Reclamation and Ecological Restoration Practices Around Rare Earth and Critical Mineral Mining Areas: Lessons From Non-Ferrous Metal Sites

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Background and Importance

- Rare earth and critical minerals are essential for modern technologies and the energy transition.
- They are widely used in magnets, batteries, electronics, and advanced industrial systems.
- Growing demand has increased mining, processing, and waste generation worldwide.
- As a result, environmental impacts and the need for reclamation and ecological restoration are also increasing.

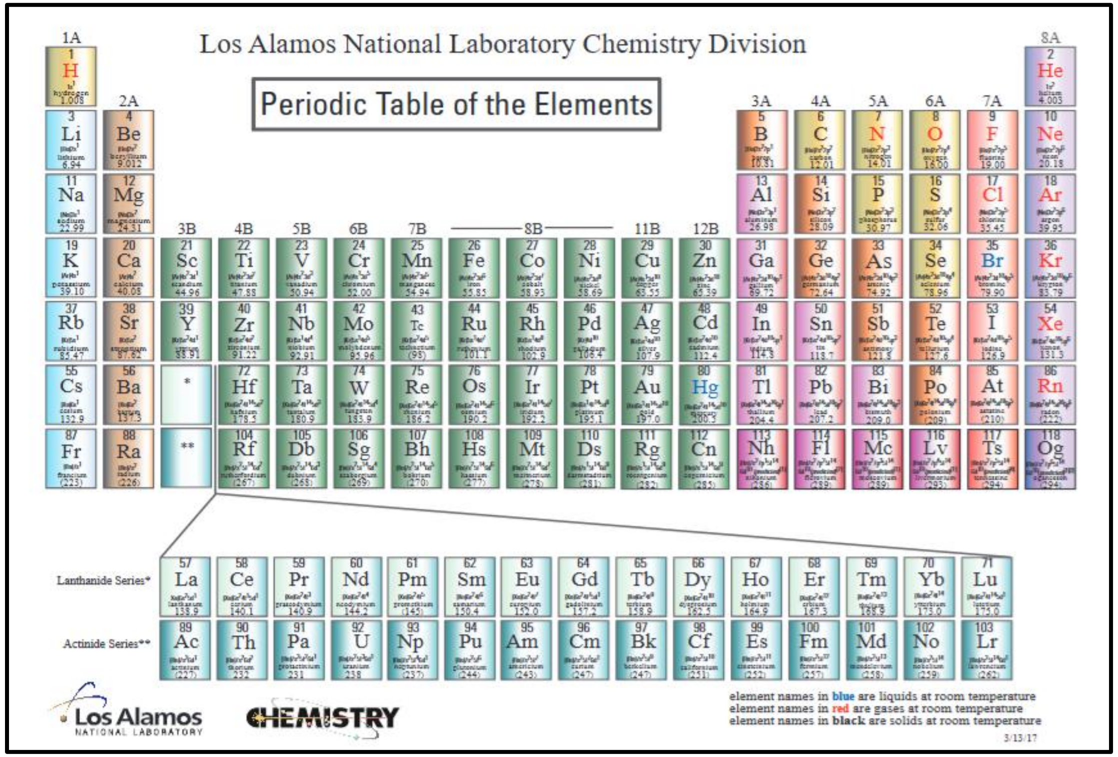


Fig 1. Periodic Table of the Elements
Source: Van Gosen et al. 2019; US Geological Survey

Primary and Secondary Sources of REEs/Critical Minerals

- **Primary sources (~85%)**
  - Newly mined ores and mineral deposits
  - Examples: bastnäsite, monazite, xenotime.
  - Main impacts: land disturbance, tailings, chemical-intensive processing.

- **Secondary sources (~15%)**
  - Recovered from waste and residual materials.
  - Examples: tailings, industrial residues, e-waste, recycled magnets.
  - Main impacts: mixed contamination, waste handling, residue management.

- **Both source types require restoration, but the contamination pathways and site conditions differ.**

Worldwide Distribution of REE Occurrences

- The USGS Global REE database contains more than 3,100 mapped REE deposits and occurrences worldwide.
- The database includes information on mineralogy, host rocks, alteration, deposit type, and resource grade.
- Over 1,590 scientific references were compiled to develop the global REE inventory.
- Major REE occurrences are concentrated in Asia, North America, Australia, and Africa.
- And Ukraine is an important European critical-mineral region.

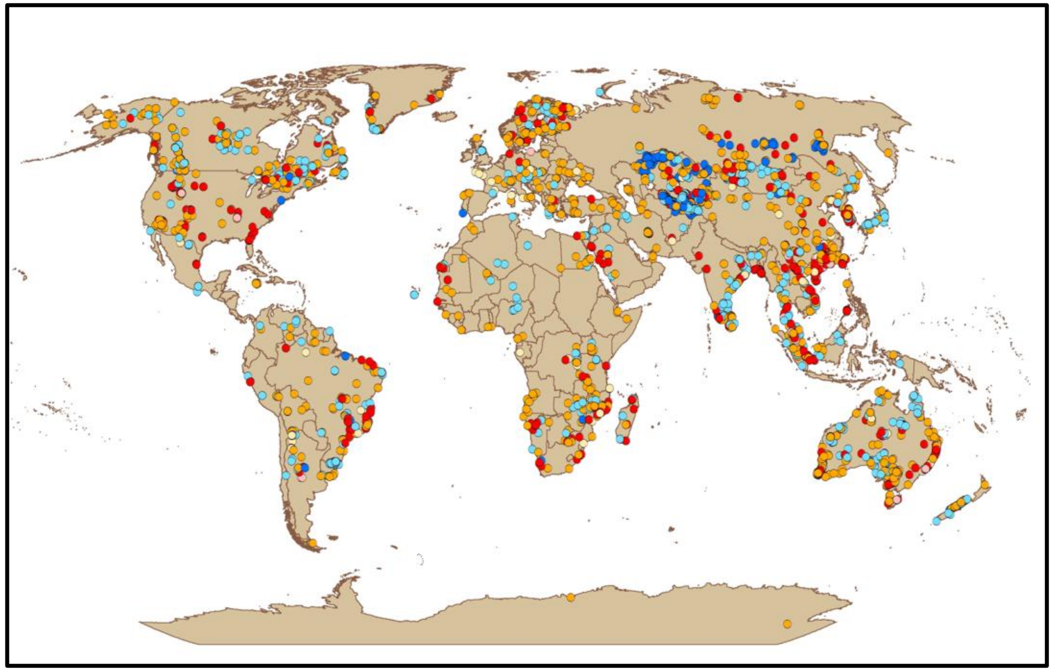


Fig 2. Worldwide Distribution of REE Deposits and Occurrences. Source: U.S. Geological Survey (2018)

Global Critical Mineral Production and Processing

- China dominates global processing of many critical minerals.
- Australia, USA, Canada, Russia, and South Africa are major production regions.
- Mineral concentration in limited countries increases supply-chain risks.
- Sustainable mining and reclamation practices are increasingly important worldwide.

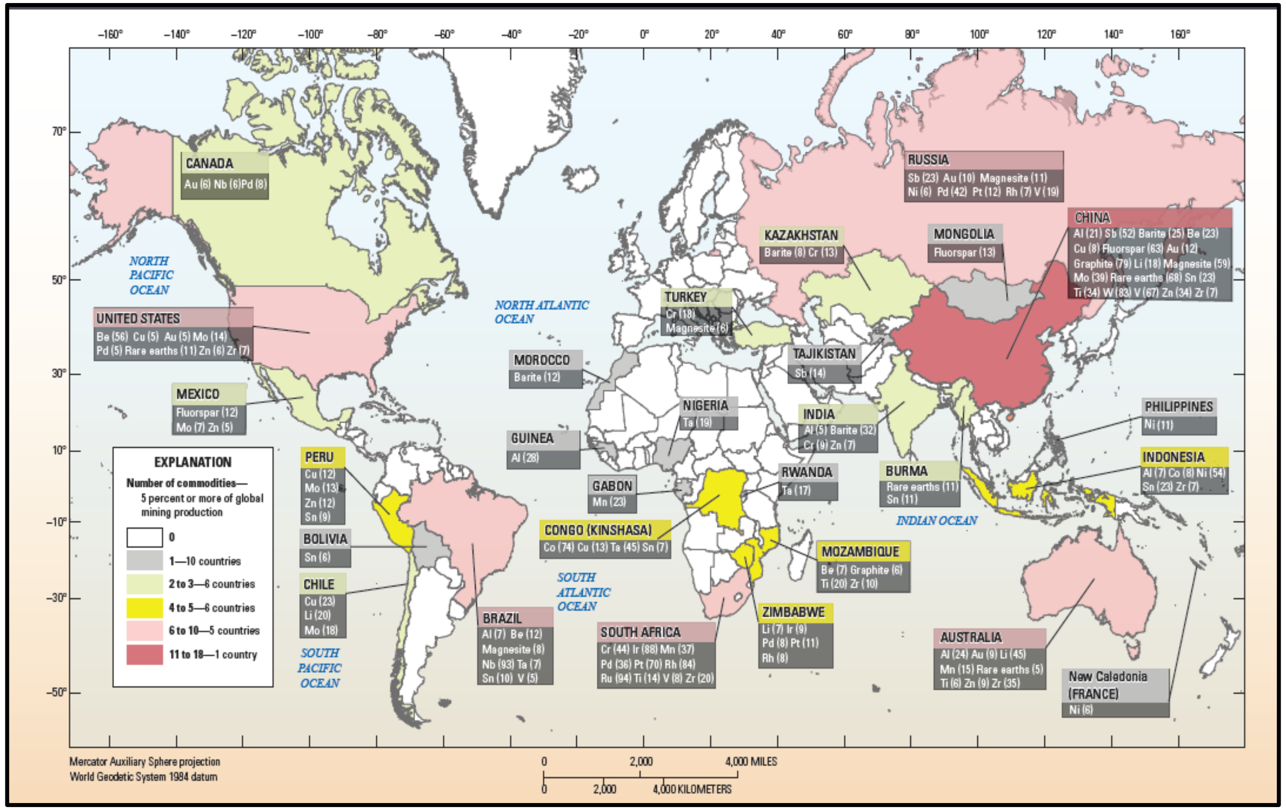


Fig 3. Global processing production of selected critical minerals by country in 2023.
Source: U.S. Geological Survey (2023)

REE Occurrence in Minerals

- REE-bearing minerals include bastnäsite, monazite, xenotime.
- Bastnäsite is a major source of light rare earth elements.
- Monazite and xenotime are important phosphate minerals containing REEs.
- Mineral type controls the processing method, waste type, and environmental risk.

Fig 4. REE-bearing minerals: A) Bastnäsite, B) Monazite sand, C) Xenotime.
Source: Van Gosen et al. 2019; US Geological Survey

Chemical Composition of Major REE-Bearing Minerals

Mineral	Idealized composition	Primary rare-earth content	Key Points
Bastnäsite	RCO_3F	R = light lanthanoids (60–70%)	Carbonate–fluoride mineral; major REE ore mineral
Monazite	RPO_4	R = light lanthanoids (50–78%)	Phosphate mineral; may contain Th/U
Xenotime	YPO_4	R = heavy lanthanoids plus Y (54–65%)	Phosphate mineral; important source of heavy REEs

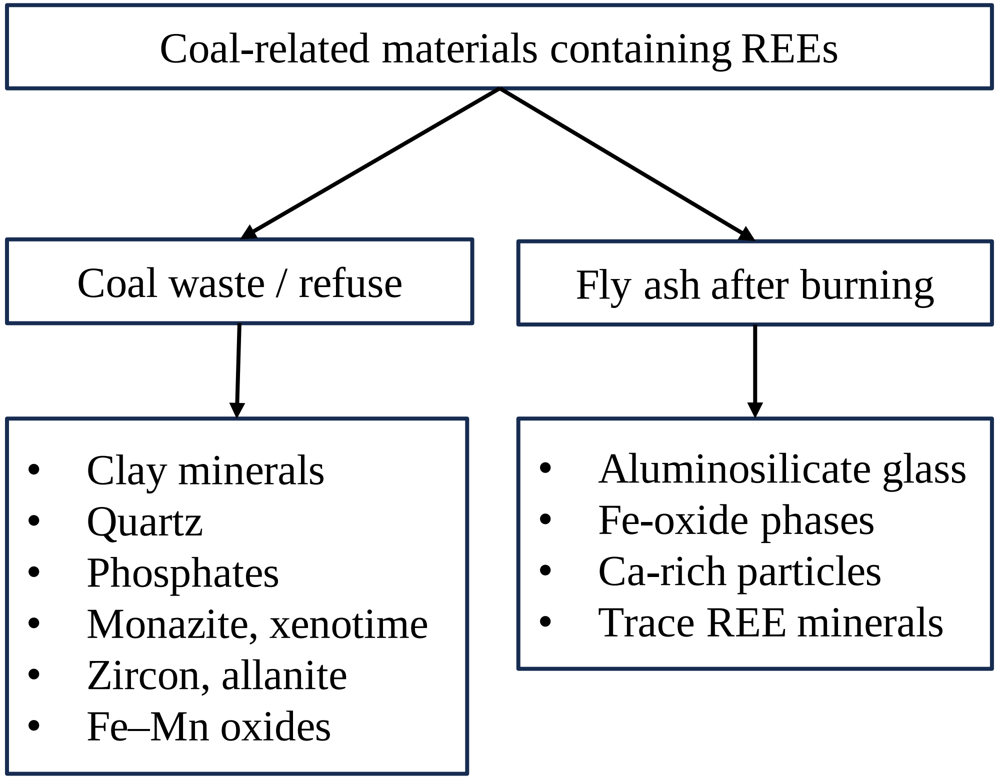
Sources: Encyclopedia Britannica; U.S. Geological Survey

➢ **Common features:**

All three are REE-bearing ore minerals. Their carbonate–fluoride or phosphate chemical composition strongly controls the processing method, type of waste generated, and possible environmental risks during mining and extraction.

Chemical and Mineral Associations of REEs in Coal Waste and Fly Ash

- REEs in coal waste and fly ash are mainly associated with mineral matter and ash phases, rather than occurring as pure REE minerals.

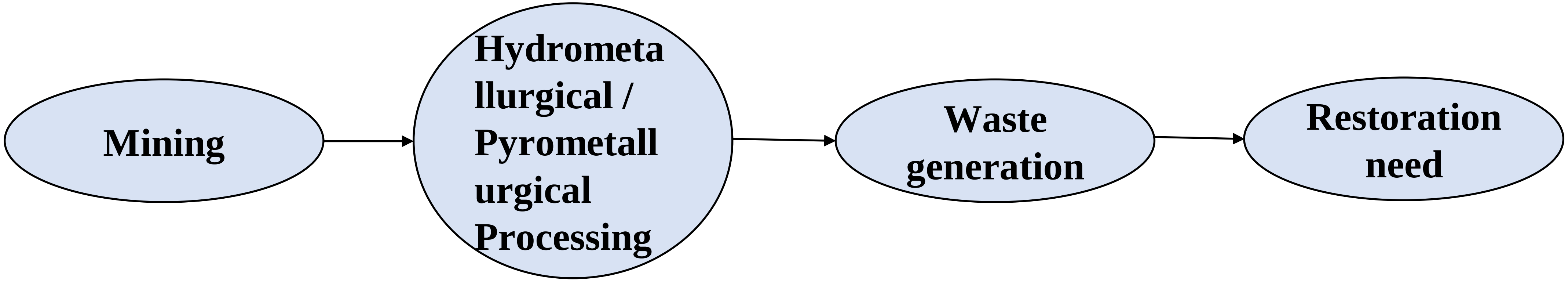


- **Coal waste:** REEs may be associated with clay minerals, quartz, phosphates, Fe–Mn oxides, and trace minerals such as monazite, xenotime, zircon, and allanite.
- **Fly ash:** During combustion, REEs are retained and enriched mainly in aluminosilicate glass and Fe-oxide phases.
- **Importance:** These associations affect REE recovery potential, leaching risk, waste stability, and reclamation planning.

Sources: USGS (2019); Franus et al. 2015

Mining and Processing Pathways

- Rare earth and critical minerals are obtained from mining, leaching, and chemical processing.
- Common pathways include open-pit mining, in-situ leaching, hydrometallurgical extraction, and pyrometallurgical processing, depending on deposit type and material characteristics.
- These processes generate tailings, residues, wastewater, and chemically disturbed soils.
- The scale and type of waste strongly influence reclamation and ecological restoration needs.



Main Environmental Problems

- Land disturbance and ecosystem degradation.
- Soil, water, and air contamination.
- Chemical and potentially radioactive waste generation (e.g., thorium and uranium).
- Long-term metal mobility and bioavailability risks.
- Contaminant spread through erosion, runoff, and leaching.

Fig 5. Mountain Pass mine, southeastern California, June 2018
Source: Van Gosen et al. 2019; US Geological Survey

Reclamation and Restoration Approaches

- **Stabilization and amendments:** lime, biochar, phosphates, and organic matter to reduce contaminant mobility.
- **Biological approaches:** phytostabilization, phytoremediation, revegetation, and reforestation.
- **Technical measures:** soil replacement, capping, soil washing, and water control.
- Combined strategies are often the most effective for long-term site recovery.

Fig 6. Example of land change before mining, during mining, and after reclamation.
Source: Cambria County Coal Waste Reclamation Project

Example Case Study: Mine Land Reclamation (USA)

- Case Title: Revloc coal refuse reclamation, Cambria County, Pennsylvania, USA
- Project period: 1989–2011
- About 3.2 million tons of coal refuse removed.
- Around 56 acres of land reclaimed.
- Cost: approximately $24 million.
- About 6 miles of South Branch Blacklick Creek improved to support aquatic life, including trout.

Rachel Site - Before **Rachel Site – In Process** **Rachel Site - After**

Fig 7. Land condition before, during, and after reclamation at the Revloc site, Pennsylvania (USA).
Source: ARIPPA – Revloc Site, Cambria County, PA

Example Case Study: Pb/Zn Smelter Waste Reclamation

- **In-situ remediation of Pb/Zn smelter slag and tailings, southern Poland**

- **Location:** Upper Silesia / southern Poland
- **Waste type:** Pb/Zn smelter slag and Pb/Zn tailings
- **Problem:** phytotoxic, metal-rich waste with poor natural vegetation
- **Treatment:** local waste lime + biosolids + seeding/revegetation
- **Outcome:** stable vegetation cover after **15+ years**
- **Lesson:** chemical stabilization plus ecological restoration can support long-term recovery of non-ferrous smelter waste sites

Fig 7. Revegetation of Pb/Zn smelter slag and tailings after amendment with biosolids and waste lime.
Source: Soil and Landscape Rehabilitation Program, Smelter Wastes project).

Few more examples: Pennsylvania Projects
Cambria Cogen – Ebensburg, PA

Ernest Site - Before

Ernest Site - After

Lucerne Site - Before

Lucerne Site - After

Fig 8. Before–after comparison illustrating reclamation effectiveness at Ernest and Lucerne sites, Pennsylvania (USA).
Source: ARIPPA – Revloc Site, Cambria County, PA

Few more examples: Ecological Restoration in Aksu Mining Area, Xinjiang, China

- Restoration followed three stages: reconstruction, ecological restoration, and natural recovery.
- **Sea buckthorn** (*Hippophae rhamnoides*) was selected as the main restoration plant species.
- Survival rate of sea buckthorn exceeded 70% by July 2023.
- Drip irrigation and fencing were used to improve plant establishment and reduce disturbance.

Fig 9: Progression of ecological restoration from degraded mining land to early vegetation recovery in Aksu, Xinjiang, China.
Source: Zhu et al. (2024)

Few more examples: Mine Land Restoration Projects in Rajasthan, India (2018)

- Restoration projects were conducted in Bhilwara (coal mine) and Barmer (zinc mine), Rajasthan, India.
- Land shaping and soil amendments were applied to restore degraded mining areas.
- Restoration covered 16 hectares coal mine and 24 hectares zinc mine sites.
- About 400 leguminous trees and shrubs per hectare were planted during reclamation.
- Restoration significantly improved vegetation cover and surface stabilization after intervention.

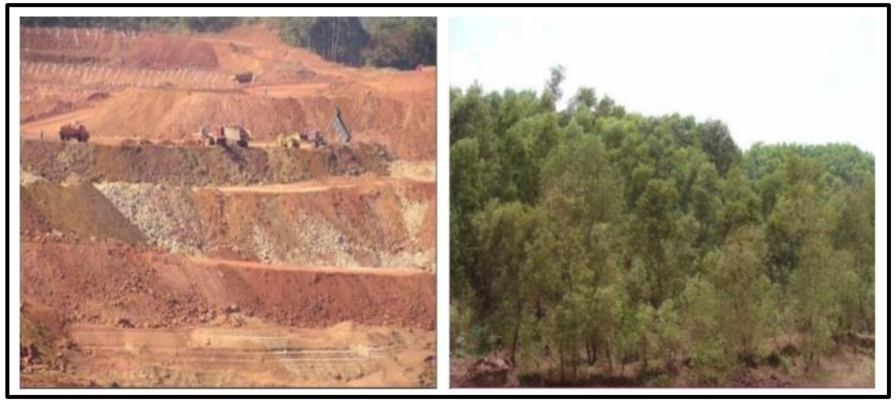


Fig 10: Before–after restoration of coal and zinc mining areas in Rajasthan, India
Source: WRI India

Few more examples: Mine Land Reclamation in Québec, Canada (2011–2024)

- Located in Abitibi-Témiscamingue, Québec, Canada; it was a former **zinc–silver mine** associated with Pb and As.
- Operated from 1952–1957.
- Reclaimed from 2011–2016 with tailings removal, ponds, and revegetation.

Fig 11: Before–after reclamation of the Lac Renzy Cu–Ni mine, Québec, Canada.
Source: Government of Québec – Restoration of mining sites

- Located in Québec, Canada; it was former **copper–nickel mine**
- Operated between 1969–1972
- Reclamation work conducted during 2018–2024 wit tailings flooding, dam construction, contaminated soil treatment, site integration

Fig 12: Before–after reclamation of the Barvue Zn–Ag mine, Québec, Canada.
Source: Government of Québec – Restoration of mining sites

Factors Controlling Reclamation and Restoration Success

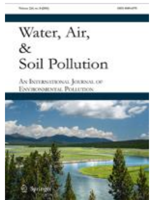
- **pH:** low pH increases metal mobility; reclamation aims to stabilize pH.
- **Water management:** poor drainage causes runoff and leaching; restoration controls flow and erosion.
- **Salinity / EC:** high salinity limits plant growth; soil cover and amendments reduce stress.
- **Metal mobility:** Cd, Zn and Pb may remain bioavailable; amendments reduce movement into soil and water.
- **Vegetation cover:** bare waste increases erosion; plant cover stabilizes soil and supports recovery.

Zn-Pb tilings pond - From a biological perspective, non-ferrous metal ore flotation sediments are characterized by, among other things: phytotoxic heavy metal content (mainly Zn, Pb, and Cd), high PEW, physical properties unfavorable for plant growth, high susceptibility to aeolian erosion.

Zn-Pb tilings pond - source by ZGH BUkowno S.A., with permission

Tailings ponds - the problem with erosion and heavy metals contamination

Photo by M. Pietrzykowski - Bukowno Zinc and Lead Mining and processing, Southern Poland



Krzaklewski, W., Barszcz, J., Małek, S. Pietrzykowski, M. *et al.* 2004 *Water, Air, & Soil Pollution* **159**, 151–164 (2004).

GENERAL DESCRIPTION OF THE TECHNOLOGY OF THE NEW METHOD OF TECHNOLOGICAL AND BIOLOGICAL STABILIZATION OF PHYTOTOXIC WASTE AFTER FLOTATION OF NON-FERROUS METAL ORES

- STAGE I 1.) Covering the flotation sediments with an appropriately modified sodium silicate (Na2SiO3) solution

- STAGE II 1.) Applying a layer (approximately 10 cm thick) of mineral soil with a mechanical composition of medium clay 2.) Appropriate mineral fertilization 3.)

- Sowing a mixture of grass and legume seeds According to the method, in the first few years after planting, it is necessary to constantly monitor heavy metal content, pH, salinity, and nutrient content in the nutrient layer, as well as appropriately selected (based on laboratory analysis results) mineral fertilization during the growing season.

Krzaklewski, W., Pietrzykowski, M. 2002. *Water, Air, & Soil Pollution* **141**, 125–141 (2002)

The 1st growing season (accumulations of Zn, Pb, Cd and PEW in the applied variants of the method in the mineral soil layer are given

Methods - Covering the flotation sediments with sodium silicate solution (Na_2SiO_3)

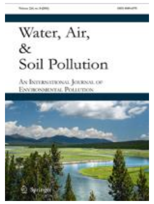
Fig. 15. June 2001, beginning of seed emergence.

Fig. Spring 2001, variant 1

Fig. Spring 2001, variant 2

Fig. Autumn 2001, variant 1

Fig. Autumn 2001, variant 2



Krzaklewski, W., Pietrzykowski, M. Selected Physico-Chemical Properties of Zinc and Lead Ore Tailings and their Biological Stabilisation. *Water, Air, & Soil Pollution* **141**, 125–141 (2002). https://doi.org/10.1023/A:1021302725532

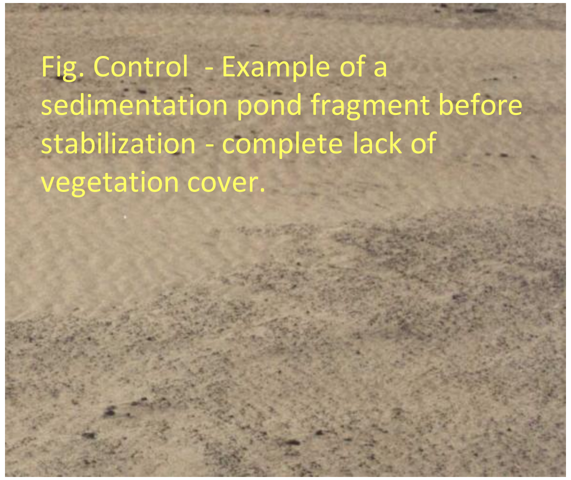


Fig. Second vegetation season, March/April 2002.

WSTĘPNE WYNIKI BADAŃ

Mineral earth over a hydrosilicate "insulating" layer
Zn 550, Pb 140, Cd 12 ppm
EC 158 µS/cm

Hydrosilicate "insulating" layer

Flotation sludge approx.:
13.000 Zn; Pb 5.500-19.500; Cd 200-300 ppm
EC 1.800 - 2.000 µS/cm

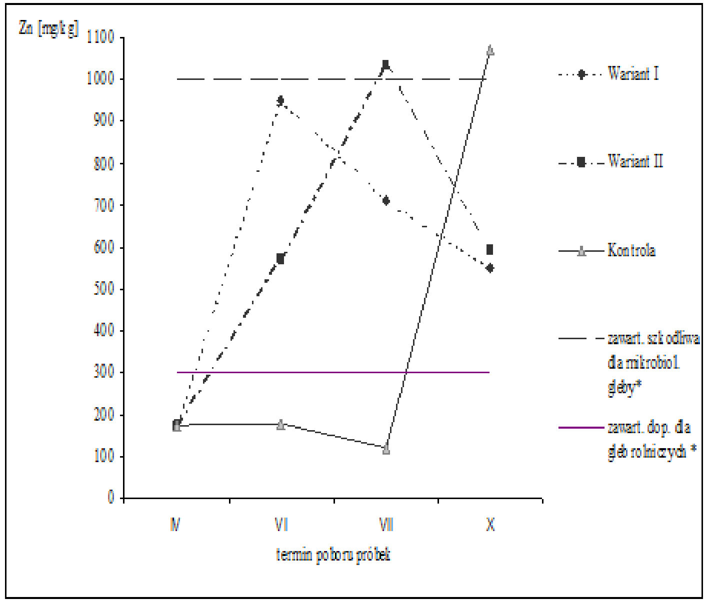


Fig. Cross-section through the layer system used in the proposed method, photo by M. Pietrzykowski

Fig. Visible plant root systems growing through the biogenic layer and entering the top layers of flotation sludge under the stabilizing layer.

Fig. Inspection and sampling of experimental plots

Introducing the mineral soil layer on hydrosilicate cover - technical phase of bigger scale method introduction - 2001 year, Zinc and Lead tilings pond, Bukowno, Southern Poland, photo by M. Pietrzykowski

The effect of method with vegetation cover, Zinc and Lead tailings pond, Bukowno, Southern Poland, summer 2001. photo by M. Pietrzykowski

Conclusion and the lesson from Zn-PB tilings stabilization with hydrosilicate method

- The proposed method should relatively quickly and effectively enable the introduction of a permanent protective vegetation cover on the tailings pond. The method with using hydrosilicate layer and high phosphorus fertilization can be used for temporary stabilization of tailings.
- After the first growing season we observed very dynamic changes in the chemical properties studied in the nutrient layer.
- The positive effect of the method was revealed in the form of a reduction in Zn and then Pb content in the nutrient layer compared to the control.
- The most important indicator of the method's effectiveness is the overall condition of the vegetation cover (no chlorotic discoloration, good physiological condition of the vegetation.

Key Messages and Future Directions

- Rare earth and critical mineral extraction creates long-term environmental pressures that require both reclamation and ecological restoration.
- Lessons from non-ferrous metal sites show that successful recovery must be site-specific, adaptive, and supported by long-term monitoring.
- Combined approaches involving stabilization, revegetation, and technical control measures are often the most effective.
- Future mine planning should integrate restoration strategies from the earliest stages of site development.

THANK YOU

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