

**PROCEEDINGS OF THE INTERNATIONAL WORKSHOP ON ADVANCES IN
SURFACE MINING FOR ENVIRONMENTAL PROTECTION AND SUSTAINABLE
DEVELOPMENT 17 OCTOBER 2025, HA NOI, VIET NAM**



**THE 60th ANNIVERSARY
OF SURFACE MINING EDUCATION**

ADVANCES IN SURFACE MINING FOR ENVIRONMENTAL PROTECTION AND SUSTAINABLE DEVELOPMENT-2025 (ASMES - 2025)



TRANSPORT PUBLISHING HOUSE, HA NOI, VIET NAM

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Overview of Carbon Storage Technologies in Mine Waste Rock: Opportunities and Challenges for TKV Open-Pit Mines

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ABSTRACT

Carbon storage in waste rock from open-pit mining has been proposed as a novel solution that offers dual benefits: reducing CO₂ emissions and addressing mine waste management. Globally, carbon storage technologies applied to mine waste rock—including mineral carbonation, enhanced weathering, and biological approaches—have demonstrated that waste rock rich in alkaline-magnesium minerals (such as ultramafic rocks and serpentinite) can react with CO₂ to form stable carbonates, enabling the potential sequestration of hundreds of millions of tonnes of CO₂ annually. Based on existing research on the characteristics of these carbon storage technologies, and considering technical, environmental, and economic feasibility, the implementation of such approaches in TKV's open-pit mines still faces substantial challenges. Nevertheless, this represents a promising research pathway aligned with the "Green" and "Sustainable" development objectives of TKV's open-pit operations, particularly in the context of the Prime Minister's commitment to achieving net-zero emissions by 2050.

Keywords: Carbon mineralization, Enhanced weathering, CO₂ sequestration, Potential for Vinacomin

1. Introduction

In the face of the increasingly evident impacts of climate change on both the environment and human society, there is an urgent need to significantly reduce atmospheric CO₂ concentrations, not only through emission cuts but also via carbon dioxide removal (CDR) strategies. The mining industry emits approximately 3.6 billion tonnes of CO₂ equivalent annually while generating vast amounts of waste rock and tailings that remain largely underutilized. Mine waste rock containing calcium- and magnesium-rich silicate minerals has the potential to react with CO₂. Numerous studies have proposed the use of mine waste as potential carbon burial sites, leveraging the extensive surface area and abundant materials left after mining. This process is generally referred to as mineral carbonation or enhanced weathering, depending on the approach and conditions employed. Building upon international research frameworks, this paper provides an overview of carbon storage technologies—including mineral carbonation, enhanced weathering, biological methods, and wastewater treatment—and assesses their technical, environmental, and economic feasibility for application in TKV's open-pit mines.

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2. Overview of Carbon Storage Technologies in Open-Pit Mine Waste Rock

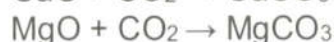
2.1. Mineral Carbonation in Mine Waste Rock

a. Principles and Chemical Reactions

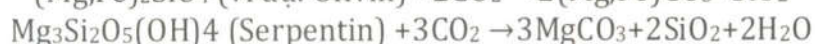
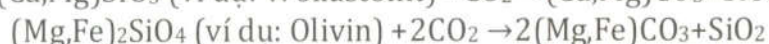
Mineral carbonation, also referred to as mineral carbonatization, is a technological process that simulates and accelerates natural weathering reactions between CO₂ and minerals containing alkali or alkaline earth metals, primarily compounds of calcium (Ca), magnesium (Mg), and iron (Fe). The outcome of this process is the formation of solid carbonate minerals that are chemically and thermodynamically stable, enabling the safe and permanent sequestration of CO₂ over timescales ranging from thousands to millions of years.

The fundamental chemical reactions of the carbon mineralization process can be represented as follows (Engineering, 2023), (MDPI, 2023):

For metal oxides:



For silicate minerals:



b. Methods of Carbon Mineralization

There are two principal approaches to carbon mineralization: in-situ and ex-situ:

- In-situ Mineralization

This method involves injecting CO₂—typically in a supercritical state or dissolved in water—directly into deep geological formations containing reactive minerals such as basalt or peridotite, or into large-scale waste rock deposits. Mineralization then occurs within the subsurface or directly inside the waste rock mass. A notable example of in-situ mineralization is the CarbFix project in Iceland, where CO₂ is dissolved in water and injected into basaltic formations. Results from the project have demonstrated that mineralization proceeds at a much faster rate than initially anticipated (MDPI, 2023).

- Ex-situ (or Surficial) Mineralization

This method involves extracting or collecting waste rock materials and processing them at the surface in reactors or specially designed systems. Ex-situ mineralization can be implemented through two main approaches.

+ **Direct:** CO₂—typically sourced from industrial emissions or ambient air—is brought into direct contact with finely ground waste rock under either dry or controlled moisture conditions. The process may occur at varying temperatures and pressures depending on the mineral type and the applied technology.

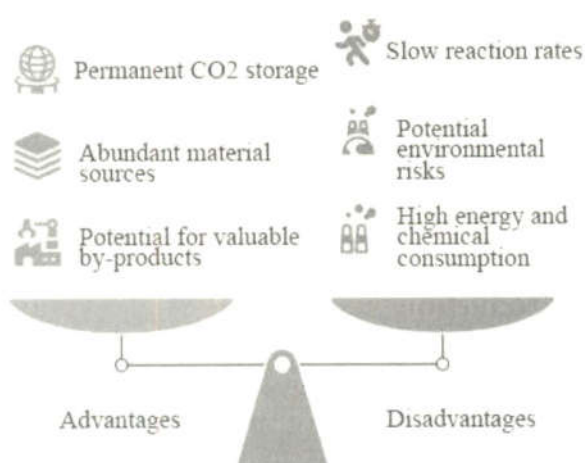


Figure 1. Advantages and Disadvantages of Carbon Mineralization Methods

Indirect: This is a multi-step process that is more complex but can achieve higher efficiency and yield purer carbonate products. The first step involves extracting reactive metal ions—primarily Ca^{2+} and Mg^{2+} —from the mineral structure using chemical solvents such as strong acids (e.g., HCl , HNO_3), weak acids (e.g., acetic acid), or ammonium salt solutions. The metal ion-rich solution is then reacted with CO_2 under controlled pH conditions to precipitate carbonates. This method enables the recovery of high-purity carbonate products, which can be utilized in various industrial applications (ResearchGate, 2022).

Several projects applying carbon mineralization for carbon storage and sequestration are summarized in Table 1.

Table 1. Representative Projects Applying Carbon Mineralization Technology

Project Name	Waste Rock Characteristics	Research Focus of the Project
Arca Project at the Mount Keith Nickel West Mine, BHP (Australia).	The waste rock contains a high concentration of magnesium-rich ultramafic rocks, which enhances the carbon mineralization process.	Natural minerals react with atmospheric CO_2 to form stable crystalline structures. The CO_2 capture capacity of waste rock can be enhanced by up to tenfold. One approach involves using microwave heating to break down the mineral structure of tailings, thereby releasing magnesium and increasing their reactivity with CO_2 .
Study at the King City Asbestos Mine, California (USA).	The mine tailings naturally absorb up to 179 tonnes of CO_2 per year.	Microwave heating is employed to treat mine tailings, breaking down the mineral structure and releasing magnesium, thereby enhancing their reactivity with CO_2 .

2.2. Enhanced Weathering (EW)

a. Mechanisms and Input Materials

Enhanced Weathering (EW) is a carbon dioxide removal technique that accelerates the natural weathering of rocks. The process involves finely grinding silicate rocks (such as basalt or olivine) or alkaline mine waste, which are then layered at disposal sites. When these fine particles come into contact with rainfall and CO_2 from the atmosphere or soil, they undergo chemical reactions that convert CO_2 into dissolved bicarbonate ions (HCO_3^-) or solid carbonate minerals. The bicarbonate ions can subsequently be leached into rivers and, ultimately, the oceans, where they may remain stable for tens to hundreds of thousands of years.

Suitable materials from mine waste for EW include silicate-rich waste rocks capable of reacting with CO_2 , particularly those generated from copper (Cu) and iron (Fe) ore mining, which contain minerals such as plagioclase feldspar, talc, serpentine-chlorite, pyroxene, and amphibole. Ultramafic and mafic rocks also represent promising sources.

b. Benefits and Challenges

Studies on enhanced weathering (EW) have highlighted its benefits and challenges, as illustrated in the following figure.

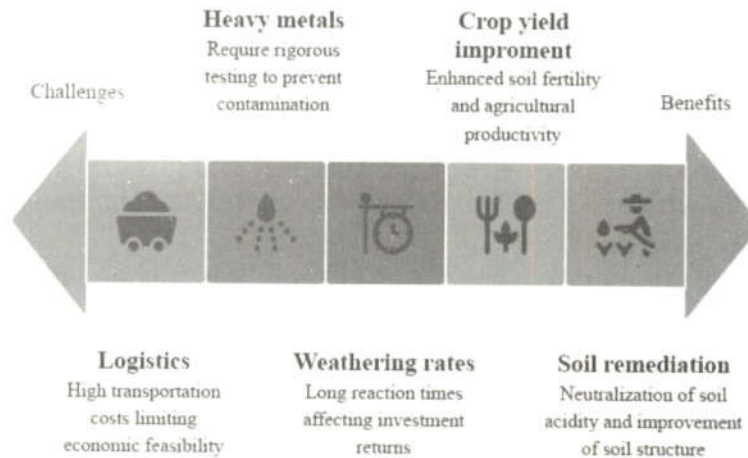


Figure 2. Benefits and Challenges of the Enhanced Weathering Method

Figure 2 illustrates that the dual benefits of enhanced weathering include soil improvement—particularly at open-pit mine waste sites—and, more importantly, the value derived from carbon credits. However, the high costs of grinding and transportation, along with the risk of heavy metal contamination, require rigorous site selection and monitoring protocols. Not all types of mine waste are suitable for this approach. Moreover, the long timescales required for weathering (often 10–20 years or more) can significantly affect the return on investment of enhanced weathering projects.

For enhanced weathering technology, representative studies include the techno-economic analysis conducted by the U.S. National Energy Technology Laboratory (NETL), which considered both natural rocks (dunite, basalt) and industrial by-products (cement kiln dust, biomass ash). Companies such as Mati, InPlanet, and Tropicarbon are pioneering the implementation of EW in tropical regions, where warm and humid climates can accelerate weathering rates and where the demand for soil improvement is also greater.

2.3. Biotechnologies: Bio-absorption and Bioremediation

a. Technological Principles

Biotechnology for carbon storage in mining leverages the capacity of microorganisms—including bacteria, microalgae, and fungi—to capture CO_2 and/or remediate contaminants in mine waste and wastewater. These microorganisms may be naturally occurring strains isolated from mining environments or genetically engineered strains with enhanced desirable traits.

One of the primary mechanisms is enhanced photosynthesis, particularly in microalgae and certain photosynthetic bacteria, where CO_2 is utilized as a carbon source for biomass synthesis. In addition, some microorganisms can be “engineered” or selectively cultivated to consume CO_2 as a feedstock for metabolic processes, generating organic compounds or other useful chemical products. These products may, in turn, be directly applied in the bioremediation of mine pollutants (ResearchGate, 2022).

b. Applications in Mine Waste Management and CO_2 Sequestration

The potential applications of biotechnology in the mining context are as follows:

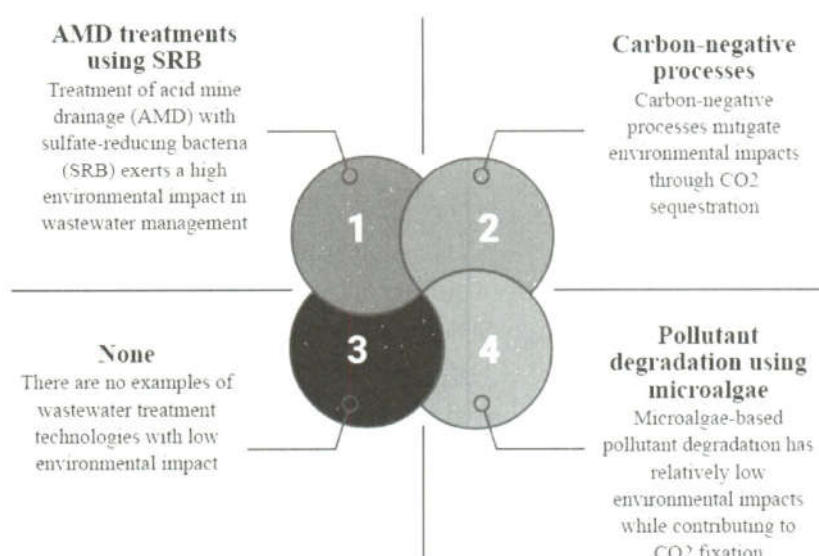


Figure 3. Potential Applications of Biotechnology in Carbon Storage

c. Key Advantages and Challenges of Biotechnology in Carbon Storage

Table 2. Key Advantages and Challenges of Biotechnology in Carbon Storage

Advantages	Challenges
Biotechnology can often be applied directly at mine sites, thereby minimizing the need for waste transportation.	The activity of microorganisms is highly sensitive to environmental conditions at mine sites, such as pH, temperature, oxygen concentration, the presence of toxic substances, and nutrient availability. Maintaining optimal conditions for microbial performance can be both challenging and costly.
It has the potential to address both pollution issues (such as heavy metals and acid) and CO ₂ sequestration.	Mine waste often contains high concentrations of heavy metals and, in the case of acid mine drainage (AMD), exhibits very low pH levels that are toxic to most microorganisms. It is therefore necessary to identify or engineer extremophile strains capable of tolerating such harsh conditions.
Compared with conventional physico-chemical treatment methods, biotechnology may offer lower operating costs in certain cases, particularly when on-site energy resources at the mine can be utilized.	For carbon fixed in microbial biomass, further research is needed on its long-term stability and on strategies to prevent its re-release into the atmosphere during biomass decomposition.

2.4. Carbon Storage in Mine Wastewater

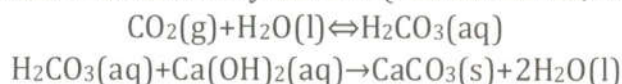
a. Principles of CO₂ Dissolution and Mineralization

Mine wastewater, particularly alkaline effluents, has the capacity to absorb CO₂ either from the atmosphere or from concentrated CO₂ sources. This alkalinity may originate from the processing of certain mineral resources or as a result of treating acid mine drainage (AMD) with neutralizing agents such as lime (Ca(OH)₂).

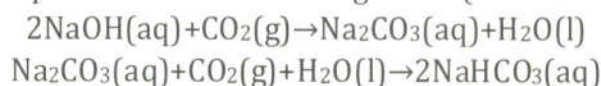
When CO₂ dissolves in water, it forms carbonic acid (H₂CO₃), a weak acid. The carbonic acid then reacts with alkaline components present in the wastewater, such as metal

hydroxides (e.g., $\text{Ca}(\text{OH})_2$, $\text{Mg}(\text{OH})_2$) or dissolved Ca^{2+} and Mg^{2+} ions, to produce sparingly soluble or insoluble carbonate minerals such as calcium carbonate (CaCO_3) and magnesium carbonate (MgCO_3). These carbonate minerals precipitate out of solution, thereby sequestering CO_2 in a stable solid form.

The relevant chemical reactions may include (ResearchGate, 2022):



Alternatively, in the presence of other strong bases (ResearchGate, 2022):



b. Mine wastewater (AMD) treatment combined with CO_2 capture

Acid mine drainage (AMD) is a serious environmental issue at many mining sites. A common treatment method for AMD is the use of lime (CaO or $\text{Ca}(\text{OH})_2$) to neutralize acidity and precipitate heavy metals. The effluent resulting from this treatment typically exhibits an alkaline pH and contains high concentrations of Ca^{2+} and Mg^{2+} ions, providing favorable conditions for subsequent CO_2 mineralization.

Studies have explored the possibility of integrating AMD treatment with CO_2 sequestration:

- **One-pot process:** This approach combines heavy metal removal from AMD (through pH adjustment) with CO_2 mineralization in a single reactor. Such integration can simplify the overall process and reduce costs.

- **Ultrasound application:** The use of ultrasonic waves has been shown to enhance the efficiency and rate of CO_2 mineralization reactions in treated AMD, likely by promoting CO_2 dissolution, particle dispersion, and the formation of new nucleation sites.

- **CO_2 capture and metal removal efficiency:** Studies have reported CO_2 sequestration capacities (e.g., up to 6.992×10^{-4} g- CO_2 /g of raw AMD solution at 80 °C in the one-pot process), along with high heavy metal removal efficiency that meets discharge standards.

3. Overview of Carbon Storage Technologies in Open-Pit Mine Waste Rock

According to Decision No. 625/QĐ-TTg dated March 17, 2025, issued by the Prime Minister approving the Development Strategy of the Vietnam National Coal and Mineral Industries Group (TKV) to 2030, with orientations toward 2045, the strategy explicitly emphasizes “sustainable development of the mining sector in association with environmental protection, minimizing negative impacts on the environment and society.” Specifically, TKV has set targets to improve the stripping ratio in line with techno-economic conditions and planning, optimize the use of internal dump sites, and implement post-mining environmental rehabilitation programs (625/QĐ-TTg, 2025). These orientations are fully aligned with and contribute to Vietnam’s commitment at COP26 to achieve net-zero emissions by 2050. TKV’s strategy also envisions building a model of “Green Mines, Modern Mines, High-Productivity Mines, and Safe Mines,” thereby laying the foundation for the adoption of advanced, environmentally friendly technologies, including carbon storage solutions.

In parallel with TKV’s strategy, the Government of Vietnam has issued key policies to promote greenhouse gas (GHG) emission reduction. Decree No. 06/2022/NĐ-CP provides detailed regulations on GHG mitigation and ozone layer protection, mandating GHG inventories for major emitting facilities and establishing the foundation for the development of a domestic carbon market. The National Climate Change Strategy to 2050 (issued under Decision No. 896/QĐ-TTg) also sets specific emission reduction targets for individual

sectors, including industry and mining. Vietnam's carbon market roadmap is currently being developed, with pilot implementation scheduled for 2025 and full operation expected between 2028 and 2029, creating opportunities for CCUS projects. At present, CCUS research and projects in Vietnam are primarily focused on coal-fired power plants and cement factories. However, given the substantial potential of the mining sector, expanding research and application of CCUS in this field represents a necessary and promising direction.

3.1. Potential for Applying Carbon Storage Technologies in TKV's Open-Pit Mines

Potential of Carbon Mineralization and Enhanced Weathering	Potential of Mine Wastewater Treatment Combined with CO₂ Storage	Potential of Biotechnology
The presence of Ca- and Mg-bearing carbonate minerals (such as ankerite, calcite, and dolomite) and silicate minerals (such as clinocllore, and potentially serpentine-chlorite, talc, pyroxene, and amphibole, if similar to TKV's waste rock types) indicates substantial potential for both carbon mineralization and enhanced weathering technologies. The contents of CaO and MgO in these minerals are the key factors determining their reactivity with CO ₂ .	For mine wastewater, if TKV's operations generate AMD, applying AMD treatment methods that produce alkaline by-products (e.g., lime treatment) would result in effluents enriched in Ca ²⁺ and Mg ²⁺ , which are highly suitable for subsequent CO ₂ mineralization. This opens up the opportunity to simultaneously address two environmental challenges. If TKV also has alkaline wastewater streams from other activities (e.g., mineral processing or downstream beneficiation plants), these effluents could likewise be considered for direct use in CO ₂ absorption.	Although still in its early stages, biotechnology also offers certain promising prospects. The application of specialized microbial strains for the remediation of heavy metal contamination and AMD in TKV's waste dumps and wastewater ponds represents a potential pathway. Such processes could be designed to integrate CO ₂ utilization from nearby emission sources (e.g., coal-fired power plants in the region or exhaust gases from mining equipment) as a carbon source for microorganisms, thereby advancing circular processes with the potential for carbon negativity.

3.2. Key Challenges in Applying Carbon Storage Technologies in TKV's Open-Pit Mines

The challenges of adopting and implementing carbon storage technologies in TKV's open-pit mines arise from the following four groups of factors:

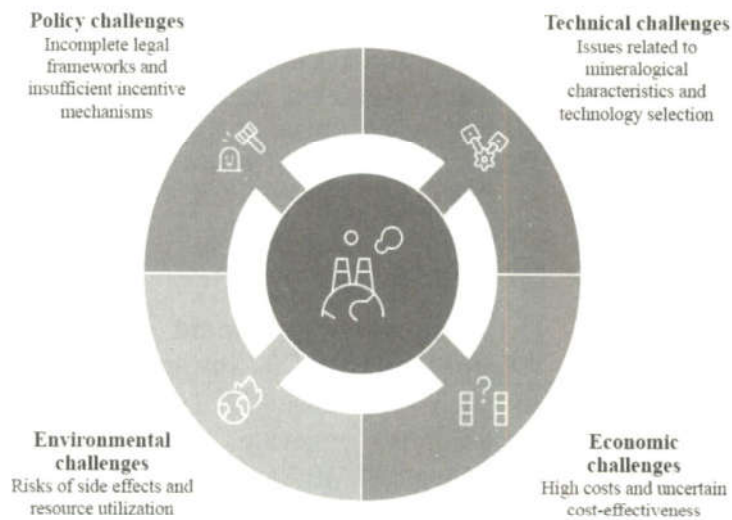


Figure 4. Key Challenges in Applying Carbon Storage Technologies

a. Technical Challenges

Heterogeneous characteristics of waste rock	Selection of the optimal technology	Process optimization	Challenges of large-scale implementation	Lack of detailed data
The mineralogical and chemical composition of waste rock can vary significantly between different mines, across distinct areas within the same mine, or with the depth of overburden layers. This heterogeneity necessitates costly and detailed survey and characterization programs before an appropriate	Given the diversity of carbon storage technologies (direct/indirect mineralization, enhanced weathering, biotechnology, and wastewater treatment), selecting the most suitable solution for the specific conditions of each mine—such as waste rock type, scale, existing infrastructure, and investment and operating costs—is a	Operational factors such as particle size, temperature, pH, CO ₂ pressure, reaction time, liquid-to-solid ratio, and the use of additives need to be systematically investigated and optimized in order to maximize CO ₂ sequestration efficiency while minimizing costs.	Scaling up technologies from laboratory or pilot scale to full industrial implementation represents a significant leap, requiring the resolution of numerous challenges related to large-scale equipment design and fabrication, automation, process control, waste stream management, and operational safety assurance.	At present, publicly available data on the precise mineralogical composition—particularly the content of highly reactive silicate minerals such as olivine and serpentine—and the total concentrations of CaO and MgO in waste rock remain limited. This represents a major barrier to reliably assessing the potential of

technology can be selected and designed..	complex decision requires thorough technical and economic evaluatio.	that and	carbon storage technologies.
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b. Economic Challenges

High investment and operating costs	Uncertain economic viability	Limited access to financing for large-scale projects
Carbon storage technologies, particularly carbon mineralization processes, often require substantial upfront investment in equipment (e.g., crushers, control systems) as well as significant operating expenditures, including energy for grinding and heating, chemical reagents, and labor	The current price of carbon credits in both international markets and the emerging domestic market in Vietnam may not yet be sufficient to fully offset the capital and operating costs of large-scale carbon storage projects. Therefore, financial support mechanisms from the government are needed, or alternative revenue streams must be pursued, such as the sale of value-added by-products (e.g., construction materials)	Mobilizing substantial investment capital for pilot projects and large-scale industrial deployment poses a considerable challenge, particularly for technologies that are still relatively new and carry certain risks.

c. Environmental Challenges

Management of ancillary risks	Energy and other resource consumption	Landscape alteration and land use change
The processes of mining, transporting, and handling waste rock can generate dust emissions, particularly fine particles and dust containing hazardous components such as asbestos fibers (if present in the waste rock) or heavy metals. Moreover, mineralization or weathering processes may increase the solubility and	Crushing, heating or CO ₂ injection operations can consume substantial amounts of energy. If this energy is not sourced from renewables, the carbon storage process itself may generate additional CO ₂ emissions, thereby increasing the carbon footprint of the system. Furthermore, certain aqueous mineralization processes also require	The construction of large-scale waste rock treatment facilities or areas designated for spreading rock in enhanced weathering applications can occupy substantial land areas and alter the local landscape.

leaching of heavy metals considerable volumes of from waste rock into water. surrounding water bodies if not carefully controlled.

d. Policy and Regulatory Challenges

Incomplete regulatory framework	Incentive and support mechanisms	Management and monitoring capacity
At present, Vietnam lacks specific regulations, technical standards, and guidelines for the appraisal, licensing, operation, and monitoring of carbon storage projects in mine waste sites. This regulatory gap creates uncertainty for investors and enterprises.	To promote the deployment of these technologies, preferential policies on taxation, fees, land access, and financial support for R&D and pilot projects are required. A clear and attractive carbon credit mechanism for CO ₂ removal projects utilizing mine waste must also be established.	It is necessary to strengthen the capacity of government regulatory agencies at both central and local levels, as well as of TKV itself, in technology appraisal, environmental impact assessment, licensing, and monitoring of carbon storage projects, in order to ensure compliance with safety and environmental standards.

Table 3. SWOT Analysis of Carbon Storage Deployment in TKV's Mines

Strengths	Weaknesses
1. Vast quantities of waste rock and tailings readily available as a low-cost feedstock. 2. Strong commitment from TKV and the Government of Vietnam to sustainable development and Net Zero goal. 3. Extensive experience in managing large-scale mining operations and waste management. 4. Existing basic infrastructure (e.g., transportation routes, hauling and loading equipment) at mine sites. 5. Favorable mineralogical potential (carbonate and Ca-, Mg-bearing silicate minerals).	1. High capital and operating costs associated with carbon storage technologies. 2. Lack of detailed and comprehensive data on the physico-chemical characteristics of waste rock, tailings, and wastewater at many mines for carbon storage purposes 3. Limited practical experience and shortage of specialized human resources in emerging CCS/CCUS technologies 4. Heterogeneity of waste rock, requiring customized solutions for each mine or waste type. 5. Potential risks of AMD generation and heavy metal pollution from waste rock.
Opportunities	Threats
1. Growth of domestic and international carbon markets, creating revenue streams from carbon credits.	1. Ancillary environmental risks (e.g., dust emissions, water pollution) if not properly managed.

2. Government policies and incentives supporting emission reduction projects and green technologies. 3. Potential to generate value-added by-products from mineralization processes (e.g., construction materials, chemicals) 4. International collaboration in research, technology transfer, and financing with experienced partners. 5. Enhanced corporate image and reputation of TKV in environmental responsibility and sustainable development. 6. Contribution to national climate change and sustainable development goals.	2. Carbon credit prices may be unstable and insufficiently attractive to offset costs. 3. Competition from alternative emission reduction solutions with lower costs or higher technology readiness levels (TRLs). 4. Incomplete and unclear legal and regulatory framework for CCS/CCUS from mine waste in Vietnam. 5. High energy and resource (e.g., water) requirements for carbon storage processes..
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4. Proposed Roadmap for Research and Deployment of Carbon Storage Technologies in TKV's Open-Pit Mines

To harness the potential of carbon storage from mine waste while addressing the opportunities and challenges identified in the SWOT analysis (Table 4), research on carbon storage for TKV's open-pit mines requires a systematic, science-based strategy with a clear roadmap. A phased approach—starting with comprehensive on-site studies and characterization before committing to large-scale pilot projects—is essential to minimize investment risks and ensure that the selected technologies are truly compatible with the unique geological and operational contexts. This approach helps avoid costly failures that may arise from applying “off-the-shelf” solutions without proper adaptation.

4.1. Research and Development (R&D)

This is a foundational step that will be decisive for the success of subsequent phases in the roadmap (Figure 4).

- Phase 1 – Comprehensive Waste Rock and Wastewater Characterization

Program: A large-scale R&D initiative should be launched, focusing on representative sampling, surveying, and detailed analysis of mineralogical composition—particularly Mg-, Ca-, and Fe-bearing reactive minerals such as olivine, serpentine, pyroxene, ankerite, dolomite, and calcite; the contents of major oxides (CaO, MgO, FeO, Fe₂O₃, SiO₂, Al₂O₃); trace elements (especially heavy metals with potential environmental risks); acid generation potential (from sulfide minerals such as pyrite); and the intrinsic buffering capacity of waste rock and tailings from all major open-pit mines. Similarly, detailed chemical analysis of key wastewater streams is required, including pH, alkalinity, Ca²⁺, Mg²⁺, SO₄²⁻, heavy metals, and flow rates.

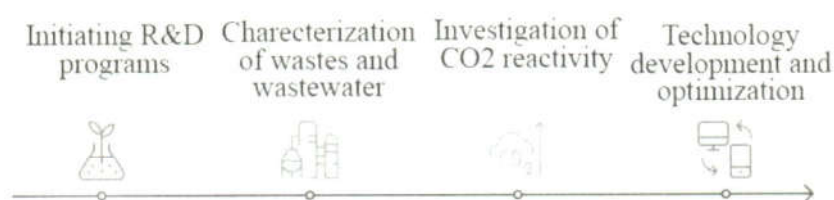


Figure 5. R&D Framework for Carbon Storage Applications

- **Phase 2 – Investigation of Waste Rock Reactivity with CO₂:** In parallel with characterization, laboratory-scale experiments should be conducted to assess the actual reactivity of representative waste rock types from TKV's open-pit mines with CO₂. These experiments should examine the influence of different conditions (temperature, pressure, particle size, pH, reaction time, CO₂ concentration, and liquid-to-solid ratio) on the efficiency and rate of carbon mineralization and enhanced weathering technologies.

- **Phase 3 – Development and Optimization of Suitable Technologies:** Collaboration with leading national research institutes (e.g., the Institute of Geological Sciences and Mineral Resources, technical universities) and experienced international partners (universities, research institutes, and technology companies involved in similar projects) is needed to research, transfer, adapt, and optimize carbon storage technologies so that they are best suited to the specific waste rock, wastewater, and operational conditions of TKV,

4.2. Pilot Projects

Once sufficient data have been obtained from the R&D phase and the most promising waste rock/wastewater types and suitable technologies have been identified, pilot projects should be implemented.

- **Phase 1 – Selection of Pilot Sites:** One or two open-pit mines with the most favorable conditions should be carefully selected—based on waste rock analysis, dump site scale, existing infrastructure, and the readiness of the mine operators—for the implementation of pilot projects. Potential technologies for pilot testing may include ex-situ carbon mineralization applied to a portion of waste rock, small-scale in-situ mineralization in a selected dump area, enhanced weathering over a limited surface, or mine wastewater treatment integrated with CO₂ sequestration.

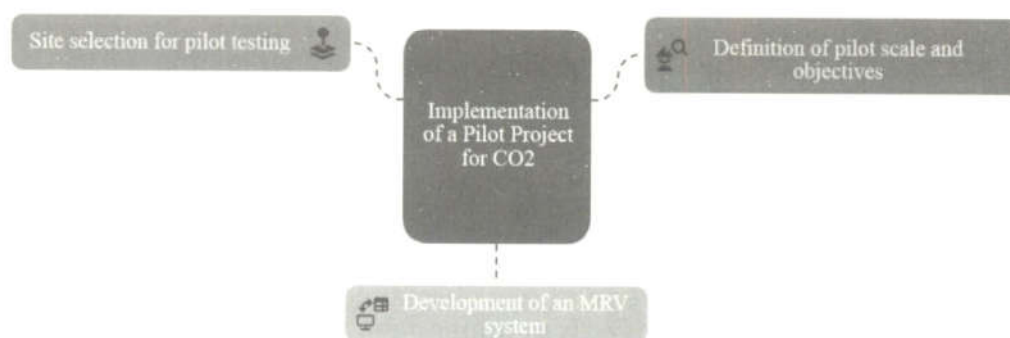


Figure 6. Implementation of Pilot Projects for CO₂ Storage Technologies

- **Phase 2 – Determination of Pilot Scale and Objectives:** The pilot project must be of sufficient scale to reliably evaluate key technical parameters (CO₂ sequestration efficiency, reaction rates, and product stability), actual operating costs, potential environmental impacts (e.g., dust emissions, metal leaching, energy and water consumption), and the feasibility of scaling up to industrial applications.

- **Phase 3 – Development of Monitoring, Reporting, and Verification (MRV) System:** A rigorous, science-based, and transparent MRV system is essential for pilot projects. This system should continuously track the amount of CO₂ sequestered, changes in the chemical composition of waste rock/wastewater, surrounding environmental quality, and other operational indicators. Data generated from MRV will provide a critical basis for evaluating performance and refining the technology.

4.3. Proposed Research Roadmap

An implementation roadmap can be divided into three main phases, as illustrated in Figure 7.

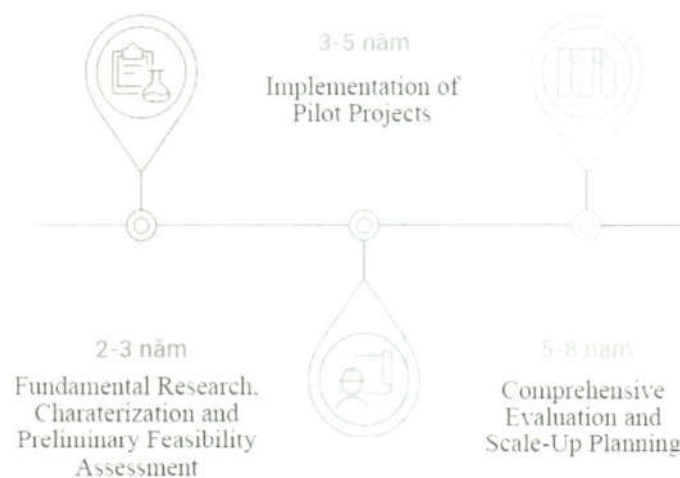


Figure 7. Research and Application Roadmap for Carbon Storage Technologies in TKV's Open-Pit Mines

Phase 1 (2–3 years): Fundamental Research, Characterization, and Preliminary Feasibility Assessment	Phase 2 (3–5 years): Implementation of Pilot Projects	Phase 3 (after 5–8 years): Comprehensive Evaluation and Scale-Up Planning
- Focus on R&D activities outlined in Section 4. - Complete detailed characterization of waste rock, tailings, and wastewater at key open-pit mines. - Conduct laboratory-scale reactivity studie. - Develop preliminary techno-economic models to assess the feasibility of the most promising technologie. - Identify priority sites and technologies for the pilot phase.	- Design, construct, and operate the selected pilot projects. - Systematically collect data on operations, technical performance, costs, and environmental impacts through the MRV system. - Optimize technological parameters based on actual results. - Conduct life cycle assessment (LCA) and detailed techno-economic analysis of the pilot technologies.	- Based on comprehensive results from the pilot projects, conduct an overall assessment of the technical, economic, social, and environmental performance of each technology. - Develop specific plans and roadmaps for scaling up the most effective technologies across other TKV mines. - Integrate carbon storage solutions into TKV's long-term development strategy and annual business plans.

5. Conclusions

Research on carbon storage technologies—including carbon mineralization (both direct and indirect, in-situ and ex-situ approaches), enhanced weathering, biotechnology-based solutions, and mine wastewater treatment integrated with CO₂ capture—demonstrates that each option has distinct principles, advantages, limitations, costs, and

levels of technological readiness. For TKV's open-pit mines (both coal and mineral operations), the potential for application is substantial. The vast annual volume of waste rock, together with the presence of calcium- and magnesium-bearing minerals, provides a solid basis for carbon mineralization and enhanced weathering. Mine wastewater, particularly alkaline streams or effluents generated after AMD treatment, also offers opportunities for CO₂ absorption. However, the deployment of these technologies within TKV faces multiple challenges, including technical, economic, environmental, and regulatory barriers. Targeted research is therefore required to clarify and address each of these challenges.

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