

Ecological and technogenic safety and phytomelioration of degraded landscapes of a limestone quarry

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Abstract. The reclamation of degraded lands, particularly limestone quarries, is a critical ecological task aimed at restoring soil cover and forming stable phytocenoses. This study evaluates the effectiveness of phytomelioration measures through an analysis of changes in the physico-chemical properties of soil and plant composition. The results showed that, after reclamation, humus content increased by 15%, contributing to improved soil structure and water retention capacity. Soil acidity (pH) rose from 4.5 to 6.1, creating favorable conditions for the development of mesophytic and eutrophic species. The concentration of macronutrients significantly increased: nitrogen from 12.3 mg/kg to 24.7 mg/kg, phosphorus from 9.8 mg/kg to 20.3 mg/kg, and potassium from 85 mg/kg to 150 mg/kg, positively affecting plant cover productivity. Phytocenosis analysis revealed an increase in meadow-steppe communities from 24.69% to 31.82% and eutrophic species from 22.22% to 34.55%, indicating ecosystem stabilization. The planting of tree species (*Pinus sylvestris*, *Robinia pseudoacacia*, *Quercus robur*) contributed to soil stabilization, reduced erosion processes, and the gradual formation of forest ecosystems. The results confirm the effectiveness of phytomelioration in restoring technogenically disturbed lands. Future research should focus on long-term monitoring of successional changes and the impact of reclamation measures on soil biogeochemical processes.

Key words: phytomelioration, technogenic landscape, reclamation, plant cover, spontaneous vegetation, environmental safety, quarry.

Introduction

Technogenic activities cause significant alterations in landscapes, particularly in limestone quarries, which are characterized by soil degradation, loss of biodiversity, and the development of erosion processes. One of the most effective methods of ecological restoration for such areas is phytomelioration - using vegetation to stabilize the soil cover and improve its properties.

Phytomelioration contributes to the preservation of ecosystem functions, prevents further soil degradation, and facilitates the formation of stable biogeocenoses. This study focuses on analyzing the impact of various types of vegetation on the

restoration of technogenically disturbed soils and on developing effective methods for the reclamation of quarry landscapes.

The restoration of technogenically transformed landscapes, particularly limestone quarries, presents a complex challenge that requires an integrated approach. The study of Oluwaseyi & Alhassan (2024) emphasizes the importance of critical planning in quarry waste management to facilitate effective reclamation and restore the landscape to an acceptable topographical level. Although this research does not specifically address phytoremediation of limestone quarries, it highlights the need for ecologically sound measures to

rehabilitate degraded areas. Such an approach is essential for ensuring soil stability and creating favorable conditions for subsequent phytomelioration efforts.

Solé et al. (2023) explore the creation of Technosols for the restoration of limestone quarries, emphasizing the use of organic amendments to improve soil quality. The application of organic matter enhances the content of organic carbon, increases the availability of nutrients, and stabilizes the physicochemical properties of the substrate. The combined effect of these factors creates favorable conditions for phytoremediation and ecological recovery - particularly relevant for Mediterranean landscapes that are prone to degradation due to mining activities. Phytomelioration is one of the most effective biological reclamation methods, promoting soil restoration and the formation of stable plant communities. It involves the use of both native and cultivated plant species to improve soil structure and stabilize ecosystems. Special attention is paid to selecting plant species capable of adapting to the extreme conditions of limestone spoil heaps and contributing to the restoration of biogeocenoses.

Study of Xiroudakis et al. (2024) emphasizes the importance of phytotechnical restoration of limestone quarries through the careful selection of plant species adapted to the specific conditions of these environments. The use of native plant communities not only improves the landscape but also supports the ecological balance of the area. In addition to compliance with regulatory requirements, effective restoration requires close collaboration with botanists and foresters, who can provide scientifically grounded strategies for restoring vegetation cover and stabilizing soils.

Semeraro et al. (2019) present a landscape regeneration project for a limestone quarry, emphasizing the use of phytomelioration to restore natural vegetation cover and form ecologically resilient biocenoses. Particular attention is given to the development of priority habitats, such as pseudosteppe plant communities, which enhance biodiversity and ecological functions within technogenic landscapes. The restoration of native vegetation improves soil stability, increases the ecological value of the area, and facilitates natural successional processes.

Study of Carabassa et al. (2020) highlight that the use of sewage sludge as an amendment in

Technosol-based quarry reclamation improves soil quality, promotes vegetation development, and supports ecosystem services such as carbon sequestration, thus contributing to phytoremediation and ecological recovery of anthropogenically altered landscapes.

Ortega et al. (2020) investigated phytomelioration in limestone quarries through increased soil fertility using organic (compost) and inorganic (zeolite) amendments, supporting the growth and survival of native Mediterranean plants essential for restoring degraded landscapes in semi-arid regions.

Study of Gentili et al. (2020) analyzes the influence of backfilling materials and soil characteristics on vegetation formation and biodiversity in limestone quarries. The findings demonstrate that appropriate selection of these components can facilitate effective phytoremediation by enhancing spontaneous recolonization processes and improving ecosystem stability in restored landscapes. The authors argue that accounting for the specific conditions of each site and conducting detailed soil assessments enables the optimization of reclamation strategies, promoting natural recovery of technogenic areas.

The formation of vegetation cover in technogenically disturbed areas follows consistent ecological patterns determined by substrate properties and the degree of anthropogenic impact. A study (Skrobala et al., 2020) show that waste dumps of coal mines in the Lviv-Volyn basin undergo gradual development of stable phytocenoses characterized by the dominance of ruderal and mesophytic species. Similar findings are reported by Skrobala et al. (2022), who demonstrated that the chemical composition of mine dumps significantly influences the structure of plant communities and succession processes.

Mathematical modeling of pollutant migration plays a crucial role in environmental risk assessment. According to Pukish et al. (2024), groundwater contamination in mining regions exhibits complex spatio-temporal patterns, which necessitate the use of integrated predictive models. In addition, Pukish et al. (2023) found that technogenic pollutants affect not only hydrosystems but also agrochemical soil properties, particularly nutrient content.

In the context of municipal waste landfills, the accumulation of heavy metals in vegetation is

a critical environmental issue. Studies demonstrate the effectiveness of spectral analysis in identifying contamination in pioneer vegetation, allowing rapid assessment of environmental conditions (Korol & Popovych, 2023). At the same time, Korol et al. (2022) showed that the chemical composition of landfill neoreliefs determines the level of toxicant accumulation and contributes to the formation of localized high-risk zones.

The effectiveness of land reclamation largely depends on the composition of backfilling materials and soil formation conditions. Research by Gentili et al. (2020) indicates that biodiversity and vegetation cover in quarry ecosystems are directly influenced by the physicochemical properties of the substrate. Similarly, (Popovych et al., 2021) demonstrated that the formation of phytogenic fields on mine dumps contributes to improving environmental safety and stabilizing soil cover.

Degraded landscapes, particularly within the Volhynian Upland and Male Polissya regions, are characterized by significant alterations in ecological parameters, including disruption of biogeochemical cycles and soil degradation (Popovych & Voloshchyshyn, 2019). This confirms the necessity of implementing integrated approaches to the restoration of such territories.

Modern research increasingly emphasizes the systemic nature of interactions affecting biological and ecological systems. Studies of Serhiyenko & Serhiyenko (2022a,b) demonstrate that metabolic disorders lead to complex functional changes in the organism, particularly within the cardiovascular system. The authors highlight the systemic nature of these processes, which develop under prolonged exposure to internal and external stress factors. This approach is further supported by Serhiyenko & Serhiyenko (2023), who showed that long-term exposure to adverse factors results in destabilization of regulatory mechanisms. Earlier findings (Serhiyenko, 2014) indicate that insulin resistance is a key driver of structural and functional changes in biological systems, supporting the concept of cumulative effects.

Within the context of environmental studies, similar patterns are observed in the analysis of technogenic impacts on soil systems. Pukish et al. (2023) established that anthropogenic pressure significantly alters the balance of soil nutrients, directly affecting soil fertility and ecosystem productivity. This highlights the need for a comprehen-

sive approach to environmental assessment that integrates both chemical and biological parameters.

An important direction of modern research is the development of regulatory approaches to environmental assessment. Adamenko et al. (2017) proposed territorial standards for evaluating hydroecosystem quality based on the integration of natural and anthropogenic factors. This approach improves the accuracy of environmental monitoring and supports more informed management decisions.

At the same time, the development of environmental management reflects a broader trend toward increasing complexity in environmental governance. As noted by Hren et al. (2021), modern environmental management concepts are based on systemic and integrated approaches that account for the multifactorial nature of ecological processes. In this context, the formation of effective environmental policy aligned with international standards becomes particularly important, as emphasized by Batyr et al. (2021), who highlight the need for harmonizing national approaches with global environmental requirements.

The Pidvysotskyi Quarry is characterized by a high degree of anthropogenic pressure, which hinders natural vegetation succession. The implementation of phytomeliorative measures helps mitigate the negative impacts of technogenic factors and creates preconditions for further ecological rehabilitation of the area.

The aim of this study is to evaluate the effectiveness of spontaneous and cultivated vegetation in restoring disturbed soils, to analyze the impact of phytomeliorative measures on the physicochemical properties of soils, and to develop practical recommendations for ecological rehabilitation.

Materials and methods

Pidvysoke is a village in Ukraine located within the Narayiv rural community of Ternopil Raion, Ternopil Oblast. The village lies along the banks of the Narayivka River amidst the hills of the Rohatyn Opillya region. The international highway E50 (Rohatyn-Berezhany section) and the Khodoriv-Ternopil railway line pass through Pidvysoke, with a railway station situated in the village. To the east of Pidvysoke lies the Opilska Cave, as well as the Pidvysoke limestone deposit.

The Pidvysoke Building Materials Plant specializes in the production of limestone-based pro-

ducts, including crushed stone, limestone flour, and quicklime. The quarry represents a technogenically disturbed area formed as a result of long-term limestone extraction. The landscape of

the quarry is characterized by significant elevation differences, exposed rocky surfaces, low soil fertility, and a high degree of erosion processes (Fig. 1).



Fig. 1. Location and appearance of the Pidvsyoke limestone quarry in Ternopil Oblast (image from Google Maps).

The climate of the study area is moderately continental, with an average annual temperature of $+8.2^{\circ}\text{C}$ and approximately 600 mm of precipitation per year. The vegetation period lasts around 200 days. The predominant soils are rendzinas and eroded chernozems, which have undergone significant degradation due to prolonged absence of vegetation cover. The radiation regime of the study site is defined by seasonal variations in the radiation balance, which is a crucial factor influencing vegetation development and soil processes. According to data presented, the highest radiation balance values are observed during the summer months - May (6.4 kcal/cm^2), June (7.8 kcal/cm^2), and July (7.7 kcal/cm^2) - due to extended daylight hours and intense heat exchange processes. In contrast, the radiation balance reaches its minimum during the winter period (November to February), which is attributed to short daylight hours and high cloud cover. Notably, in November and December, radiation balance values approach zero ($0.3\text{--}0.0 \text{ kcal/cm}^2$), indicating very low energy input to the surface. The annual radiation balance in the study area amounts to 39.8 kcal/cm^2 , which is typical for the western regions of Ukraine. These data are important for assessing the conditions of vegetation recovery and the effectiveness of phytomeliorative measures, as solar radiation directly

influences photosynthesis and the biological productivity of plants.

The floristic composition of the area is represented by successional communities dominated by light-loving herbaceous and shrubby species, typical of the early stages of natural regeneration. The main challenges of reclamation include insufficient organic matter content, low nutrient availability in the soil, and limited water-holding capacity. A comprehensive approach was employed in the research, incorporating field, laboratory, and statistical methods of analysis. During the field stage, $10 \times 10 \text{ m}$ sample plots were established within the quarry to assess vegetation cover. On each plot, a description of both spontaneous and cultivated vegetation was conducted. Plant vitality was evaluated using a scoring scale, which allowed for the determination of species resilience under quarry conditions.

Regarding soil analysis, samples were collected from two depths — 0–10 cm and 10–30 cm. For humus content analysis, 10 grams of air-dried soil were mixed with a solution of chromic acid and sulfuric acid, then heated, and the remaining chromium was titrated. Soil pH was determined using a potentiometric method, whereby a soil suspension was prepared in a 1:2.5 soil-to-water ratio, stirred, allowed to settle, and the pH was measured using an electronic pH meter.

Particle size distribution was determined using the pipette method, which involved dispersing the soil sample in a special solution, allowing the particles to settle, and then sampling from different levels of the suspension to determine the textural composition. Soil moisture capacity was measured using the gravimetric drying method, in which soil samples were dried at 105°C until a constant mass was achieved. The difference in weight was used to calculate the moisture content. The effectiveness of phytomelioration was evaluated by analyzing biomass productivity on both control and reclaimed plots, measuring vegetation growth, changes in soil properties, and assessing the stability of phytocenoses. The data were processed using statistical methods, including analysis of variance (ANOVA) and correlation analysis, with Microsoft Excel software. This approach enabled the identification of patterns and

the assessment of the effectiveness of the applied phytomeliorative measures.

Results

To identify vegetation succession and inform the development of ecological restoration measures, an analysis of the floristic composition of the quarry site was conducted. This approach focuses on maximizing the natural regenerative capacity of disturbed ecosystems, which helps reduce secondary anthropogenic pressure and significantly lowers the economic cost of landscape recovery. A total of 141 plant species were identified within the quarry area, belonging to 99 genera, 34 families, 30 orders, and 5 classes. The least represented class was Equisetopsida (horsetails), with only 1 species, while the most numerous group was dicotyledons, comprising 110 species. The monocotyledons were represented by 20 species, conifers by 2 species, and mosses by 8 species (Table 1, Fig. 2).

Table 1. Taxonomic structure of the flora in the limestone quarry.

Class	Order	Family	Number of Genera		Number of Species	
			Abs.	%	Abs.	%
Bryopsida	3	4	5	5.05	8	5.67
Equisetopsida	1	1	1	1.01	1	0.71
Liliopsida	4	4	13	13.13	20	14.18
Magnoliopsida	22	24	78	78.79	110	78.01
Pinopsida	1	1	2	2.02	2	1.42
Total	30	34	99	100	141	100

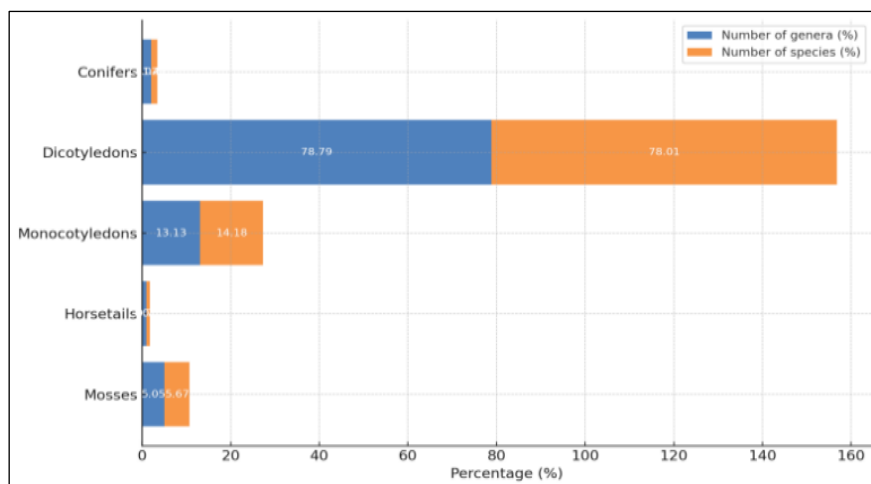


Fig. 2. Ratio of the number of genera and species among different plant classes.

The obtained results demonstrate considerable plant biodiversity within the quarry, indicating active natural processes of ecosystem recovery. The largest group identified was dicotyle-

donous species, with a predominance of representatives from the families Asteraceae (daisies), Fabaceae (legumes), and Poaceae (grasses). These are typical species of meadow and ruderal plant

communities, which rapidly colonize disturbed areas due to their high seed productivity and capacity for vegetative reproduction.

The presence of coniferous species and bryophytes suggests the gradual formation of more stable plant communities. Mosses play an important role in primary soil formation, contributing to the accumulation of organic matter and the retention of moisture. Although represented by only two species, coniferous trees may serve as key elements in the formation of forest ecosystems on reclaimed lands.

The spectral distribution of hygromorphs within the flora of the limestone quarry was analyzed across two substrate types - embryozems and technosols. The results indicate a dominance of the mesophytic group, which reflects relatively stable hydrological conditions within the studied plots. Mesophytes represent the most abundant group, accounting for 45.68% (37 species) on embryozems and 48.18% (53 species) on technosols. This suggests the prevalence of moderately moist conditions favorable for plants with intermediate

water requirements. Xeromesophytes are the second most represented group and are considerably more prevalent on technosols (30.91%) than on embryozems (22.22%). This may be attributed to the lower water retention capacity of technosols, which favors more drought-tolerant species. Hygromesophytes and mesohygrophytes show similar proportions in both environments - 14.81% on embryozems and 13.64% on technosols - indicating the presence of areas with elevated moisture levels. The proportion of mesoxerophytes is significantly higher on embryozems (11.11%) compared to technosols (3.64%), which may reflect gradual improvements in the moisture retention capacity of technosols as a result of reclamation activities. Xerophytes, which are adapted to dry conditions, comprise 4.94% on embryozems and only 1.82% on technosols, indicating a reduction in aridity in the reclaimed plots. Hygrophytes are represented by a minimal number of species - 1.23% on embryozems and 1.82% on technosols - suggesting the absence of significantly waterlogged areas within the study site (Table 2, Fig. 3).

Table 2. Hygromorph spectrum of the flora in the limestone quarry.

Hygromorph Group	Embryozems		Technosols	
	No. (units)	Proportion (%)	No. (units)	Proportion (%)
Xerophytes	4	4.94	2	1.82
Mesoxerophytes	9	11.11	4	3.64
Xeromesophytes	18	22.22	34	30.91
Mesophytes	37	45.68	53	48.18
Hygromesophytes, Mesohygrophytes	12	14.81	15	13.64
Hygrophytes	1	1.23	2	1.82
Total	81	100	110	100

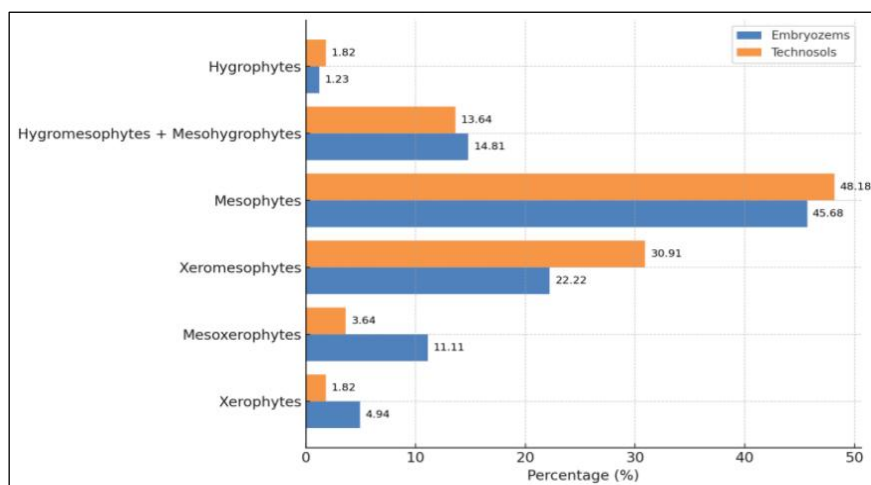


Fig. 3. Hygromorph spectrum of the flora in the limestone quarry.

The formation of ecologically stable plant communities on technogenically disturbed substrates, dominated by mesophytic and xeromesophytic species, may indicate the stabilization of the hydrological regime during the course of phytomeliorative processes. This, in turn, supports the progression toward the development of more stable phytocenoses.

The trophomorph spectrum of the limestone quarry flora reflects the trophic differentiation of plant species across two substrate types – embryozems (naturally formed soils) and technosols (anthropogenically transformed, reclaimed soils). This analysis allows for the assessment of soil fertility levels and the dynamics of nutrient regimes following the implementation of phytomeliorative measures.

The results indicate that mesotrophs, which prefer moderately fertile soils, constitute the dominant group on both embryozems (33.33%, 27 species) and technosols (33.64%, 37 species), indicating relative stability in soil conditions throughout the quarry and supporting the development of vegetation with intermediate nutrient demands. The second most abundant group is eutrophs – species that thrive in nutrient-rich soils. Their proportion is significantly higher on technosols (34.55%, 38 species) compared to embryozems (22.22%, 18 species), which can be attributed to the application of organic and mineral fertilizers that improved soil fertility and created favorable conditions for eutrophic vegetation development. Mesoeutrophs, which occupy an intermediate position between mesotrophs and eutrophs, account for 18.52% (15 species) on embryozems and 14.55% (16 species) on technosols. The slight decrease in their share on technosols may result from progressive substrate enrichment, leading to

the transition of some mesoeutrophic species into the eutrophic category. A notable contrast between the two soil types is seen in oligotrophs – species adapted to nutrient-poor conditions. On embryozems, they account for 12.35% (10 species), while on technosols their presence decreases to 4.55% (5 species). This reflects an overall improvement in soil nutrient status due to reclamation efforts, making technosols less suitable for nutrient-stress-adapted species. At the same time, oligomesotrophs, which prefer moderately impoverished soils, show nearly identical proportions across both substrates – 9.88% (8 species) on embryozems and 10.00% (11 species) on technosols – suggesting stable ecotopic conditions for this category of plants. The least represented group consists of megatrophs – species requiring excessively nutrient-rich conditions. They are represented by three species in both embryozems (3.70%) and technosols (2.73%), indicating the absence of sites with overly high trophic status within the studied area (Table 3, Fig. 4).

Phytomeliorative measures have contributed to improving the fertility of technosols, as evidenced by the substantial increase in eutrophs and the reduction in oligotrophs. Mesotrophic species remain dominant in both environments, indicating a generally moderate level of soil fertility throughout the quarry. The decrease in mesoeutrophs and increase in eutrophs on technosols suggests a gradual ecological shift from poorer to more nutrient-rich conditions. The low presence of megatrophs in both environments confirms the absence of excessive nutrient accumulation, even after reclamation. The slight decline in oligomesotrophs on technosols may indicate localized areas with less favorable conditions for plant development.

Table 3. Trophomorph spectrum of the flora in the limestone quarry.

Trophomorph Group	Embryozems		Technosols	
	No. (units)	Proportion (%)	No. (units)	Proportion (%)
Oligotrophs	10	12.35	5	4.55
Oligomesotrophs	8	9.88	11	10.00
Mesotrophs	27	33.33	37	33.64
Mesoeutrophs	15	18.52	16	14.55
Eutrophs	18	22.22	38	34.55
Megatrophs	3	3.70	3	2.73
Total	81	100	110	100

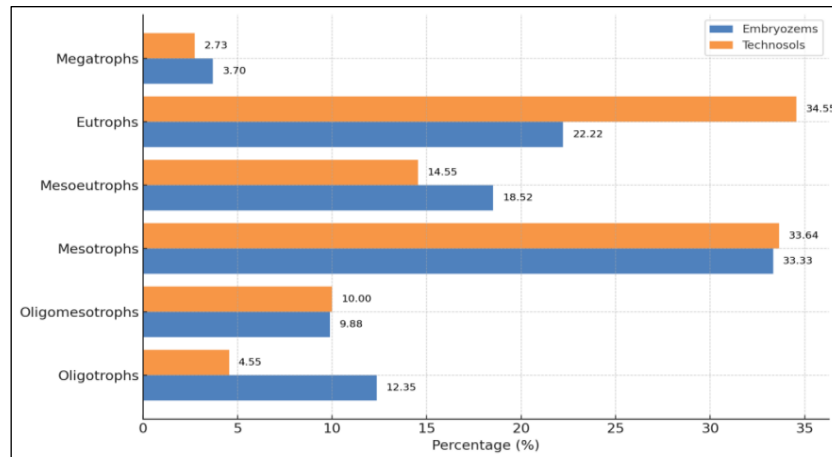


Fig. 4. Trophomorph spectrum of the flora in the limestone quarry.

The analysis of the biomorph spectrum of the limestone quarry flora reveals differences in life strategies between plants growing on natural soils (embryozeims) and those on anthropogenically altered substrates (technosols) that have undergone reclamation. The biomorphological structure of vegetation is an important indicator of ecosystem stability and the nature of its recovery.

Hemicryptophytes represent the most abundant group on both soil types, accounting for 55.56% on embryozeims and 59.09% on technosols. These are perennial herbaceous plants that overwinter with buds at ground level, allowing them to effectively adapt to disturbed landscape conditions. The increase in their proportion on technosols indicates active establishment of vegetation cover and improved conditions for ecosystem stabilization. Phanerophytes, which include trees and tall shrubs, form the second most numerous group; however, their proportion decreases on technosols - from 28.40% on embryozeims to 18.18%. This may be due to limited soil fertility or the constrained development of deep root systems in reclaimed soils. Cryptophytes, which survive unfavorable conditions via underground organs (rhizomes, bulbs, tubers), significantly increase in proportion on tech-

nosols (15.45%) compared to embryozeims (6.17%). This suggests that techno-genic substrates provide favorable conditions for the establishment and spread of plants with subterranean buds, known for their high ecological resilience. There is also an increase in therophytes - annual plants that complete their life cycle within a single season - from 3.70% on embryozeims to 7.27% on technosols. This is typical of early successional stages, where fast-growing species with high seed productivity play a leading role in colonization. Chamaephytes - low-growing shrubs and subshrubs - are absent in both environments, indicating that current site conditions are unfavorable for this group of plants.

The biomorphological analysis indicates that technosols are actively colonized by perennial herbs and subterranean regenerative forms, which contribute to substrate stabilization and the development of phytocenotic stability. Meanwhile, the reduced presence of woody species may point to the need for additional measures to improve conditions for their growth. These findings confirm the effectiveness of phytomeliorative interventions in promoting the formation of more stable and ecologically resilient plant communities on disturbed quarry lands (Table 4, Fig. 5).

Table 4. Biomorph spectrum of the flora in the limestone quarry.

Biomorph Group	Embryozeims		Technosols	
	No. (units)	Proportion (%)	No. (units)	Proportion (%)
Therophytes	23	28.40	20	18.18
Hemicryptophytes	-	-	-	-
Cryptophytes	45	55.56	65	59.09
Phanerophytes	5	6.17	17	15.45
Chamaephytes	3	3.70	8	7.27
Total	81	100	110	100

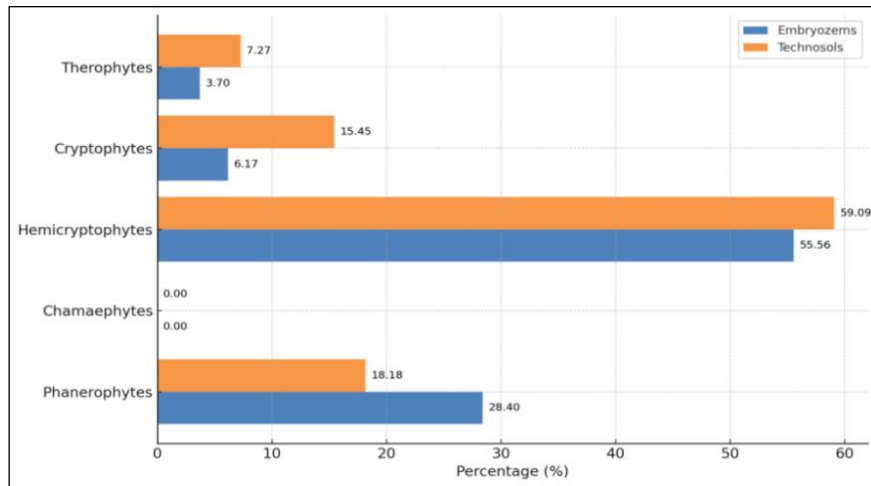


Fig. 5. Biomorph spectrum of the flora in the limestone quarry.

The distribution of vegetation by florocoenotic complexes provides insight into the structure of plant cover, the ecological conditions of its formation, and the successional processes occurring within the quarry. An analysis of Table 5 shows that ecosystem recovery occurs through a variety of plant community types, with technosols exhibiting a shift in dominant florocoenotic complexes toward meadow-steppe and agro-ruderal vegetation.

The forest-shrub complex remains dominant within the limestone quarry flora, comprising 53.09% (43 species) on embryozems and 48.18% (53 species) on technosols. This suggests that the formation of stable plant communities on disturbed quarry lands is largely driven by woody and shrubby vegetation. The reduction in the proportion of this complex on technosols may be due to insufficient soil moisture or limited conditions for the natural regeneration of woody species. The meadow-steppe complex shows an increasing trend, growing from 24.69% (20 species) on embryozems to 31.82% (35 species) on technosols. This may be attributed to more favorable conditions for herbaceous steppe species in reclaimed areas affected by anthropogenic activities. The agro-ruderal complex also exhibits a slight increase on technosols (14.55%) compared to embryozems (13.58%), indicating the influence of soil disturbances and the spread of ruderal (weedy) vegetation typical of early successional stages. The hydrophilous complex, which includes species of moist habitats, increases its share on technosols (4.55%) compared to embryozems (2.47%), sug-

gesting the presence of areas with sufficient moisture levels. In contrast, the hydrophilous and forest-meadow florocoenotic complexes disappear entirely from technosols. Hydrophilous plants - those adapted to waterlogged conditions - account for 1.23% (1 species) only on embryozems and are absent on technosols, possibly due to lowered groundwater levels or the lack of suitable wet conditions following reclamation. The forest-meadow complex, which occupied 3.70% (3 species) on embryozems, also disappears from technosols, indicating a reduction in ecologically stable transitional communities between forest and meadow ecosystems. Ruderal species, typical of anthropogenically disturbed lands, show minimal presence, with little change in proportion (1.23% on embryozems and 0.91% on technosols). This indicates gradual ecosystem stabilization, as ruderal species tend to dominate at early stages of recovery. The forest-shrub complex remains dominant, confirming the quarry's significant potential for the restoration of woody vegetation. The increase in the meadow-steppe complex on technosols points to a natural successional process favoring herbaceous species adapted to drier conditions. The ongoing spread of agro-ruderal vegetation on technosols may indicate instability in the soil cover in certain areas. The disappearance of hydrophilous and forest-meadow complexes from technosols reflects a change in the hydrological regime and less favorable conditions for moisture-loving species.

The natural recovery of flora on technogenically disturbed soils occurs through the gradual

expansion of meadow-steppe and agro-ruderal complexes, which are typical of early successional stages. At the same time, the decline in woody

vegetation suggests the need for additional measures to stimulate forest development and improve hydrological conditions (Fig. 6).

Table 5. Florocoenotic complex spectrum of the flora on embryozems and technosols in the limestone quarry.

Florocoenotic Complex	Embryozems		Technosols	
	No. (units)	Proportion (%)	No. (units)	Proportion (%)
Agro-ruderal	11	13.58	16	14.55
Hygrophilous	2	2.47	5	4.55
Hydrophilous	1	1.23	-	-
Forest-meadow	3	3.70	-	-
Forest-shrub	43	53.09	53	48.18
Meadow-steppe	20	24.69	35	31.82
Ruderal	1	1.23	1	0.91
Total	81	100	110	100

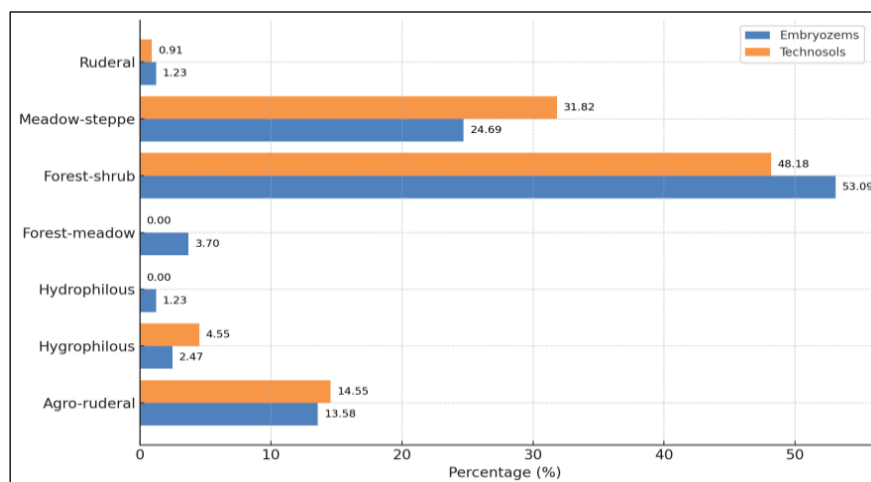


Fig. 6. Comparative spectrum of florocoenotic complexes on embryozems and technosols in the limestone quarry.

The distribution of vegetation by light preference groups provides insight into environmental light availability and the adaptive capacity of plant communities under the conditions of a limestone quarry. According to the obtained data, the majority of species belong to heliophytic (light-loving) groups, which is typical for open ecosystems with limited shading and intense solar radiation.

Heliophytes - plants that prefer full sunlight - constitute the dominant group on both embryozems (56.79%, 46 species) and technosols (48.18%, 53 species). The high proportion of heliophytes reflects the open character of the quarry environment and the scarcity of shaded microhabitats. The slight decrease in their share on technosols may be associated with the gradual spread of

woody and shrubby vegetation, which creates microenvironments with differentiated light conditions. Facultative heliophytes, capable of growing in both full sun and partial shade, show a substantial increase on technosols (34.57% on embryozems and 46.36% on technosols). This may indicate an improvement in the structural diversity of plant cover on reclaimed land, where conditions favorable for species with broader light requirements are gradually emerging. Sciophytes - shade-tolerant species - are poorly represented, accounting for only 4.94% (4 species) on embryozems and 3.64% (4 species) on technosols. This low presence confirms that the ecosystem has not yet reached a successional stage in which closed-canopy forest communities with high shading levels develop. Indifferent species - those with no

specific light preferences - make up 3.70% (3 species) on embryozems and 1.82% (2 species) on technosols. Their slight decline on reclaimed areas may be due to the active spread of light-demanding species, which tend to be more competitive in open habitats with exposed soil (Table 6, Fig. 7).

Heliophytes remain the dominant group across both soil types, confirming the open nature of the quarry ecosystem and its early successional stage, where light-loving species have the greatest competitive advantage. The increasing proportion of facultative heliophytes on technosols suggests the gradual formation of more diverse lighting conditions, possibly due to the growth of woody

and shrubby vegetation. Sciophytes remain scarce, indicating the absence of well-developed forest communities and limited shading. Indifferent species show a decreasing trend on technosols, which may suggest the progressive specialization of plant communities in response to local light regimes.

The prevalence of heliophytic vegetation - typical for early succession stages on disturbed quarry lands - combined with the increased proportion of facultative heliophytes on technosols may signal the onset of more complex phytocoenotic development. This is a positive indicator of the effectiveness of the reclamation measures implemented.

Table 6. Light preference spectrum of the flora on embryozems and technosols in the limestone quarry.

Light Group	Embryozems		Technosols	
	No. (units)	Proportion (%)	No. (units)	Proportion (%)
Heliophytes	46	56.79	53	48.18
Facultative heliophytes	28	34.57	51	46.36
Sciophytes	4	4.94	4	3.64
Indifferent species	3	3.70	2	1.82
Total	81	100	110	100

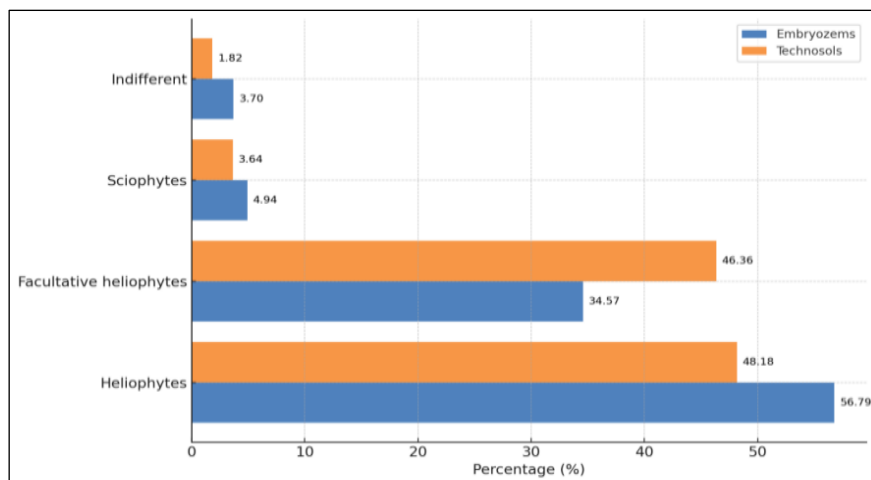


Fig. 7. Comparative spectrum of light preference groups on embryozems and technosols in the limestone quarry.

Discussion

Surface preparation of lands disturbed by mining operations is carried out on areas where extraction activities have been completed and further exploitation is not planned. The choice of planning method depends on the intended future use of the reclaimed land. Three main approaches are distinguished: complete, partial, and terraced planning.

Complete planning is used for preparing land for agricultural purposes and involves surface leveling with slopes suitable for agricultural machinery. Partial planning focuses on leveling while preserving natural microrelief and is optimal for forest reclamation. In the case of ridge-shaped spoil heaps, the crests are leveled to create flat areas at least 10 meters wide. If the spoil surface is slightly undulated, it can be used for fo-

restry without further planning. Terraced planning is applied for establishing forest plantations or orchards. It involves forming terraces that stabilize slopes and reduce erosion. Spoil heap leveling is carried out in two stages: primary (rough) and final (fine) planning. Primary planning is done during active mining and includes basic earthworks for preliminary surface leveling using bulldozers, scrapers, and excavators. Final planning is carried out 1–2 years later, before applying a fertile soil layer. It involves correcting microrelief and redistributing small volumes of overburden.

Research indicates that loess-like loamy materials can be effectively used for pasture and hayfield establishment even without applying additional layers of fertile soil or chernozem. However, the productivity of such areas largely depends on the thickness of the artificially applied soil horizon. Therefore, it is essential to determine the optimal thickness of the soil layer based on the planned land use. A rational approach to surface planning significantly enhances land productivity and ensures the long-term effectiveness of reclamation measures. Reclamation of quarry-disturbed lands is a crucial stage in ecosystem restoration and the return of areas to productive use. Phytomeliorative measures aim to restore soil fertility and stabilize the ecosystem by creating conditions for both natural and managed vegetation recovery.

The proposed reclamation method is forest restoration, involving the step-by-step establishment of forest plantations on disturbed areas using various tree species. In the first year, soil preparation includes fertilization, disc cultivation to a depth of 20–22 cm, and non-inversion loosening to 50–60 cm with the simultaneous application of peat (300 kg/ha). In the second year, 1-year-old seedlings of Scots pine (*Pinus sylvestris*) and black locust (*Robinia pseudoacacia*) are planted in a pattern of three rows of pine to one row of locust. Additional manual maintenance is carried out (weeding, soil loosening).

In the third and fourth years, replanting of forest species is conducted (25% and 20% of the initial number, respectively), along with mechanical inter-row cultivation and expansion of manual care areas. In the fifth and sixth years, the focus is on mechanical maintenance. In the sixth year, the plantations are classified as forested areas, after which standard silvicultural practices are applied for further management.

The analysis of phytomeliorative effectiveness revealed significant improvements in the soil properties of disturbed lands. As shown in Table 7, the main indicators of soil fertility demonstrated positive changes as a result of biological reclamation efforts.

The results indicate a positive impact of phytomeliorative measures on soil characteristics. Humus content significantly increased compared to the control, reaching 3.5% on reclaimed Plot 2. This suggests improved pedogenesis, enhanced biological activity, and increased accumulation of organic matter. Soil pH increased from 4.5 to 6.1, indicating gradual neutralization of acidity as a result of organic fertilization and root system activity. Nitrogen content more than doubled on reclaimed plots, attributed to biological enrichment and nitrogen fixation by leguminous species. Phosphorus and potassium - both essential for plant development - also showed steady increases, indicating soil balance restoration and improved substrate productivity (Fig. 8).

Phytomeliorative interventions also influenced the development of vegetation cover. Spontaneous vegetation, represented by species such as *Betula pendula*, *Populus tremula*, and *Calamagrostis epigejos*, contributed to soil stabilization and the development of a functioning biogeocenosis. However, its growth was limited in areas with low humus content and high acidity.

The planting of *Pinus sylvestris*, *Robinia pseudoacacia*, and *Quercus robur* ensured more effective ecosystem restoration. These species contributed to a 12% increase in soil organic matter, which positively affected moisture retention capacity. The application of organic fertilizers and the use of perennial grasses helped reduce erosion and enhance phytocoenotic stability. Soil analysis demonstrated a number of positive changes resulting from phytomeliorative treatments. One key trend was an increase in pH by 0.8 units, indicating reduced soil acidity - a critical factor for the healthy development of most plant species. This shift is linked to the application of organic amendments, the activation of microbial processes, and the improvement of the soil's buffering capacity. Another important parameter is the 15% increase in humus content, which directly contributes to soil fertility. Humus plays a vital role in maintaining soil structure, moisture and nutrient retention, and supporting the development of plant

root systems. Its accumulation was made possible through biological enrichment, the use of green manure crops, and the gradual decomposition of organic matter.

Phytomelioration also improved soil texture, enhancing the water-holding capacity of the upper soil horizons. As a result, surface moisture levels became more stable, allowing vegetation to more effectively utilize available water even during dry periods. These improvements are parti-

cularly important for lands degraded by mining activities. Importantly, the concentration of heavy metals remained within permissible limits, confirming the environmental safety of the applied reclamation methods. The use of organic fertilizers and perennial grasses contributed to natural soil purification, while forest plantations served as a biological filter that helped immobilize potentially hazardous elements.

Table 7. Dynamics of soil property changes on control and reclaimed plots.

Parameter	Control Plot	Reclaimed Plot 1	Reclaimed Plot 2
Humus content (%)	1.5	3.1	3.5
Soil pH	4.5	5.8	6.1
Nitrogen content (mg/kg)	12.3	22.1	24.7
Phosphorus content (mg/kg)	9.8	18.5	20.3
Potassium content (mg/kg)	85	134	150

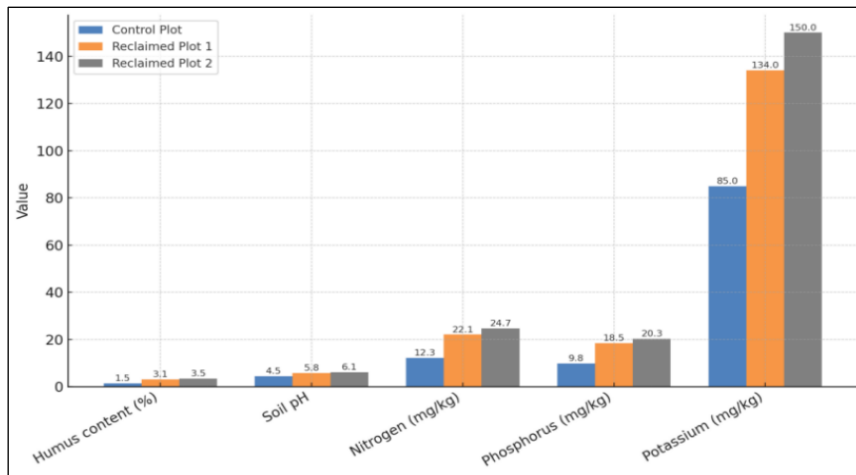


Fig. 8. Comparative changes in soil physicochemical parameters across control and reclaimed plots

Conclusions

The results of the study confirm the effectiveness of phytomelioration in restoring technogenically disturbed limestone quarry landscapes. The analysis revealed that biological reclamation improves the physicochemical properties of the soil, stabilizes vegetation cover, and facilitates the formation of ecologically resilient plant communities. Following the implementation of phytomeliorative measures, humus content increased by 15%, indicating enhanced pedogenesis and improved substrate fertility. Soil pH rose from 4.5 to 6.1, demonstrating reduced acidity and improved buffering capacity.

There was also a notable increase in the concentration of essential macronutrients: nitrogen

rose from 12.3 mg/kg on control plots to 24.7 mg/kg on reclaimed plots, reflecting biological enrichment and the effectiveness of nitrogen-fixing species; phosphorus increased from 9.8 mg/kg to 20.3 mg/kg, indicating improved nutrient availability; potassium increased from 85 mg/kg to 150 mg/kg, a crucial factor for vegetation sustainability. These changes contributed to higher soil fertility and provided favorable conditions for the further development of phytocoenoses. Floristic analysis identified 141 plant species belonging to 99 genera and 34 families on reclaimed areas, highlighting the potential of phytomelioration for biodiversity restoration. The hygromorph spectrum indicated a dominance of mesophytes and xeromesophytes (48.18% and 30.91%, respectively), sug-

gesting stabilization of the hydrological regime and vegetation adaptation to new environmental conditions. Trophomorph analysis showed an increase in eutrophic species from 22.22% to 34.55%, indicating improved soil nutrient status. Meanwhile, the proportion of oligotrophic species declined by more than half (from 12.35% to 4.55%), reflecting a transition from poor to more fertile ecosystem conditions. The distribution of florocoenotic complexes showed an increase in meadow-steppe communities on technosols (from 24.69% to 31.82%), typical of mid-successional stages, while the share of forest-shrub complexes decreased (from 53.09% to 48.18%), suggesting a need for additional measures to stimulate the development of woody vegetation. Biomorph analysis revealed that hemicryptophytes were the most dominant group on technosols (59.09%), highlighting their key role in stabilizing vegetation cover. The notable increase in cryptophytes (from 6.17% to 15.45%) indicates their effectiveness in substrate stabilization due to well-developed underground organs. The share of phanerophytes (woody plants) declined from 28.40% to 18.18%, possibly due to less favorable conditions or the insufficient duration of successional processes. Light regime remains a determining factor in phytocoenotic development. Heliophytes remained dominant on technosols (48.18%), while facultative heliophytes increased from 34.57% to 46.36%, indicating growing ecological heterogeneity and structural ecosystem stability. Sciophytes remained scarce (3.64%), confirming the lack of well-developed forest communities and shading, and suggesting that the ecosystem has not yet reached late successional stages.

The results confirm that phytomelioration is an effective method of ecological restoration for technogenically degraded landscapes. The measures implemented contributed to improved soil fertility, stabilized plant cover, and the formation of more resilient biocenoses. The most significant improvements were recorded in soil fertility indicators (increased humus, macronutrients, reduced acidity) and in the structure of vegetation cover (increased biodiversity, stabilized phytocoenoses). However, further optimization is needed for the recovery of woody plant communities and the formation of ecologically stable forest ecosystems. Achieving full ecosystem stability will require long-term monitoring, additional fertility enhancement

measures, and stimulation of tree species development.

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