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Some technological orientations for safe and environmentally friendly mining technology of coastal placer titanium deposits in Vietnam

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ABSTRACT

Vietnam possesses significant potential in coastal placer titanium resources, particularly in central provinces such as Binh Thuan, Binh Dinh, and Khanh Hoa. However, current mining operations mainly rely on outdated technologies with low recovery efficiency and cause serious environmental consequences, including degradation of soil and water quality, ecological disruption, and radiation safety concerns. This paper synthesizes and analyzes several technological orientations for safe and environmentally friendly mining technology, aiming to modernize the titanium mining sector in Vietnam towards sustainability.

Based on geological surveys of two representative regions (Binh Dinh and Binh Thuan), the study proposes suitable mining and processing equipment to enhance the recovery of heavy minerals while minimizing land and water impacts. The integration of gravity, magnetic, electrostatic separation technologies, alongside the control of natural radiation from monazite and xenotime, is recommended as an essential step in radiation safety management. Geotechnical modeling tools such as Plaxis and Geo-Slope assist in designing stable mine slopes, thereby reducing the risks of landslides and subsidence. A water circulation system integrated with IoT-based sensors helps conserve water resources and minimize effluent discharge. Furthermore, ecological restoration solutions using native plant species, biochar materials, and radiation-degrading microorganisms have proven effective in soil improvement and post-mining ecosystem rehabilitation. Notably, the application of artificial intelligence and machine learning models (e.g., Random Forest, Artificial Neural Networks, XGBoost) enables accurate prediction of mineral distribution, supporting optimal mine planning and design.

The findings serve as a critical foundation for advancing safe and environmentally friendly titanium placer mining technology in coastal Vietnam, contributing to a green, intelligent, and sustainable development trajectory in the era of digital transformation and circular economy.

Keywords: Ecological restoration, Environmentally friendly and safe, Mining technology, Placer titanium, Water circulation.

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1. Introduction

Placer titanium is considered one of Vietnam's strategic mineral resources, playing a critical role in supplying raw materials for the pigment, metallurgy, electronics, and aerospace industries. With an estimated reserve of approximately 664 million tons of ore, these deposits are primarily distributed along the central coastal provinces such as Binh Dinh, Khanh Hoa, Binh Thuan, and Ninh Thuan. The ore bodies predominantly consist of ilmenite (FeTiO_3), accounting for 53–91% of the mineral composition, accompanied by zircon, rutile, monazite, and anatase (Institute of Mining and Metallurgical Science and Technology, 2016; Le Qui Thao et al., 2014).

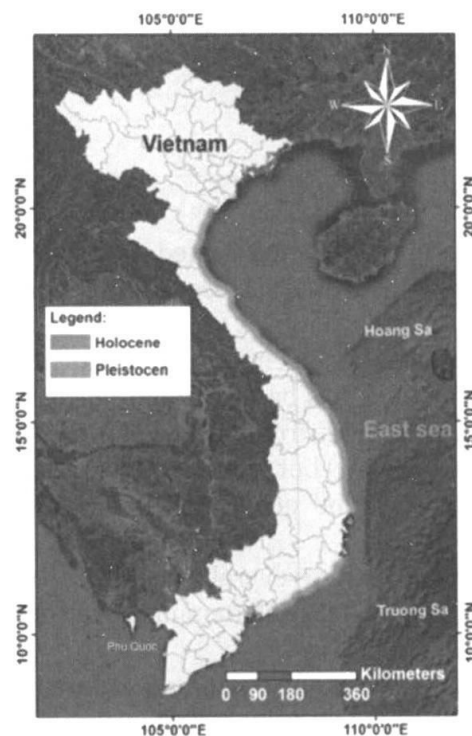


Figure 1. Distribution of coastal placer titanium deposits in Vietnam (Qui-Thao Le et al., 2020)

Vietnam is considered one of the countries with the greatest potential for coastal placer titanium resources globally. However, the development of the domestic titanium mining sector still faces numerous limitations, particularly in terms of technology, extraction efficiency, and environmental impact. Most titanium placer mines in Vietnam still employ traditional extraction techniques such as dredge pumping, gravity separation, and magnetic-electrostatic separation. These operations are typically small-scale, scattered, and lack integrated environmental monitoring and treatment systems. Consequently, mineral recovery rates remain low, resource losses are substantial, and significant environmental issues have emerged, including excessive water consumption, terrain erosion, the release of naturally occurring radioactive materials, soil degradation, and disruption of local ecosystems. These consequences not only increase post-mining remediation costs but also pose long-term threats to public health and the sustainable development of coastal regions, which are already highly sensitive to climate change and water scarcity (Vietnam Union of Science and Technology Associations, 2007).

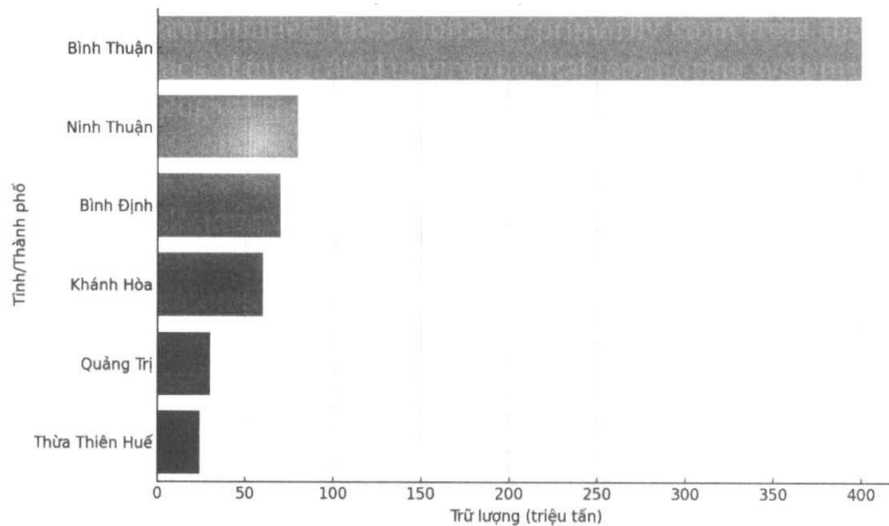


Figure 2. Reserves of coastal placer titanium in selected coastal provinces of Vietnam (Institute of Mining and Metallurgical Science and Technology, 2016).

In this context, the urgent need for technological innovation toward safe, intelligent, and environmentally friendly titanium mining has become increasingly apparent. This demand is not only driven by legal obligations under national environmental and mining laws (e.g., the 2010 Mineral Law and the 2020 Environmental Protection Law) but also constitutes a prerequisite for the titanium industry to integrate into global supply chains and access markets with strict environmental and social responsibility standards.

This paper aims to synthesize and analyze several technological orientations that have the potential to improve both the efficiency and sustainability of titanium placer mining in Vietnam. The key focus areas include:

- Selection of mining and mineral processing equipment tailored to local geological conditions;
- Control of radiation hazards and management of radioactive mineral components;
- Application of geotechnical modeling tools (e.g., Plaxis, Geo-Slope) to ensure slope stability and prevent geohazards;
- Development of water recirculation systems integrated with IoT-based environmental monitoring;
- Ecological restoration using bio-based solutions, such as biochar and radiation-degrading microorganisms; and
- Application of artificial intelligence and machine learning to construct spatial mineral grade maps to support optimal mine design.

By analyzing both domestic and international case studies, particularly in the actively mined provinces of Binh Thuan, Binh Dinh, and Khanh Hoa, this study provides a comprehensive overview of cutting-edge technological trends in titanium mining. It further proposes a practical implementation roadmap adapted to Vietnam's unique geological and socio-economic conditions, thereby contributing to the advancement of a modern, efficient, and sustainable titanium industry.

2. Current Mining Practices and Environmental Issues

Vietnam possesses significant potential in coastal placer titanium resources, particularly concentrated in the central and south-central coastal provinces. However, the current mining activities of this mineral are causing substantial negative impacts on both the natural environment and local communities. These impacts primarily stem from the use of outdated mining technologies, the lack of integrated environmental monitoring systems, and the absence of a clear roadmap for ecological restoration (Figure 3).

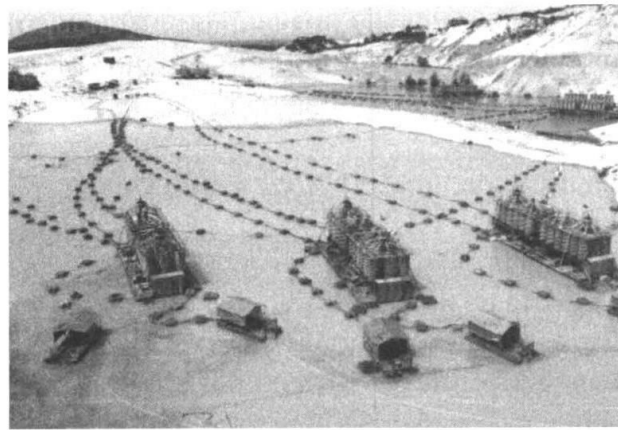


Figure 3. Current status of titanium mining in Binh Thuan Province (Tuoi Tre Online, July 9, 2017)

2.1. Water Consumption and Liquid Waste Generation in Titanium Mining

In general, coastal placer titanium mining involves four main stages: ore breaking, transportation, primary concentration, and sand tailings discharge. At each of these stages, both mechanical equipment and hydraulic methods may be employed (Figure 4). In Vietnam, the predominant method currently used for coastal placer titanium extraction is dredge pumping, followed by gravity concentration using spiral classifiers and shaking tables, and subsequently by magnetic and electrostatic separation to recover heavy minerals, such as ilmenite, leucoxene, rutile, and zircon.

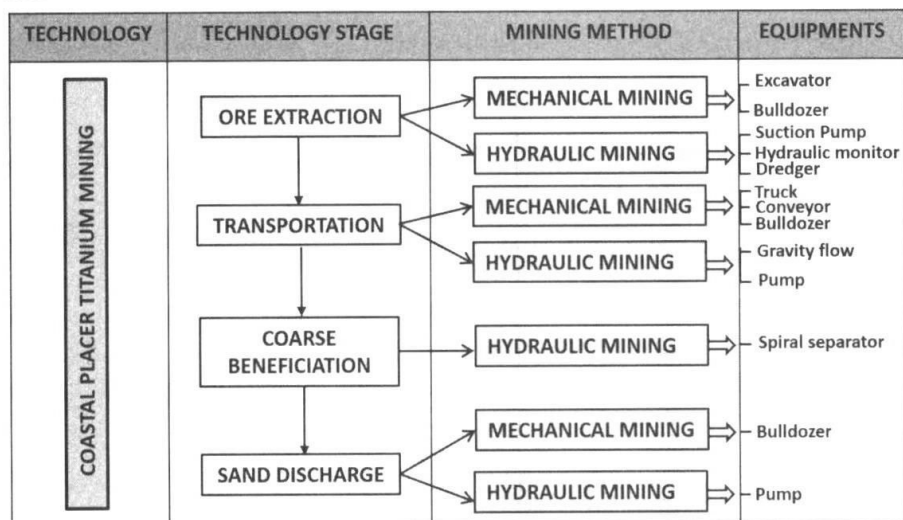


Figure 4. General process diagram of coastal placer titanium mining technology (Le Qui Thao et al., 2015)

However, this process requires a substantial volume of clean water to operate machinery and wash ores, typically between 300 and 400 m³ per ton of run-of-mine ore. Excessive water consumption in water-scarce areas such as Bac Binh (Binh Thuan Province) places considerable pressure on groundwater resources, leading to declining water tables, saltwater intrusion, and negative impacts on local agriculture.

Moreover, due to the absence of standardized water recirculation or wastewater treatment systems, wastewater is frequently discharged directly into the environment. In many cases, the discharged water contains elevated concentrations of suspended solids, naturally occurring

radioactive minerals such as monazite and xenotime, and heavy metal compounds including Fe and Mn often exceeding permissible environmental limits. This issue is particularly severe in mining sites located near residential areas, resulting in pollution of ponds and lakes and posing serious risks to public health (Institute of Mining and Metallurgical Science and Technology, 2016).

2.2. Terrain Deformation, Erosion, and Pit Slope Failures

Most mining operators do not conduct comprehensive geotechnical investigations or apply geotechnical modeling tools such as Plaxis or Geo-Slope. As a result, pit slope designs often fail to meet stability criteria, leading to severe erosion and landslides, especially during the rainy season. In several sites such as Pho Yen (Khanh Hoa) and My Thanh (Binh Dinh), heavy rainfall has triggered mass movements of excavated materials into adjacent areas, damaging local infrastructure and threatening worker safety (Nguyen Hoang et al., 2015).

In addition, improper leveling and earthworks have altered surface flow patterns and natural drainage paths, causing the formation of deep gullies, topsoil erosion, and sedimentation in irrigation canals. In Binh Thuan Province, post-mining erosion rates have been recorded at up to 80 tons/ha/year, well above acceptable limits.

2.3. Ecological Degradation and Ineffective Rehabilitation

One of the major challenges in titanium placer mining is ecological restoration following site closure. According to Le Thi Le (2019), more than 70% of post-mining land in Binh Thuan Province remains unvegetated or is only superficially covered with grasses, which are insufficient for restoring natural ecosystems. Post-mining soils are typically nutrient-poor, lacking organic humus, and dominated by sand, which results in low water retention capacity and poor vegetation growth.

Moreover, local ecosystems, both flora and fauna, are significantly disrupted. Many native species have disappeared due to habitat destruction, and no effective measures have been implemented to reestablish ecological balance. The study recommends the use of biological materials such as biochar to improve soil physico-chemical properties and the application of mineral-decomposing microorganisms to support natural rehabilitation processes. However, in practice, these solutions have not been widely implemented due to funding limitations and the absence of local government support mechanisms.

2.4. Radiation Risks and Inadequate Environmental Monitoring Systems

Among the associated minerals in ilmenite and zircon concentrates, monazite often contains thorium (Th) and uranium (U) at concentrations ranging from 0.1% to 0.5%, exceeding safety thresholds when accumulated in significant quantities. The lack of segregation and containment of radioactive minerals poses a high risk of radiation dispersion into air, groundwater, and local ecosystems through bioaccumulation.

Nevertheless, most current mining sites do not employ personal radiation monitoring for workers, nor do they install radiation detection equipment in processing or storage areas. This increases occupational hazards and potential public health risks. As highlighted in the 2022 report by the Department of Information and Statistics, the environmental monitoring and radiation safety management systems at titanium mines in Vietnam remain highly fragmented and insufficient.

In summary, the environmental status of coastal placer titanium mining in Vietnam presents numerous challenges that require urgent intervention through comprehensive policies, advanced technologies, and firm commitment from mining operators. If left unaddressed, the

cumulative impacts on water, soil, ecosystems, and public health could severely compromise the sustainable development potential of Vietnam's titanium industry.

3. Environmentally Friendly Mining Technology Directions

3.1. Selection of Equipment Appropriate to Geological Conditions

The selection of titanium mining equipment should be based on the specific geological characteristics of each region to ensure economic and technical efficiency while minimizing environmental impact (Le Qui Thao, 2020). In Vietnam, two typical regions for titanium mining in Binh Dinh and Binh Thuan provinces, exhibit distinct geological conditions, requiring different technical solutions and equipment configurations.

3.1.1. Binh Dinh Region

In the coastal area of Binh Dinh, titanium ore typically lies at greater depths (6–10 m), covered by thick clayey silt layers and unevenly distributed. Mining in this environment faces challenges related to ground stability, ore body accessibility, and the management of clay-laden wastewater. The recommended equipment for this area includes:

- High-capacity modern slurry pumps capable of operating in both diluted and dense sludge environments, combined with flexible soft piping systems;
- Multi-stage gravity separation systems designed to efficiently extract heavy minerals even under conditions of non-uniform input materials;
- Sedimentation ponds with water recirculation systems to enable reuse of process water, reduce freshwater demand, and prevent surface water pollution.

3.1.2. Binh Thuan Region

In contrast, titanium ore in Binh Thuan is found at shallow depths (1–3 m), within homogenous red sand formations and under relatively stable topographic conditions. This allows for the application of strip mining technology with inclined surfaces to optimize mineral recovery while limiting erosion. The technical approach includes:

- Designing the working surface with a stable inclined slope ($\sim 15\text{--}25^\circ$) to guide sand flow toward a centralized recovery system;
- Crawler excavators and mobile screening–washing units, which are well-suited to coastal terrain and offer ease of maintenance;
- Combined magnetic and electrostatic separation systems to enhance the recovery of ilmenite, rutile, and zircon from red sand deposits.

Table 1. Technical Comparison between Binh Dinh and Binh Thuan Mining Areas

Technical Criteria	Binh Dinh (deep ore, clayey silt)	Binh Thuan (red sand, shallow depth)
Mining depth	6–10 m	1–3 m
Terrain type	Flat, weak ground	Stable, red sand
Main ore types	Ilmenite, rutile mixed with clayey silt	Ilmenite, zircon in red sand
Primary equipment	Slurry pumps, gravity separation systems	Excavators, magnetic–electrostatic separators
Water system	Settling ponds with water recirculation	Water-saving, no complex recirculation needed
Estimated recovery efficiency	70–80%	85–90%

The selection of appropriate equipment and technologies for titanium mining must be based on detailed geological surveys and assessments of the ore-bearing strata (Le Qui Thao, 2020). Solutions such as the use of high-pressure slurry pumps in Binh Dinh and inclined-strip mining with stable slopes in Binh Thuan have proven to be highly effective. These methods can significantly reduce environmental impacts when combined with water recirculation systems and proper waste rock management.

3.2. Mineral Separation and Radiation Control

Vietnam's titanium placer deposits commonly contain a mixture of heavy minerals, including ilmenite, rutile, zircon, monazite, and xenotime. Among these, monazite and xenotime may contain radioactive elements such as thorium (Th) and uranium (U), which must be separated and handled in accordance with nuclear and radiation safety regulations.

3.2.1. Heavy Mineral Separation Technologies

The beneficiation process for heavy minerals typically involves three main stages:

- Gravity separation: Equipment such as shaking tables, spiral concentrators, or screw classifiers are used to perform primary separation of heavy minerals from sand, based on differences in specific gravity. This stage produces a mixed concentrate of ilmenite, zircon, monazite, rutile, and xenotime;
- Magnetic separation: Magnetic separators are used to isolate strongly magnetic ilmenite from the remaining minerals. Low-intensity magnetic separation (~0.5–1 Tesla) targets ilmenite, while high-intensity separation can extract weakly magnetic minerals such as xenotime;
- Electrostatic separation: This technique exploits differences in surface electrical conductivity to separate rutile (high conductivity) from zircon (low conductivity), and simultaneously isolate monazite and xenotime into a distinct radioactive fraction.

3.2.2. Handling and Control of Radioactive Minerals

Monazite and xenotime typically contain ThO₂ concentrations ranging from 3–10%, potentially higher depending on the deposit, and may emit alpha radiation. According to Circular No. 19/2020/TT-BKHCN issued by the Ministry of Science and Technology, minerals with specific radioactivity exceeding 1 Bq/g must be classified as Naturally Occurring Radioactive Materials (NORM) and managed under strict regulatory control.

The following steps are recommended for safe handling:

- Segregation of monazite and xenotime after electrostatic separation using specialized conveyors and designated storage areas;
- Temporary storage in isolated zones with radiation shielding (typically >1 m of clay or concrete) and monitoring systems including handheld detectors or fixed radiation sensors;
- Periodic reporting of radiation concentration and documentation submitted to regulatory authorities (e.g., the Department of Radiation and Nuclear Safety);
- Collaboration with licensed NORM handling entities, such as the Institute for Rare Radioactive

Technology, for chemical treatment, immobilization, or transport for safe disposal in compliance with national regulations. Radiation control during titanium mining is not only a legal obligation but also a critical factor in protecting the health of workers and nearby communities. Therefore, in addition to investing in modern mineral processing systems, mining enterprises must enhance their capacity for radiation environmental monitoring, provide

specialized training in radiation safety, and implement integrated management systems based on ISO 14001 and ISO 45001 standards. These measures are essential to ensure safe and sustainable titanium mining operations.

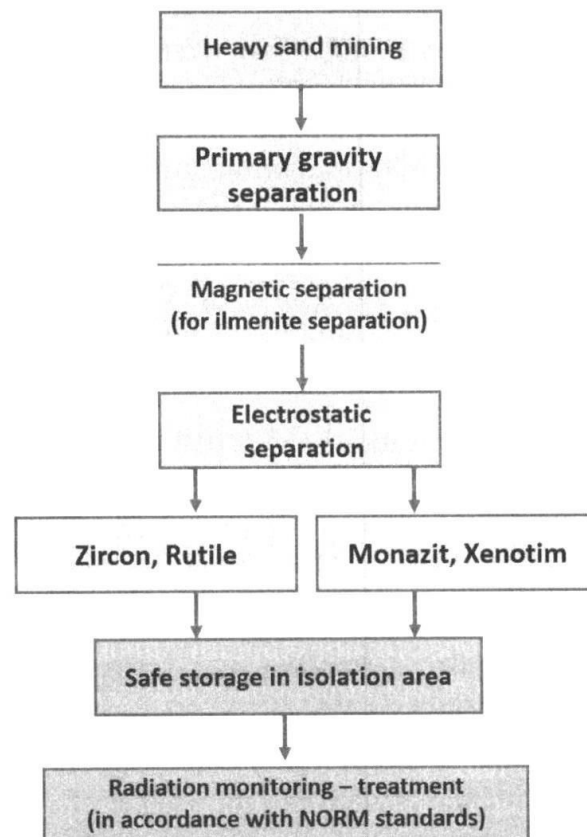


Figure 5. Flow diagram of mineral separation and radiation control

3.3. Slope Stability Simulation

In coastal placer titanium mines in Vietnam, the geological setting typically consists of unconsolidated sedimentary layers, including sand, sandy silt, organic clay, and shallow groundwater tables. As a result, there is a high risk of slope failure, excavation base subsidence, or groundwater intrusion undermining mine structures if designs are not properly engineered. Specialized geotechnical software such as Plaxis (Finite Element Method – FEM) and Geo-Slope (Limit Equilibrium Method – LEM) are widely used for simulating and designing safe pit slope configurations.

3.3.1. Simulation Using Plaxis (FEM – Finite Element Method)

Plaxis 2D/3D enables the nonlinear deformation modeling of soil behavior under various loading conditions. In titanium mining applications:

- The typical geological cross-section includes:
 - + A fine sand layer ($\gamma = 17.5 \text{ kN/m}^3$; $\phi = 30^\circ$; $c = 1 \text{ kPa}$);
 - + A weak clayey silt layer ($\gamma = 16.0 \text{ kN/m}^3$; $\phi = 18^\circ$; $c = 5 \text{ kPa}$);
 - + An underlying stiff clay layer ($\phi = 25^\circ$; $c = 15 \text{ kPa}$).
- Loading from slurry pumps or heavy machinery is modeled as either uniformly distributed or concentrated loads.
- Groundwater levels fluctuate between 0.5–1.5 m, significantly affecting slope stability.

Simulation results by Pham Van Viet et al. (2017) indicate:

- With an inclined slope of 27–30°, excavation heights ≤ 8 m, and a factor of safety (FS) ranging from 1.31 to 1.45, the design meets Vietnamese standards (TCVN 9437:2012) without requiring reinforcement;

- When excavation height exceeds 10 meters or groundwater levels rise, FS drops to 1.1–1.2, indicating a marked increase in instability risk.

3.3.2. Analysis Using Geo-Slope (SLOPE/W – Limit Equilibrium Method)

Geo-Slope (SLOPE/W) applies limit equilibrium methods such as Bishop, Janbu, and Morgenstern-Price to evaluate FS along potential slip surfaces in slope cross-sections. This software is particularly effective for:

- Optimizing pit slope angles: determining safe slope configurations for various soil types;
- Assessing the influence of groundwater, rainfall, and erosion: incorporating water table levels, permeability coefficients, and saturation lines into stability analysis.

This study also found that:

- With slope angles of 25–28°, excavation heights of 6–8 m, and groundwater controlled via dewatering wells, FS ranges from 1.4 to 1.6;

- In the absence of a drainage system, FS decreases to around 1.2, indicating a risk of localized slope failure.

Table 2. Summary of Pit Slope Stability Simulations under Different Scenarios

Simulation Scenario	Software	Slope Angle (°)	Height (m)	Groundwater	FS (Safety Factor)	Recommended Measures
Dry conditions, stable sandy base	Plaxis	30	8	No	1.45	No reinforcement needed
High groundwater level	Plaxis	30	8	Yes	1.20	Bench slope design, lower groundwater table
Clayey silt base, high excavation level	Geo-Slope	25	10	Yes	1.10	Dewatering, gentle slopes, embankment construction
Slurry-based strip mining, weak bottom	Geo-Slope	26	6	Yes	1.30	Stepwise excavation, avoid intensive mining operations

Technical Recommendations:

- Develop a comprehensive slope stability mapping system for the entire mining area, updated regularly in accordance with operational phases;

- Install a monitoring system for displacement and groundwater levels, with data integrated into real-time FS prediction software;

- Apply strip mining techniques instead of full-surface excavation to prevent large-scale slope instability and collapse;
- Enhance the use of 3D modeling technologies, integrating Plaxis and Geo-Slope simulations for cross-validation to increase reliability.

3.4. Water Recirculation

In titanium mining and processing, particularly in gravity, magnetic, and electrostatic separation-water plays an essential role, typically accounting for 70–80% of the input mass in wet processing systems. Uncontrolled water usage can lead to several adverse consequences:

- Increased operating costs due to pumping, treatment, and supply requirements;
- Environmental pollution risks from wastewater containing fine sediments and chemicals;
- Depletion of freshwater resources, especially in coastal areas such as Binh Thuan and Ninh Thuan, where hydrological conditions are limited.

To address these issues, many enterprises have adopted closed-loop water recirculation systems that incorporate sedimentation, filtration, sludge separation, and smart monitoring via IoT. These systems aim to reuse over 50% of the consumed water while significantly reducing environmental discharge.

3.4.1. Structure of the Water Recirculation System

The water recirculation system in titanium processing typically comprises the following components:

- Wastewater collection channels from the processing system: slurry-laden water is conveyed through pipelines to the primary settling tank;
- Primary and secondary settling tanks: solid particles and fine sediments are separated, while clarified water is collected from the upper layers;
- Sludge separation devices (e.g., filter presses, hydrocyclones): these help reduce Total Suspended Solids (TSS) to <50 mg/L in the recycled water;
- Clean water storage tanks: clarified water is pumped back into the processing system for reuse;
- Pipeline networks, pumps, and control valves: ensure efficient flow management between system components;
- IoT-based monitoring sensors: integrated sensors measure real-time flow rates, pH, turbidity, and leakage, enhancing operational control and efficiency.

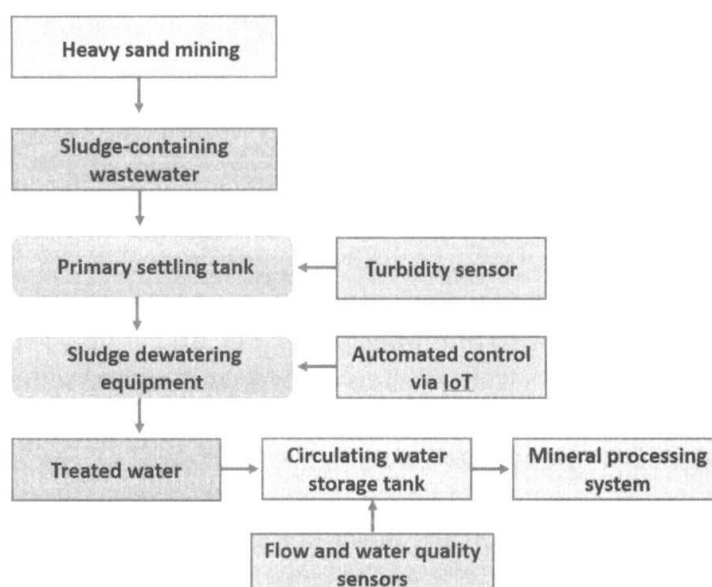


Figure 6. Schematic diagram of the water recirculation system in titanium processing

3.4.2. IoT Applications in Monitoring and Controlling Water Recirculation

Sensor systems and Industrial Internet of Things (IIoT) platforms enable the following functionalities:

- Real-time monitoring of water flow rate, pressure, and abnormal leaks;
- Automated alerts triggered by abnormal pH levels or excessive suspended solids (sludge concentration) in process water;
- Operational data logging, supporting the optimization of pumping, filtration, and treatment costs;
- Integration with central control software, compatible with ERP or SCADA systems for comprehensive process automation.

Table 3. Summary of the Effectiveness of Water Recirculation Technologies

Indicator	Before Improvement	After Improvement (with Recirculation)
Water reuse rate	<10%	50–70%
Raw water consumption (m ³ /ton of ore)	5.5	2.0–2.5
Volume of sludge discharged into environment	High	Reduced by >60%
Water supply and treatment costs	High	Reduced by 40–50%
Legal risk related to wastewater discharge	Medium	Low

Additional Recommendations:

- All active titanium mines should adopt water recirculation systems, especially in water-scarce areas;
- These systems should be aligned with ISO 14046 water footprint management models, with periodic reporting of key operational indicators;

- Priority should be given to high-efficiency sludge separation technologies, such as belt filter presses, combined with polymer flocculants for sludge treatment and safe reuse or disposal;
- Policy support in the form of tax incentives and preferential credit schemes should be introduced to encourage investment in smart water recirculation systems and promote broader adoption.

3.5. Ecological Restoration

Titanium mining, especially via open-pit or dredging methods, causes substantial alterations to landscapes, soil structure, and local ecosystems. Post-mining areas are typically severely degraded, characterized by the loss of organic topsoil, low soil fertility, residual natural radioactivity, and disturbed groundwater levels. Therefore, ecological restoration not only serves to improve aesthetics but plays a vital role in reestablishing soil biological functions, restoring environmental balance, and supporting local livelihoods (Vietnam Union of Science and Technology Associations, 2010).

3.5.1. Planting Native Drought-Tolerant Species and Using Biochar for Soil Improvement

In arid regions such as Binh Thuan and Ninh Thuan, post-mining soils are nutrient-depleted and highly prone to erosion. Plant species selection must consider:

- Tolerance to drought and salinity, and rapid recovery capacity;
- High ecological compatibility, with ties to local ecosystems to prevent invasive species proliferation.

Recommended species include: *Casuarina equisetifolia* (Australian pine), *Cassia fistula* (golden shower tree), *Acacia auriculiformis*, *Swietenia macrophylla* (mahogany), salt-tolerant *Eucalyptus* species, and ground-cover grasses such as *Vetiver*.

Biochar, a type of biomass-derived charcoal (e.g., from rice husks, sawdust), has been proven to:

- Improve water retention, increase cation exchange capacity (CEC), and stabilize soil pH;
- Absorb heavy metals and light radioactive elements from the soil;
- Enhance the abundance of beneficial soil microbes, accelerating natural soil regeneration.

A study conducted at the Phan Thiet titanium mine showed that, after 18 months, areas rehabilitated using biochar and *Acacia auriculiformis* achieved a vegetative cover rate of 78%, compared to only 45% in untreated areas.

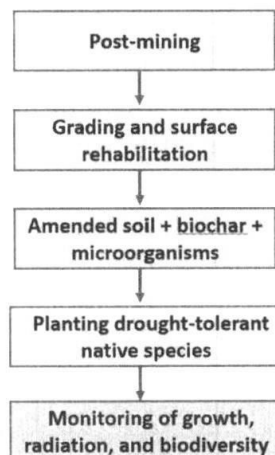


Figure 7. Flow diagram of the ecological restoration process after titanium mining

3.5.2. Application of Microorganisms for Radioactive Soil Remediation and Ecosystem Stabilization

Post-separation waste areas may retain trace amounts of radioactive minerals such as monazite and xenotime, presenting low but persistent radiation hazards. Bioremediation, using microorganisms to break down or immobilize radioactive minerals, is being piloted at several coastal titanium mine sites.

Potential microbial strains include:

- *Pseudomonas putida*: capable of decomposing thorium phosphate in monazite;
- *Bacillus megaterium*: produces biofilms that encapsulate radioactive particles;
- *Aspergillus niger*: secretes organic acids that dissolve rare earth-bearing minerals and stabilize heavy metals.

Implementation strategy:

- Inoculate microorganisms into rehabilitated soils, in combination with biochar;
- Add organic nutrients (e.g., compost, peat) to facilitate microbial growth;
- Conduct regular monitoring of radiation levels, pH, trace elements, and soil biological structure.

Table 4. Summary of Ecological Restoration Solutions

Restoration Category	Key Solutions	Ecological Objectives
Soil improvement	Biochar + topsoil cover + organic fertilizer	Enhance fertility, moisture retention, reduce heavy metal content
Natural radioactivity stabilization	Microorganisms (<i>Pseudomonas</i> , <i>Bacillus</i> , <i>Aspergillus</i>)	Reduce Th and U concentrations, improve environmental stability
Vegetation ecosystem recovery	Native species: <i>Casuarina</i> , <i>Acacia</i> , <i>Swietenia</i> , <i>Vetiver</i> grass	Restore landscape, control erosion
Long-term management	IoT monitoring + radiation and biological surveillance	Ensure sustainable safety and performance

Additional Recommendations:

- Integrate ecological restoration planning into initial mine design, rather than postponing until post-mining stages;
- Establish national standards for titanium mine land restoration, including indicators such as biological cover, soil fertility, and radiation safety thresholds;
- Promote collaboration among mining enterprises, biological research institutes, and local communities in restoration efforts;
- Implement pilot ecological nurseries at large titanium mines to supply native plant species and propagate beneficial microorganisms for land rehabilitation.

3.6. Artificial Intelligence and Machine Learning

The rapid advancement of Artificial Intelligence (AI) and Machine Learning (ML) is transforming the global mining sector. Particularly, as geological and geophysical datasets become more abundant and granular, ML models are being leveraged not only to predict the distribution and concentration of mineral deposits, but also to support optimized decision-

making in mine design, identify high-value zones, reduce exploration drilling costs, and minimize environmental impacts.

3.6.1. Application of Machine Learning Algorithms for Mineral Prediction

Yingli et al. (2020) demonstrated the feasibility of applying two machine learning models in titanium placer mining:

- Random Forest (RF): a decision-tree ensemble algorithm known for its robustness to noise and ability to handle nonlinear data;
- Artificial Neural Network (ANN): a deep learning model capable of learning complex relationships between input variables such as mineral composition, density, depth, and stratigraphic features.

These models were trained on geological datasets collected from over 150 drilling points at a coastal placer deposit in Southeast Asia. The results showed that prediction accuracy for ilmenite, zircon, and monazite concentrations achieved R^2 values between 0.88 and 0.91, outperforming traditional interpolation methods like Kriging or Inverse Distance Weighting (IDW).

3.6.2. XGBoost Model and Its Deployment Potential in Vietnam

The same study by Yingli et al. (2020) also evaluated the Extreme Gradient Boosting (XGBoost) model, a gradient-boosted decision tree algorithm, and found it to be particularly effective in predicting heavy mineral concentrations. Key highlights include:

- The model was trained using over 300 titanium placer samples from Binh Thuan Province, incorporating variables such as grain composition, heavy mineral content, pH, conductivity, sediment type, ore-bearing layer depth, and geophysical indicators (e.g., gamma-ray, resistivity);
- XGBoost achieved $R^2 > 0.95$ and a mean absolute error (MAE) below 10%, enabling the construction of high-resolution mineral distribution maps;
- Unlike “black-box” models like ANN, XGBoost provides feature importance analysis, helping geologists understand which input factors most strongly influence the accumulation of ilmenite, rutile, or monazite, thus enabling more informed and efficient mine design.

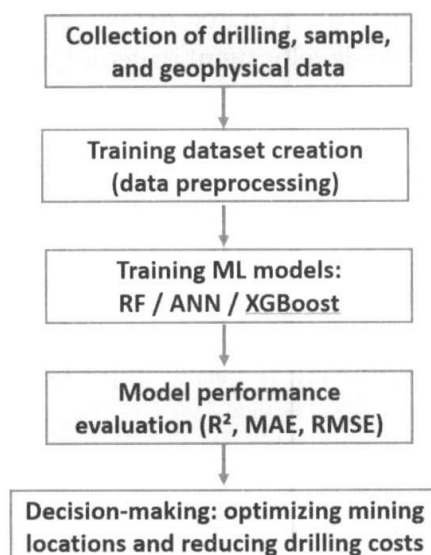


Figure 8. Workflow diagram of machine learning application in titanium mineral prediction

Table 5. Performance Comparison of Machine Learning Models for Mineral Prediction

Algorithm	Average R ²	MAE (%)	Main Advantages	Main Disadvantages
Kriging (traditional)	0.70–0.80	>15%	Easy to implement, widely known	Poor at modeling nonlinear relationships, noise-sensitive
Random Forest	0.85–0.90	10–12%	Stable, no need for data normalization	Limited interpretability of physical mechanisms
ANN (Artificial Neural Network)	0.88–0.91	9–11%	Handles complex, high-dimensional data well	“Black-box” model, requires large datasets
XGBoost	0.95–0.97	<10%	High accuracy, provides feature importance analysis	Requires careful data preprocessing and parameter tuning

Further Recommendations:

- Integrate AI models with GIS platforms and 3D geological mapping to generate spatial-grade distribution maps for resource management and mine planning;
- Prioritize mines with detailed drilling datasets (e.g., Quang Tri, Binh Dinh, Binh Thuan) for pilot implementation of XGBoost and Random Forest models;
- Foster interdisciplinary collaboration among universities, research institutes, and mining companies to develop open, continuously updated AI systems;
- Promote AI-focused workforce development in geology and mining through postgraduate programs specializing in "AI in Geotechnics and Natural Resources".

4. Conclusion and Recommendations

Despite Vietnam’s abundant titanium placer resources, the mining sector continues to face significant challenges in terms of technical efficiency, environmental management, and sustainability requirements. Based on a synthesis of the latest studies and case analyses from Binh Thuan, Binh Dinh, and Khanh Hoa, this paper demonstrates that the shift toward environmentally friendly technologies is not only an inevitable trend but a fundamental solution for improving mining efficiency, reducing negative impacts, and moving toward a green and intelligent mining industry.

The technological directions proposed herein have proven technically and environmentally feasible, specifically:

- Selecting extraction equipment tailored to geological conditions enhances mineral recovery while lowering post-mining remediation costs;
- Controlling radioactive minerals such as monazite and xenotime in accordance with radiation safety standards helps protect the health of workers and surrounding communities;

- Geotechnical simulation tools like Plaxis and Geo-Slope support safe slope design and help mitigate risks of erosion and subsidence;
- Water recirculation systems combined with IoT-based monitoring reduce freshwater consumption and minimize legal risks related to wastewater discharge;
- Ecological restoration using native vegetation, biochar, and beneficial microorganisms shows strong potential for rapid and effective ecosystem rehabilitation;
- Finally, AI-based models such as Random Forest, ANN, and XGBoost have demonstrated high accuracy in predicting mineral distributions, paving the way for the creation of high-resolution resource maps that support precision mine design.

Based on these findings, the following recommendations are proposed:

- Develop a technology transition roadmap for titanium mining that integrates technical innovation, environmental protection, and digital transformation;
- Establish national technical standards for environmental restoration and radiation monitoring in titanium mines;
- Facilitate access to green finance and provide tax incentives for projects implementing environmentally friendly technologies;
- Strengthen collaboration between research institutions, mining enterprises, and regulatory authorities to pilot and scale green mining models;
- Invest in advanced technical training, especially in geotechnical modeling and AI applications for geology and mineral resources.

These strategic directions will contribute significantly to realizing the goal of developing Vietnam's titanium mining industry in a safe, efficient, and sustainable manner amid the global shift toward green transition and circular economy.

Contributions of authors

Le Qui Thao, Do Ngoc Le Dung, Nguyen Thi Thuc Anh, Do Ngoc Hoan - writing & editing, supervision; Xuan-Nam Bui- conceptualization, reviewing & corresponding.

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