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Natural phytomelioration processes on rock dumps of abandoned coal mines (Ukraine)

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Abstract

Mining is accompanied by direct irreversible changes in the biosphere. Analysing the results of recent studies on the anthropogenic hazard of coal mine tailings and the peculiarities of tailings reclamation and phytoremediation on a global scale, it necessitates the investigation of the ecological state and natural phytoremediation of the Nadiya mine tailings in the Lviv-Volyn coal basin. The stages of succession processes on the rock dump surface have been determined. The phytomeliorative efficiency coefficient has been calculated for all periods of the phytomeliorative process on the rock dump surface. The total area of the studied site is 280 m^2. Based on the calculations of changes in the dynamics of the phytomeliorative efficiency coefficients at different stages of the phytomeliorative process (K_{FM}=0.155-4.485), it is expedient to conduct reclamation and phytomeliorative operations on the rock dump surface. The coal mining industry causes a significant technogenic burden on the environment, affects human health and transforms living conditions regardless of the place or country of extraction. Waste heaps are the most dangerous factors of environmental degradation. Studies of the impact of coal mine waste heaps on the human body and biota are conducted in almost all industrialised countries as well as countries where mineral mines are operated.

Keywords:
ecological hazard; succession; natural overgrowth; phytomelioration efficiency

1. Introduction

Coal mining is accompanied by irreversible direct and indirect environmental changes, which lead to the formation of disturbed lands of various types, scales and genesis. Numerous studies are being conducted in Ukraine to restore devastated landscapes formed as a result of waste rock storage. In particular, in order to select the areas of further use of waste heaps, scientists in **Kolesnik et al. (2012)** presented an algorithm of rock management technologies based on an improved technological passport. Environmental passports of waste heaps provide an opportunity to develop long-term action plans to reduce waste generation and prevent their negative impact on the environment and human health.

A lot of scientific works of domestic and foreign scientists are devoted to the edaphic research of mine waste rock. In particular, the main measures for the formation and restoration of coal mine dumps and their environmental hazards were discussed at various domestic events. **Schwabe et al. (2018)** notes that the mining industry causes the formation of contaminated areas, which, despite being full of valuable metals, have high concentrations of toxic heavy metals that pollute the environment. One of these contaminated regions is the Sokal district of Lviv region, where the Lviv-Volyn coal basin operates. The functioning of the coal basin causes significant pollution of all components of the biosphere and causes morbidity among the population (**Popovych et al., 2019**). It is noted that vegetation can extract valuable metals from waste heaps, the extraction of which is not economically viable. The success of phytoremediation (especially phytoextraction) largely depends on the bioavailability of elements, which, among other things, is a function of soil mineral phases, soil organic matter, pH, and redox potential. One of the most promising ways to combat the environmental hazards of mine

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dumps is phytomelioration. To reduce the negative impact of coal mines on the environment, it is necessary to monitor and implement environmental protection measures (**Yuan et al., 2018**).

The exploitation of the Lviv-Volyn coal basin has led to many negative changes in flora and fauna, the atmosphere, hydrosphere, biosphere, and has significantly affected the lives and health of people in the border areas of Ukraine and the Republic of Poland (**Karabyn et al., 2019; Bosak et al., 2020**). Let's consider some scientific studies of mine tailings in a global context.

The study in **Wu et al. (2019)** was focused on the rock dumps of the Chenzhuang mine, located in the Chinese province of Shanxi. The results of the programmed heating tests helped to determine that CO and C_2H_4 can be used as index gases when predicting the degree of coal rock spontaneous heating. The results have determined that insulation methods by laying loess soil can effectively inhibit spontaneous heating processes. In addition, CO emissions and O_2 consumption by the rock is reduced. The study has also found that in the case of layered laying loess soil, the inhibitory effect on the spontaneous coal rock combustion increases with an increase in the thickness of the loess soil layers.

Forest fires occurring in watersheds, formed in mining areas and reclaimed, pose a unique threat to downstream water supplies. A fire near Boulder, Colorado, which destroyed a wooded watershed recovering from mining disturbances that occurred 80 to 160 years ago, has allowed for an assessment of the pollution by arsenic and metals in streams draining the burned area over a five-year period after the forest fire, and the identification of hydrological factors affected by fire that transport arsenic and metals to surface waters. The predicted increase in the frequency, size and intensity of forest fires in the western United States, a region with widespread historic mines, suggests that the intersection of obsolete mining operations and hydrological response after forest fires poses a growing risk for water supply (**Murphy et al., 2020; Petrean et al., 2023; Woch et al., 2018**).

The paper **Vo et al. (2022)** presents an analysis of literature sources on geochemical, geotechnical and engineering-technical properties of coal rock geomaterials to assess the possibility of replacing both aggregates and binding materials in concrete and cement composites (in contrast to reviewing the properties of these products themselves). It has been determined that coal mining wastes are indeed good candidates (as raw materials) for use and processing for construction purposes. From a geochemical perspective, knowing their mineral composition (which is usually not the same and varies from one mine to another) and the processes they experience when they become components of new materials is the key to a successful recycling operation. The work (**Kalybekov et al., 2020**) substantiates a technological scheme for the bulldozer dump formation, taking into account the suitability of rocks for reclamation purposes, which makes it possible to reduce the negative impact of mining operations on the environment. An algorithm for calculating the bulldozer dump parameters has been developed and a digital topographic model of selective dump formation has been created. In **Moshynskyi et al. (2020)**, scientists have developed a mathematical model for the process of filtering the pollutants through the soil mass and provided recommendations for the environmentally safe storage and processing of phosphogypsum waste. A technology for the complex processing of phosphogypsum waste for the production of anti-radiation building products and concomitant extraction of rare earth elements is proposed.

The work **Terekhov et al. (2021)** analyzes the influence of technical means of mechanization for reclamation works on the quality of the lands exposed to reclamation in conditions of surface mining operations. A methodical approach to the choice of mechanization variant for the land reclamation works is proposed in terms of the existing quality indicators of technogenic agricultural lands as a factor in their monetary evaluation and the level of costs for their reclamation. Recommendations have been developed for managing the quality of technogenic lands by providing technical support for the process of forming their consumer properties, aimed at achieving a favorable ratio, on the one hand, between the quality and, accordingly, the monetary value of technogenic lands, and on the other hand, the cost of their reclamation.

The research paper by **Amrani et al. (2020)** examines the potential reuse of coal mine tailings as an alternative road construction material for natural resource conservation and sustainable mine waste management. It has been revealed that the main supply of waste rocks to the surface occurs as a result of stope operations with rock undercut – 39% and underground mine workings – 33%. It is proposed to differentiate all waste rock outcropped after mining operations into 2 categories: difficult to dispose of and prospective for disposal (**Petlovanyi, Malashkevych et al., 2020**).

In **Blyuss et al. (2020)**, scientists have developed "Recommendations on substantiating the parameters for the processes of pond storage capacity recovery using hydromechanization tools" and "Methods for calculating the parameters of hydrotransportation of highly concentrated hydromixtures", which can be useful for design organizations, as well as mining and metallurgical enterprises to increase service life of tailing dumps. In particular, in **Petlovanyi, Zubko et al. (2020)**, the strength and microstructural properties of the backfill mass when filling the underground cavities, which pose a threat of rock caving in the process of mining mineral deposits, have been studied and assessed.

Physical-chemical studies of substrates within the boundaries of the Novovolynsk mining complex are presented in the work (**Popovych et al., 2019**). It has been determined that in the studied soils, the content of iron oxides is high in the middle (alluvial) horizons and decreases when approaching the parent rock. This is caused by podzolization (destruction of aluminosilicates and the displacement of their products into the lower horizons). The content of heavy metals in soil profiles is uneven due to disturbance of genetic horizons, changes in acidity, inhibition of the cycle of elements and significant technogenic impact during the mine operation. The low absorption capacity and porosity of soils lead to the washing-down of heavy metals into the parent rock.

To analyse the latest results of research on technogenic safety in coal mine waste heaps and the peculiarities of phytomelioration and reclamation of coal mine waste heaps in the global context, it is necessary to study the ecological state and natural phytomelioration of the Nadiya mine waste heaps.

Mining areas have a significant impact on the environment and require a comprehensive study. In addition, there are many factors that affect the environmental safety of the area under study. Therefore, studying the interaction of natural and artificial subsystems in coal mining areas is an urgent issue of sustainable development. In accordance with the above, the purpose of the scientific article is to study the specific impact of abandoned coal mines on natural objects and biodiversity conservation using phytomelioration methods in mining areas.

2. Overview of the research object and methodology

2.1. Overview of coal mine sites under study

The city of Chervonohrad is located in the northern part of Lviv region, at a distance of 80 kilometres from the regional centre and 70 km from the border with Poland. The territory covers 21 km² (Chervonohrad city - 17.8 km²; Sosnivka city – 2.0 km²; Hirnyk town – 1.2 km²). The administrative-territorial division includes Chervonohrad, Sosnivka, Hirnyk with a population of over 80 thousand people and a population density of 3833 persons/km². The region's specialisation is industrial, dominated by processing and mining industries. The city of Chervonohrad is located in the Western Ukrainian forest-steppe zone and Small Polissia, at the confluence of the Solokia and Rata tributaries into the Western Bug River. Chervonohrad is located in a humid, moderately warm agroclimatic zone with sufficient soil moisture. The climate is temperate continental, characterised by mildness and high humidity. The main natural resources: Zabuzhske and Mezhyrychanske coal deposits. One of the largest in the Lviv-Volyn coal basin is the "Nadya" mine (see **Figure 1**). The ash content of the mine rock is over 83%, sulphur content is over 2.5%, and the rock density is over 2.25 kg/m³. The base area of the waste heap is more than 120,000 m², the height is 53 m, the horizontal angle is 36°, and the annual consumption of the waste heap is 9,800 m³ (Passport of the waste heap of Nadiya mine). In general, rock dumping began in August 1962, and spontaneous combustion of rock began in September 1963, and continues to this day from many sources. Intensive rock combustion occurred from 1975 to 1979. Currently, the waste heap surface is inhabited by pioneer species, including moss *Campylopus introflexus*. In a relatively short period of time, *Campylopus introflexus* has significantly increased the projective cover on the rock dump. In addition, the species contributes to the accumulation of organic carbon and the formation of a humus layer of the substrate. It is noted that a decrease in the ratio of chlorophyll *a/b*, an increase in the content of chlorophyll relative to carotenoids under conditions of inhibition of the photochemical activity of chlorophyll play an important role in protecting the photosynthetic system *C. introflexus* (**Sokhanchak et al., 2013**). The aim of this work is to study the specifics of the impact of abandoned coal mines on natural objects and biodiversity conservation using phytomelioration methods in mining areas.

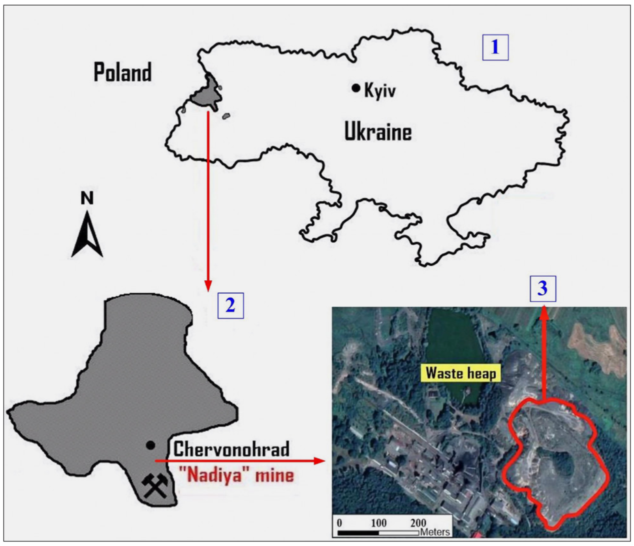

Figure 1: The location of the study object:
1 – map of Ukraine with the Lviv-Volyn coal basin;
2 – map of the Nadiya mine; 3 – map of the Nadiya mine with the waste heap marked using Google Maps

The radiation background at the studied sites is measured using the Soeks environmental ecotester in accordance with the provisions of the Radiation Safety Standards of Ukraine (NRBU-93). The illumination intensity is determined using a digital light-intensity meter with a remote sensor (model LX1010BS, measurement range is 1-100000 Lx), measurement accuracy is ±4%, and working temperature of the medium is -10°C…+ 50°C. Humidity and temperature of the air are determined using a UNI-T UT333 digital thermo-hygrometer (at a humidity of 0-100%; temperature: -10°C…+60°C), error ±1°C/± 5%. Wind velocity is measured using a HT-383 mini-

Table 1: Characteristic of the studied sites at the Nadiya mine rock dump

Location	Radiation background, μSv/hr	Illumination intensity, lux	Air humidity, %	Wind velocity, m/s	Substrate temperature, °C
South, foot	0.27	28350	82	3.6	5
West, slope	0.18	30170	80	3.9	6
North, slope	0.29	32100	79	4.1	6
East, foot	0.21	25390	84	2.5	4
Top	0.42	34630	72	4.5	6
Control of 3 km to the south	0.12	22480	83	1.6	5
Water body	0.17	–	–	–	–

anemometer, measurement accuracy is ±1.5 m/s, and the measurement range is 0…30 m/s. The substrate temperature is measured using an AMT-300 model analyser, the temperature error is ±1°C, and the measurement range is -9°C to +50°C. The general characteristic of the studied sites and sampling points (see **Table 1**).

2.2. *Calculation of the coefficient of phytomeliorative efficiency of vegetation cover*

The rock dump natural phytomelioration is modelled using *Landscaping Designs* computer program. To substantiate the effect of the future phytomeliorative process by using herbaceous and tree-shrub material at the devastated site of the studied waste heap, the phytomeliorative efficiency coefficient of vegetation cover has been calculated, which is estimated in points. To determine the phytomeliorative efficiency coefficient, the following formula (**Kucheriavyi**, **2003**) is used.

$$K_{FM} = \frac{(S_p \cdot b + S_a \cdot b + S_{pm} \cdot b + S_f \cdot b + S_v \cdot b + S_{sv3} \cdot b + S_{sv1} \cdot b + S_{st} \cdot b + S_r \cdot b)}{S} \quad (1)$$

Where:

S_x – is the area occupied (m²) by:
p – pratocoenosis,
a – agrocenosis,
pm – pomologocenosis,
f – frutocenosis,
v – vitocenosis,
sv3 – two-layered sylvacenosis,
sv1 – one-layered sylvacenosis,
st – stripocenosis,
r – ruderocenosis,
b – the number of points obtained by the cenosis,
S – total area (m²).

The phytomeliorative efficiency was calculated for the waste heap of the Nadiya mine on the test plots 100 m from the foot of the waste heap, north; average slope exposure (north), top. Such uneven distribution of the sample plots is due to the heterogeneity of the waste heap surface and uneven development of certain tree and shrub vegetation on its surface. The phytomeliorative efficiency of the species composition of vegetation on devastated landscapes that have not been subjected to reclamation works is low. It should be noted that the assessment of the phytomeliorative effectiveness of vegetation cover within the Lviv-Volyn coal basin was reflected in the scientific works of Kucheryavyi V. P., Bashutska U. B., Henyk Y. V. and others. The scientists came to the conclusion that, depending on favourable edaphic and climatic conditions, the surface of waste heaps is suitable for vegetation development, and therefore has appropriate phytomeliorative efficiency, albeit low.

3. Results

3.1. *Current phytomelioration of coal mine spoil heaps*

One of the most acceptable engineering-technical and aesthetic methods for reducing the level of environmental and technogenic hazards of rock dumps at coal mines is reclamation and its main component – phytomelioration. At the studied rock dump, natural phytomeliorative processes with the participation of synanthropic vegetation are observed at the sites where there are no processes of rock dumping and a peculiar edaphotope and microclimatope have been formed (see **Figure 2**).

At the studied site No.1, the herbaceous cover is represented by: *Plantago lanceolata* L., *Taraxacum officinale* Webb. ex Wigg., *Poa angustifolia* L.. Among the trees are *Betula pendula* Roth. (7-9 m), *Pinus sylvestris* L. (1-2 m, higher on a slope of 6-7 m), and *Robinia pseudoacacia* L. (3-6 m). Among those growing singly are *Rosa canina* L., *Crataegus monogyna* Jacq. (3-5 m), *Quercus robur* L. (2-4 m), and *Salix caprea* L. (2-5 m). The projective herbaceous cover is 65%, trees – 55-60%.

At the studied site No.2, the herbaceous cover is mosaic, isolated, caused by significant steepness of the slope (40-45°) and surface water washoff. Narrow-leaved bluegrass (*Poa angustifolia* L.) and chimney sweep (*Plantago lanceolata* L.) occur here. Among the trees are drooping birch (*Betula pendula* Roth.) – 0.5-2 (3) m (at the slope bottom 5-8 m), common pine (*Pinus sylvestris* L.) – 0.5-1 (2) m (near the slope foot up to 5-6 m). The projective herbaceous cover is 30-35%, trees – 30%.

The studied site No.3 has a large number of water erosions (1-1.5 m wide, 0.5-1.0 m deep), ventilation (wind

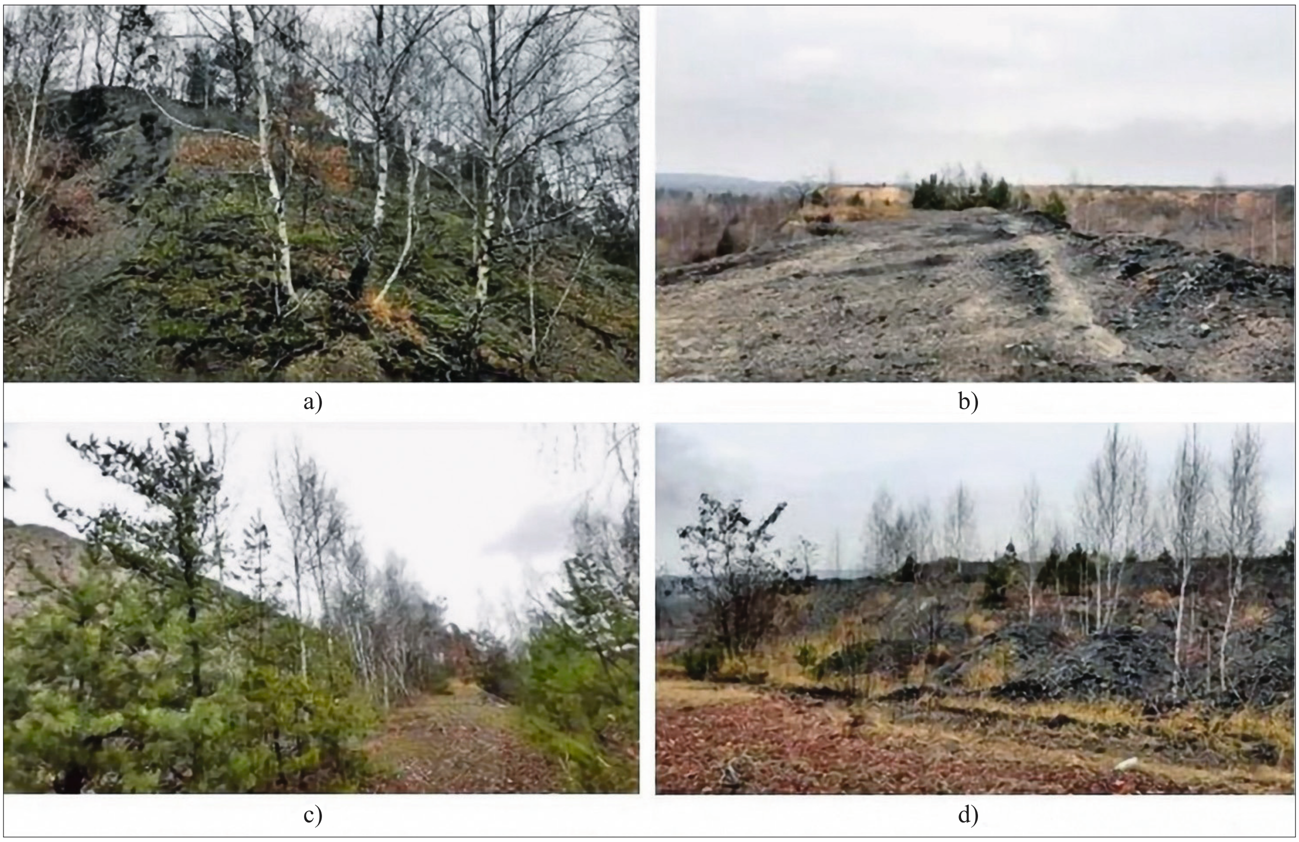

Figure 2: Natural phytomelioration of the Nadiya mine rock dump: a) from the south near the foot involving a drooping birch (*Bétula péndula*); b) from the north on the slope terrace involving a common pine (*Pinus silvestris*); c) from the east near the foot; d) on top.

erosion) outlets, fire sites, fuel and lubricant discharge sites, and domestic discharge sites. Soil density is increasing, which has led to an almost complete cover of grass on the ground. The herbaceous cover is represented by isolated groups of *Poa angustifolia* L.. Among the trees are *Betula pendula* Roth. (2-6) m, and *Pinus sylvestris* L. (1-3) m. The projective herbaceous cover is 10-15%, trees – 20-30%.

At the studied site No.4, in some places, there are traces of soil erosion and exposure of tree root systems (danger of the trees falling). The vegetation cover is represented by *Pinus sylvestris* L. (10-13 m). There is a significant layer of forest leaf-litter and mossy above-soil cover (indicator of humid environmental conditions), *Quercus robur* L. (9-10 m), *Betula pendula* Roth. (8-9 m), *Robinia pseudoacacia* L. (5-7 m), *Cytisus scoparius* **(**L.) Link. The projective herbaceous cover is – 45-50%, trees – 60%.

The studied site No.5 is the top of the waste heap. It is mainly of a flat type with small hilly sites and slight relief depressions. The herbaceous cover is represented by *Poa angustifolia* L., *Taraxacum officinale* Webb. ex Wigg., *Plantago lanceolata* L., *Lupinus angustifolius* L.. Among the trees are *Betula pendula* Roth. (4-9 m), *Pinus sylvestris* L. (0.5-5 m), *Salix caprea* L. (3-6 m), *Hippophae rhamnoides* L. (3-7 m), *Robinia pseudoacacia* L. (5-6 m), *Quercus robur* L. (3-5 m). There is a significant amount of natural self-sown plants and dry wood.

The studied site No.6 is under control. It is located at a distance of 3 km from the waste heap in the forest zone with practically no anthropogenic impact (there are spontaneous forest roads). Among the trees are *Pinus sylvestris* L. (7-11 m), thick forest leaf-litter. The projective tree cover is 60%.

Field studies conducted at the studied site No.3, located at the elevation of the northwestern slope, testified to difficult natural conditions. On the terraced slope, there are numerous places of water-erosion outlets, some of which are up to 1-1.5 m wide and 0.5 to 1.0 m deep, deflation, places of sporadic ignition, draining of fuel and lubrication materials. The substrate is bulk, mainly formed from bulk mined-out coal. Difficult conditions have caused an increased soil cover density, low intensity of aeration processes in the surface horizons of the techno-soil substrate, and difficult exchange of moisture and nutrient minerals. The consequence is the almost complete absence of above-soil herbaceous cover. The composition of the available tree material includes a natural regeneration of *Betula pendula* Roth. from 2 to 5 m high (individual specimens up to 6 m), *Pinus sylvestris* L. (1-3 m). The herbaceous cover is formed by isolated groups of *Poa angustifolia* L., which belongs to the grass family *Poaceae* Bamhart. The analysis of the trial areas confirms the following projective cover: herbaceous cover – 10-15%, trees – 20-30%.

It has been revealed by **Skrobala et al. (2020)** that the vegetation cover of rock dumps in the Lviv-Volyn coal basin mines is characterized by an ecological-coenotic space, the assessment of which is based on the ordination of species on the axes of complex environmental gradients. Moreover, the center of this space is occupied by meadow and synanthropic species, which demonstrate the greatest stability in the conditions of rock dumps of mines. Open space and activated erosion processes indicate the need for a stagewise phytomeliorative process involving tree-shrub material and herbaceous cover.

3.2. Recultivation at coal mines

Since the studied object belongs to very strongly changed conditions of overgrowth sites, which cause significant natural disbalance, waste masses penetrating into the environment, the impact on the water regime, the movement of air currents, and the landscape potential weakening, then the approach to creating a future multi-layered phytomeliorative cover should be exclusively stagewise.

When conducting the technical stage of reclamation, it is necessary to take into account a number of peculiarities:

1. soil restoration by a technical method, which is conducted through a covering of a dump with a layer of substrate material mixed with the rock;
2. soil restoration by agrotechnical methods with the introduction during the first two years of leguminous plants as green manures, which enrich the soil with nitrogen necessary for growth and development;
3. afforestation with the use of complex fertilizers (or without them).

Proceeding from recommendations by **Kopiy et al. (2019)**, the phytomeliorative process of vegetation cover development on waste heaps takes place in the following stages:

- initial stage: dead rock is first planted with higher plants (*Embryophytes*), the development of which is not limited to competition for space, moisture and mineral nutrition;
- stage of avant-garde species development, such as perennial and annual herbaceous plants; certain species form a continuous vegetation cover, are assimilated by the soil, enriching it;
- stage of avant-garde species development, such as tree-shrub vegetation; shrub and tree species undemanding to soil and climatic conditions create the necessary preconditions for further development;
- stage of tree vegetation development: more demanding tree and shrub species form stable multi-layered phytocenoses.

The plant material used should satisfy a number of requirements: low requirements for edaphic conditions: the ability to satisfy the growth even on a substrate that is relatively poor in mineral nutrition; rapid growth at the initial stage of above-soil organs and root system development; resistance to high temperatures and wind currents (**Kucheriavyi, 2003**).

The stagewise phytomeliorative process is based on the mechanism of creating phytogenic fields with vegetation cover, the area of which is constantly increasing and, at the final stage, will cover the devastated site as much as possible, thereby contributing to a faster restoration of disturbed overgrowth sites. A phytogenic field means a part of space (biotope), within which the medium acquires new properties under the influence of a certain plant organism. It consists of the phytosphere surrounding the above-soil part of the plant, the necropodium – the soil surface area covered by the annual plant deposits, which decomposing, provides a cyclic circulation of substances, as well as the rhizosphere – the soil part filled with root systems. It is within this space that light and shadow, moisture, and nutrients are redistributed, positive temperature vertical and horizontal gradients are created, the soil surface is transformed, and its mechanical properties are changed (**Kucheriavyi**, **2016**).

It is recommended to conduct reclamation at the studied site, consisting of several stages: mining-engineering stage, within the framework of which surface formation and terracing are conducted, as well as the application of a fertile and biological soil layer to the levelled surface is implemented, during which, in accordance with the project, a multi-layered vegetation cover is created. Proceeding from this, the studied waste heap surface is classified as phytotoxic and conditionally unsuitable for vegetation growth. It is necessary to create a shielding protective layer of rocks, which blocks the access of phytotoxic compounds and salts from the lower to the upper horizons, as well as reduces the soil stratum temperature. The thickness of the shielding protective layer depends on the granulometric composition of the rock in the range from 0.5 to 1.5 m and consists of a mixture of gravel and loam. From above, it is necessary to apply a fertile soil layer with a thickness of 1.0 m (**Henyk and Dyda, 2019**).

As part of the biological stage of reclamation (phytomelioration), it is recommended to use significant material for planting vegetation. Tree species: *Betula pendula* Roth., *Populus tremula* L., *Robinia pseudoacacia* L., *Pinus sylvestris* L. and *Quercus robur* L.. Shrub species: *Frangula alnus* Mill., *Sambucus nigra* L. and *Amorpha fruticose* L..

Herbaceous species: foalfoot (*Tussilago farfara* L.), creeping trefoil (*Trifolium repens* L.), sedge grass (*Carex pilosa* Scop.), felon herb (*Artemisia vulgaris* L.), pig weed (*Chenopodium album* L.) and bluegrass (*Poa pratensis* L.). All species offered in the range are adapted to the natural-climatic conditions of the region, difficult

Figure 3: Projective vegetation cover of a devastated slope: 1) current state before the beginning of phytomeliorative process; 2) for the 3rd year of the phytomeliorative process; 3) for the 5th year of the phytomeliorative process; 4) for the 10th year of the phytomeliorative process.

soil conditions and have increased growth and development energy, as well as a branched root system.

3.3. Analysis phytomelioration process on the research spoil heap

In the proposed phytomeliorative process, successional changes in the vegetation cover and an increase in the area of projective cover are observed. Tree (T) and shrub (Sh) species are recommended to be planted in rows at intervals from 2.5×2.5 m to 0.75×0.75 m between plants, based on the individual biological characteristics of a particular species, its growth energy and habitus of the future crown. The tree and shrub cover formation on the slope surface should be carried out according to the following planting scheme: T–Sh–T–Sh–T–Sh… and Sh–T–Sh–T–Sh–T…

During the course of the phytomeliorative process, three "marker" comparative stages for the 3rd, 5th and 10th year of development are distinguished.

The primary stage, even before the beginning of the phytomelioration stages, is characterized by pronounced negative exogenous signs: water-erosion galls, gulleys, petrified rock landslides, traces of wind erosion impact. The vegetation "mosaic" cover is represented by isolated specimens of *Betula pendula* Roth. from 2-5 m high and *Pinus sylvestris* L. about 1 m high. The fragmentary herbaceous cover is formed by a few groups of *Poa angustifolia* L.. Projective cover of the area is in the range of 5-10% (see **Figure 3**).

The phytomeliorative process analysis in the third year indicates the occurrence of the initial primary succession stage, in which the devastated rock is covered with the first higher herbaceous plants that grow and develop almost without competition for space, moisture, and mineral nutrition. At this stage, each plant and its small groups begin to form an individual phytogenic field. In addition, avant-garde perennial and annual herbaceous plant species develop, enriching the soil with their deposits and increasing its aeration level. The energy of the erosion process development is reduced by almost 50%.

Herbaceous groups of a number of species are formed: *Tussilago farfara* L., *Trifolium repens* L., *Carex pilosa* Scop., *Artemisia vulgaris* L., *Chenopodium album* L. and *Poa pratensis* L. Vegetation cover from the "mosaic" is transformed into a group one, a number of plant

Table 2: Successions of the studied waste heap vegetation cover

Syngenetic succession	Initial endoecogenetic succession	Mature endoecogenetic succession
Projective cover 35-40%	**Projective cover 55-60%**	**Projective cover 70-85%**
Tussilago farfara L. + *Trifolium repens* L. + *Carex pilosa* Scop. + *Artemisia vulgaris* L. + *Chenopodium album* L. + *Poa pratensis* L.	*Tussilago farfara* L. + *Trifolium repens* L. + *Carex pilosa* Scop. + *Artemisia vulgaris* L. + *Chenopodium album* L. + *Poa pratensis* L. + *Frangula alnus* Mill. + *Sambucus nigra* L. + *Amorpha fruticose* L. + *Amorpha fruticose* L. + *Betula pendula* Roth. + *Pinus sylvestris* L.	*Carex pilosa* Scop. + *Artemisia vulgaris* L. + *Chenopodium album* L. + *Poa pratensis* L. + *Frangula alnus* Mill. + *Sambucus nigra* L. + *Amorpha fruticose* L. + *Betula pendula* Roth. + *Populus tremula* L. + *Robinia pseudoacacia* L. + *Pinus sylvestris* L. + *Quercus robu* L.

groups merge. The projective cover of the area is in the range of 35-40% (see **Figure 2b**).

In the fifth year of the phytomeliorative process, signs of the avant-garde species development stage of tree and shrub vegetation appear, in which shrub and tree species, undemanding to soil-climatic conditions and prevailing wind currents, create the necessary preconditions for the further development of phytogenic fields. Thus, green areas acquire significant dimensions and there is a merge of herbaceous cover in almost the entire area. The studied site is entering the stage of secondary succession. Sites on the slope are strengthened and the influence of water and wind erosion is practically raised to a minimum. The planted vegetation composition is diversified, numerous shrub species are added, which also form their own phytogenic fields, places of surface shading appear and the second vegetation layer is formed in certain places. Among the shrub species are *Frangula alnus* Mill. and *Amorpha fruticosa* L. The plantation is enriched with biogroups of a number of tree species, in particular *Betula pendula* Roth. and *Pinus sylvestris* L. The vegetation cover is transformed into a group one, resulting in competition for overgrowth space, moisture and nutritious mineral resources. The soil, in turn, due to the vegetation cover, is significantly structured. The projective vegetation cover increases to 55-60% (see **Figure 2c**).

From the 7th-8th years, the stage of tree vegetation development begins. The planted vegetation composition is enriched with more demanding tree and shrub species that form a stable multi-layered phytocenoses. Shrub species *Sambucus nigra* L. and tree species *Populus tremula* L., *Robinia pseudoacacia* L., *Quercus robur* L are added. A stable three-layered plantation is formed with the participation of herbaceous, shrub and tree species. Competition for overgrowth space, moisture and nutritious mineral resources is intensifying. Certain species, confined to open growth sites, find themselves in the shade under conditions unfavorable for growth and development, and then disappear. The planted vegetation enters a phase that may require sanitary thinning and partial felling in the coming years. The projective vegetation cover increases to 70-85%, (see **Figure 2d**).

The process of phytocenoses formation on the Nadiya mine rock dump surface gives a possibility to distinguish plant successions and stages of their overgrowth (see **Table 2**).

The phytomeliorative efficiency coefficient has been calculated for all periods of the phytomeliorative process. The total area of the studied site is 280 m^2. At the primary stage, preceding phytomeliorative measures, the studied site is represented mainly by ruderocenoses – 15% (42 m^2) and isolated groups of pratocoenoses – 5% (14 m^2). Formula 1 takes the following form:

$$K_{FM} = \frac{(S_p \cdot b + S_r \cdot b)}{S} \quad (2)$$

The period of the 3rd year of the phytomeliorative measures is characterized by the presence of the following plant material groups: ruderocenoses – 30% (84 m^2) and pratocoenoses – 10% (28 m^2), but already with a noticeably large projective cover of the studied area. Formula 1 takes the following form:

$$K_{FM} = \frac{(S_p \cdot b + S_r \cdot b)}{S} \quad (3)$$

The period of the 5th year of the phytomeliorative process is characterized by the presence of ruderocenoses – 15% (42 m^2), pratocoenoses – 20% (56 m^2), frutocenoses – 15% (42 m^2) and two-layered silvacenoses – 10% (28 m^2). Formula 1 takes the following form:

$$K_{FM} = \frac{(S_p \cdot b + S_f \cdot b + S_{sv1} \cdot b + S_r \cdot b)}{S} \quad (4)$$

The period of 7th-8th years of the phytomeliorative process is characterized by the presence of the following plant material: ruderocenoses – 10% (28 m^2), pratocoenoses – 15% (42 m^2), frutocenoses – 20% (56 m^2) and two-layered silvacenoses – 35% (98 m^2). Formula 1 takes the following form:

$$K_{FM} = \frac{(S_p \cdot b + S_f \cdot b + S_{sv2} \cdot b + S_r \cdot b)}{S} \quad (5)$$

For the complete calculation of the phytomeliorative efficiency coefficient, an important role is played by indicator *b*, which takes into account in points the complexity of the effective impact of a particular plant cenosis. This includes the following indicators: seasonal phytomass, oxygen production level, filtering properties, which are conditioned by the habitus and type of vegetation cover, impact on the microclimate, noise absorption

Table 3: Average values of points (*b*) of green mass (**Kucheryavy, 2003**)

Phytocenosis type	Green mass, (*b*)
Pratocoenosis	0.7
Ruderocenosis	0.8
Frutocenosis	4.0
One-layered silvacenosis	9.0
Two-layered silvacenosis	10.0

and optical influence. The average values of points (*b*) of green mass see **Table 3**.

As a result of calculating the phytomeliorative efficiency coefficients, the following data have been obtained. At the primary stage, which is characterized by an active adverse effect of geological and erosional factors, as well as the minimum area occupied by vegetation, the phytomeliorative efficiency coefficient value is $K_{FM} = 0.155$. At the stage of the 3rd year of the phytomeliorative process, which is characterized by a gradual transition of the vegetation cover from the predominance of pioneer vegetation to the avant-garde one, as a result of which the area of the devastated site vegetation cover doubles, the phytomeliorative efficiency coefficient is $K_{FM} = 0.31$. At the stage of the 5th year of the phytomeliorative process, the peculiarity of which is an increase in the soil stratum fertility and, as a consequence, the occurrence of shrub species (frutocenoses) and trees (one-layered silvacenosis) in the vegetation composition, the value of phytomeliorative efficiency coefficient increases and is $K_{FM} = 1.76$. At the stage of the 7th-8th years of the phytomeliorative process, during which a stable, multi-species and several-layered plant phytocenosis is formed, a number of light-loving species (heliophytes) are displaced, as a result of a layered crown tent formation. Then, the "liberated" biotope niche is occupied by shade-tolerant and shade-loving species. The value of the phytomeliorative efficiency coefficient increases by 2.5 times and is $K_{FM} = 4.485$.

4. Discussion

This scientific article establishes the role of natural phytomelioration in the renaturalisation of the subsystem of artificial objects in coal mining regions. The factors of formation of ecological and technogenic hazards of natural and technical geosystems of abandoned coal mines are investigated. The main stages of natural phytomelioration of the subsystem of natural objects are highlighted. It has been established that the natural and technical geosystem of abandoned coal mines consists of three interrelated components - a subsystem of natural objects, a subsystem of artificial objects, and human activity. The subsystem of artificial objects causes a significant anthropogenic load on the subsystem of natural objects by means of pollutants entering the soil, underground and surface water bodies, air, and biota. As part of the biological stage of natural and artificial *phytomelioration* reclamation, we recommend using the following species composition: tree species – *Betula pendula* Roth, *Robinia pseudoacacia* L., *Pinus sylvestris* L., *Quercus robur* L.; shrub species – *Frangula alnus* Mill., *Sambucus nigra* L., *Amorpha fruticosa* L.; herbaceous species – *Tussilago farfara* L., *Trifolium repens* L., *Carex pilosa* Scop., *Artemisia vulgaris* L., *Chenopodium album* L., and *Poa pratensis* L.

We recommend planting tree and shrub species in rows with intervals from 2.5×2.5 m to 0.75×0.75 m between plants, based on the individual biological characteristics of a particular species, its growth energy and the habitat of the future crown.

5. Conclusions

Having studied the natural phytomeliorative processes on the rock dump surface, it has been determined that initially the syngenetic stage is characterized by a projective cover of 35-40% and is accompanied by pioneer species – *Tussilago farfara* L. + *Trifolium repens* L. + *Carex pilosa* Scop. + *Artemisia vulgaris* L. + *Chenopodium album* L.+ *Poa pratensis* L. The initial endoecogenetic succession is characterized by a projective cover of 55-60% and is accompanied by the development of the following species: *Tussilago farfara* L. + *Trifolium repens* L. + *Carex pilosa* Scop. + *Artemisia vulgaris* L. + *Chenopodium album* L. + *Poa pratensis* L. + *Frangula alnus* Mill. + *Sambucus nigra* L. + *Amorpha fruticose* L. + *nigra* L. + *Amorpha fruticose* L. + *Betula pendula* Roth. + *Pinus sylvestris* L. Mature endoecogenetic succession is characterized by a projective cover of 55-60% and is accompanied by the development of the following species: *Carex pilosa* Scop. + *Artemisia vulgaris* L. + *Chenopodium album* L. + *Poa pratensis* L. + *Frangula alnus* Mill. + *Sambucus nigra* L. + *Amorpha fruticosa* L. + *Betula pendula* Roth. + *Populus tremula* L. + *Robinia pseudoacacia* L. + *Pinus sylvestris* L. + *Quercus robur* L.

In general, 49 types of vegetation, which arose in the process of natural overgrowth and which belong to 23 families, were found on the tailings of coal mines in the studied region. Proceeding from the performed calculations of changes in the dynamics of the phytomeliorative efficiency coefficients at different stages of the phytomeliorative process (K_{FM}= 0.155-4.485), it is expedient to perform reclamation and phytomeliorative operations on the rock dump surface.

Today, the practical implementation of the natural phytomelioration stage is partially carried out, as it is primarily affected by Russia's armed aggression. Coal mine waste heaps are objects of economic activity of the fuel and energy complex and are subject to state supervision (control) in the field of industrial and fire safety. Coal mine waste heaps are classified as high-risk facilities in accordance with the hazardous events that may occur, such as an emergency, fire, or accident. In accordance with the above, in most cases, a number of features of the technical stage of reclamation should be taken into account at the Nadiya mine test site: soil restoration by technical means, carried out by covering the waste heap with a layer of substrate material including mixing with the rock; soil restoration by agrotechnical methods with the introduction of legumes as green manure during the first two years, which enrich the soil with nitrogen necessary for growth and development; afforestation using a complex of fertilisers.

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SAŽETAK

Prirodni fitomeliorativni procesi na odlagalištima kamenoga materijala napuštenih rudnika ugljena (Ukrajina)

Rudarstvo prate izravne nepovratne promjene u biosferi. S obzirom na analizu rezultata nedavnih studija o antropogenoj opasnosti na odlagalištima kamenoga materijala u rudnicima ugljena i osobitosti njihove rekultivacije i fitomelioracije na globalnoj razini, potrebno je istražiti ekološko stanje i prirodnu fitoremedijaciju odlagališta rudnika Nadiya u Ljvivsko-volinskome ugljenom bazenu (Ukrajina). Utvrđene su određene faze sukcesijskih procesa na površini odlagališta. Koeficijent fitomeliorativne učinkovitosti izračunan je za sva razdoblja fitomeliorativnoga procesa na površini odlagališta. Ukupna je površina istraživanoga lokaliteta 280 m^2. Na temelju proračuna promjene dinamike koeficijenata fitomeliorativne učinkovitosti u različitim fazama fitomeliorativnoga procesa (K_{FM} = 0,155 – 4,485), svrsishodno je provesti meliorativne i fitomeliorativne zahvate na površini odlagališta. Rudarska industrija ugljena uzrokuje znatno tehnogeno opterećenje okoliša, utječe na zdravlje ljudi i mijenja životne uvjete bez obzira na mjesto ili državu eksploatacije. Gomile otpada najopasniji su čimbenici degradacije okoliša. Studije o utjecaju odlagališta na ljudsko tijelo i ukupnost života na Zemlji provode se u gotovo svim industrijaliziranim zemljama i zemljama u kojima rade rudnici minerala.

Ključne riječi:
ekološka opasnost, sukcesija, prirodno obrastanje, fitomeliorativna učinkovitost

Author's contribution

Vasyl Popovych (1) (Dr. Sci. (Engin.), Professor, Vice-Rector for research and development Lviv State University of Life Safety) proposed and defined the idea of the scientific article, managed the field research, provided suggestions for interpretation of the results and graphical presentation of the data, adjustment of the article. **Andriy Voloshchyshyn (2)** (PhD, Lecturer at the department of environmental safety Lviv State University of Life Safety), **Nazar Lysyi (3)** (Postgraduate student of the department of environmental safety Lviv State University of Life Safety), **Mykhailo Petlovanyi (4)** (PhD (Engin.), Assistant, Associate Professor at the Department of mining engineering and education, National Technical University "Dnipro Polytechnic") and also **Taras Shuplat (5)** (PhD (Agricul.), Senior lecturer at the Department of environmental safety Lviv State University of Life Safety) performed the field work, provided funding for the fieldwork, data collection and modelling, participation in the field research and analysis, graphically presented the data, and gave input into the discussion and conclusion sections.