. For olivine, incubation studies have shown pH elevation sufficient to mitigate Al toxicity, while also highlighting differences from agricultural lime in CO₂ emission behavior and carbonate-system responses (Dietzen et al. 2018). This soil-chemistry logic can be extended cautiously to Mg-silicates more broadly, while recognizing that serpentinite weathering kinetics, trace-metal inventories, and fibrous-phase risks are more variable and lithotype-dependent than those of many basaltic materials (Swoboda et al. 2022, Levy et al. 2024). Accordingly, serpentinite is best positioned as a potential Mg amendment for carefully selected Mg-deficient acidic soils, particularly where nutrient supply and pH correction are both desired. Its use should remain conditional on feedstock testing, trace-metal assessment, and crop/soil monitoring rather than being presented as a direct substitute for conventional Mg fertilizers or agricultural lime in all settings (Swoboda et al. 2022, Viana et al. 2021, Viana et al. 2024, MATHEWS and KAWADING 2022, Dietzen et al. 2018).

Critical constraint: Ni–Cr release and lithotype/particle-size dependence

The principal constraint for serpentinite in agricultural deployment is the potential mobilization of Ni and Cr, and locally Co, during weathering, especially when applied as fine powders (Fig. 6). Environmental assessments of ERW explicitly identify trace-metal release, monitoring, and mitigation as major determinants of acceptable deployment, particularly for ultramafic feedstocks and small particle sizes that accelerate dissolution (Fig. 6; Table 3) (Levy et al. 2024, Dupla et al. 2023, Suhrhoff 2022). Work on olivine amendments provides a relevant cautionary analogue. Pot experiments showed that while olivine can increase

bioavailable Mg, it may also increase bioavailable Ni and plant Ni uptake (Ten Berge et al. 2012).

The implication for serpentinite is practically important: finer particle sizes that improve Mg release and alkalinity generation can simultaneously increase trace-metal fluxes. Therefore, serpentinite use is inherently feedstock-specific and particle-size-specific rather than a generic ERW or remineralization intervention (Levy et al. 2024, Dupla et al. 2023). This constraint is particularly important in food-chain contexts, where soil-to-plant transfer of Ni and Cr must be evaluated before any field-scale deployment. In addition, where serpentinite contains chrysotile or other elongated mineral particles, agricultural spreading may introduce dust and inhalation concerns that are not captured by soil geochemistry alone. Thus, safe use requires combined mineralogical, geochemical, agronomic, and exposure-risk assessment (Levy et al. 2024, Dupla et al. 2023, Suhrhoff 2022, Ten Berge et al. 2012).

Practical, evidence-aligned deployment logic

A technically defensible deployment strategy for serpentinite as an ERW amendment and Mg source must be explicitly risk-governed and lithotype-resolved. Feedstock qualification should include mineralogical screening, including assessment for fibrous phases where relevant; quantification of total and potentially bioavailable Ni–Cr; and baseline leach testing aligned with established ERW monitoring and mitigation frameworks (Fig. 6; Table 3) (Swoboda et al. 2022, Levy et al. 2024, Dupla et al. 2023). Dose and particle-size design should avoid unnecessarily fine powders unless field response data justify the trade-off. Deployment studies should quantify Mg delivery, soil pH response, alkalinity generation, trace-metal mobilization, crop uptake, and net CDR performance, while also accounting for life-cycle emissions and comminution energy, consistent with evidence that grinding energy can materially affect net benefit (Beerling et al. 2020, Renforth et al. 2015).

Field monitoring, reporting, and verification should track soil pH, exchangeable Mg, crop response, and Ni/Cr concentrations in soil, drainage water, and plant tissues during trials, reflecting both the agronomic evidence base and the environmental emphasis on trace-metal control (Fig. 6; Table 3) (Levy et al. 2024, Viana et al. 2021). The most defensible near-term use cases are Mg-deficient acidic soils where both nutrient supply and liming-like benefits are valuable. Sensitive food-chain contexts should be avoided unless robust field evidence demonstrates acceptably low metal transfer and exposure risk under local soil, crop, and climatic conditions (Dupla et al. 2023, Dietzen et al. 2018). In summary, serpentinite can support agricultural applications as a slow-release Mg amendment and as a possible ERW

material contributing to alkalinity generation and potential CO₂ removal. However, these uses should be treated as lithotype-specific, monitored, and risk-governed pathways, not as mature or universally deployable agricultural technologies. Responsible deployment must explicitly manage Ni–Cr mobility, particle-size effects, life-cycle emissions, and, where relevant, fibrous-mineral hazards (Fig. 6) (Swoboda et al. 2022, Levy et al. 2024, Dupla et al. 2023).

Serpentinite in carbon capture, utilization, and storage

Fundamentals of serpentinite carbonation

Carbonation of serpentinite involves the reaction of Mg-bearing serpentine minerals with CO₂ to produce stable magnesium carbonate phases together with silica-rich products. Because the carbon becomes incorporated into solid carbonate minerals, serpentinite is widely considered an attractive feedstock for permanent geological CO₂ storage rather than temporary sequestration (Fig. 7; Table 4). This principle has been consistently emphasized in both early and contemporary studies of mineral carbonation targeting Mg-silicate minerals such as serpentines and olivines (Lacinska et al. 2017, Maroto-Valer et al. 2005, Olajire 2013, Nisbet et al. 2024).

A critical control on carbonation efficiency is not the total MgO content alone, but the availability of reactive Mg²⁺ released from the silicate lattice. In serpentinite, this depends on several mineralogical and structural factors including serpentine polymorph type, degree of structural disorder, abundance of brucite, accessibility of reactive surfaces, and the effectiveness of fluid–rock interaction (Fig. 7; Table 4). Experimental investigations of Oman–UAE ophiolitic ultramafics show that carbonation commonly occurs preferentially along external surfaces and fracture networks, highlighting the combined influence of mineralogy, texture, and permeability architecture on reaction progress (Lacinska et al. 2017). Mechanistic analyses further demonstrate that carbonation kinetics are governed by dissolution rates and by the morphology of secondary carbonate precipitates, which may either maintain reactive pathways or progressively restrict them through passivation and pore clogging (Dlugogorski and Balucan 2014, Nisbet et al. 2024, Neil et al. 2024). Thermodynamically, serpentinite carbonation is favorable because Mg-carbonate minerals such as magnesite and hydrated Mg-carbonates are stable over geological timescales. Consequently, once the reaction proceeds sufficiently, mineral trapping provides a robust mechanism for long-term CO₂ storage (Farough and Karrasch 2019, Olajire 2013).

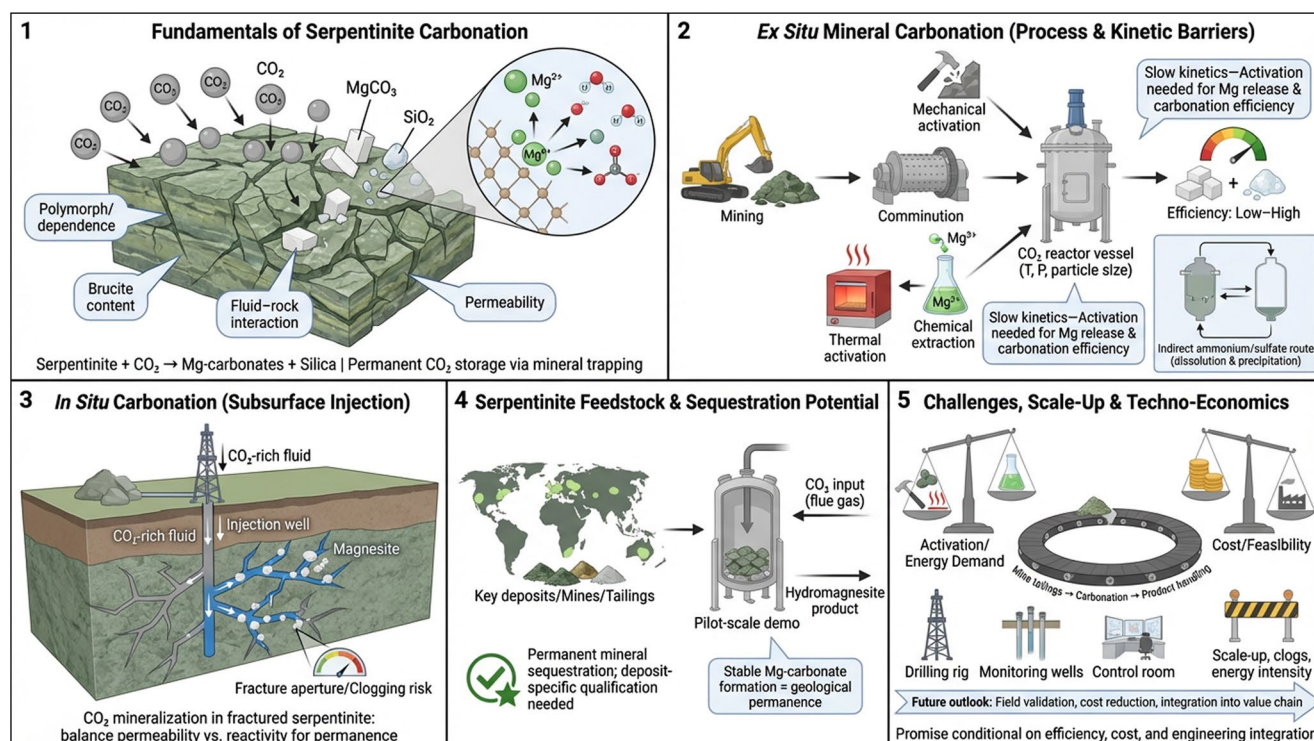


Fig. 7 Conceptual overview of serpentine carbonation pathways for CO₂ sequestration, showing (1) mineralogical controls on carbonation reactions, (2) ex situ mineral carbonation processes and kinetic barriers,

(3) in situ carbonation through subsurface CO₂ injection in fractured ultramafic rocks, (4) global serpentine resources and sequestration potential, and (5) scale-up, energy, and techno-economic constraints

Ex situ mineral carbonation: kinetics, activation, and process intensification

In ex situ mineral carbonation, serpentine is mined or collected, mechanically processed, and reacted with CO₂ under controlled conditions (Fig. 7; Table 4). This approach enables optimization of particle size, temperature, pressure, fluid composition, and reaction time. However, a central challenge is that natural carbonation of serpentine minerals is intrinsically slow because magnesium is strongly bound within the layered crystal structure and because silica-rich reaction products may form passivating barriers that inhibit further dissolution (Fig. 7) (Pasquier et al. 2014, Dlugogorski and Balucan 2014, Maroto-Valer et al. 2005, Olajire 2013). To overcome these kinetic limitations, several process-intensification strategies have been developed. These include mechanical activation to increase surface area and defect density, thermal activation to induce controlled dehydroxylation and structural disorder (forming more reactive “metaserpentine”), and indirect chemical routes in which magnesium is first extracted into solution prior to carbonate precipitation (Dlugogorski and Balucan 2014, Olajire 2013).

For serpentine residues, heat pretreatment has been shown to substantially enhance aqueous carbonation performance under flue-gas-relevant conditions, demonstrating

that activation represents a key lever for improving conversion efficiency (Fig. 7; Table 4) (Pasquier et al. 2014). Indirect carbonation approaches using recyclable ammonium salts or sulfate-assisted extraction separate magnesium dissolution from carbonate precipitation, thereby mitigating kinetic constraints, although they introduce additional complexity related to reagent management and process integration (Farough and Karrasch 2019, Wang et al. 2024). Overall, the literature consistently indicates that ex situ serpentine carbonation is technically feasible, but that successful implementation depends on appropriate pretreatment and optimized reaction engineering to overcome intrinsic kinetic barriers (Fig. 7) (Pasquier et al. 2014, Wang et al. 2024, Dlugogorski and Balucan 2014).

In situ carbonation in fractured ultramafic formations

In situ carbonation involves the injection of CO₂-bearing fluids directly into reactive mafic or ultramafic formations, where dissolution of Mg-bearing host minerals and precipitation of carbonate phases occur within the subsurface (Fig. 7; Table 4). For serpentine-bearing systems, the key controls are fracture permeability, connected fluid pathways, reactive surface availability, mineral dissolution rates, carbonate precipitation geometry, and the evolution

Table 4 Representative quantitative indicators for serpentinite carbonation and permanent CO₂ sequestration pathways

Carbonation pathway/control	Representative system	Quantitative indicators	Performance meaning	Ref.
Theoretical carbonation capacity	Ideal serpentinite, Mg ₃ Si ₂ O ₅ (OH) ₄	Theoretical CO ₂ capacity: 0.476 g CO ₂ g ⁻¹ serpentinite, equivalent to 476 kg CO ₂ t ⁻¹	Defines the upper stoichiometric limit; practical uptake is lower because of Mg accessibility, passivation, kinetics, and process losses.	(Steinthorsdottir 2025, Al Kalbani et al. 2024, Pasquier et al. 2014, Dlugogorski and Balucan 2014)
Pretreatment intensity for reactive carbonation	Activated Mg-rich serpentinite/serpentinite feedstocks	Reported pretreatment examples include grinding to <37 µm, heat treatment up to ~650 °C, and carbonation conditions up to 125 atm, 185 °C, and 6 h	Shows why activation improves reactivity but can impose major energy and cost penalties.	(Dlugogorski and Balucan 2014, Maroto-Valer et al. 2005)
Direct aqueous carbonation under flue-gas conditions	Heat-activated serpentinite mining residue	Finely ground, heat-activated serpentinite residue contacted with industrial flue gas in aqueous systems	Demonstrates technical feasibility of direct flue-gas mineralization, but performance depends on activation, Mg dissolution, gas–liquid transfer, and solids handling.	(Pasquier et al. 2014)
Pilot-scale aqueous carbonation	Serpentinite tailings in cement-plant flue gas	18.7 L reactor; flue gas 14–18 vol% CO ₂ ; solid/liquid ratio 150 g L ⁻¹ ; 22 ± 3 °C; 2–10 bar	Confirms movement beyond laboratory scale under industrial-gas conditions.	(Kemache et al. 2016)
Pilot-scale CO ₂ uptake and carbonate formation	Same serpentinite-tailings pilot process	CO ₂ dissolved: 72.5% with liquid recirculation vs. 77% with fresh liquid; captured CO ₂ : 0.215 g CO ₂ g ⁻¹ residue with recirculation and 0.211 g CO ₂ g ⁻¹ residue without recirculation; total capacity ≈ 0.47 g CO ₂ g ⁻¹ residue; carbonate-form efficiency < 9%	Shows that CO ₂ dissolution and total uptake can be significant, but carbonate precipitation and process efficiency remain limiting.	(Kemache et al. 2016)
Indirect carbonation with recyclable ammonium sulfate	Serpentine + (NH ₄) ₂ SO ₄ sulfation–leaching–carbonation route	Roasting 390–480 °C; optimum 420 °C, 2 h; (NH ₄) ₂ SO ₄ /serpentine mass ratio 3; leaching 80 °C, 1 h, liquid/solid ratio 1; Mg extraction 76%; CO ₂ storage capacity 204 kg CO ₂ t ⁻¹ serpentinite	Provides quantitative support for indirect carbonation, but also shows process dependence on reagent recycling, roasting, leaching, and mass-transfer control.	(Wang et al. 2024)
Hydromagnesite production route	Serpentinite converted to hydrated Mg-carbonate products	Finnish Mg-silicate deposits estimated as sufficient to store 10 Mt CO ₂ yr ⁻¹ for 200–300 years in one regional assessment	Demonstrates the scale potential of Mg-rich serpentinite resources and stable carbonate-product formation, but regional estimates require site-specific validation.	(Farough and Karrasch 2019)
Laboratory in situ carbonation analogue	Oman–UAE lizardite-dominated serpentinite cores	Core length 3 cm; 70 °C; 100 bar CO ₂ ; 246 days; wet supercritical CO ₂ or CO ₂ -saturated brine	Provides controlled evidence for fracture- and surface-controlled carbonation under subsurface-relevant conditions.	(Lacinska et al. 2017)
In situ carbonation performance	Same serpentinite core experiment	Approximately 0.7 g CO ₂ captured by ~23 g serpentinite; equivalent to ~30 kg CO ₂ t ⁻¹ rock and ~3% carbonation over about half a year; adjusted net value may be ~2% after accounting for recycled carbonate	Demonstrates mineral-trapping feasibility but also shows slow bulk-rock conversion and strong dependence on fractures, veins, and accessible reactive surfaces.	(Lacinska et al. 2017)
Scale-up and techno-economic sensitivity	Serpentinite-residue carbonation of raw flue gas	Modeled process based on laboratory mass balance; flue gas around 18 vol% CO ₂ ; key sensitivities include rock transport, treatment efficiency, energy requirement, and carbonate by-product value	Indicates that feasibility is controlled not only by CO ₂ uptake, but also by energy demand, logistics, process integration, and marketable carbonate products.	(Pasquier et al. 2016)

of permeability during reaction. Because serpentinite commonly has low matrix porosity, effective in situ carbonation depends strongly on fracture, vein, and grain-boundary networks that provide access for CO₂-rich fluids (Fig. 7) (Lacinska et al. 2017, Nisbet et al. 2024).

Experimental carbonation studies using wet supercritical CO₂ and CO₂-rich fluids show that lizardite-dominated serpentinite can carbonate preferentially along fractures, grain boundaries, and exposed surfaces, indicating that fractured serpentinite can act as a reactive mineral-trapping medium when fluid access is maintained (Lacinska et al. 2017). However, this evidence should be interpreted as proof of geochemical feasibility rather than confirmation of mature field-scale deployment. The broader proposal that peridotite and serpentinized ultramafic formations may serve as large-capacity mineral storage reservoirs remains technically promising, but it requires site-specific validation of injectivity, permeability persistence, reaction rates, monitoring capacity, and long-term storage security (Kelemen and Matter 2008). Recent syntheses emphasize that successful in situ mineralization depends on maintaining a balance between carbonate precipitation, which provides permanent CO₂ storage, and preservation of permeability and injectivity, which allows continued fluid circulation (Fig. 7; Table 4). Excessive carbonate or silica precipitation can clog fractures, reduce flow, and self-limit the reaction system (Nisbet et al. 2024, Neil et al. 2024). This permeability–reaction feedback is one of the main reasons why in situ serpentinite carbonation should be treated as an emerging, reservoir-controlled technology rather than a universally deployable storage solution.

Natural analogues further illustrate the coupled nature of carbonation, fluid flow, and rock-property evolution. Carbonation within creeping fault zones can generate talc–magnesite assemblages and silica–carbonate rocks through dissolution–precipitation reactions, while simultaneously modifying rock mechanics, frictional behavior, and rheology (Klein et al. 2013, Klein et al. 2022). Therefore, in situ carbonation should be viewed not only as a CO₂-storage mechanism, but also as a subsurface rock-transformation process in which reaction progress, permeability evolution, mechanical behavior, and monitoring requirements are strongly linked (Klein et al. 2013, Klein et al. 2022, Nisbet et al. 2024). Overall, fractured serpentinite formations represent promising candidates for permanent mineral trapping, but practical deployment requires integrated geological characterization, reactive-transport modeling, injectivity testing, and pilot-scale field validation before large-scale implementation can be justified.

Serpentinite as a feedstock for permanent CO₂ sequestration

Serpentinite is widely recognized as a promising feedstock for permanent CO₂ sequestration, as carbonation converts gaseous CO₂ into thermodynamically stable carbonate minerals over geological timescales (Fig. 7; Table 4). Both ex situ and in situ approaches have been investigated. Pilot-scale aqueous carbonation of serpentinite tailings using industrial flue gas provides clear proof-of-concept beyond laboratory-scale experiments (Kemache et al. 2016). In addition, techno-economic analysis of serpentinite-residue carbonation processes treating industrial flue gas streams supports feasibility under realistic process conditions, while highlighting the importance of energy optimization and integration with existing industrial infrastructure (Pasquier et al. 2014).

The permanence of this approach derives from the formation of stable Mg-carbonate minerals such as magnesite and hydrated magnesium carbonates (Fig. 7; Table 4). Experimental process schemes have demonstrated the engineered production of hydromagnesite from serpentinite feedstocks, confirming the stability and practicality of these reaction products (Fig. 7) (Farough and Karrasch 2019). Experimental carbonation studies on Oman–UAE ophiolitic serpentinites further show that reaction capacity and kinetics depend strongly on mineralogy and fracture-controlled surface accessibility (Lacinska et al. 2017). Consequently, serpentinite should be considered a highly promising but geologically heterogeneous feedstock, requiring deposit-specific characterization and process-specific qualification (Lacinska et al. 2017, Nisbet et al. 2024).

Challenges in scale-up, energy demand, and techno-economic feasibility

Despite its strong scientific basis, serpentinite carbonation remains constrained by scale-up, energy demand, process integration, and techno-economic feasibility. In ex situ processes, substantial energy input may be required for comminution, thermal activation, and solids handling. Although these treatments can significantly enhance Mg accessibility and carbonation kinetics, they also increase capital and operational costs (Fig. 7; Table 4). Additional process constraints include reagent recovery, liquid–solid separation, water management, residue handling, and integration with existing industrial operations (Pasquier et al. 2014, Dlugogorski and Balucan 2014, Pasquier et al. 2016). Thermal activation illustrates the central trade-off: controlled dehydroxylation

can improve magnesium release and reaction efficiency, but the associated energy demand can reduce or even offset the net benefit unless the process is coupled with waste heat, low-carbon energy, or other industrial synergies (Dlugogorski and Balucan 2014, Pasquier et al. 2016).

For this reason, the most credible near-term ex situ pathways are likely to involve serpentinite mine tailings, quarry fines, and pre-ground industrial residues, where part of the comminution burden has already been incurred and where carbonation can be incorporated into circular processing flowsheets (Olajire 2013, Pasquier et al. 2016). Such residue-based routes may improve feasibility by reducing grinding costs, lowering disposal liabilities, and enabling co-location with CO₂ point sources. However, their practical viability still depends on feedstock consistency, activation requirements, water availability, product handling, and the ability to maintain acceptable life-cycle performance under realistic operating conditions (Pasquier et al. 2014, Dlugogorski and Balucan 2014, Pasquier et al. 2016).

For in situ carbonation, the cost and risk profile differs substantially from ex situ processing. Major requirements include drilling, injection infrastructure, reservoir characterization, reactive-transport modeling, monitoring, and management of permeability evolution during continued CO₂ injection (Fig. 7; Table 4). Recent comprehensive reviews indicate that mineralization in mafic–ultramafic reservoirs is promising but remains pre-commercial in many contexts, with key uncertainties related to injectivity, reaction-driven clogging, permeability loss, and long-term monitoring of mineral-trapping performance (Nisbet et al. 2024). A recent technical assessment by the International Energy Agency Greenhouse Gas Programme similarly emphasizes the need for integrated field trials, monitoring frameworks, and site-specific validation before subsurface mineralization technologies can be deployed at large scale (IEAGHG 2025).

Overall, serpentinite carbonation offers a promising route for permanent CO₂ storage because of the abundance of Mg-rich ultramafic rocks and the long-term stability of carbonate products. However, large-scale deployment should be considered conditional rather than established. Progress depends on reducing activation and comminution costs, improving reaction efficiency, managing water and reagent requirements, maintaining injectivity and permeability in subsurface systems, and integrating carbonation into broader industrial value chains (Fig. 7) (Nisbet et al. 2024, Pasquier et al. 2016, IEAGHG 2025). Therefore, serpentinite carbonation is best framed as a technically credible but site- and process-dependent carbon-management pathway that requires further pilot-scale validation, techno-economic optimization, and life-cycle assessment before widespread implementation.

Serpentinite and the geologic hydrogen opportunity

Hydrogen generation in serpentinite-bearing terranes is intrinsically tied to serpentinization, the hydration of olivine- and pyroxene-dominated ultramafic rocks during interaction with water (Fig. 8; Table 5). As reaction progresses, ferrous iron in primary silicates is oxidized, commonly with concomitant magnetite formation, while water is reduced to molecular hydrogen. The resulting fluids are typically alkaline and strongly reducing, and under favorable geochemical and structural conditions they may contain H₂-rich gas phases and associated reduced species (Fig. 8A; Table 5) (Klein et al. 2013, Klein et al. 2022, Sleep et al. 2004, McCollom and Bach 2009, McCollom et al. 2020). This coupled redox mechanism is widely recognized as a principal abiotic pathway for geologic hydrogen in ultramafic provinces and ophiolite belts, forming the scientific basis for recent evaluations of hydrogen prospectivity across Arabian ophiolitic systems (Saidy et al. 2024, Liu et al. 2025). However, this should be interpreted as evidence of generation potential rather than proof of economically recoverable hydrogen resources.

Crucially, hydrogen prospectivity is not guaranteed by the mere presence of serpentinite. Productivity is governed by multiple interacting controls: (i) protolith composition and Fe availability, which define redox capacity and potential H₂ yield; (ii) temperature regime, which influences reaction pathways and kinetics; (iii) serpentinization stage and degree, including the distribution of brucite and magnetite and the buffering behavior of the rock–fluid system; and (iv) fracture-network geometry and connectivity, which determine sustained water supply, reactive transport, and gas migration efficiency (Fig. 8A; Table 5) (Klein et al. 2013, Klein et al. 2022, McCollom and Bach 2009, McCollom et al. 2020, Liu et al. 2025). These constraints support the contemporary “resource system” view of geologic hydrogen, in which viable accumulations require generation rates that exceed physical leakage and chemical or microbial consumption, together with effective migration pathways and credible trapping or sealing conditions that limit rapid dissipation (Liu et al. 2025).

Structural architecture commonly emerges as the decisive variable at exploration scale. In the northern Semail Ophiolite of Ras Al Khaimah, UAE, near-surface gas observations indicate spatially variable hydrogen anomalies and implicate faults as preferential migration corridors, consistent with fracture-controlled transport from serpentinized source domains (Pasquet et al. 2024). In parallel, regional perspectives for Arabia suggest that ophiolites overlain by sedimentary cover may, in principle, provide a favorable

Table 5 Representative quantitative indicators for serpentinite-related geologic hydrogen, electrochemical/osmotic-energy, and thermal-management pathways

Application		Representative quantitative values	Interpretation for the review synthesis	Evidence maturity	Ref.,
Geologic hydrogen	H ₂ occurrence in the northern Semail Ophiolite, Ras Al Khaimah, UAE	H ₂ up to 87 vol% in bubbling springs; up to 88 vol% after air correction; alkaline blue pools around pH~9	Supports active H ₂ generation/migration potential in serpentinite-bearing ophiolites, but not by itself commercial accumulation.	Emerging exploration evidence	(Pasquet et al. 2024, Liu et al. 2025)
	Source–migration–trap controls	Key measurable indicators: H ₂ concentration, H ₂ /N ₂ ratio, pH, fault/fracture association, temporal gas variability, leakage/sink assessment	Reinforces that serpentinite presence alone is insufficient; resource significance requires generation-rate, migration, trapping, and monitoring data.	Emerging/resource-system screening	(Saidy et al. 2024, Pasquet et al. 2024, Liu et al. 2025, Cherkose et al. 2026)
	Geophysical targeting beneath cover	Magnetotelluric phase-tensor anisotropy used to infer serpentinitization/fracture fabrics	Useful as a targeting tool, but not direct confirmation of H ₂ accumulation. Requires integration with gas measurements, hydro-geochemistry, structural mapping, and subsurface validation.	Early exploration workflow	(Cherkose et al. 2026a, Cherkose et al. 2026b)
Electrochemical materials	Serpentinite-derived magnesium iron silicate battery precursor	Calcination/sintering at 900 °C; sulfidation layer about 20 nm; charge plateaus around 2.4 V and 2.8 V; Mg ²⁺ concentration after first charge 611 ppb	Shows that serpentinite-derived Mg–Fe silicate can participate in electrochemical reactions after strong processing and surface modification.	Early-stage device/material evidence	(Momčilović et al. 2016, Randelović et al. 2017, Zhao et al. 2023, Shi and Yu 2016)
	Discharge capacity of sulfidized serpentinite-derived material	Initial discharge capacities: 28.1 mAh g ⁻¹ at 700 °C, 35.6 mAh g ⁻¹ at 800 °C, 46 mAh g ⁻¹ at 900 °C; 65.45 mAh g ⁻¹ for MFS-S-900 at 75 °C	Provides direct quantitative evidence, but capacities remain early-stage and require cycling, conductivity, and device-level validation.	Early-stage/proof-of-concept	(Zhao et al. 2023)
Osmotic-energy concepts	Serpentinite-hosted hydrothermal precipitates	Selective transport of Na ⁺ , K ⁺ , H ⁺ , and Cl ⁻ ; layered hydroxide nanopores span millimeters in hydrothermal-vent walls	Demonstrates natural ion-selective transport in serpentinitization-related Mg-hydroxide architectures; should be framed as geomimetic inspiration, not a bulk-serpentinite device.	Early-stage/inspiration-based	(Lee et al. 2024)
Packed-bed TES	Serpentinite as sensible-heat storage rock	Thermal capacity up to 3450 kJ m ⁻³ K ⁻¹ at 500 °C; recommended operating limit around 500 °C; irreversible deserpentinization near 600 °C	Supports serpentinite as a low- to mid-temperature TES medium, conditional on thermal stability and cyclic durability.	Early to moderate	(El Alami 2025, Katayama et al. 2010, Amiri et al. 2024)
Thermal stability	Serpentine dehydroxylation during heating	Principal dehydroxylation commonly around 600–700 °C, depending on polymorph	Explains why TES operation and thermal products must avoid or control dehydroxylation/deserpentinization.	Established thermal constraint	(El Alami 2025, Dlugogorski and Balucan 2015, Auyeshov et al. 2024a, 2024b, Amiri et al. 2024)

Table 5 (continued)

Application		Representative quantitative values	Interpretation for the review synthesis	Evidence maturity	Ref.,
Building-envelope/porous ceramic products	Serpentine-based heat-insulation ceramics	Forsterite synthesis starts near 600 °C; forsterite content reported above 70% in serpentine–diatomite porous ceramic compositions	Supports engineered porous ceramic products, not raw serpentine as conventional insulation.	Niche/engineered ceramic pathway	(Il'Ina 2013)
Thermal-mass/insulation-adjacent use	Dense serpentine or serpentine-derived ceramic components	Quantitative evaluation should report thermal conductivity, volumetric heat capacity, porosity, density, cyclic stability, and dust/fiber release	Use is system-dependent; most defensible as thermal mass or engineered porous ceramic, not as primary insulation.	Niche/application-specific	(Thomaidis and Kostakis 2015, Vakalova et al. 2022, El Alami 2025, Dlugogorski and Balucan 2015, Klemczak et al. 2024, Urban et al. 2011, Il'Ina 2013)

fracture systems capable of sustaining water–rock reaction and transmitting gas; (iii) surface expressions such as hyperalkaline waters, alkaline springs or pools, and evidence of active carbonation; and (iv) geophysical signatures that may capture alteration, anisotropy, and fracture-controlled conductive pathways (Fig. 8A; Table 5). These indicators are useful for screening and prioritization, but they should be followed by direct geochemical measurements, temporal monitoring, and subsurface validation before resource significance is inferred.

The UAE provides convergent observations consistent with several of these criteria. Shallow-marine seepage linked to serpentinization-influenced fluids has been documented in the Upper Cretaceous Qahlah Formation, confirming the presence of alkaline, ophiolite-sourced fluid systems (Eickmann et al. 2021). More directly, Ras Al Khaimah observations associate hydrogen anomalies with fault structures and alkaline pools accompanied by active carbonate mineralization (Pasquet et al. 2024). At depth, magnetotelluric phase-tensor approaches have been proposed to delineate electrical anisotropy patterns consistent with serpentinization and aligned fracture networks in UAE ophiolitic blocks, providing a plausible geophysical workflow for identifying hydrogen-generating domains beneath cover (Cherkose et al. 2026). However, such geophysical interpretations should be considered targeting tools rather than direct confirmation of hydrogen accumulation, and they require integration with gas measurements, hydrogeochemistry, structural mapping, and drilling or subsurface validation.

Overall, serpentine is increasingly conceptualized as part of a broader class of reactive ultramafic geological

systems capable of hydrogen generation, alkaline-fluid production, and, under suitable boundary conditions, carbonate mineral trapping (Fig. 8A). The current evidence supports geologic hydrogen as a scientifically credible but still emerging exploration opportunity in serpentine-bearing terranes. The priority is therefore to move beyond occurrence-based reporting toward quantified generation-rate constraints, temporal monitoring of hydrogen flux, evaluation of leakage and consumption pathways, and integrated environmental-risk assessment (Pasquet et al. 2024, Liu et al. 2025). For the UAE, the combined evidence for active serpentinization, fault-controlled migration, alkaline hydrochemical signatures, and emerging geophysical targeting tools justifies systematic evaluation. However, any commercial framing should remain contingent on demonstrable generation rates, effective containment, recoverable accumulations, and environmentally responsible development pathways.

Advanced electrochemical and energy materials from serpentine

(i) Battery and electrochemical-material precursors from serpentine-derived Mg–Si phases

Although serpentine does not possess intrinsic electronic conductivity, it has been explored as an early-stage Mg–Si precursor platform that can be transformed through thermal and chemical processing into phases of potential relevance for electrochemical materials design (Fig. 8B; Table 5). The

rationale is not that natural serpentinite functions directly as a battery or supercapacitor material, but that activation treatments can liberate magnesium into soluble streams suitable for producing $\text{Mg}(\text{OH})_2$ or MgO , while also generating disordered Mg–Si phases, commonly described as metaserpentine, together with silica-rich residues (Fig. 8B). These products may subsequently be incorporated into porous frameworks, functional fillers, or hybrid architectures when combined with conductive matrices.

Thermal activation is the principal enabling step in this transformation pathway. Calcination destabilizes the original 1:1 serpentine lattice through progressive dehydroxylation and structural disordering, producing more reactive magnesium–silicate phases and, at higher temperatures, more crystalline assemblages such as forsterite (Fig. 8B; Table 5). Temperature-resolved activation studies demonstrate a characteristic sequence in which low-temperature heating primarily removes adsorbed water, intermediate-temperature treatment promotes lattice breakdown and maximizes chemical reactivity for downstream processing, and further heating drives recrystallization toward stable Mg–silicate phases that may reduce dissolution reactivity (Dlugogorski and Balucan 2014, Auyeshov et al. 2024a, 2024b). These observations show that activation conditions must be carefully controlled when serpentinite is used as a precursor for functional or electrochemical composite materials.

Electrochemical investigations provide preliminary evidence that serpentinite-derived minerals can influence behavior within composite electrode systems (Fig. 8B). Experiments involving serpentinite and forsterite powders incorporated into carbon paste electrodes have shown measurable electrocatalytic responses during cyclic voltammetry relative to unmodified electrodes (Momčilović et al. 2016). A related voltammetric investigation further demonstrated that electrodes modified with serpentinite powder exhibited enhanced electrocatalytic performance compared with conventional carbon paste systems (Randelović et al. 2017). These results should be interpreted cautiously. They do not establish serpentinite as a direct battery electrode material or as a mature electrochemical technology. Rather, they indicate that serpentinite-derived phases can act as functional modifiers within composite electrode architectures, where they may influence surface chemistry, adsorption behavior, ion interaction, and electrochemical response.

Serpentinite may also serve as a raw material for producing magnesium compounds with broader electrochemical relevance. Dissolution–precipitation processing routes can convert activated serpentinite into $\text{Mg}(\text{OH})_2$ or MgO , and magnesium recovery efficiency is strongly controlled by activation-induced changes in mineral structure, dissolution behavior, and silica-residue formation (Fig. 8B) (Auyeshov et al. 2024a, 2024b). In electrochemical engineering, MgO

and $\text{Mg}(\text{OH})_2$ can be used as basic supports, stabilizing additives, protective components, or constituents of hybrid materials. However, translation of serpentinite-derived phases into battery, supercapacitor, or electrocatalytic systems requires integration with conductive frameworks such as carbon networks, conductive polymers, or metallic scaffolds because magnesium silicate and hydroxide phases have intrinsically low electronic conductivity (Zhao et al. 2024, Zhao et al. 2023, Shi and Yu 2016).

From a materials-design perspective, serpentinite-derived products are therefore best regarded as supporting structural or chemical components within hybrid electrochemical materials rather than as stand-alone active phases. MgO - or $\text{Mg}(\text{OH})_2$ -rich domains may provide alkaline or high-surface-area scaffolds for stabilizing catalytic or electroactive species, while silica-rich residues generated during serpentinite processing may serve as porous supports for dispersing active materials (Fig. 8B). Where chemical exfoliation or delamination is possible, serpentinite-derived nanosheets may also provide two-dimensional mineral supports for immobilizing redox-active phases. In all cases, however, conductive backbones and engineered interfaces remain essential for achieving meaningful electrochemical performance (Zhao et al. 2023, Shi and Yu 2016). Accordingly, this pathway should be classified as early-stage and composite-dependent, requiring further validation of charge-storage behavior, rate capability, cycling stability, conductivity enhancement, and scalability before any battery- or supercapacitor-related application can be considered technologically mature.

(ii) Ion-selective and osmotic-energy concepts inspired by serpentinitization-hosted brucite lamellar architectures

A separate emerging research direction involves geomimetic energy-harvesting concepts inspired by serpentinitization environments, particularly ion-selective transport across naturally formed nanostructures associated with ultramafic hydrothermal systems (Fig. 8B; Table 5). Experimental observations from serpentinite-hosted deep-sea hydrothermal settings demonstrate that mineral precipitates generated during serpentinitization can form interconnected nanoporous architectures capable of selective ion transport. In these systems, hydrothermal precipitates contain nanoscale channels with variable surface charge that permit selective transport of ions such as Na^+ , K^+ , H^+ , and Cl^- , enabling conversion of ionic concentration gradients into electrical energy through osmotic-energy harvesting mechanisms (Lee et al. 2024).

A key structural feature of these systems is the formation of brucite-rich lamellar walls composed of aligned

nanocrystals that generate ordered nanoporous channels (Fig. 8B). These lamellar structures act as confined ion-transport pathways and resemble, at a conceptual level, the functional principles used in engineered nanofluidic membranes for salinity-gradient or “blue-energy” conversion technologies (Lee et al. 2024). However, this evidence should not be interpreted as showing that bulk serpentinite itself is an ion-selective membrane or an osmotic-energy device. Instead, it demonstrates that serpentinitization-related Mg-hydroxide systems can naturally generate nanoscale architectures with charge-regulated transport behavior. The engineering implication is therefore conceptual and geomimetic. Serpentinization-hosted brucite lamellae provide a natural analogue for designing synthetic $\text{Mg}(\text{OH})_2$ -based or layered hydroxide frameworks with controlled nanoscale porosity and surface charge. Magnesium derived from serpentinite processing streams could, in principle, be used to synthesize analogous lamellar hydroxide architectures through controlled precipitation, templating, or hybrid-membrane fabrication routes (Fig. 8B). Once produced and stabilized within engineered supports, such structures may be investigated for ion-selective transport, salinity-gradient energy harvesting, or related nanofluidic functions (Lee et al. 2024).

At present, however, this pathway should be treated as early-stage and inspiration-based rather than as a demonstrated serpentinite utilization technology. The strongest

evidence supports natural ion-selective behavior in serpentinite-hosted hydrothermal precipitates, while the translation to scalable devices remains unproven. Future work should therefore focus on reproducible synthesis of serpentinite-derived or serpentinite-inspired Mg-hydroxide lamellae, membrane integration, ion-selectivity testing, power-density evaluation, durability, fouling resistance, and scale-up assessment. Thus, serpentinite’s role in osmotic-energy concepts is best framed as a source of Mg-rich precursors and geomimetic design principles, not as a ready-to-use energy material.

Water–energy systems and thermal management

Packed-bed thermal energy storage using serpentinite as a rock medium

Natural rocks are increasingly investigated as sensible-heat storage media in packed-bed thermal energy storage (TES) systems because they are relatively inexpensive, widely available, and mechanically robust compared with many engineered granular storage materials (Fig. 9; Table 5) (Amiri et al. 2024). Within this category, serpentinite has been proposed as a candidate storage medium because ophiolitic regions can provide large volumes of Mg-rich rock

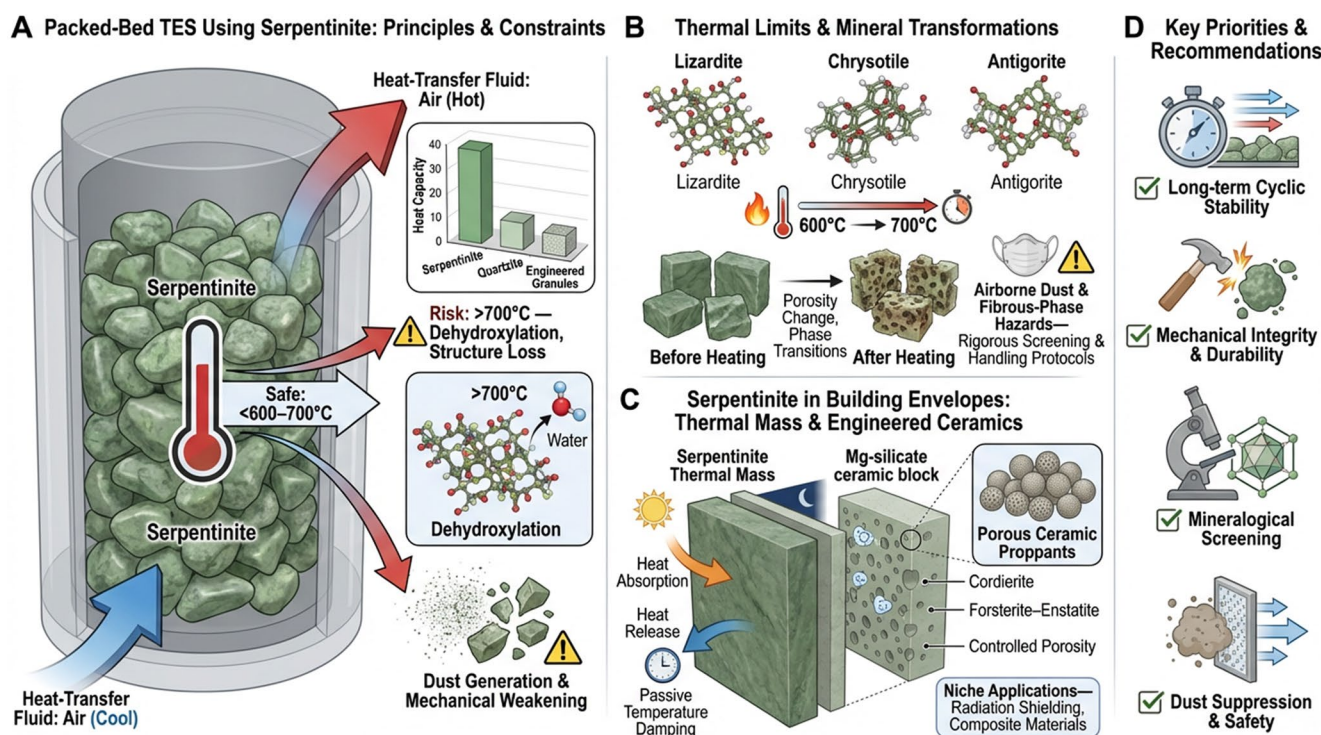


Fig. 9 Thermal-management applications of serpentinite. **A** Packed-bed thermal energy storage with temperature stability constraints. **B** Thermal transformations of serpentinite polymorphs during heating. **C**

Building-envelope uses via thermal mass and Mg-silicate ceramics. **D** Key deployment priorities including durability, mineralogical screening, and dust control

and because its volumetric heat capacity may support thermal-energy storage under appropriate operating conditions. However, serpentinite should be considered a temperature-sensitive TES candidate rather than a universally stable rock filler, because serpentine-group minerals undergo dehydroxylation and structural transformation when exposed to elevated temperatures (Fig. 9) (Dlugogorski and Balucan 2014, Auyeshov et al. 2024a, 2024b).

Experimental assessment of serpentinite in packed-bed TES systems has been reported by El Alami et al. (Alami 2025), who evaluated serpentinite as a granular storage medium in a packed-bed configuration using high-temperature heat-transfer fluids such as air. The results indicate that serpentinite can function as a natural-rock storage medium under tested conditions, provided that thermal stability constraints are respected and system design accounts for mineralogical transformation thresholds (Alami 2025). The key implication is that serpentinite can be considered for TES only where operating temperatures remain below ranges that induce substantial dehydroxylation or deserpentinization. Structural water loss and mineral transformation may modify porosity, increase dust generation, and reduce mechanical integrity during repeated thermal cycling (Alami 2025, Dlugogorski and Balucan 2014). These thermal constraints are closely linked to serpentine mineralogy. Serpentine polymorphs exhibit distinct thermal decomposition behaviors, and thermogravimetric and differential thermal analyses commonly place the principal dehydroxylation reactions in the approximate range of 600–700 °C or slightly higher, with characteristic peak temperatures varying among lizardite, chrysotile, and antigorite (Fig. 9) (Dlugogorski and Balucan 2014). From an engineering perspective, this behavior suggests that serpentinite is most defensibly positioned as a low- to mid-temperature TES medium, whereas higher-temperature operation would require sufficient thermal margins and extensive validation of cyclic stability under repeated heating and cooling (Alami 2025, Dlugogorski and Balucan 2014).

Current research therefore highlights several priorities for serpentinite-based TES systems: long-term cyclic stability under realistic airflow and heat-transfer conditions, assessment of attrition and dust formation during thermal cycling, mineralogical monitoring of polymorph-dependent transformations, and evaluation of post-cycling mechanical integrity and particle durability (Alami 2025, Amiri et al. 2024). Addressing these factors is essential before serpentinite can be considered a mature TES medium for extended industrial operation. At present, the evidence supports serpentinite as a promising but application-specific natural-rock TES filler, with feasibility governed by operating temperature, mineralogical composition, particle durability, and safety screening.

Thermal insulation and thermal-mass roles in niche building-envelope applications

Serpentinite is not generally considered a conventional insulation material because its intrinsic thermal conductivity is typically higher than that of specialized insulating materials such as mineral wool, polymeric foams, or other highly porous insulation products (Fig. 9; Table 5). Consequently, its most realistic contributions within building envelopes are system-dependent and niche-oriented, rather than as a primary insulation material. One potential role is as a thermal-mass component, for example in dense stone cladding, masonry blocks, or interior surfaces that can moderate indoor temperature fluctuations through heat storage and delayed release. Such thermal-mass strategies may be relevant in hot or arid climates, where passive temperature damping can contribute to thermal comfort and reduce cooling demand, although their effectiveness depends on full envelope design rather than on serpentinite alone.

A more technically defensible pathway involves engineered ceramic or composite building products derived from serpentinite. When serpentinite is thermally processed to produce Mg-silicate ceramic phases such as forsterite–enstatite or cordierite-related assemblages, these phases can be incorporated into controlled-porosity matrices where thermal behavior, mechanical durability, and chemical stability are adjusted through formulation and firing conditions (Fig. 9; Table 5). More broadly, building-physics analyses emphasize that envelope performance depends on integrated system design, including thermal-bridge mitigation, geometry-dependent heat-flow pathways, moisture behavior, and the overall envelope configuration, rather than on the intrinsic conductivity of a single material component (Klemczak et al. 2024, Urban et al. 2011). In serpentinite-focused construction reviews, serpentinite-containing products are therefore more commonly discussed for specialized functional roles, particularly radiation-shielding concretes, than for conventional insulation applications (Jain et al. 2023).

The most plausible “insulation-adjacent” route is through serpentinite-derived porous ceramics rather than direct use of untreated serpentinite. Serpentinite- or olivinite-bearing compositions have been used in cordierite ceramic systems in which density, porosity, mechanical performance, and thermal expansion can be controlled through formulation and firing conditions (Fig. 9) (Thomaidis and Kostakis 2015). Similarly, magnesia–silicate ceramics and ceramic proppants derived from serpentinite can be engineered through phase-control strategies involving forsterite and enstatite development to improve densification and mechanical strength (Vakalova et al. 2022). Earlier studies also describe porous heat-insulation ceramics produced from

serpentine-based formulations, illustrating that Mg-silicate ceramic processing can create products with thermal-management relevance when porosity and phase assemblage are deliberately controlled (Il'Ina 2013). However, these examples should be interpreted as evidence for engineered ceramic product development, not as evidence that raw serpentine is itself a conventional insulation material.

For both TES and building-product applications, durability and safety considerations remain critical. Where serpentine contains chrysotile veins or other elongated mineral particles, strict mineralogical screening and dust-control procedures are required. Applications that generate airborne dust must be avoided or carefully managed through appropriate processing, encapsulation, and handling protocols (Fig. 9; Table 5) (Marzini et al. 2024, Punturo et al. 2023). Taken together, the most defensible thermal-management roles for serpentine currently include its use as a packed-bed TES filler operated below critical dehydroxylation temperatures and as a precursor for engineered ceramic or composite materials in which phase evolution, porosity, and durability are deliberately controlled. In both cases, successful deployment depends on mineralogical characterization, controlled processing, cyclic or service-condition testing, and rigorous management of potential fibrous-phase hazards (Vakalova et al. 2022, Marzini et al. 2024, Il'Ina 2013).

Techno-economic and sustainability assessment

Before evaluating techno-economic and sustainability constraints, the major serpentine application pathways reviewed above are compared according to evidence maturity, controlling mineralogical variables, functional advantages, principal limitations, and deployment implications. This synthesis highlights that serpentine valorization is not governed by abundance alone, but by lithotype-specific mineralogy, processing intensity, environmental risk, and the degree to which each application has progressed from laboratory demonstration to realistic deployment (Table 6).

Resource availability and value-chain positioning

Serpentine occurs widely in ophiolite belts and ultramafic massifs and typically enters the economy through two parallel resource streams: primary quarried products (dimension stone and crushed rock) and large-volume secondary outputs such as quarry fines, cutting sludge, beneficiation tailings, and mine wastes (Fig. 10). This dual supply profile is strategically important because secondary streams are already partially comminuted, thereby reducing the comminution burden—often the most energy-intensive unit

operation—for many higher-value and reactive applications (Cavallo 2018, Pasquier et al. 2016). From a value-chain perspective, serpentine can be placed into four broad market lanes. The first is conventional construction (aggregates and stone), where demand is high but margins are low and logistics typically dominate feasibility. The second is its role as an industrial mineral feedstock for refractory and ceramic manufacture, where controlled firing and phase evolution can convert Mg–Si raw stone into higher-value engineered products (Fig. 10) (Cheng et al. 2002, Nemat et al. 2016). The third lane is serpentine as a reactive feedstock in Mg recovery and mineral carbonation, where its Mg-rich chemistry is exploited for chemical products and permanent CO₂ mineral trapping (Pasquier et al. 2014, Pasquier et al. 2016). The fourth lane comprises engineered functional materials—including adsorption media, shielding concretes, and specialized composites—where property engineering rather than bulk tonnage is the primary value driver (Dąbrowski et al. 2022, Diab et al. 2025b). A first-order techno-economic constraint across all lanes is logistics and proximity. High-volume, low-margin uses such as aggregates and fill generally remain viable only when transport distances are limited. In contrast, higher-value niche products—such as ceramic proppants, functional adsorbents, and specialized shielding concretes—can sustain longer supply chains if they deliver a clear performance premium (Fig. 10) (Cavallo 2018, Jain et al. 2023). For carbon-management roles, proximity to CO₂ point sources and availability of low-cost water and energy frequently dominate feasibility, and thus strongly shape the most attractive deployment geographies (Pasquier et al. 2014, Kemache et al. 2016, Pasquier et al. 2016).

Processing cost versus functional performance

Across serpentine-based technologies, cost–performance trade-offs are typically governed by three coupled drivers: comminution, activation (thermal and/or chemical), and separation/purification (Fig. 10). In conventional stone and aggregate applications, processing costs are relatively low, but performance is constrained by heterogeneity in texture, porosity, alteration state, and, where relevant, occupational and environmental constraints associated with dust and elongated mineral particle release (Fig. 10). Consequently, petrographic and durability qualification, together with risk screening, becomes central to performance assurance and responsible handling (Dąbrowski et al. 2022, Marzini et al. 2024, Punturo et al. 2023).

In refractory and ceramic value chains, costs increase substantially because calcination and sintering are intrinsic to product formation; however, performance gains can be substantial when phase evolution is controlled to develop targeted Mg-silicate assemblages such as

Table 6 Critical synthesis of serpentinite application pathways

Application pathway	Evidence maturity	Main mineralogical/processing control	Key advantage	Main limitation	Deployment implication	Ref.,
Dimension stone, ornamental stone, aggregates, and geotechnical fill	Mature for conventional use, but strongly lithotype-dependent	Fabric, alteration degree, porosity, mechanical strength, weathering state, deformation class, chrysotile or elongated mineral-particle occurrence	Established bulk markets; local availability; attractive ornamental appearance; potential use in aggregate and fill applications	Variable durability; possible fiber release during quarrying, cutting, crushing, and compaction; Ni–Cr-bearing ultramafic signature may require screening	Suitable only after petrographic, petrophysical, geochemical, durability, and NOA/fiber-risk screenings; massive low-fiber lithotypes are preferable for open construction uses	(Cavallo 2018, Cheng et al. 2002, Jain et al. 2023, Obminski and Świątkowska 2026, Visalli et al. 2025, Marzini et al. 2024, Punturo et al. 2023)
Refractory and ceramic products	Relatively mature and industrially credible	Mg–Si composition, serpentinite/olivine content, firing temperature, sintering behavior, and formation of forsterite, enstatite, cordierite, or MgO-rich phases	Converts serpentinite and serpentinite wastes into durable, higher-value fired products; suitable for high-temperature and specialty ceramic applications	Firing energy demand; need for controlled phase evolution; variability in feedstock mineralogy; fibrous-phase screening required before processing	One of the strongest near-term valorization routes, especially for controlled industrial processing of quarry wastes, cutting residues, and Mg-rich by-products	(Cheng et al. 2002, Ramezani et al. 2018, Nemat et al. 2016, Cavallo et al. 2021, Thomaidis and Kostakis 2015, Vákalova et al. 2022, Mymrin et al. 2020, Kalaitzidou et al. 2022, Kulikova et al. 2020, Oto et al. 2024, Il'Ina 2013)
Serpentinite-bearing concrete and radiation-shielding materials	Moderate; strongest evidence in specialized concretes and doped ceramics	Hydrous serpentinite phases, aggregate porosity, water absorption, magnetite association, interfacial transition zone quality, and thermal stability	Structurally bound hydroxyls support neutron attenuation; possible use in radiation-shielding concretes and shielding ceramics	Wider or more porous aggregate–paste interfacial zones; durability sensitivity; chloride/carbonation transport risks; high-temperature dehydration effects	Promising for specialized protective concrete and ceramic shielding, but not a general aggregate replacement without durability and thermal-performance testing	(Dąbrowski et al. 2022, Wu et al. 2025, Jain et al. 2023, Scrivener et al. 2004, Stroeve 2022, Oto et al. 2024)
Low-carbon binders, M–S–H systems, and CO ₂ -aware construction products	Emerging to moderate	Serpentine polymorph, thermal activation window, Mg/Si availability, degree of dehydroxylation, curing regime, carbonation conditions	Potential for clinker reduction, Mg-silicate hydrate formation, low-pH binders, residue valorization, and carbonation-linked construction products	Activation energy; slower strength development relative to ordinary Portland cement; curing sensitivity; incomplete long-term durability evidence	Best positioned for targeted low-carbon binders, immobilization matrices, carbonation-cured products, and circular construction routes rather than universal Portland cement replacement	(Ivanova et al. 2022, Pasquier et al. 2014, Mymrin et al. 2020, Jain et al. 2023, Balucan et al. 2013, Balucan and Dlugogorski 2013, Dlugogorski and Bulacan 2014, Bernard 2022, Sreenivasan et al. 2024, Marsiske et al. 2023)
Mineral carbonation and permanent CO ₂ sequestration	Moderate; supported by laboratory, process, and pilot-scale evidence	Mg accessibility, brucite content, serpentinite polymorph, particle size, thermal/mechanical activation, fracture-controlled fluid access, fluid chemistry	Converts CO ₂ into stable Mg-carbonate minerals, enabling permanent carbon storage; can use mine tailings and pre-ground residues	Slow natural kinetics; silica-rich passivation layers; comminution and activation energy; water/reagent requirements; possible permeability clogging in situ	Most feasible where serpentine residues, CO ₂ point sources, water management, waste heat, and industrial infrastructure are co-located	(Steinhorsdottir 2025, Al Kalbani et al. 2024, Farough and Karrasch 2019, Hamed et al. 2025, Krevor and Lackner 2011, Sanna et al. 2014, Godard et al. 2022, Pasquier et al. 2014, Kemache et al. 2016, Wang et al. 2024, Balucan et al. 2013, Balucan and Dlugogorski 2013, Dlugogorski and Bulacan 2014, Lacinska et al. 2017, Maroto-Valer et al. 2005, Olajire 2013, Nisbet et al. 2024, Neil et al. 2024, Kelemen and Matter 2008, Pasquier et al. 2016, IEAGHG 2025)

Table 6 (continued)

Application pathway	Evidence maturity	Main mineralogical/processing control	Key advantage	Main limitation	Deployment implication	Ref.,
Magnesium recovery and Mg-chemical production	Moderate; process routes are technically demonstrated but purification-sensitive	MgO content, serpentine polymorph, activation temperature, acid-leaching conditions, silica-residue behavior, Ni–Cr–Fe impurity profile	Production of Mg(OH) ₂ , MgO, Mg salts, and Mg-carbonate intermediates from abundant Mg-silicate feedstocks	Impurity removal; silica gel/passivation; reagent consumption and recovery; residue handling; need for product-grade purity	Viable where high-Mg, low-risk lithotypes are combined with efficient purification, residue management, and possible silica/Mg co-product strategies	(Fedoročková et al. 2012, Beglaryan et al. 2023, Taheri and Larachi 2025, Chen et al. 2023, Auyeshov et al. 2025, El-Sayed et al. 2023, Auyeshov et al. 2024a, Auyeshov et al. 2024b)
Adsorption, remediation, and engineered porous materials	Laboratory promising; limited pilot-scale validation	Surface hydroxyl groups, exfoliation/intercalation method, mesoporosity, particle size, Mg–Si nanosheet formation, surface charge, spent-sorbent stability	Chemical activation and exfoliation can strongly improve heavy-metal uptake and create reactive porous Mg–silicate platforms	Reagent cost; washing and water demand; spent-sorbent handling; regeneration uncertainty; limited continuous-flow and field evidence	Promising for water-treatment and remediation materials, but requires pilot testing, regeneration studies, leachability evaluation, and scale-up assessment	(HUANG et al. 2026, Diab et al. 2025a, 2025b, Shemy et al. 2025, Auyeshov et al. 2024a, Auyeshov et al. 2024b)
Agriculture, enhanced rock weathering, and Mg fertilization	Emerging and risk-sensitive; some agronomic evidence exists	Particle size, dissolution rate, Mg release, soil pH, hydrology, weathering kinetics, Ni–Cr content, fibrous-mineral risk	Can supply Mg, increase alkalinity in acidic soils, provide liming-like effects, and potentially contribute to CO ₂ removal through enhanced weathering	Slow field weathering rates; grinding-energy burden; possible Ni/Cr mobilization and plant uptake; dust and fiber-risk concerns	Only appropriate for lithotype-specific, monitored deployment with soil/plant metal tracking, particle-size control, and life-cycle assessment	(Hartmann et al. 2013, Beerling et al. 2020, Swoboda et al. 2022, Levy et al. 2024, Dupla et al. 2023, Renforth et al. 2015, Iff et al. 2024, Viana et al. 2021, Viana et al. 2024, Mathews et al. 2022, Dietzen et al. 2018, Suhrhoff 2022, Ten Berge et al. 2012)
Geologic hydrogen systems	Emerging exploration field	Fe-bearing phases, magnetite and brucite formation, serpentinization degree, water supply, temperature, fracture/fault connectivity, migration and trapping conditions	Serpentinization can generate abiotic H ₂ and alkaline fluids; ophiolitic serpentinite belts may represent prospective natural hydrogen systems	Generation rates, leakage, microbial/chemical sinks, migration pathways, trap integrity, and commercial recoverability remain uncertain	Should be treated using a full source–migration–trap resource-system framework; exploration potential is not guaranteed by serpentinite presence alone	(Isah et al. 2025, Kim 2025, Saïdy et al. 2024, Pasquet et al. 2024, Cherkose et al. 2026, Klein et al. 2013, Sleep et al. 2004, McCollom et al. 2009, McCollom et al. 2020, Preiner et al. 2018, McCollom and Donaldson 2016, Heikal et al. 2024, Eickmann et al. 2021, Liu et al. 2025, Cherkose et al. 2026)
Electro-chemical, ion-selective, and osmotic energy concepts	Early-stage or proof-of-concept	Activated Mg–Si phases, MgO/Mg(OH) ₂ production, brucite-rich lamellar architectures, nanoporosity, surface charge, conductive hybridization	Serpentinite-derived phases can act as functional modifiers, supports, or geometric precursors for ion-selective and energy-related materials	Low intrinsic electrical conductivity; limited direct battery/supercapacitor evidence; scalability remains uncertain	Best framed as an emerging materials-design direction involving hybrid composites and geometric Mg-hydroxide architectures, not a mature stand-alone energy material	(Zhao et al. 2024, Lee et al. 2024, Auyeshov et al. 2024a, Auyeshov et al. 2024b, Momčilović et al. 2016, Randelović et al. 2017, Zhao et al. 2023, Shi and Yu 2016)
Thermal energy storage and thermal-management products	Early to moderate for packed-bed TES; niche for building-envelope and ceramic products	Volumetric heat capacity, serpentine dehydroxylation temperature, polymorph thermal stability, thermal cycling behavior, porosity, attrition, ceramic phase evolution	Low-cost natural-rock storage medium; potential use in packed-bed TES, thermal-mass products, and Mg-silicate ceramics	Deserpentinization/dehydroxylation at elevated temperature; dust generation; mechanical degradation during cycling; fiber-risk screening required	Most defensible in low- to mid-temperature TES and engineered ceramic products after cyclic stability, mineralogical, and dust/fiber-risk testing	(Thomaidis and Kostakis 2015, Vakalova et al. 2022, El Alami 2025, Dlugogorski and Balucan 2014, Auyeshov et al. 2024a, Auyeshov et al. 2024b, Marzini et al. 2024, Punturo et al. 2023, Amiri et al. 2024, Klemczak et al. 2024, Urban et al. 2011, Il'Ina 2013)

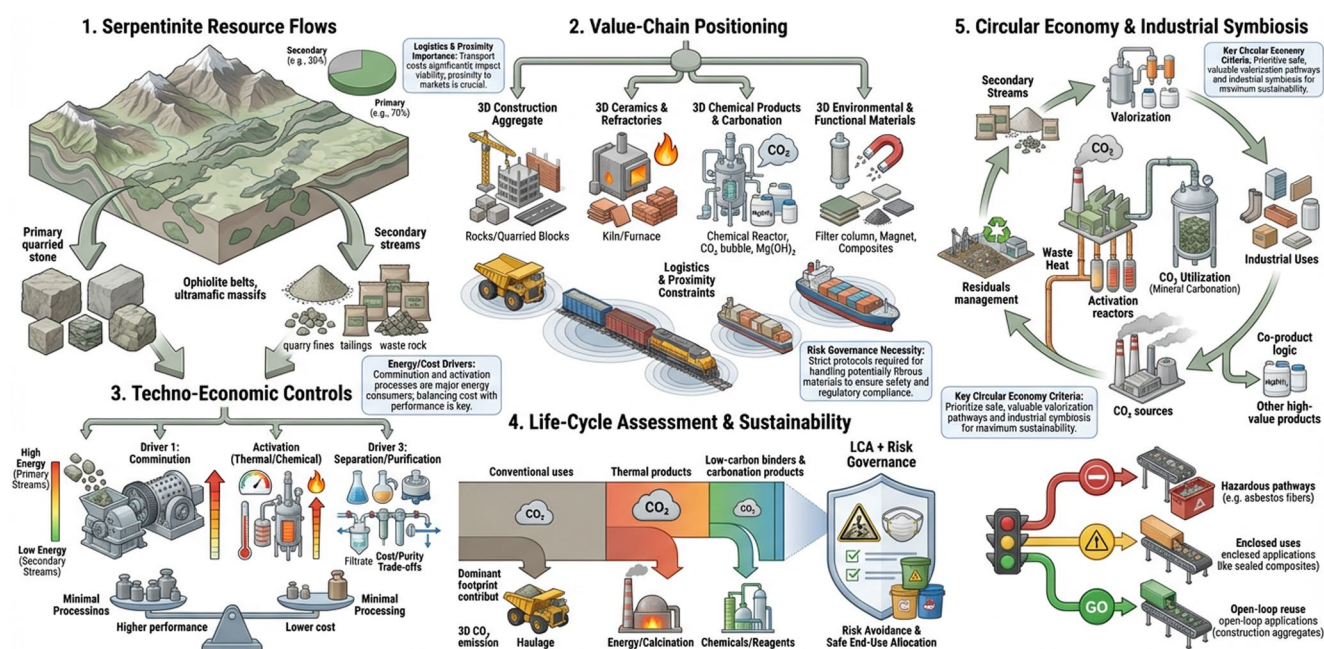


Fig. 10 Techno-economic and sustainability framework for serpentinite, showing resource flows, value-chain positioning, processing cost–performance controls, life-cycle and risk-based sustainability

forsterite–enstatite or cordierite-related products (Fig. 10). In this lane, serpentinite is not valued as a rock per se but as a compositionally suitable precursor whose firing behavior can be engineered to deliver high-temperature and mechanical functionality (Cheng et al. 2002, Nemat et al. 2016, Vakalova et al. 2022, Kalaitzidou et al. 2022). For carbon-utilization and Mg-recovery routes, the dominant cost is often activation energy because both Mg liberation and serpentine carbonation are kinetically hindered under mild conditions. Thermal activation and/or high-energy milling are therefore used to increase Mg accessibility, but these steps can dominate operating cost unless integrated with waste heat, co-product recovery, or existing industrial infrastructure that lowers marginal energy and handling burdens (Pasquier et al. 2014, Długogorski and Balucan 2014, Pasquier et al. 2016).

In engineered environmental and functional-material pathways, the limiting costs often shift from comminution to chemical modification, effluent handling, and post-treatment washing and solids management. Exfoliation and functionalization can markedly improve sorption performance, yet reagent cost, water demand for purification, and spent-material handling frequently determine scalability (Diab et al. 2025b). For this reason, many deployment concepts converge toward “moderate activation” strategies that unlock reactive sites and porosity without introducing chemical or energy inputs that overwhelm the value created.

assessment, and circular-economy/industrial-symbiosis pathways for primary and secondary serpentinite streams

Life-cycle assessment and sustainability framing for serpentinite-based products

Life-cycle assessment (LCA) of serpentinite-based products should explicitly recognize that serpentinite participates in both conventional and reactive value chains. Methodologically, LCA should follow established standards for goal and scope definition, inventory analysis, impact assessment, and interpretation (ISO 14040:2006) (Fig. 10). For construction products, LCA and environmental product declaration practice are commonly aligned with construction product category rules such as EN 15,804. In conventional aggregate, stone, and fill uses, the dominant footprint contributors are typically quarrying, crushing, hauling, and dust management; accordingly, the strongest sustainability lever is often transport minimization together with responsible waste and dust governance (Fig. 10) (Cavallo 2018, Punturo et al. 2023). For thermal products such as refractories and ceramics, firing and calcination usually dominate energy and emissions, and sustainability hinges on kiln efficiency, fuel source, substitution benefits relative to alternative ceramics, and—importantly—the ability to utilize secondary streams rather than primary quarried stone (Cheng et al. 2002, Nemat et al. 2016, Kalaitzidou et al. 2022).

For low-carbon binders and carbonation-driven products, the LCA logic becomes more nuanced because serpentinite can enable CO₂ uptake while simultaneously requiring energy-intensive activation steps. Net benefit depends

on system boundaries and on explicit accounting for CO₂ source and compression energy, water use, reagent loops and recovery, residue handling, and product fate, with activation energy often constituting the pivotal determinant of net performance (Fig. 10) (Pasquier et al. 2014, Kemache et al. 2016, Dlugogorski and Balucan 2014, Pasquier et al. 2016). Finally, sustainability framing must integrate environmental-health governance as a co-equal dimension with emissions and energy. Where chrysotile-bearing lithotypes or elevated Ni–Cr signatures are present, sustainability requires life-cycle control of airborne dust, waste classification, and safe end-use assignment rather than relying on carbon and energy metrics alone (Obminski and Świątkowska 2026, Marzini et al. 2024, Punturo et al. 2023). In practical terms, serpentinite sustainability should be evaluated as LCA plus risk governance, not LCA in isolation.

Circular-economy potential and industrial symbiosis

Serpentinite exhibits strong circular-economy potential because substantial volumes are generated as wastes or low-value by-products, including quarry fines, cutting sludge, beneficiation tailings, and dust fractions (Fig. 10). Circular pathways are most compelling where they can consume large secondary volumes, reduce disposal burdens and dust liabilities, and deliver products with stable demand. Dimension-stone waste valorization has been explicitly highlighted as a practical opportunity, provided that waste composition is consistent and that asbestos-bearing veins are excluded through appropriate screening (Fig. 10) (Cavallo 2018). Ceramic and refractory routes can also absorb significant quantities by transforming serpentinite-derived wastes into forsterite-rich products, cordieritic bodies, and engineered Mg-silicate ceramics, effectively converting fines and residues into durable high-temperature commodities (Cheng et al. 2002, Nemat et al. 2016, Thomaidis and Kostakis 2015, Vakalova et al. 2022, Kalaitzidou et al. 2022).

Industrial symbiosis becomes particularly powerful when serpentinite resources co-locate with CO₂-producing industries such as cement, steel, or refining operations and where waste heat can be harnessed to offset activation energy (Fig. 10). Pilot-scale mineralization using industrial flue gas and process-level energy/economic evaluations of serpentinite-residue carbonation support the conclusion that the most attractive sites are those where serpentinite supply, CO₂ point sources, and industrial infrastructure coincide (Pasquier et al. 2014, Kemache et al. 2016, Pasquier et al. 2016). Symbiosis can also be strengthened by co-product platforms, for example where Mg recovery to Mg(OH)₂ contributes additional revenue streams and improves overall system economics when purification and residue handling are appropriately engineered (Auyeshov et al. 2025).

A realistic circular strategy must remain selective because not all serpentinite wastes are suitable for open-loop reuse. Naturally occurring asbestos risk, compositional variability, and trace-element release potential can restrict certain applications and necessitate fit-for-purpose allocation (Fig. 10). In practice, lower-risk massive lithotypes can be routed into controlled aggregate and stone markets; fines and tailings are often more appropriately directed to enclosed, regulated industrial uses such as ceramics, engineered binders, or carbonation reactors; and higher-risk fibrous fractions should be excluded from reuse or immobilized via compliant hazardous-waste pathways and high-temperature stabilization where appropriate (Mymrin et al. 2020, Obminski and Świątkowska 2026, Marzini et al. 2024, Punturo et al. 2023).

The United Arab Emirates as a case study

The United Arab Emirates (UAE) provides a focused geological case study for applying the structure–property–function framework developed in this review because it exposes well-preserved segments of the northern Semail Ophiolite in the Oman–UAE Mountains. In this setting, serpentinite forms an important component of altered mantle peridotites and has recently been examined in three convergent research directions: mineralogical–geochemical characterization of UAE serpentinites, documentation of serpentinitization-influenced seepage and carbonate formation in the stratigraphic record, and assessment of serpentinitization-related natural hydrogen prospectivity (Fig. 11) (Sami et al. 2026, Pasquet et al. 2024, Eickmann et al. 2021). The UAE case is therefore not presented as a fully developed serpentinite-utilization model, but as a geographically constrained example showing how mineralogical variability, resource potential, decarbonization opportunities, hydrogen exploration, and environmental risk must be evaluated together.

Geological distribution, geochemistry, and mineralogy of serpentinite

In the UAE, serpentinite is concentrated within the mountainous belt of the northern and eastern Emirates, where the Hajar Mountains expose ophiolitic crustal and mantle units (Fig. 11). A regional synthesis of the country's geology and geography notes that this mountain environment occupies most of Fujairah, much of Ras Al Khaimah, and parts of Sharjah, including the Dubai (Hatta) and Ajman (Masfut) enclaves, thereby delineating the principal zone of ophiolitic exposure in the UAE (Feulner 2023). At the locality scale, serpentinite occurs as altered mantle peridotite within the Semail Ophiolite and is particularly well described in

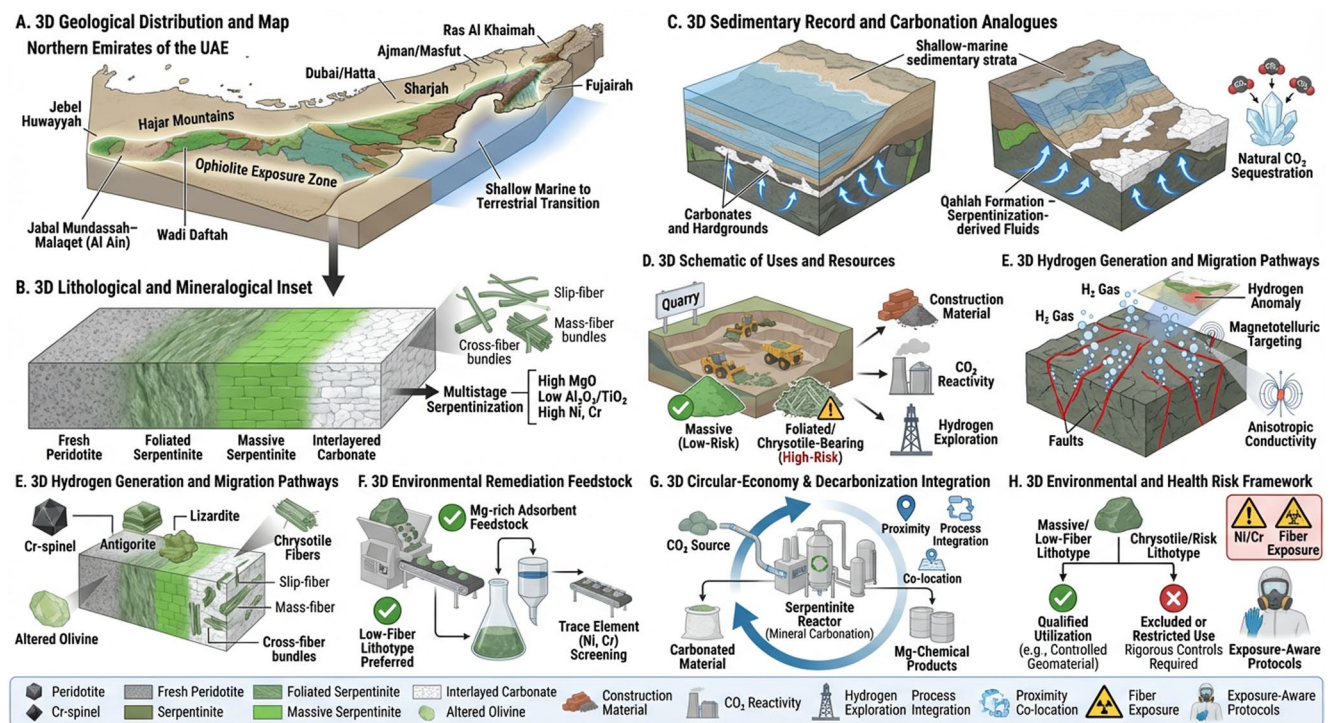


Fig. 11 UAE serpentinite framework showing ophiolite distribution, lithological variability, natural carbonation analogues, resource uses, hydrogen pathways, remediation potential, circular-economy integration, and environmental risk controls

the Jabal Mundassah–Malaqet area near Al Ain, where both massive and foliated serpentinite bodies have been reported (Sami et al. 2026). Complementing these exposures, chrysotile-bearing serpentinite has also been documented at Wadi Daftah within the UAE ophiolite belt, confirming that serpentinite occurs across structurally distinct ophiolitic settings and is not confined to a single exposure style (Heikal et al. 2024). Independent stratigraphic evidence further supports the regional significance of serpentinization-related processes. The Upper Cretaceous Qahlah Formation at Jebel Huwayyah, near Al Ain, preserves seepage signatures and carbonate features consistent with ophiolite-sourced alkaline fluids influencing shallow-marine sediments soon after obduction and during subsequent intervals (Fig. 11) (Eickmann et al. 2021).

Recent studies have strengthened constraints on the mineralogy and geochemistry of UAE serpentinites. In the Jabal Mundassah–Malaqet system, serpentinites include massive and foliated lithotypes dominated by intergrown lizardite and antigorite, with relict Cr-spinel and altered olivine preserved locally. These features are consistent with an altered mantle protolith and a multistage serpentinization history (Fig. 11) (Sami et al. 2026). Whole-rock data are characterized by high MgO, very low Al₂O₃ and TiO₂, and elevated Ni and Cr, supporting derivation

from a highly depleted refractory ultramafic protolith with fore-arc/supra-subduction-zone affinity (Sami et al. 2026). From an applied perspective, this composition is important because it indicates Mg-rich feedstock potential, but also highlights the need for impurity-aware screening where Ni–Cr mobility may become relevant during weathering, crushing, leaching, or other processing routes.

Mineralogical variability in the UAE is not limited to lizardite–antigorite assemblages. At Wadi Daftah, chrysotile occurs in multiple structurally controlled habits, including slip-fiber, mass-fiber, and cross-fiber forms (Heikal et al. 2024). This observation is important because it shows that asbestiform serpentine can occur locally within UAE serpentinite bodies. Therefore, any applied use involving quarrying, cutting, comminution, aggregate production, chemical activation, or residue handling must include mineralogical screening for fibrous phases and exposure-aware handling protocols (Heikal et al. 2024). Overall, UAE serpentinites illustrate why serpentinite cannot be assessed only by bulk chemistry or regional abundance. Lithotype, deformation fabric, polymorph assemblage, accessory phases, Ni–Cr inventory, and fibrous-mineral occurrence must all be considered before assigning a material to a specific utilization pathway.

Resource context, decarbonization opportunities, and emerging utilization pathways

Although UAE-focused serpentinite studies have so far concentrated more strongly on mineralogical–geochemical evolution and emerging energy significance than on detailed production statistics, serpentinite clearly occurs within a regionally important hard-rock province dominated by ophiolitic lithologies that support construction-stone and aggregate supply chains across the northern Emirates (Fig. 11) (Feulner 2023). At the same time, the UAE case demonstrates that serpentinite should not be treated as equivalent to more compositionally uniform aggregate rocks. The contrast between massive and foliated serpentinite, together with the confirmed occurrence of chrysotile-bearing zones, highlights the need for lithotype-specific classification, mineralogical screening, durability testing, and risk-aware qualification before any large-scale geomaterial use (Sami et al. 2026, Heikal et al. 2024).

Beyond conventional resource use, the UAE provides a scientifically valuable setting for research on mineral carbonation and CO₂ sequestration because reactive ultramafic rocks coexist with preserved natural analogues of carbonate formation. Evidence from the Qahlah Formation at Jebel Huwayyah records shallow-marine seepage influenced by serpentinization-derived fluids, together with associated carbonate features and hardgrounds, demonstrating that serpentinite-linked carbonate mineralization is preserved in the UAE stratigraphic record (Fig. 11) (Eickmann et al. 2021). This strengthens the rationale for treating UAE ultramafic terrains as natural reference systems for understanding alkaline fluid flow, carbonate precipitation, and long-term mineral trapping. However, this evidence should be interpreted as support for geological and process-screening studies rather than direct proof of immediate engineered CO₂-storage feasibility. Any future engineered carbonation assessment in the UAE would still require site-specific evaluation of reactive rock volume, fracture permeability, water availability, CO₂-source proximity, monitoring capacity, and environmental risk.

In parallel, the UAE represents a scientifically relevant regional example for ophiolite-hosted geologic hydrogen assessment. Field measurements from the northern Semail Ophiolite in Ras Al Khaimah have identified hydrogen anomalies and suggest that faults and lineaments may act as preferential migration pathways, consistent with a structurally controlled source–migration framework in serpentinite-bearing terranes (Fig. 11) (Pasquet et al. 2024). These findings are consistent with broader Arabian assessments that identify serpentinite-rich ophiolites as prospective exploration settings where reactive source rocks, fracture systems, fluid circulation, and potential trapping conditions

are sufficiently developed (Saidy et al. 2024). However, the presence of hydrogen anomalies and favorable geological indicators should be treated as evidence for exploration potential rather than confirmation of commercial accumulations. Demonstrating resource significance would require repeated gas monitoring, generation-rate estimates, assessment of leakage and consumption pathways, subsurface validation, and evaluation of trapping or sealing conditions.

Geophysical methods may support this screening process. Magnetotelluric phase-tensor analysis has been proposed as a targeting tool for the UAE, with anisotropic conductivity patterns interpreted as possible indicators of serpentinization and aligned structural fabrics beneath cover (Cherkose et al. 2026). This approach is promising as part of an integrated exploration workflow, but it should not be regarded as direct evidence of hydrogen accumulation. Instead, geophysical targeting should be combined with structural mapping, gas measurements, hydrogeochemistry, and, where justified, subsurface testing.

From an applied materials perspective, prospects for UAE serpentinite-derived environmental remediation media remain at an early stage. At present, this pathway is best regarded as a feedstock-screening and laboratory-development opportunity rather than a mature application chain. Nevertheless, the Mg-rich chemistry and mineralogical characteristics documented for UAE serpentinites provide a basis for selecting low-fiber lithotypes for activation studies and for evaluating adsorption performance in parallel with trace-element stability, leachability, and safety constraints (Fig. 11) (Sami et al. 2026, Heikal et al. 2024). Similarly, Mg-chemical valorization and carbonation-linked industrial pathways may be promising where suitable low-risk serpentinite streams, CO₂ sources, energy, water management, and processing infrastructure are co-located, but these remain conditional on techno-economic and environmental validation.

Taken together, these features position UAE serpentinite at the intersection of quarry-resource utilization, decarbonization research, Mg-chemical valorization, environmental-material development, and geologic hydrogen exploration. The most defensible near-term strategy is not broad, undifferentiated use of serpentinite, but integrated value-chain screening. Such a strategy would link lithotype-qualified quarry streams, especially fines and secondary materials where available, to controlled CO₂-reactive, Mg-chemical, ceramic, or environmental-material pathways in locations where reactive feedstock, CO₂ sources, utilities, water-management options, and infrastructure are co-located. This approach is consistent with broader circular-economy and mineralization frameworks, which emphasize proximity, process integration, risk governance, and coupling of parallel value streams as central determinants of feasibility.

Environmental risk management and safe utilization in the UAE context

The UAE case study underscores that serpentinite utilization must be explicitly risk-governed. Chrysotile occurrence modes documented at Wadi Daftah demonstrate that serpentinite bodies cannot be assumed uniformly suitable for open construction use without prior mineralogical screening and exposure-aware handling protocols (Heikal et al. 2024). In parallel, elevated Ni and Cr levels reported for the Jabal Mundassah–Malaqet serpentinites are geologically expected for depleted ultramafic rocks, but they become environmentally relevant during crushing, weathering, chemical leaching, carbonation, or residue handling where mobility and exposure pathways may increase (Sami et al. 2026).

Accordingly, serpentinite utilization in the UAE should follow a fit-for-purpose classification approach. Massive, lower-risk lithotypes may be candidates for controlled geomaterial, ceramic, carbonation, Mg-chemical, or advanced-material applications after appropriate qualification. In contrast, chrysotile-bearing, highly fractured, strongly foliated, cataclastic, or strongly weathered serpentinites should be excluded from open dust-generating uses unless rigorous exposure controls, compliant handling procedures, and monitoring protocols can be demonstrably implemented (Sami et al. 2026, Heikal et al. 2024). Screening should include serpentine polymorph identification, petrographic assessment of fibrous phases, textural classification, geochemical quantification of Ni–Cr and other trace elements, leachability testing where weathering or chemical processing is expected, and application-specific durability or performance testing.

In practical terms, UAE serpentinite should be managed as a heterogeneous resource rather than a single commodity. Lower-risk materials may be directed toward controlled industrial value chains, while higher-risk fibrous or trace-metal-sensitive fractions should be avoided, isolated, or routed only to enclosed and regulated processing pathways where immobilization or compliant disposal can be ensured. This risk-governed approach allows the UAE case study to illustrate the broader conclusion of this review: serpentinite valorization is feasible only when mineralogical qualification, process design, environmental safety, and end-use allocation are treated as linked decision steps rather than separate considerations.

Research gaps and future perspectives

Need for mineral-specific and texture-specific performance databases

A central gap in the field is the absence of standardized, mineral- and texture-resolved performance databases that

explicitly link serpentinite attributes to application outcomes. Many contributions still treat serpentinite as a single, broadly defined material class, despite well-established variability driven by serpentine polymorph assemblage (lizardite–chrysotile–antigorite), degree of serpentinization, brucite abundance, fracture density, and deformation style. This heterogeneity is especially consequential in hazard and engineering contexts, where massive, foliated, and cataclastic serpentinites can exhibit markedly different fiber-release potential and durability-critical petrophysical behavior (Marzini et al. 2024, Punturo et al. 2023).

Future databases should therefore be designed as integrated, multi-parameter resources that combine mineralogy (XRD, Raman, FTIR), texture and structural class (petrography and deformation state), petrophysics (density, porosity, UCS, wave velocities), geochemistry (Ni–Cr and trace elements), reactivity metrics (dissolution, activation response, carbonation rates), and—where relevant—emission or release indices. The broader geochemical community has already demonstrated the scientific and practical value of mineral-specific rate databases used in reactive-transport and geochemical modeling, including comprehensive internally consistent dissolution-rate compilations and derivative tools for rate calculation and model integration (Heřmanská et al. 2022, Heřmanská et al. 2023, Oelkers and Addassi 2025, Oelkers and Addassi 2025). A comparable database architecture tailored to serpentinite would directly address the persistent disconnect between “rock name” and “engineering performance,” enabling fit-for-purpose qualification across construction, carbonation, Mg recovery, adsorption, and risk-governed reuse.

Bridging laboratory reactivity with pilot-scale deployment

A second enduring gap is the mismatch between laboratory demonstrations and pilot-scale performance. Laboratory studies commonly rely on idealized particle sizes, simplified fluids, short residence times, and controlled impurity levels, whereas pilot and industrial deployments must accommodate feedstock variability, realistic process fluids, solids-handling constraints, and continuous operation. This scale dependence is particularly pronounced in mineral carbonation, where field-relevant performance depends not only on chemistry but also on permeability evolution, precipitation geometry, and the preservation of fracture-controlled access pathways (Pasquier et al. 2014, Lacinska et al. 2017, Nisbet et al. 2024).

Pilot-scale aqueous carbonation provides a clear illustration: once systems move beyond bench scale, operational variables that may be underemphasized in batch tests—including water management, liquid recirculation, solids

handling, and product separation—often become dominant determinants of outcome (Kemache et al. 2016). Techno-economic evaluations similarly show that feasibility is frequently controlled by energy demand, comminution and activation cost, and integration with existing industrial streams rather than conversion yield alone (Pasquier et al. 2016). Comparable bridging work is needed for remediation and binder routes, where high laboratory performance obtained by exfoliation or thermal activation must be translated into pilot evidence addressing reagent recovery, effluent treatment, durability of spent solids and final products, and the consequences of realistic feedstock heterogeneity (Ivanova et al. 2022, Diab et al. 2025b).

Integrating geology, materials science, and environmental engineering

A third gap is that serpentinite research remains fragmented across disciplinary silos. Geological studies emphasize distribution, textures, and alteration histories; materials science studies focus on activation, phase control, and performance optimization; and environmental work concentrates on exposure pathways and risk. In practice, serpentinite valorization requires a unified framework because performance is co-governed by mineralogy and microstructure together with processing conditions, while hazard profiles depend strongly on deformation state, weathering, and dust-generation pathways during quarrying and comminution (Marzini et al. 2024, Punturo et al. 2023).

This integration is particularly critical in geologic hydrogen and in situ carbonation contexts. In these systems, serpentinite must be treated as a reactive rock mass in which fracture networks, fluid flow, and reaction kinetics are coupled, and where success depends on system-scale behavior rather than isolated batch reactivity. Systems-oriented hydrogen syntheses emphasize a source–migration–trap framework and monitoring-based evaluation, rather than single-criterion screening approaches (Pasquet et al. 2024, Liu et al. 2025). Carbonation syntheses similarly emphasize coupled thermo–hydro–mechanical–chemical feedbacks and the evolution of permeability and reaction fronts, rather than interpreting reactivity solely from short-duration laboratory experiments (Nisbet et al. 2024, Neil et al. 2024, IEAGHG 2025). A coherent cross-disciplinary workflow would therefore align geological qualification, engineered processing, and risk governance as a single decision pathway.

Strategic priorities for serpentinite valorization in arid-region economies

In arid-region economies, including the UAE, serpentinite valorization must be framed by constraints that often

dominate at scale. Water availability is a primary limiting factor because many promising processing routes—aqueous carbonation, acid leaching, and intensive washing after modification—are water-intensive. Scalable deployment in arid settings will therefore favor closed-loop water recycling, brine-tolerant chemistries where feasible, and dry or semi-dry process concepts when compatible with target products and performance requirements (Pasquier et al. 2014, Kemache et al. 2016).

A second priority is co-location with industrial infrastructure. Feasibility improves strongly when serpentinite resources, CO₂ point sources, and utilities are geographically aligned, especially when serpentinite is accessible as comminuted secondary streams such as quarry fines and tailings that reduce grinding penalties and lower entry costs for reactive applications (Cavallo 2018, Pasquier et al. 2016). Third, feedstock selection must be explicitly risk-governed because serpentinite is not a uniform commodity. Massive, lower-release lithotypes may be suitable for controlled applications after qualification, whereas foliated or cataclastic serpentinites and chrysotile-veined materials require strict control or exclusion from open dust-generating uses (Marzini et al. 2024, Punturo et al. 2023). Fourth, the most credible scaling pathway lies in value-chain coupling and circularity, particularly through industrial symbiosis in which serpentinite wastes and by-products are integrated into ceramics, binders, and carbonation processes embedded within mining and construction supply chains under compliant governance (Cavallo 2018, Pasquier et al. 2016). In summary, the field must transition from treating serpentinite as merely an abundant rock to treating it as a qualified, fit-for-purpose resource. Achieving this requires mineral- and texture-resolved datasets, rigorous pilot-scale validation, integrated cross-disciplinary workflows, and arid-region deployment strategies that are explicitly designed around water constraints and risk governance (Sami et al. 2026, Marzini et al. 2024, Punturo et al. 2023, Pasquier et al. 2016).

Conclusions

Serpentinite is increasingly recognized as a multifunctional geomaterial rather than merely a hydrated ultramafic rock or low-value industrial stone. This review demonstrates that its performance is fundamentally controlled by polymorph assemblage, degree of serpentinitization, accessory phases, and microstructural heterogeneity, which together govern density, porosity, mechanical behavior, Mg accessibility, dissolution kinetics, carbonation efficiency, and environmental risk. The literature confirms a dual technological significance for serpentinite. It remains an established material in conventional applications such as dimension stone, aggregates,

and refractory/ceramic products, while also showing strong potential in emerging fields including low-carbon binders, magnesium-chemical production, mineral carbonation, adsorption systems, shielding materials, catalytic supports, and engineered porous composites. Its Mg-rich composition and hydroxyl-bearing structure are central to these opportunities, particularly in decarbonization and advanced materials design.

At the same time, serpentinite cannot be treated as a uniform resource. Application feasibility is strongly lithotype-dependent, and responsible utilization requires explicit consideration of mineralogical variability, activation response, and safety constraints. Chrysotile occurrence, elongated mineral particles, and possible Ni–Cr mobility remain critical limitations that must be addressed through rigorous screening, controlled processing, and fit-for-purpose allocation. Overall, serpentinite has substantial promise for sustainable construction, carbon management, environmental remediation, and energy-related technologies. Future progress should prioritize polymorph-resolved characterization, pilot-scale validation, and integrated techno-economic and environmental-risk assessment to translate this geological resource into safe, scalable, and high-value applications.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

AI tools AI tools were used during manuscript preparation for language editing and refinement of schematic figures under the authors' supervision, who reviewed all outputs and take full responsibility for the final content.

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References

- Ahmad M, Tsegab Gebretsadik H, Siddiqui NA, Adam M, Ali SA, Orakzai AU (2025) Review on Carbon Dioxide Mineralization in Mafic/Ultramafic Rocks: From Fundamentals to Field Applications. *Energy Fuels* 39(49):22963–22997
- Al Kalbani M, Serati M, Hofmann H, Ritchie T, Bore T (2024) Optimizing in-situ CO₂ mineralisation: geomechanics and scalability in dunite and serpentinite rocks—examples from Australia and New Zealand. *Sci Total Environ* 927:172277
- Amiri L, Ermagan H, Kurnia JC, Hassani F, Sasmito AP (2024) Progress on rock thermal energy storage (RTES): a state of the art review. *Energy Sci Eng* 12(2):410–437
- Auyeshov A, Arynov K, Satimbekova A, Yeskibayeva C, Alzhanov K (2024a) The thermal activation of serpentinite from the Zhitikarsky deposit (Kazakhstan). *Molecules* 29(18):4455
- Auyeshov A, Arynov K, Yeskibayeva C, Dikanbayeva A, Auyeshov D, Raiymbekov Y (2024b) Transformation of silicate ions into silica under the influence of acid on the structure of serpentinite. *Molecules* 29(11):2502
- Auyeshov A, Arynov K, Yeskibayeva C, Ibrayeva A, Zhumadildayeva A (2025) Efficient production of high-purity magnesium hydroxide from serpentinite. *Molecules* 30(17):3484
- Ballotin FC, Cibaka TE, Ribeiro-Santos TA, Santos EM, de Carvalho Teixeira AP, Lago RM (2016) K₂MgSiO₄: a novel K⁺-trapped biodiesel heterogeneous catalyst produced from serpentinite Mg₃Si₂O₅ (OH)₄. *J Mol Catal A Chem* 422:258–265
- Balucan RD, Dlugogorski BZ (2013) Thermal activation of antigorite for mineralization of CO₂. *Environ Sci Technol* 47(1):182–190
- Balucan RD, Dlugogorski BZ, Kennedy EM, Belova IV, Murch GE (2013) Energy cost of heat activating serpentinites for CO₂ storage by mineralisation. *Int J Greenhouse Gas Control* 17:225–239
- Beerling DJ, Kantzas EP, Lomas MR, Wade P, Eufrazio RM, Renforth P, Sarkar B, Andrews MG, James RH, Pearce CR, Mercure JF (2020) Potential for large-scale CO₂ removal via enhanced rock weathering with croplands. *Nature* 583(7815):242–248
- Beglaryan H, Isahakyan A, Zulumyan N, Melikyan S, Terzyan A (2023) A study of magnesium dissolution from serpentinites composed of different serpentine group minerals. *Miner Eng* 201:108171
- Bernard E (2022) Research progress on magnesium silicate hydrate phases and future opportunities. *RILEM Tech Lett* 7:47–57
- Carmignano ORD, Vieira SS, Brandão PRG, Bertoli AC, Lago RM (2020) Serpentinites: Mineral structure, properties and technological applications. *J Braz Chem Soc* 31:2–14
- Cavallo A (2018) Serpentinic waste materials from the dimension stone industry: Characterization, possible reuses and critical issues. *Resour Policy* 59:17–23
- Chen Y, Yang X, Wu L, Tong L, Zhu J (2023) Recovery of Mg from H₂SO₄ Leaching Solution of Serpentine to Precipitation of High-Purity Mg (OH)₂ and 4MgCO₃·Mg(OH)₂·4H₂O. *Minerals* 13(3):318
- Cheng TW, Ding YC, Chiu JP (2002) A study of synthetic forsterite refractory materials using waste serpentine cutting. *Miner Eng* 15(4):271–275

- Cherkose BA, Zhang M, Li Y (2026) Detecting serpentinization-related electrical anisotropy using magnetotelluric phase tensor: application in geologic hydrogen exploration. *J Geophys Eng* 23(4):1109–1120
- Cherkose BA, Zhang M, Li Y (2026) Finding geologic hydrogen generation in UAE ophiolites: insights from MT phase tensor mapping of serpentinization. *Discover Appl Sci* 8(4):460
- Cox S, Fagereng Å, MacLeod CJ (2021) Shear zone development in serpentinized mantle: implications for the strength of oceanic transform faults. *J Geophys Res Solid Earth* 126(5):e2020JB020763
- Dąbrowski M, Józwiak-Niedźwiedzka D, Bogusz K, Glinicki MA (2022) Influence of serpentinite aggregate on the microstructure and durability of radiation shielding concrete. *Constr Build Mater* 337:127536
- Diab AS, Allam AA, Rudayni HA, Abdelfadil KM, Arman H, Al Zoubi W, Abukhadra MR (2025a) Clay nanostructures in geotechnical engineering: a critical review of mechanisms, performance, and sustainable soil stabilization. *Mater Today Sustain* 33: 101284. <https://doi.org/10.1016/j.mtsust.2025.101284>
- Diab AS, Mohamed RA, Alqhtani HA, Al Zoubi W, El-Sherbeeney AM, Abdelghany O, Abukhadra MR (2025b) Comparative exfoliation of serpentinite using potassium acetate and potassium nitrate: adsorption and statistical physics insights into cadmium and lead removal. *Colloids Surf A Physicochem Eng Asp* 733: 139274 <https://doi.org/10.1016/j.colsurfa.2025.139274>
- Dietzen C, Harrison R, Michelsen-Correa S (2018) Effectiveness of enhanced mineral weathering as a carbon sequestration tool and alternative to agricultural lime: an incubation experiment. *Int J Greenh Gas Control* 74:251–258
- Đlugogorski BZ, Balucan RD (2014) Dehydroxylation of serpentine minerals: Implications for mineral carbonation. *Renew Sustain Energy Rev* 31:353–367
- Dupla X, Möller B, Baveye PC, Grand S (2023) Potential accumulation of toxic trace elements in soils during enhanced rock weathering. *Eur J Soil Sci* 74(1):e13343
- Eberhard L (2021) Serpentinite phase relations: An experimental study on redox conditions and fluid migration in subduction zones. *Universitaet Bayreuth* (Germany)
- Eickmann B, Little CT, Peckmann J, Taylor PD, Boyce AJ, Morgan DJ, Bach W (2021) Shallow-marine serpentinization-derived fluid seepage in the Upper Cretaceous Qahlah Formation, United Arab Emirates. *Geol Mag* 158(9):1561–1571
- El Alami K (2025) Experimental study of serpentinite rocks as storage materials for a packed-bed thermal energy storage system. *Procedia Comput Sci* 265:770–775
- El-Sayed D, Ismail AK, El-Hosiny FI (2023) Magnesium chloride crystals with studying mechanism and leaching kinetics of serpentinite ore by hydrochloric acid. *Trans Indian Inst Met* 76(6):1439–1446
- Evans BW (2004) The serpentinite multisystem revisited: chrysotile is metastable. *Int Geol Rev* 46(6):479–506
- Evans BW, Hattori K, Baronnet A (2013) Serpentinite: what, why, where? *Elements* 9(2):99–106
- Farough A, Karrasch AK (2019) Correlation of elastic moduli and serpentine content in ultramafic rocks. *Geosciences* 9(12):494
- Fedoročková A, Hreus M, Raschman P, Sučík G (2012) Dissolution of magnesium from calcined serpentinite in hydrochloric acid. *Miner Eng* 32:1–4
- Feulner GR (2023) Geography and geology of the United Arab Emirates: A naturalist's introduction. *A Natural History of the Emirates*. Springer Nature Switzerland, Cham, pp 13–64. https://doi.org/10.1007/978-3-031-37397-8_2
- SamiM, Gamaleldien H, Ntafos T, Li CF, Sanislav IV, Zhao X, Kamaunji VD, Mahmoud B, Fathy D, Abukhadra MR, Abdelfadil K (2026) Geochemical constraints on the evolution and tectonic setting of United Arab Emirates Ophiolitic Serpentinites. *J Asian Earth Sci* 300:p106990. <https://doi.org/10.1016/j.jseaes.2026.106990>
- Godard M, Gouze P, Benezeth P, Martinez I, Escario S, Decrausaz T, Leprovost R, Roubinet D, Pézard P (2022) October. In situ CO₂ mineralization in mantle-derived ultramafic basements: insights from laboratory experiments and field studies (Oman Ophiolite). In *16th International Conference on Greenhouse Gas Control Technologies, GHGT-16* (p. 4285227)
- Hamed H, Gonzales-Calienes G, Shadbahr J (2025) Ex situ carbon mineralization for CO₂ capture using industrial alkaline wastes—optimization and future prospects: a review. *Clean Technol* 7(2):44
- Hartmann J, West AJ, Renforth P, Köhler P, De La Rocha CL, Wolf-Gladrow DA, Dürr HH, Scheffran J (2013) Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification. *Rev Geophys* 51(2):113–149
- Heikal MTS, Surour AA, Said AA (2024) Chemical, thermal and infrared characterization of chrysotile modes from the Wadi Daftah serpentinite (Semail ophiolite), United Arab Emirates. *Discover Geoscience* 2(1):87
- Heřmanská M, Voigt MJ, Marieni C, Declercq J, Oelkers EH (2022) A comprehensive and internally consistent mineral dissolution rate database: part I: primary silicate minerals and glasses. *Chem Geol* 597:120807
- Heřmanská M, Voigt MJ, Marieni C, Declercq J, Oelkers EH (2023) A comprehensive and consistent mineral dissolution rate database: part II: secondary silicate minerals. *Chem Geol* 636:121632
- Iff N, Renforth P, Pogge von Strandmann PA (2024) The dissolution of olivine added to soil at 32° C: the fate of weathering products and its implications for enhanced weathering at different temperatures. *Front Clim* 6:1252210
- Il'Ina VP (2013) Ceramic heat-insulation materials based on serpentinite. *Glass Ceram* 70(7):285–288
- Isah A, Samouei H, Okoroafor ER (2025) Assessing the effect of mineralogy and reaction pathways on geological hydrogen (H₂) generation in ultramafic and mafic (Basaltic) rocks. *Hydrogen* 6(4):76
- Ivanova TK, Kremenetskaya IP, Marchevskaya VV, Slukovskaya MV, Drogobuzhskaya SV (2022) Magnesium silicate binding materials formed from heat-treated serpentine-group minerals and aqueous solutions: structural features, acid-neutralizing capacity, and strength properties. *Materials (Basel)* 15(24):8785
- Jain A, Agrawal V, Gupta R (2023) Using serpentinite in concrete: A literature review. *Mater Today: Proc.* <https://doi.org/10.1016/j.matpr.2023.03.138>
- Kalaïtizou K, Pagona E, Stratigousis P, Ntampou X, Zaspalis V, Zouboulis A, Mitrakas M (2022) Hematite nanoparticles addition to serpentine/pyroxenes by-products of magnesite mining enrichment process for the production of refractories. *Appl Sci (Basel)* 12(4):2094
- Katayama I, Kurosaki I, Hirauchi KI (2010) Low silica activity for hydrogen generation during serpentinization: an example of natural serpentinites in the Mineoka ophiolite complex, central Japan. *Earth Planet Sci Lett* 298(1–2):199–204
- Kelemen PB, Matter J (2008) In situ carbonation of peridotite for CO₂ storage. *Proc Natl Acad Sci* 105(45):17295–17300
- Kemache N, Pasquier LC, Mouedhen I, Cecchi E, Blais JF, Mercier G (2016) Aqueous mineral carbonation of serpentinite on a pilot scale: the effect of liquid recirculation on CO₂ sequestration and carbonate precipitation. *Appl Geochem* 67:21–29
- Kim HS (2025) Thermodynamic modeling of the serpentinization of ultramafic rocks from the Korean Peninsula: insights into natural hydrogen (H₂) generation. *Episodes* 49: 57–74. <https://doi.org/10.18814/epiugs/2025/025007>

- Klein F, Bach W, McCollom TM (2013) Compositional controls on hydrogen generation during serpentinization of ultramafic rocks. *Lithos* 178:55–69
- Klein F, Goldsby DL, Lin J, Andreani M (2022) Carbonation of serpentinite in creeping faults of California. *Geophys Res Lett* 49(15):p.e2022GL099185
- Klemczak B, Kucharczyk-Brus B, Sulimowska A, Radziejewicz-Winnicki R (2024) Historical evolution and current developments in building thermal insulation materials—a review. *Energies* 17(22):5535
- Krevor SC, Lackner KS (2011) Enhancing serpentine dissolution kinetics for mineral carbon dioxide sequestration. *Int J Greenhouse Gas Control* 5(4):1073–1080
- Kulikova SA, Vinokurov SE, Khamizov RK, Vlasovskikh NYS, Belova KY, Dzheloda RK, Konov MA, Myasoedov BF (2020) The use of MgO obtained from serpentinite in the synthesis of a magnesium potassium phosphate matrix for radioactive waste immobilization. *Appl Sci* 11(1):220
- Lacinska AM, Styles MTS, Bateman K, Hall M, Brown PD (2017) An experimental study of the carbonation of serpentinite and partially serpentinised peridotites. *Front Earth Sci* 5:37
- Lee HE, Okumura T, Ooka H, Adachi K, Hikima T, Hirata K, Kawano Y, Matsuura H, Yamamoto M, Yamamoto M, Yamaguchi A (2024) Osmotic energy conversion in serpentinite-hosted deep-sea hydrothermal vents. *Nat Commun* 15(1):8193
- Levy CR, Almaraz M, Beerling DJ, Raymond P, Reinhard CT, Suhrhoff TJ, Taylor L (2024) Enhanced rock weathering for carbon removal—monitoring and mitigating potential environmental impacts on agricultural land. *Environ Sci Technol* 58(39):17215–17226
- Lu X (2025) *The detection and quantification of reactivity in ultramafic rocks, minerals and mine waste for carbon dioxide removal via carbon mineralization* (Doctoral dissertation, University of British Columbia)
- Maroto-Valer MM, Fauth DJ, Kuchta ME, Zhang Y, Andrésen JM (2005) Activation of magnesium rich minerals as carbonation feedstock materials for CO₂ sequestration. *Fuel Process Technol* 86(14–15):1627–1645
- Marsiske MR, Köser R, Bäumle B, Ruiz-Agudo C (2023) Uncovering the early stages of magnesium silicate hydrate formation: a non-classical multistep pathway. *ACS Appl Eng Mater* 1(1):696–707
- Marzini L, Iannini M, Giorgetti G, Bonciani F, Conti P, Salvini R, Viti C (2024) Asbestos Hazard in Serpentine Rocks: Influence of Mineralogical and Structural Characteristics on Fiber Potential Release. *Geosciences* 14(8):210
- Mathews J, NG, J., Mohanaraj, S. and, Kawading O (2022) Evaluation of Ground Serpentine Rock and Ground Magnesium Limestone as Magnesium Sources for Oil Palm Nursery Seedlings. *The Planter, Kuala Lumpur*, 98 (1154): 333–344
- Urban B, Engelmann P, Kossecka E, Kosny J (2011) May. Arranging insulation for better thermal resistance in concrete and masonry wall systems. In *Proceedings of the 9th Nordic Symposium on Building Physics, Tampere, Finland* (Vol. 29)
- McCollom TM, Bach W (2009) Thermodynamic constraints on hydrogen generation during serpentinization of ultramafic rocks. *Geochim Cosmochim Acta* 73(3):856–875
- McCollom TM, Donaldson C (2016) Generation of hydrogen and methane during experimental low-temperature reaction of ultramafic rocks with water. *Astrobiology* 16(6):389–406
- McCollom TM, Klein F, Moskowitz B, Berquó TS, Bach W, Templeton AS (2020) Hydrogen generation and iron partitioning during experimental serpentinization of an olivine–pyroxene mixture. *Geochim Cosmochim Acta* 282:55–75
- Momčilović MZ, Randelović MS, Purenović MM, Đorđević JS, Onjia A, Matović B (2016) Morpho-structural, adsorption and electrochemical characteristics of serpentinite. *Sep Purif Technol* 163:72–78
- Mymrin V, Presotto P, Alekseev K, Avanci MA, Rolim PH, Petukhov V, Taskin A, Gidarakos E, Valouma A, Yu G (2020) Application of hazardous serpentine rocks' extraction wastes in composites with glass waste and clay-sand mix to produce environmentally clean construction materials. *Constr Build Mater* 234:117319
- Neil CW, Yang Y, Nisbet H, Iyare UC, Boampong LO, Li W, Kang Q, Hyman JD, Viswanathan HS (2024) An integrated experimental–modeling approach to identify key processes for carbon mineralization in fractured mafic and ultramafic rocks. *PNAS Nexus* 3(9):p.pgac388
- Nemat S, Ramezani A, Emami SM (2016) Possible use of waste serpentine from Abdasht chromite mines into the refractory and ceramic industries. *Ceram Int* 42(16):18479–18483
- Nisbet H, Buscarnera G, Carey JW, Chen MA, Detournay E, Huang H, Hyman JD, Kang PK, Kang Q, Labuz JF, Li W (2024) Carbon mineralization in fractured mafic and ultramafic rocks: a review. *Rev Geophys* 62(4):p.e2023RG000815
- Oelkers EH, Addassi M (2025) A comprehensive and consistent mineral dissolution rate database: part III: non-silicate minerals including carbonate, sulfate, phosphate, halide, and oxy-hydroxide minerals. *Chem Geol* 673:122528
- Oelkers EH, Addassi M (2025) Kinect v3: a computer database for the calculation of the dissolution rates of the major rock forming minerals. *Chem Geol* 695: 123041. <https://doi.org/10.1016/j.chemgeo.2025.123041>
- Olajire AA (2013) A review of mineral carbonation technology in sequestration of CO₂. *J Petrol Sci Eng* 109:364–392
- Ten Berge HF, Van der Meer HG, Steenhuizen JW, Goedhart PW, Knops P, Verhagen J (2012) Olivine weathering in soil, and its effects on growth and nutrient uptake in ryegrass (*Lolium perenne* L.): a pot experiment. *PLoS ONE* 7:e42098. <https://doi.org/10.1371/journal.pone.0042098>
- Omori T, Suzuki S, Michibayashi K, Okamoto A (2023) Super-resolution of X-ray CT images of rock samples by sparse representation: applications to the complex texture of serpentinite. *Sci Rep* 13(1):6648
- Oto B, Çakar N, Kavaz E, Madak Z (2024) An experimental study on gamma radiation attenuation effectiveness of magnetite and serpentine doped ceramics. *Prog Nucl Energy* 169:105079
- Pasquet G, Loiseau K, Diatta M, Firpo G, Swire P, Amey A, Burckhart T, Moretti I (2024) Natural hydrogen in the northern Semail Ophiolite: a case study in the Emirate of Ras Al Khaimah, UAE. *Int J Hydrogen Energy* 110:787–796
- Pasquier LC, Mercier G, Blais JF, Cecchi E, Kentish S (2014) Parameters optimization for direct flue gas CO₂ capture and sequestration by aqueous mineral carbonation using activated serpentinite based mining residue. *Appl Geochem* 50:66–73
- Pasquier LC, Mercier G, Blais JF, Cecchi E, Kentish S (2016) Technical & economic evaluation of a mineral carbonation process using southern Québec mining wastes for CO₂ sequestration of raw flue gas with by-product recovery. *Int J Greenhouse Gas Control* 50:147–157
- Pereira D, Monterrubio S, Bloise A (2025) The transformation from serpentinite to talcose rocks and its consequences. A pilot study in Cabo Ortegal, an ultramafic Massif in NW Spain. *Environ Earth Sci* 84(20):587
- Preiner M, Xavier JC, Sousa FL, Zimorski V, Neubeck A, Lang SQ, Greenwell HC, Kleineremanns K, Tüysüz H, McCollom TM, Holm NG (2018) Serpentinization: connecting geochemistry, ancient metabolism and industrial hydrogenation. *Life (Basel)* 8(4):41
- Punturo R, Visalli R, Cirrincione R (2023) A Review of the Mineralogy, Petrography, and Geochemistry of Serpentine from Calabria Regions (Southern Italy): Problem or Georesource? *Minerals* 13(9):1132
- Ramezani A, Emami SM, Nemat S (2018) Effect of waste serpentine on the properties of basic insulating refractories. *Ceram Int* 44(8):9269–9275

- Randelović MS, Momčilović MZ, Nikolić G, Đorđević JS (2017) Electrocatalytic behaviour of serpentinite modified carbon paste electrode. *J Electroanal Chem* 801:338–344
- Ray SS, Tersur Orasugh J, Temane LT (2025) Structure and properties of natural nanoclays. *Nanoclays: Materials Properties and Advanced Applications*. Springer Nature Switzerland, Cham, pp 33–72. https://doi.org/10.1007/978-3-031-85304-3_2
- Renforth P, Von Strandmann PP, Henderson GM (2015) The dissolution of olivine added to soil: Implications for enhanced weathering. *Appl Geochem* 61:109–118
- Saidy K, Fawad M, Whattam SA, Al-Shuhail AA, Al-Shuhail AA, Campos M, Sulistiyohariyanto FA (2024) Unlocking the H₂ potential in Saudi Arabia: exploring serpentinites as a source of H₂ production. *Int J Hydrogen Energy* 89:1482–1491
- Sanna A, Uibu M, Caramanna G, Kuusik R, Maroto-Valer MM (2014) A review of mineral carbonation technologies to sequester CO₂. *Chem Soc Rev* 43(23):8049–8080
- Şaşmaz A, Kılıç AD, Konakçı N (2024) Chemical and thermal changes in Mg₃Si₂O₅(OH)₄ polymorph minerals and importance as an industrial material. *Appl Sci* 14(22):10298
- Scrivener KL, Crumie AK, Laugesen P (2004) The interfacial transition zone (ITZ) between cement paste and aggregate in concrete. *Interface Sci* 12(4):411–421
- Segal D (2024) Critical Materials for a Low-carbon Economy. Royal Society of Chemistry
- Cavallo A, Bussolesi M, Grieco G (2021) Serpentinites: from dimension stones to valuable industrial minerals
- Shemy MH, Mohamed RA, Abdel-Khalek AA, Alqhtani HA, Al Zoubi W, Abukhadra MR (2025) Engineering high-performance CTAB-functionalized magnesium silicate nano-adsorbent for efficient removal of Cd²⁺, Co²⁺, and Cu²⁺ from single-metal aqueous solutions. *Front Chem* 13:1583305
- Shi Y, Yu G (2016) Designing hierarchically nanostructured conductive polymer gels for electrochemical energy storage and conversion. *Chem Mater* 28(8):2466–2477
- Sideridis A, Anevlavi V, Tombros SF, Hauzenberger C, Koutsovit P, Boumpoulis V, Jakobitsch T, Petrounias P, Aggelopoulou A (2025) Developing a Provenance Framework for Ancient Stone Materials: A Subduction-Related Serpentine Case Study from Tinos, Cyclades, Greece. *Minerals* 15(6):568
- Sleep NH, Meibom A, Fridriksson T, Coleman RG, Bird DK (2004) H₂-rich fluids from serpentinization: geochemical and biotic implications. *Proc Natl Acad Sci* 101(35):12818–12823
- Obminski A, Świątkowska B (2026) Soil contamination caused by chrysotile and antigorite fibres during serpentinite mining in oolite rock in south-western Poland. *J Hazard Mater* 504:141071
- Sreenivasan H, Bernard E, Santos HS, Nguyen H, Moukannaa S, Adediran A, Provis JL, Kinnunen P (2024) A critical review of magnesium silicate hydrate (MSH) phases for binder applications. *Cem Concr Res* 178:107462
- Steinthsordottir K (2025) *Feasibility of in-situ carbon mineralization in serpentinite via shallow injection, British Columbia, Canada* (Doctoral dissertation, University of British Columbia)
- Stroeve P (2022) Interfacial transition zone in concrete: its relevance for engineering applications. *HERON* 67(2):79
- Suhrhoff TJ (2022) Phytoremediation of heavy metal contamination from terrestrial enhanced weathering: can plants save the day? *Front Clim* 3:820204
- Swoboda P, Döring TF, Hamer M (2022) Remineralizing soils? The agricultural usage of silicate rock powders: a review. *Sci Total Environ* 807:150976
- Taheri B, Larachi F (2025) Mineral-Based Magnesium Extraction Technologies: Current and Future Practices. *Processes* 13(9):2945
- Tarling MS, Demurtas M, Smith SA, Rooney JS, Negrini M, Viti C, Petriglieri JR, Gordon KC (2022) Crystallographic orientation mapping of lizardite serpentinite by Raman spectroscopy. *Eur J Mineral* 34(3):285–300
- Huang Y, Xiuxia Yang, Peiyue LIU, Xinyu Chen, Hongyan Zhu, Chengcheng Wang, Yangping Wen, Shang Q (2026) Thermally activated serpentine: A dual-function adsorbent for simultaneous heavy metal immobilization and soil pH regulation in acidified agricultural systems. *Pedosphere*
- Thomaidis E, Kostakis G (2015) Synthesis of cordieritic materials using raw kaolin, bauxite, serpentinite/olivine and magnesite. *Ceram Int* 41(8):9701–9707
- Vakalova TV, Sergeev NP, Maksimova VE, Rusinov PG, Balamygin DI (2022) Improvement of sinterability and mechanical properties of magnesia-silicate ceramics with enstatite phase from mixtures of serpentinite with silica additives. *J Ind Eng Chem* 106:86–102
- Viana JH, Coelho AM, Thomazini A, Carvalho MPD (2021) Evaluation of the agricultural potential of the serpentinite rock as a soil remineralizer. *An Acad Bras Cienc* 93:e20201614
- Viana JHM, Coelho AM, Thomazini A, de Carvalho MPF, França ACF, de Paula Clemente E (2024) Dry matter production and nutrient extraction by three successive crops fertilized with serpentinite rock as a soil remineralizer. *Observatório de La Economía Latinoamericana* 22(4):e4112–e4112
- Visalli R, Navarro R, Buccione R, Indelicato V, Rizzo G, Cirrincione R, Punturo R (2025) Multi-analytical characterization of serpentinite rocks employed as stone material: an example from Andalusia (Southern Spain), Basilicata, and Calabria (Southern Italy). *Minerals (Basel)* 15(5):522
- Viti C, Collettini C, Tesei T, Tarling MS, Smith SA (2018) Deformation processes, textural evolution and weakening in retrograde serpentinites. *Minerals (Basel)* 8(6):241
- Wang L (2026) Serpentine (Asbestos). *Manual of Mineral Material Science*. Springer Nature Singapore, Singapore, pp 469–475. https://doi.org/10.1007/978-981-97-7558-3_106
- Wang B, Chen S, Feng X, Yuan Z, Chen W, Liu W, He M, Liu Q (2024) CO₂ sequestration by indirect mineral carbonation of serpentine with (NH₄)₂SO₄ as a recyclable extractant. *Process Saf Environ Prot* 191:2082–2094
- Wicks FJ, Whittaker EJW (1977) Serpentine textures and serpentinization. *Can Mineral* 15(4):459–488
- Wu D, Liu Z, Chen Z, Wu Q, Tao Q (2025) Effect of elevated temperature on mechanical properties and shielding performance of magnetite-serpentine radiation-proof concrete. *Materials* 18(12):2686
- Yin F, Zhang C, Yu Y, Lv C, Gao Z, Lu B, Su X, Luo C, Peng X, McFadzean B, Cao J (2024) Review on the challenges of magnesium removal in nickel sulfide ore flotation and advances in serpentinite depressor. *Minerals* 14(10):965
- Zhao JR, Chen KJ, Hung FY, Tsai YY, Wu PT (2023) A Study on Surface Modification Characteristics and Charge-Discharge Mechanism of Natural Serpentine Ore Secondary Battery. *Inorganics* 12(1):13
- Zhao D, Sun H, Peng T, Zeng L (2024) Ionic dissolution and structural evolution of chrysotile and lizardite at the mineral-water interface: reactions in sulfuric acid solution. *Clays Clay Miner* 72:p.e32
- IEAGHG (2025) Review of CO₂ storage via in situ mineralisation in mafic-ultramafic rocks, 2025-03, August <https://doi.org/10.6284/9/2025-03>
- Liu M, Warner T, Zhao Y, Xia Z, Zhang D, Zhan P, Frohman R, Creason C, Seol Y (2025) Geologic hydrogen: from natural occurrences to anthropogenic generation—A review of fundamentals, potential, challenges and prospects. *Earth Science Reviews*, 274(2026)