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Restoration of the ecosystem of the Yavoriv State Mining and Chemical Enterprise "Sirka" tailings storage facility

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ABSTRACT

The article addresses the problem of ecosystem restoration of the Yavoriv Mining and Chemical Enterprise "Sirka" tailings storage facility, which is one of the largest sources of anthropogenic environmental impact in western Ukraine. The work highlights the main environmental risks associated with the presence of sulfide waste, which causes the formation of acid drainage and migration of heavy metals into the soil-water environment. A comprehensive approach to land reclamation was proposed, including geotechnical preparation, formation of a fertile layer, use of microbial inoculants, sowing of pioneer grasses, and phased planting of tree species. Special attention was paid to the selection of phytoremediation plants capable of soil stabilization and reduction of toxicant content. The results of pilot work were presented, which confirmed the effectiveness of combining engineering and biological methods in forming sustainable plant communities and reducing environmental risks. It was proven that successful ecosystem restoration depends on adapting technologies to local conditions, applying systematic monitoring, and regulatory support. The obtained results can be used as a model for developing long-term reclamation strategies for other technogenically disturbed territories.

Keywords: tailings storage facility, reclamation, bioremediation, phytoremediation, ecosystem restoration.

INTRODUCTION

Tailings storage facilities from sulfur production remain long-term sources of environmental pollution and landscape degradation. The Yavoriv tailings storage facility (State Mining and Chemical Enterprise "Sirka") is one of the largest technogenic disturbances in Western Ukraine and creates constant risks to the quality of soils, surface and groundwater, air environment, as well as local biodiversity.

The restoration of this ecosystem holds strategic importance for the region and the country as a whole, encompassing several key aspects. First, the ecological safety of the area depends on the effectiveness of reclamation measures, as toxic substances contained in sulfur production waste can penetrate aquifers and soils, deteriorating environmental quality. Second, biological restoration will gradually return the territory to its natural state, which will contribute to biodiversity restoration and improvement of soil cover quality. Third, reclaimed lands can be used for agricultural or forestry, recreational zones, or other environmentally safe activities.

Pilot reclamation work demonstrated that multi-stage technological interventions can transform part of the territory into semi-functional ecosystems suitable for forestry and low-demand use. However, scaling such measures requires clear technical protocols, continuous monitoring, and integrated policy instruments.

Globally, reclamation of tailings storage facilities and industrial dumps combines engineering (isolation, capping, drainage), chemical (pH correction, immobilization), and biological (phytoremediation, microbial additives) approaches. The research by Bradshaw (1997), Mendez and Maier (2008), and more recent syntheses (Dyczko et al., 2022, Beesley et al., 2010; Pulford and Watson, 2003, Nahurskyi et al., 2025) emphasized that the success of reclamation depends on substrate suitability (depth and quality of topsoil), species selection (pioneer or late-successional), and long-term management for soil profile development.

Tailings storage facilities of sulfur mining enterprises pose a significant environmental threat due to the presence of sulfide fractions, which, upon oxidation, form acid mine drainage (AMD) and associated mobile forms of heavy metals, leading to acidification of soils and water systems, reduction of biodiversity, as well as increased risk of technogenic accidents (Dmytruk and Klymenko, 2018; Havryliuk and Lutsyk, 2020; Hrytsulyak, and Onyshchuk, 2019). Ukrainian studies record extremely low pH values in the soils around tailings storage facilities (pH ≈ 2.8–3.2), elevated concentrations of sulfates and mobile metals (Sr, Pb, As), as well as significant degradation of soil and vegetation cover, requiring priority measures to control hydrological flows, limit oxygen access to sulfides, and local stabilization of toxicants before implementing long-term biological solutions (Ivanyshyn and Nykytyuk, 2017; Kharytonov et al., 2017). Engineering and geotechnical measures – terrain leveling, dam reinforcement, drainage system design, and use of geosynthetics – are fundamental for minimizing erosion, ensuring mass stability, as well as creating conditions for subsequent covering and vegetation; these solutions must account for local climatic and hydrogeological features and be designed considering extreme precipitation and peak hydraulic loads (European Commission, 2009; European Parliament and Council, 2006). Barrier covers (cappings) with multi-layer construction – drainage layer, compacted clay or geomembrane, and protective fertile layer – effectively limit water infiltration as well as oxygen access to sulfides, reducing AMD formation, but require significant capital investment, ensuring tightness, and long-term control for mechanical damage or layer degradation (European Commission, 2009; Lottermoser, 2010). Chemical amelioration (primarily liming and fixative application) provides a rapid effect in the form of pH increase and metal precipitation and is often used as a primary measure or for rapid correction of effluent parameters; the disadvantage is the possibility of repeated applications with a constant oxidation source and the need to manage formed sediments (Johnson and Hallberg, 2005; Kumpiene et al., 2019; Nejad et al., 2018). Biological methods, particularly phytoamelioration using acid- and metal-tolerant grasses (e.g., Deschampsia, Festuca) and tree species (pine, birch, sea buckthorn) combined with mycorrhizal and symbiotic bacteria inoculation, provide long-term soil stabilization, restoration of ecosystem functions, as well as reduction of erosion processes, although their action is slow and requires years to achieve noticeable results (Kharytonov et al., 2017; Tsyliuryk and Rudko, 2022).

Phytostabilization using salt- and acid-resistant grasses and shrubs combined with targeted phytoextraction of metals using accumulating species is a common strategy for the tailings contaminated with heavy metals. Microbial inoculants – particularly plant growth-promoting rhizobacteria (PGPR) and mycorrhiza – are gaining increasing importance for improving plant rooting under stress conditions. EU policy emphasizes the «polluter pays» principle, integrated waste management, and environmental risk assessment; harmonization of national legislation with EU directives increases incentives and technical reclamation standards. This international experience was taken into account when designing reclamation work for the territory of the sulfur production tailings storage facility by the flotation method of the liquidated Yavoriv Mining and Chemical Enterprise «Sirka».

MATERIAL AND METHODS

Reclamation was carried out on a site measuring 120 × 50 m located within the tailings storage facility. The site selection was justified by representative substrate conditions (low organic content, elevated sulfate and metal content, high acidity) and the possibility of operation repetition.

On the basis of the conducted ecosystem studies of the tailings storage facility territory, study of vegetation state, soil environment conditions (Nahurskyi et al., 2025), and assessment of biotic potential (Oliferchuk et al., 2023), it was proposed to conduct reclamation according to the following algorithm:

Stage 1: Geotechnical preparation

- Construction of a road through the tailings storage facility dam to enable engineering equipment access to the work site;

- Surface leveling and filling of subsidence areas;
- Formation of channels for tree planting.

Stage 2: Formation of reclamation layer
- Surface covering with a fertile soil layer;
- Biological remediation using bacteria and fungi that promote plant establishment and effective growth.

Stage 3: Sowing herbaceous plants
- Sowing pioneer species for soil stabilization and improvement of soil water-holding properties.

Stage 4: Tree planting
Stage 5: Monitoring and adjustment of measures

The selection of primary producers for ecosystem restoration was carried out taking into account the specifics of technogenically disturbed territories of the tailings storage facility. It was important to choose the plant species capable of withstanding extreme conditions. Primarily, producer species were selected that met the following criteria:
- Ability to survive at low soil pH;
- Contribution to organic matter accumulation and improvement of soil structure;
- Resistance to heavy metal contamination and salinization;
- Ability for bioremediation and nitrogen fixation;
- Contribution to the formation of stable vegetation cover that provides protection from erosion and maintains the hydrological regime.

For effective ecosystem restoration of the Yavoriv State Mining and Chemical Enterprise «Sirka» TSF, the composition of primary producers was determined as a combination of herbaceous, shrub, and tree species. These included herbaceous plants (pioneer species):
- Tufted hair-grass (*Deschampsia caespitosa*) – This species has high resistance to acidic soils and heavy metal contamination. Its dense turf cover promotes soil stabilization and moisture retention.
- Red fescue (*Festuca rubra*) – This species is well adapted to poor soils, helps stabilize soil, and promotes organic matter accumulation.
- Colonial bent (*Agrostis tenuis*) – This species is adapted to saline soils, allowing it to be useful for the restoration of heavily contaminated territories.
- Birdsfoot trefoil (*Lotus corniculatus*) – A legume plant capable of nitrogen fixation, enriching soil with nitrogen and improving its fertility.
- White clover (*Trifolium repens*) – Also a powerful nitrogen fixer that increases the biological activity of soils and provides nutrients for subsequent plant generations.
- As well as the following shrub and tree species:
- White willow (*Salix alba*) – One of the most resistant plants to acidic and saline soils, it strengthens soil well, preventing erosion, and has high bioremediation capacity.
- Silver birch (*Betula pendula*) – Participates in humus formation, helps improve soil structure, and withstands harsh conditions.
- Scots pine (*Pinus sylvestris*) – This species can withstand acidic soils and is important for forming a sustainable forest ecosystem on technogenically disturbed lands.
- Sea buckthorn (*Hippophae rhamnoides*) – Capable of nitrogen fixation, improves soil structure, and has high resistance to contamination, making it an ideal candidate for such ecosystems.

Phytoremediation plants play a special role in the reclamation process, as they can clean soils of heavy metals and toxic substances. Such species include white willow (*Salix alba*), red fescue (*Festuca rubra*), colonial bent (*Agrostis tenuis*), and birdsfoot trefoil (*Lotus corniculatus*). They are capable not only of stabilizing erosion-unstable soils but also of promoting their gradual restoration.

An important aspect of effective restoration is ensuring balance between natural and anthropogenic factors. Research shows that natural succession can be significantly accelerated through biotechnological methods, such as using mycorrhizal fungi, bioengineering technologies, and targeted introduction of plant species resistant to extreme conditions (Tsyliuryk and Rudko, 2022).

The main condition for effective restoration is the adaptation of reclamation measures to specific ecological conditions. Using local plant species adapted to the specific environment allows increasing ecosystem resilience to changes and ensuring its long-term functioning.

The general stages of the reclamation and monitoring process are shown in Figure 1. The diagram illustrates the sequential integration of geotechnical, biological, and analytical procedures, as well as a feedback monitoring system that enables adjustment of the restoration strategy based on the obtained results.

RESULTS AND DISCUSSION

Geotechnical preparation of the tailings storage facility surface

Construction of a road through the tailings storage facility dam is necessary to ensure unimpeded passage of engineering equipment to the work site. This is important for operational transportation of construction machinery, materials, and personnel engaged in task execution. The presence of quality road surface increases movement safety, reduces the risk of emergencies, and ensures dam structure stability. Additionally, a properly constructed road helps minimize negative environmental impact by preventing soil erosion and possible water body contamination. It also contributes to efficient work execution without unnecessary delays, which is especially important when implementing projects under hard-to-reach or technically complex conditions. Figure 2 shows the photographs of access road construction work through the tailings storage facility dam.

Subsequently, surface leveling, slope reinforcement of dumps, and filling of subsidence areas were carried out, aimed at preventing erosion and landslides, as slope reinforcement reduces the risk of rock sliding under the influence of precipitation and wind. Surface leveling promotes uniform water distribution, preventing water stagnation and wetland development. It also provides optimal conditions for applying a reclamation soil layer, which anchors better on stable relief, improving agrotechnical properties and promoting plant growth.

Simultaneously, filling subsidence areas and territory leveling reduces the risk of settling and increases site safety, preventing karst process formation. This is important not only for ecological stability, but also for safe future use of the territory. Vegetation develops better on leveled, stable surfaces, ensuring faster natural environment restoration. The results of the work performed are presented in Figure 3.

The presented research results showed a practical absence of soil cover, which necessitated covering the surface with a fertile soil layer (Nahurskyi et al., 2025). According to (Beesley et al., 2010; DSTU, 2017), the thickness of the soil layer for successful rooting and tree development is:

- Minimum thickness – 50–60 cm, sufficient for root system development of undemanding trees (birch, willow, acacia).
- Optimal thickness – 80–100 cm, providing good conditions for the growth of most trees, including oak, pine, and ash.

Applying a layer of fertile soil of the necessary thickness over the entire reclamation territory was not feasible. To reduce costs, channels were formed for tree planting with a depth of 0.6 m (Figure 4).

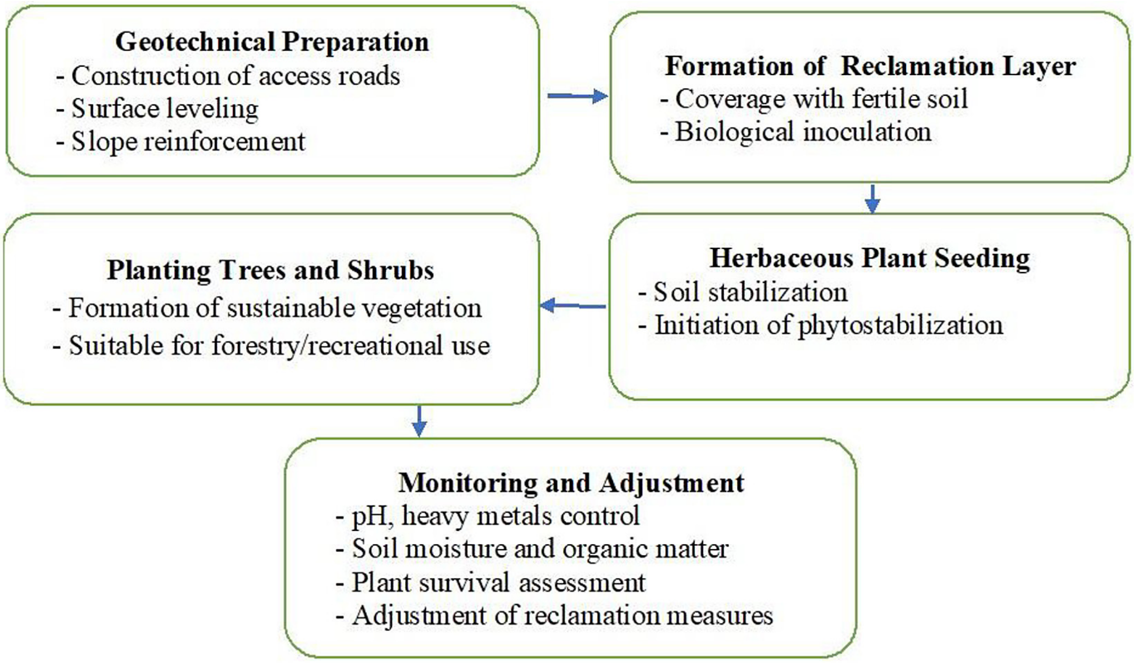

Figure 1. Conceptual diagram of the reclamation process and feedback monitoring system

a) *b*)

Figure 2. Construction of road through tailings storage facility dam to enable engineering equipment access to work site: *a* – initial stage of equipment work, *b* – engineering equipment passage

Figure 3. Results of surface leveling and filling subsidence areas of part of the tailings storage facility territory

Formation of the reclamation layer

To cover the surface with a fertile layer, the soil from undamaged adjacent territories was used. A general soil cover 20 cm thick was created, optimal for herbaceous plants (Beesley et al., 2010; DSTU, 2017). Then, the fertile layer thickness at tree planting locations equaled 80 cm (Figure 5).

To promote plant establishment and their effective growth as well as fruiting under the conditions of covering disturbed territories with a fertile soil layer, plant inoculation with bacterial preparations was used. Such preparations contain specific strains of microorganisms that interact with plants, promoting nutrient assimilation, particularly nitrogen, phosphorus, and other elements. Plant inoculation with bacterial preparations was carried out by introducing them into the soil with irrigation water. For this, the following mixtures were used: «Mikovital» – 3 parts (active agent Vitasergia svidasoma Oliferchuk IMB F-100106), «Planriz-Bio» – 10 parts (active agent Pseudomonas fluorescens), «Azotfiksator» – 30 parts (active agent Bradyrhizobium japonicum), «Florabatsilin» – 10 parts (active agent Bacillus subtilis), Whey – 10 parts (active agent lactobacilli), Fertilizer «Agrobolik universal» – 3 parts (used as a micronutrient deficiency corrector in plants, as a stimulator of their intensive growth and development, as an immunity enhancer. It contains leonardite extract (highly oxidized brown coal type), humates from ocean brown algae, and a complex of microelements of natural origin in readily available form for plants. The composition is dominated by biologically active components: humic and fulvic acids, which increase humus concentration and soil fertility, fertilizer «Bor Agrobolik» – 3 parts (same composition as «Agrobolik universal» fertilizer plus molybdenum and boron) (Lottermoser, 2010). To ensure mineral nutrition, encapsulated slow-release NPK fertilizers were used. (Shkvirko et al., 2024).

Sowing herbaceous plants

Sowing herbaceous plants was carried out to anchor soil, prevent erosion, and create favorable conditions for fertile layer restoration. Grasses quickly form a root system that promotes surface strengthening and reduces soil washout or weathering. They also improve soil structure, increase its water-holding capacity, and promote organic matter accumulation. Additionally, herbaceous plants perform phytoameliorative functions by adsorbing heavy metals and other pollutants, promoting soil cleaning. Their sowing creates conditions for the gradual formation of stable biocenoses and subsequent ecosystem restoration, including the possibility of planting tree and shrub species at subsequent reclamation stages. First shoots appeared 14 days after sowing, followed by primary rooting and plant strengthening (Figure 6).

Tree planting

Tree planting on the tailings storage facility territory was the final reclamation stage aimed at creating sustainable green plantings. Trees play an important role in soil stabilization, prevent erosion processes, improve microclimate, and promote biodiversity restoration.

Important measures for reducing the forest fire risk on reclaimed territories include the application of fire-prevention corridors. Fire-prevention corridors are narrow strips of deciduous trees (e.g., birch, aspen, linden) planted among coniferous plantings or around territories with increased fire hazard. Deciduous trees, particularly

Figure 4. Construction of depressions to create the necessary soil layer thickness at tree planting locations

Figure 5. Surface coverage of reclamation with a fertile soil layer

birch, have high moisture content and less propensity for ignition compared to coniferous species. They effectively slow fire spread, as their leaves and bark contain few resinous substances. Creating fire-prevention corridors with deciduous species between coniferous plantings reduces the probability of fire occurrence and spread.

Trees were planted according to a strip (row) scheme – in rows with certain intervals. The distance between rows was 4 m, whereas between trees in row – 1.2 m. The size of the reclaimed site was 120 × 50 m. 10 rows of trees were formed, planting density was approximately 2.0 thousand units/ha. Total number of seedlings 1000 units. To form fire-prevention corridors, 6 rows of pine and 4 rows of birch were alternately planted. Two-year-old pine and birch seedlings were used as planting material (Figure 7).

Plant care and environmental monitoring of reclaimed territory

After completing territory reclamation, an important stage is care for planted plants and constant environmental monitoring, which allows assessing ecosystem restoration effectiveness and timely identifying possible problems. Plant care includes regular watering, especially at initial rooting stages, weed control that may compete for resources, and soil fertilization that promotes faster vegetation development. For tree plantings, it is important to provide formative pruning that stimulates healthy growth, as well as protection from pests and diseases through biological or agrotechnical methods.

Environmental monitoring includes soil cover assessment, determination of its chemical

Figure 6. Germination of herbaceous plants on reclamation territory

Figure 7. Pine row on reclaimed territory

composition, moisture, and contamination level with heavy metals or other toxic elements. Also, plant growth and development should be regularly tracked, assessing their survival rate, environmental adaptation, and cover density. Hydrological regime control enables preventing water stagnation or erosion processes that may complicate territory restoration. Table 1 presents the monitoring schedule.

Long-term monitoring implementation enables correcting reclamation measures and adapting the greening strategy to achieve maximum environmental effect. After 12 months of reclamation activities, compared with the initial data (Nahurskyi et al., 2025), positive changes in soil parameters were observed. Specifically, the bulk density decreased from 1.42 to 1.28–1.30 kg/m³, indicating the formation of a looser structure, while porosity increased from 41.56% to 47–49%. The density of the solid phase remained stable (≈2.45 kg/m³), which indicates the constancy of the mineralogical composition.

The soil acidity shifted toward the neutral range (pH 6.8–7.0) due to liming. A primary humus horizon (0.25–0.35%) appeared in the surface layer, indicating the activation of biological processes and the formation of organo-mineral complexes.

Chemical analysis revealed a reduction in the content of toxic elements: sulfur – from 28.55% to 18–20%, calcium – from 68.83% to 55–58%, cadmium – from 0.04% to 0.025%, barium – from 0.82% to 0.60%, and strontium – from 0.712% to 0.50%. This indicates the stabilization of the salt composition and a decrease in ecotoxicity. The vegetation cover reached 68–72%, with *Festuca rubra* and *Agrostis tenuis* being the dominant species.

The obtained results confirm the positive dynamics of detoxification processes and the effectiveness of phytostabilization during the first year of biological reclamation. At the same time, the fertility level remains low; therefore, continued biological reclamation and monitoring are required to achieve a stable ecosystem state.

Similar results have been obtained in analogous reclamation experiments abroad. In Polish zinc tailings, the combined use of organic amendments and microbial inoculants led to pH stabilization at 5.5–6.0 within two years (Dyczko et al., 2022). In Spain, Pérez-López et al. (2010) reported a 30% reduction of available Pb and Cu after vegetation with tolerant grasses. Comparable trends were also observed in Canadian nickel tailings (Nkongolo et al., 2022). Thus, the results obtained for the Yavoriv sulfur tailings are consistent with international experience, confirming the universal efficiency of integrated biological–geochemical approaches.

The present study was limited by the short observation period (12 months) and the relatively small experimental area, which may influence the representativeness of the obtained results. Further research should focus on long-term monitoring of microbial dynamics, heavy metal immobilization stability, and the succession of plant communities. It is also recommended to test various bioinoculant combinations and organic amendments under different climatic conditions to improve the reproducibility and scalability of the applied reclamation approach.

Table 1. Monitoring schedule for reclaimed territory

Parameter	Depth/unit	Frequency	Purpose
Soil pH	0÷0.1, 0.1÷0.3 m	t0, t1, t2, t3, annually	Acidity tracking
Organic carbon	0÷0.1 м	t0, t2, t3, annually	SOM accumulation
Heavy metals	0÷10, 0.1÷0.3 m	t0, t2, t3, annually	Contamination trends
Vegetation cover	Survey	t1, t2, t3, annually	Succession, density
Soil moisture	0–0.3 м	seasonally (4×/year)	Hydrology, plant stress

CONCLUSIONS

Pilot reclamation work on the Yavoriv Mining and Chemical Enterprise «Sirka» tailings storage facility site demonstrated that a phased approach – combining geotechnical preparation, selective (trench) application of fertile substrate, application of microbial and organic additives, early sowing of pioneer grasses, and phased tree planting – can initiate sustainable ecosystem restoration on technogenically disturbed soils. Practical conclusions include the feasibility of trench soil application to reduce costs while creating conditions for trees, the effectiveness of inoculation through irrigation for large-scale application, and the critical role of early grass crop sowing in surface stabilization. Meanwhile, the main costs involve care and long-term monitoring, i.e. scaling approaches require life cycle economic analysis, financial guarantees, and regulatory support («polluter pays» mechanisms, national guidelines, integrated monitoring in permitting procedures). Study limitations – small pilot time scale – require multi-year monitoring of soil profile and pollutant mobility, as well as additional controlled studies to optimize microbial consortia and plant selection for phytoextraction and phytostabilization.

REFERENCES

1. Beesley, L., et al. (2010). Metal immobilisation and plant growth improvements in mine waste using organic amendments and phosphorus. *Journal of Environmental Quality, 39*(2), 329–339.
2. Bradshaw, A.D. (1997). Restoration of mined lands – using natural processes. *Ecological Engineering*, *8*(4), 255–269. https://doi.org/10.1515/jlecol-2015-0007
3. Derakhshan Nejad, Z., Jung, M. C., Kim, K. H. (2018). Remediation of soils contaminated with heavy metals with an emphasis on immobilization technology. *Environmental geochemistry and health, 40*(3), 927–953. https://doi.org/10.1007/s10653-017-9964-z
4. Derzhavniy Standart Ukrainy (DSTU). (2017). DSTU 8757:2017. Environmental protection. Recultivation of disturbed lands. *General requirements. Kyiv: Ministry of Economic Development and Trade of Ukraine.*
5. Dmytruk, Y. M., Klymenko, V. (2018). Soil degradation in the sulphur mining areas of Western Ukraine. *Environmental Problems*, *3*(2), 81–87. https://doi.org/10.23939/ep2018.02.081
6. Dyczko, A., Ryś, K., Radosz, Ł., Woźniak, G. (2022). Current Reclamation Practices and their Successfulness. In Green Scenarios: Mining Industry Responses to Environmental Challenges of the Anthropocene Epoch. *CRC Press* 361–372. https://doi.org/10.1201/9781003271604
7. European Commission. (2009). *Reference Document on Best Available Techniques for Management of Tailings and Waste-Rock in Mining Activities (BREF)*. Luxembourg: Office for Official Publications of the European Communities.
8. European Parliament and Council. (2006). Directive 2006/21/EC on the management of waste from extractive industries. *Official Journal of the European Union, L102,* 15–33.
9. Havryliuk, O., Lutsyk, D. (2020). Geochemical features of soils around sulphur mining tailings in Rozdil and Yavoriv districts. *Visnyk of Lviv University. Series Geography, 54,* 36–44.
10. Hrytsulyak, V., Onyshchuk, V. (2019). Accumulation of sulphur tailings in the Dniester basin: ecological risk assessment. *Scientific Bulletin of UNFU, 29*(3), 170–173. https://doi.org/10.15421/40290336
11. Ivanyshyn, V., Nykytyuk, T. (2017). Monitoring of the state of reclaimed lands of the sulfur mining industry in Ukraine. *Ecological Safety and Balanced Resource Use, 2*(16), 75–81.
12. Johnson, D. B., Hallberg, K. B. (2005). Acid mine drainage remediation options: A review. *Science of the Total Environment*, *338*(1–2), 3–14. https://doi.org/10.1016/j.scitotenv.2004.09.002
13. Karaca, O., Cameselle, C., Reddy, K.R. (2018). Mine tailing disposal sites: contamination problems, remedial options and phytocaps for sustainable remediation. *Rev Environ Sci Biotechnol 17,* 205–228. https://doi.org/10.1007/s11157-017-9453-y
14. Kharytonov, M., Babenko, O., Pidlisnyuk, V. (2017). Application of phytotechnologies for remediation of sulfur and mining tailings in Ukraine. *Environmental Research, Engineering and Management, 73*(3), 26–34. https://doi.org/10.5755/j01.erem.73.3.20091
15. Kumpiene, J., Antelo, J., Brännvall, E., Carabante, I., Ek, K., Komárek, M., Wårell, L. (2019). In situ chemical stabilization of trace element-contaminated soil–Field demonstrations and barriers to transition from laboratory to the field–A review. *Applied Geochemistry, 100,* 335–351. https://doi.org/10.1016/j.apgeochem.2018.12.003
16. Lottermoser, B. (2010). *Mine wastes: Characterization, treatment, and environmental impacts* (3rd ed.). Springer.
17. Mendez, M.O., Maier, R.M. (2008). Phytostabilization of mine tailings in arid and semiarid environments – an emerging remediation technology.

Environmental Health Perspectives 116(3), 278 – 283. https://doi.org/10.1289/ehp.10608

18. Nahurskyi, O., Vykhivska, K., Krylova, H., Vasiichuk, V., Kachan, S., Nahursky, A., Bogatov, O., Pavlenko, O., Orobchuk, O. (2025). Study of ecosystem edaphic components in the tailings storage of a decommissioned sulfur mining enterprise. *Ecological Engineering & Environmental Technology, 26*(4). https://doi.org/10.12912/27197050/200623
19. Nahurskyi, O., Krylova, H., Vasiichuk, V., Kachan, S., Nahursky, A., Orobchuk, O., Anna Romaniv, A., Soltysik, R., Chornenkyi V. (2025). Experimental-analytical assessment of ecosystem resources of the tailings storage facility: Case study. *Ecological Engineering & Environmental Technology, 26*(11). https://doi.org/10.12912/27197050/212566
20. Nkongolo, K. K., Spiers, G., Beckett, P., Narendrula-Kotha, R. (2022). Inside old reclaimed mine tailings in Northern Ontario, Canada: A microbial perspective. *Ecological Genetics and Genomics, 23*, https://doi.org/10.1016/j.egg.2022.100118
21. Oliferchuk, V., Kendzora, N., Hotsii, N., Shukel, I., Olejniuk-Puchniak, O., Samarska, M., Nagurskyy, O., Vasiichuk, V. (2023). Changes in the structure of soil microscopic fungi in the territories of Yavoriv and Podorozhenie sulfur quarries. *Ecological Engineering & Environmental Technology, 24*(3), *120–134*. https://doi.org/10.12912/27197050/159629
22. Palansooriya, K. N., Shaheen, S. M., Chen, S. S., Tsang, D. C., Hashimoto, Y., Hou, D., Ok, Y. S. (2020). Soil amendments for immobilization of potentially toxic elements in contaminated soils: A critical review. *Environment international, 134,* 105046. https://doi.org/org/10.1016/j.envint.2019.105046
23. Pérez-López, R., Nieto, J. M., de la Rosa, J. D. (2010). Environmental risks and remediation of sulphide mining wastes in the Iberian Pyrite Belt (SW Spain). *Water, Air, and Soil Pollution*, *207*, 113–126. https://doi.org/10.1007/s11270-009-0122-2
24. Pulford, I.D., Watson, C. (2003). Phytoremediation of heavy metal-contaminated land by trees—a review. *Environment International, 29*(4), 529–540. https://doi.org/10.1016/S0160-4120(02)00152-6
25. Sun, W., Ji, B., Khoso, S.A. (2018). An extensive review on restoration technologies for mining tailings. *Environ Sci Pollut Res 25,* 33911–33925. https://doi.org/10.1007/s11356-018-3423-y
26. Shkvirko, O., Grechanik, R., Malovanyy, M., Tymchuk, I., Nagursky, O., Wojciech, L. (2024). Evaluation of the influence of encapsulated mineral fertilizers on plant growth kinetics. *Environmental Problems, 9*(1), 1–7. https://doi.org/10.23939/ep2024.01.001
27. Tsyliuryk, O., Rudko, H. (2022). Environmental problems of sulfur mining enterprises in Western Ukraine and ways of their reclamation. *Environmental Problems*, *7*(1), 82–90. https://doi.org/10.23939/ep2022.01.082