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# Experimental-analytical assessment of ecosystem resources of the tailings storage facility: Case study

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## ABSTRACT

The study provides an experimental-analytical assessment of ecosystem resources at the Yavoriv State Mining and Chemical Enterprise (SMCE) tailings storage facility in Lviv region, Ukraine. After sulfur production ceased, the site became a technogenically disturbed landscape with acidified soils, elevated concentrations of toxic elements, and sparse vegetation. The objectives were to map vegetation status, assess plant physiological condition and species composition, and evaluate natural restoration potential to inform reclamation planning. Methods combined satellite-image analysis and cartographic zoning (central, transitional, peripheral), twelve 10 × 10 m sample plots, floristic surveys, projective coverage estimates, chlorophyll measurements, and diversity and succession metrics (Shannon index, succession coefficient). Results revealed strong zonal differentiation – the central zone had minimal coverage (~6.5%) and low chlorophyll (~9.5 mg/g); the transitional zone showed highest diversity and coverage (~61.3%, chlorophyll ~21.3 mg/g); the periphery displayed moderate recovery (~32.5%, chlorophyll ~15.2 mg/g). A succession coefficient (~0.19) indicates slow spontaneous recovery since 2006. We have concluded that spontaneous regeneration is insufficient, so active reclamation is used to improve the soil, using substrate biotechnologies and planting species that are resistant to metals and acids.

**Keywords:** Yavoriv State Mining and Chemical Enterprise, tailings storage facility, ecosystem assessment, phytoremediation, ecological succession, reclamation planning.

## INTRODUCTION

The Yavoriv State Mining and Chemical Enterprise (SMCE) «Sirka» was one of Ukraine's largest industrial facilities associated with sulfur extraction and processing. As a result of the enterprise's activities, significant areas of technogenically disturbed lands were formed in the Lviv region, among which tailings storage facilities pose particular danger. These territories are characterized by increased soil acidity, high concentrations of toxic elements, and low biological productivity (Nahurskyi et al., 2025; Yavoriv State Mining, 2006; Socio-Economic and Environmental Problems, 1995; Project for Restoration of Ecological Balance, 2003; Henyk et al., 2013).

The degraded post-technogenic landscape of the Yavoriv State Mining and Chemical Enterprise «Sirka» tailings storage facility (TSF) represents a source of prolonged environmental burden and potential danger to the population. Under current global challenges – climate change, biodiversity loss, and soil degradation – the problem of their restoration becomes particularly relevant.

Ecosystem restoration means cleaner air and water, mitigation of extreme weather events, improved public health, and biodiversity recovery

(UN, 2021). Ecosystem resources (healthy soils, vegetation cover, water bodies, etc.) form the basis of such sustainable restoration: they ensure water and air purification, climate stabilization, and support life's food chains (Biodiversity, 2025).

Research on ecosystem resources of the Yavoriv SMCE «Sirka» tailings storage facility has crucial significance for planning and successful implementation of reclamation measures, as a comprehensive assessment of soil, water resources, microbiota, and biota as a whole enables adequate determination of initial conditions, ecological risks, and the territory's actual restoration potential. Soil research determines the possibility of plant rooting, the need for ameliorants or creation of a fertile layer, and directions for biotechnological substrate improvement; without them, selection of phyto- and agrotechnical solutions risks being ineffective (Nahurskyi et al., 2025; FAO, 2021; Millennium Ecosystem Assessment, 2005). Assessment of plant and animal cover is important for designing nature-oriented succession. Selection of pioneer plant species, agroforestry belts, and gradual fauna return ensures substrate stabilization, organic matter accumulation, and ecosystem function restoration. Based on such research, practical reclamation measures are formulated considering long-term stability under climate change conditions (European Commission. 2019; European Commission, 2020. Rockström et al., 2009). Local studies, particularly regarding the Yavoriv TSF, document significant changes in soil and hydrological characteristics and limitations of natural succession, emphasizing the need for preliminary detailed ecological research as a mandatory component of reclamation preparation (Ilyin, 2018; Yavorsky et al., 2020; Oliferchuk et al., 2023). Thus, systematic study of ecosystem resources is a primary stage that ensures scientifically based selection of restoration technologies, increases investment efficiency, and guarantees long-term ecological and social benefits from reclamation works.

The the aim of the research is a comprehensive experimental-analytical assessment of ecosystem resources of the Yavoriv SMCE «Sirka» tailings storage facility, determining spatial differentiation of vegetation cover status, plant physiological condition, species structure, and the territory's capacity for natural restoration, with subsequent development of scientifically-based recommendations for reclamation measures.

## MATERIAL AND METHODS

The research was conducted using combined field, laboratory, and statistical methods. Based on satellite image and cartographic material analysis, boundaries of three functional zones were determined, and four stationary sample plots (10 × 10 m) were established in each zone; floristic surveys were conducted on each plot, determining species projective coverage and recording stress phenotypic signs.

Sample plot methods and geobotanical mapping were used to analyze vegetation cover status. Research was conducted on 12 sample plots covering different TSF zones:

- Central part (most contaminated, open surface without significant vegetation);
- TSF periphery (conditionally more stable areas, partially colonized by plants);
- Control zone (adjacent natural ecosystems for comparative analysis).
- Main research parameters:
- Plant species composition and their projected coverage;
- Plant physiological condition (presence of chlorosis, deformations);
- Presence of succession processes (spread of mosses, lichens, herbaceous plants).

During the vegetation status research on the Yavoriv SMCE «Sirka» tailings storage facility territory, comprehensive field and laboratory surveys were conducted to obtain the most objective picture of the territory's ecological condition.

At the initial stage, research territory boundaries were determined based on topographic maps and satellite images. This allowed dividing the TSF into three zones differing in vegetation cover degradation degree: the central part, the periphery, and the transitional zone bordering natural ecosystems. Territory division into these three main zones allowed assessment of vegetation cover restoration using various indicators (Figure 1).

After determining zone boundaries, 12 sample plots were established, 4 in each zone. A size of 10 × 10 m was chosen for each plot, allowing accurate assessment of vegetation coverage and growing species. This specific plot size choice was determined by the need to consider all factors, such as species diversity, coverage density, and local ecological conditions. Sample plot placement ensures representative

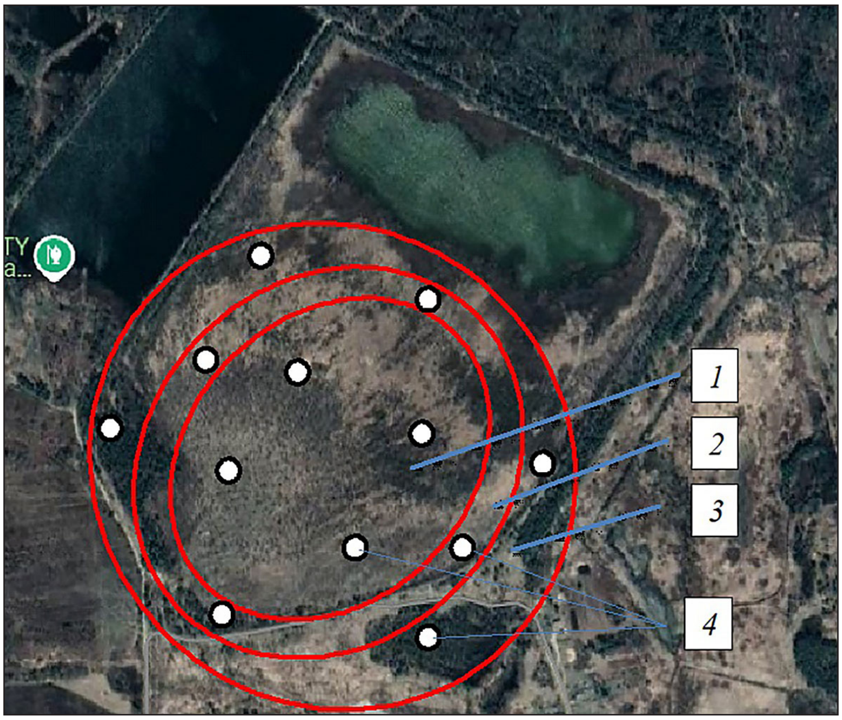


**Figure 1.** Tailings storage facility zones: 1 – central part, 2 – TSF periphery, 3 – control zone, 4 – sample plot locations

coverage of all TSF ecological zones: central part (maximum contamination zone), transitional zone, and periphery. Sample plots were arranged according to the following scheme:

- TSF central part (most contaminated zone) – plots evenly distributed across the central area, oriented along the main pollution axis;
- Transitional zone (partial restoration zone) - plots at the boundary between central and adjacent territory, include vegetation beginning to recover;
- TSF periphery (zone with best conditions) - plots in natural vegetation near tailings storage facility boundaries.

To assess the physiological condition of the plants, leaf samples were collected and analyzed using a portable chlorophyll meter. Leaf samples were taken from the dominant species on each of the 12 sampling plots (four plots per zone): Rumex confertus, Urtica dioica, Calamagrostis epigejos, Salix viminalis, and Betula pendula. Only fully developed, undamaged leaves from the upper or middle portion of the shoot (the sun-exposed side) were selected to minimize within-plant variability. On each plot, 10 individuals of each species were sampled, and 1–2 leaves per individual were collected for measurements.

Measurements were performed with a portable, non-destructive chlorophyll meter, the Opti-Sciences CCM-200Plus, which determines the chlorophyll content index (CCI) by optical transmission at two wavelengths (≈653 and 931nm). It provides rapid measurements over an area of approximately 9.5 mm in diameter, and its results correlate well with chemical (extraction) methods. Readings were taken in situ without removing leaves. Prior to measurement, the leaf blade was gently wiped with a dry tissue to remove dust and visible contaminants. On each sampled leaf three independent readings were taken at different positions on the lamina (near the base, at the middle, and closer to the apex). The mean of the three readings was used as the value for each plant. For each plot, the mean across all plants was calculated (n = 10 plants/plot).

Parallel to vegetation coverage measurement, floristic surveys were conducted to identify plant species composition on each plot. Using plant identification guides and based on field research experience, plant species identification was performed for each sample plot. Additionally, each species' occurrence frequency was determined – an indicator characterizing how often a certain plant or animal species occurs in the studied area (He et al., 2000; Dorazio et al.. 2006). It is calculated as the percentage of samples (e.g., plots or observation points) where a certain species was detected, from the total number of samples:

$$F = \frac{n}{N} \times 100\% \quad (1)$$

where: $F$ – occurrence frequency (%),
$n$ – number of samples where the species was recorded, $N$ – total number of samples.

Biotic potential assessment methods included (Moldovan et al., 2013):
- Shannon diversity index (H) for determining biodiversity level;
- Succession coefficient – calculation of natural overgrowth level.

Calculating the Shannon species diversity index is an important stage in determining ecosystem biotic potential. This index allows quantitative assessment of species diversity in a certain territory, considering both the number of species and their proportional representation.
Formula for Shannon index calculation:

$$H' = -\sum(p_i \cdot \ln p_i) \quad (2)$$

where: $p_i$ – proportion of each plant species in total plant number on the plot;
$\ln p_i$ – natural logarithm of species proportion.

Next, the succession coefficient (also known as succession index) was determined – an indicator reflecting the ecosystem or biocenosis development degree during succession, i.e., during changes in plant and animal cover structure and composition over time.

The succession coefficient typically expresses the speed or direction of species composition changes, often serving as one indicator of ecosystem stability. Calculation was performed using the formula:

$$K = \frac{H_2 - H_1}{T_2 - T_1} \quad (3)$$

where: $H_1$ – diversity index at the initial stage, $H_2$ – diversity index at a later succession stage (after more years),
$T_1$ – time at the initial stage, $T_2$ – time at the late succession stage.

Species and quantitative structurization were processed with the calculation of occurrence frequency and projective coverage. Quantitative diversity assessment was determined using the Shannon index $H'$. Statistical data processing was performed using descriptive statistics, normal distribution testing, and subsequent intergroup comparisons. Correlation analysis was used to identify relationships between physiological and ecological indicators.

## RESULTS AND DISCUSSION

An important aspect of ecosystem restoration is assessing the territory's biotic potential. Biotic potential determines the ecosystem's ability to maintain stable biodiversity, recover from disturbances, and adapt to new conditions. In natural ecosystems, this potential ensures population balance and their resistance to environmental changes, while in technogenically disturbed landscapes, its restoration requires active ecological management and application of nature-based approaches to reclamation.

The main indicators of biotic potential are biodiversity level, vegetation cover restoration, animal abundance and diversity, trophic chain stability, and the ecosystem's self-regulation capacity. Research on plant species composition in post-technogenic territories enables assessment of their survival ability under extreme conditions and natural succession mechanisms.

Visual assessment of vegetation coverage and establishment of quadrats (0.25 m²) for more accurate calculation of herbaceous plant density were used to record plant projective coverage on each plot. This allowed obtaining data on general plant coverage level in respective plots. Table1 presents experimental results and calculated average values:

The results of experimental studies of floristic analysis to identify the species composition of plants in each area are shown in Table 2.

Analysis of the obtained results showed that mosses and annual grasses predominated in the tailings storage facility's central part, while shrubs such as willow and birch appeared in the periphery. In the transitional zone, vegetation cover was most diverse, with dominance of perennial grasses and trees.

Additionally, chlorophyll content in plant leaves was measured on each plot. This allowed assessment of stress levels faced by plants due to environmental toxicity. It was found that in the tailings storage facility's central part, chlorophyll level was reduced (9.5 mg/g), indicating high

**Table 1.** Research results for the general plant coverage level

| No. | Plot | Vegetation coverage (%) | |
|---|---|---|---|
| | | Per plot | Average |
| 1 | C1 (center) | 7 | 6.5 |
| 2 | C2 (center) | 5 | |
| 3 | C3 (center) | 8 | |
| 4 | C4 (center) | 6 | |
| 5 | P1 (periphery) | 30 | 32.5 |
| 6 | P2 (periphery) | 25 | |
| 7 | P3 (periphery) | 35 | |
| 8 | P4 (periphery) | 40 | |
| 9 | T1 (transitional zone) | 60 | 61.25 |
| 10 | T2 (transitional zone) | 50 | |
| 11 | T3 (transitional zone) | 65 | |
| 12 | T4 (transitional zone) | 70 | |

**Table 2.** Results of floristic analysis of the studied territory

| Species | Central part (F, %) | Peripheral part (F, %) | Transitionalz (F, %) |
|---|---|---|---|
| *Rumex confertus* | 100% | 60% | 20% |
| *Urtica dioica* | 70% | 80% | 50% |
| *Betula pendula* | 0% | 45% | 90% |
| *Salix viminalis* | 0% | 50% | 85% |
| *Calamagrostis epigejos* | 10% | 75% | 95% |
| *Cirsium* | 0% | 35% | 80% |

plant stress levels. In the periphery, chlorophyll level was at a medium level (15.2 mg/g), while in the transitional zone it was normal (21.3 mg/g), indicating a healthy vegetation cover status.

Visual assessment of plant condition established that mass leaf damage, chlorosis, and necrosis were observed in the tailings storage facility's central part, indicating severe contamination and plant stress. In the periphery, plant leaves were yellowed but not as damaged as in the central part. In the transitional zone, plants appeared healthy with no obvious signs of disease or stress.

Thus, data analysis showed significant variation in vegetation cover status across the TSF territory depending on the zone. The central part is most contaminated and degraded, with a low vegetation coverage level and significant signs of toxic stress in plants. In the periphery, the restoration process proceeds slowly, while significant improvement in vegetation status is observed in the transitional zone to natural ecosystems.

The ecosystem's ability to maintain stable biodiversity, regulate natural processes, and recover after external factor impacts determines its biotic potential.

Under natural conditions, this potential is ensured by extensive trophic connections and the high adaptability of living organisms. However, in technogenic ecosystems formed at industrial facility sites, biotic potential is substantially reduced due to soil degradation, water regime changes, and chemical contamination. For each plot during field research, the number of plants of each species and their proportion in the total plant number on the plot were determined. Research results are presented in Table 3.

Thus, using the results of the Shannon index ($H'$) calculation (Table 3), it is possible to assess the level of species diversity in each of the zones. The central part has low species diversity due to high contamination, while the periphery and transitional zone have significantly higher biodiversity levels, indicating greater ecosystem restoration capacity.

Formula (3) gives an idea of the rate of change in species diversity and, accordingly, indicates the succession coefficient, which allows us to assess the process of ecosystem development.

**Table 3.** Determination of species diversity on the studied tailings storage facility plots

| Plant species | Number of plants | | |
|---|---|---|---|
| | Central part | Periphery | Transitional zone |
| Species 1 (herbaceous) | 10 | 30 | 20 |
| Species 2 (herbaceous) | 5 | 20 | 15 |
| Species 3 (shrub) | - | 10 | 10 |
| Species 4 (herbaceous) | 3 | - | - |
| Species 5 (shrub) | - | 5 | 5 |
| Species 6 (tree) | - | 5 | 5 |
| Other species | 6 | 10 | 10 |
| Σ Total plants | 24 | 80 | 55 |
| Shannon Index, $H'$ | 1.28 | 2.15 | 2.80 |

At the time of sulfur production closure in 2006, the TSF territory was characterized by the complete absence of plants. Then, for the central part of the TSF, assuming that the Shannon index in the central part is taken to be 0 and the time between succession stages is 15 years, the succession coefficient calculated using formula (3) is $K$=0.19. A succession coefficient value up to 0.20 indicates a slow natural restoration process.

## CONCLUSIONS

Obtained results indicates significant unevenness of vegetation cover across the tailings storage facility territory. Based on this characteristic, the tailings storage facility territory can be divided into three conditional zones: central, transitional, and periphery. The central part is most contaminated and degraded, with low vegetation coverage level and significant signs of toxic stress in plants. In the periphery, the restoration process proceeds slowly, while significant improvement in vegetation status is observed in the transitional zone to natural ecosystems. Measurements of chlorophyll levels in plants and assessment of species diversity using the Shannon index showed that the tailings storage facility's central part has the lowest indicators of biotic self-restoration potential.

We concluded that natural self-restoration is insufficient for complete ecosystem rehabilitation; therefore, active reclamation measures are necessary, such as soil composition improvement, planting of toxic substance-resistant plants, and creating favorable conditions for biodiversity restoration.

## REFERENCES

1. Biodiversity. (2025). *World Haelth Organization.* https://www.who.int/news-room/fact-sheets/detail/biodiversity#:~:text=People%20depend%20on%20biodiversity%20in,cause%20or%20increase%20political%20conflict
2. Dorazio, R. M., Royle, J. A., Söderström, B., Glimskär, A. (2006). Estimating species richness and accumulation by modeling species occurrence and detectability. *Ecology, 87*(4), 842–854.
3. European Commission. (2019). *The European Green Deal. Publications Office of the European Union.* https://ec.europa.eu
4. European Commission. (2020). EU Biodiversity Strategy for 2030: Bringing nature back into our lives. *Publications Office of the European Union*. https://ec.europa.eu
5. FAO. (2021). The state of the world's land and water resources for food and agriculture: *Systems at breaking point. Food and Agriculture Organization of the United Nations.* https://doi.org/10.4060/cb7654en
6. He, F., & Gaston, K. J. (2000). Estimating species abundance from occurrence. *The American Naturalist, 156*(5), 553–559. https://doi.org/10.1086/303403
7. Henyk, Y.V.,. Zayachuk, V.Y. (2013). Vegetation succession on post-technogenic territories in the activity zone of Yavoriv State Mining and Chemical Enterprise «SIRKA». *Scientific Bulletin of UNFU.* 23(16), 93–99.
8. Ilyin, V.V., Melnyk, L.H. (2018). Reclamation of technogenically disturbed lands: ecological and economic aspects. *Ecological Bulletin, 1*, 15–22. https://doi.org/10.32014/2020.2224-526X.30
9. Millennium Ecosystem Assessment. (2005). Ecosystems and human well-being: Synthesis. Island Press. https://www.millenniumassessment.org/documents/document.356.aspx.pdf

10. Moldovan, O. T., Meleg, I. N., Levei, E.-A. (2013). A simple method for assessing biotic indicators and predicting biodiversity in the hyporheic zone of a river polluted with metals. *Ecological Indicators, 24,* 412–420. https://doi.org/10.1016/j.ecolind.2012.07.019
11. 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. *Ecol. Eng. Environ. Technol 4.* https://doi.org/10.32846/2306-9716/2025.eco.1-58.42
12. Oliferchuk, V., Kendzora, N., Hotsii, N., Shukel, I., Olejniuk-Puchniak, O., Samarska, M.,..., 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*, 120-134. https://doi.org/10.12912/27197050/159629
13. On Approval of the Project for Restoration of Ecological Balance and Reclamation of Lands Disturbed by Mining Operations of Yavoriv State Mining and Chemical Enterprise «Sirka». (2003). *Order of the Cabinet of Ministers of Ukraine dated February 24,* 2003, No. 87-r. https://www.kmu.gov.ua/npas/152879?utm_source=chatgpt.com.
14. On Solving Socio-Economic and Environmental Problems in Yavoriv and Zhydachiv Districts of Lviv Region. (1995). *Resolution of the Cabinet of Ministers of Ukraine dated June 21,* 442. https://zakononline.com.ua/documents/show/176837___176902?utm_source=chatgpt.com
15. On the Cessation of Yavoriv State Mining and Chemical Enterprise «Sirka». (2006). *Order of the Ministry of Industrial Policy of Ukraine dated. June 27,* 230. https://zakon.rada.gov.ua/rada/show/v0230581-06#Text.
16. Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E.,..., Foley, J. (2009). A safe operating space for humanity. *Nature, 461*(7263), 472–475. https://doi.org/10.1038/461472a
17. UN calls on countries to meet commitments to restore one billion hectares of land (2021). *Becoming Generation Restoration: Ecosystem Restoration for People, Nature and Climate.* https://www.unep.org/ru/novosti-i-istorii/press-reliz/oon-prizyvaet-strany-vypolnit-obyazatelstva-po-vosstanovleniyu-odnogo
18. Yavorsky, N.I. (2020). Features of the ecological condition of the Yavoriv SMCE «Sirka» territory and prospects for its reclamation. *Visnyk of Lviv University. Geographical Series, 54*, 120–129.