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Natural phytomelioration of the coastal water zone of man-made reservoirs in mining areas

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Abstract. Coal mine waste heaps are technogenic hazards that have been polluting the air, surface and groundwater, soil for years. At the UN Climate Conference COP26, held in November 2021 in Glasgow (Scotland), Ukraine and developed countries committed to carbon neutrality by 2060 and to abandoning fossil fuels by 2035. One of the largest technogenic factors in waste heaps is subterranean wastewater. Wastewater accumulates in the man-made reservoirs at the foot of the coal mine waste heaps. In our case, one of the most effective means of improving coal mining regions' environmental quality is phytomelioration, particularly coastal and water reclamation. The article presents the results of research within the Lviv-Volyn coal basin (Ukraine). During the study of natural phytomelioration processes in the coastal zone of man-made reservoirs, it was found that vegetation develops within four zones: I – underwater vegetation that is permanently covered by water (22% of the total number of species); II – vegetation of fluctuating water levels (32%); III – vegetation of the coastal zone (14%); IV – vegetation above the coastal zone (32%). The species composition includes 37 species belonging to 20 families. By family composition, the largest share of the species composition belongs to representatives of *Asteraceae* (15%), *Poaceae* (11%), *Potamogetonaceae* (8%). The study of the species composition and family spectrum of coastal and aquatic phytomelioration processes is important in implementing environmental protection and ecological measures to improve the quality of the environment of technogenically affected coal mining areas.

1 Introduction

In Ukraine, as well as worldwide, coal mining is accompanied by the accumulation of coal mining waste on the earth's surface [1 – 3]. Apart from several negative anthropogenic factors, coal mining causes the release of hazardous substances into the surface and underground water bodies as a result of precipitation on the waste heaps [4, 5]. It is quite common to observe waterlogging around coal mine waste heaps, which is formed because of rain and meltwater runoff. Artificial reservoirs and ditches are created at the foot of coal mine waste heaps to direct the wastewater into the required channel and collect it in a

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controlled reservoir. However, in the region under study, the engineering and technical solutions for controlling water flows are broken, and the wastewater itself enters the environment, forming local man-made reservoirs. Discharged wastewater from waste heaps is characterised by high toxicity, high heavy metal content, salinity, and mineralisation, becoming a focus of research for many scientists [6]. The aquatic and coastal vegetation that has developed in such man-made reservoirs is characterised by several physical and chemical parameters and physiological resistance to the effects of hazardous substances, compounds, and chemical elements [7]. Its peculiarity lies primarily in the fact that it occupies ecotones - transition zones between the aquatic and terrestrial environment and provides a link between two ecologically different biosystems. The flower groups of different colours located right next to the shore add even more aesthetic value to the landscape [8]. The study the progress of coastal and aquatic flora on abandoned coal waste dumps is an important and relevant scientific problem.

The study [9] aimed to analyse the transfer and accumulation of Sr in nine different terrestrial plants from Elyazig municipal wastewater, as well as determine the levels of Pb-Zn in Kebane wastewater and Cu in Maden wastewater (Turkey). Plants were categorized as candidate, bioaccumulator and hyperaccumulator based on their ECR and ECS. These values were obtained by calculations using root and shoot enrichment ratios. The groups indicate candidate plants: *Salix sp. and Tamarix tetrandra*; bioaccumulator plants: *Pragmites sp*. and *Xanthium*, and hyperaccumulator plants: *Typha latifolia, Bolboscholnus ascbersus* and *Lythnium salicaria* for Sr. It was concluded that the studied plants can be useful for rehabilitation studies of municipal and mine soils contaminated with Sr.

The impact of water erosion on the development of endogenous fires in coal dumps was investigated in [10]. Meteorological data collected from the waste heap in Libiąż, Poland, confirmed that frequent heavy precipitation caused surface erosion on the slope. Gully erosion was observed on the western slope of the waste heap, extending up to 1.6 m deep. The data showed that there was a significant difference in measured temperatures and gas concentrations between the areas with and without water erosion, determining the intensity of the fire. The erosion contributed to self-heating in such a way that the internal temperature increased to +52.9 ºC.

Study [11] for the first time evaluates the environmental performance of the wastewater treatment plant in Dębęsko in the Upper Silesian Coal Basin in Poland, as coal mine wastewater needs treatment to eliminate the current environmental impact on surface water bodies (rivers). The existing wastewater treatment system includes reverse osmosis, evaporation, and crystallisation technology. In the case of the new Zero Brine methodology, the laboratory data is scaled up and used for nanofiltration, reverse osmosis, electrodialysis, and crystallisation technologies.

Numerous research studies have proven that aquatic plants are the sinks for wastewater treatment, and they are also used in the treatment process for reducing or limiting wastewater pollution. The treated wastewater was of acceptable quality according to international standards for irrigation wastewater [12]. For instance, a scientific paper [13] proposes the use of wetlands as a phytoremediation strategy for mining and marine areas in southeastern Spain. Macrophytes resistant to potentially toxic elements (PTEs) (*Phragmites australis, Juncus effusus, and Iris pseudacorus*), resistant to salinity, were used. The transfer of As, Pb, Zn, and Cu was studied, and their content in the rhizosphere and plants (aboveground and belowground parts) was determined. From these data, TF and BCF were calculated for each plant in 15 different substrates. The results indicate the tolerance of metallophytes to these PTEs, which can contribute to a naturalised habitat acting as an effective protective barrier for the ecosystem, that is easy to maintain and avoids the risk of transmission into the trophic chain.

In [8], the author concludes that the following species of coastal and aquatic plants are promising for use in the territory of the integrated green zone of Lviv: *Acorus calamus, Alisma lanceolatum, A. plantagoaquatica, Asparagus officinalis, Bidens cernua, Butomus umbellatus, Caltha palustris, Carex acuta, C. cespitosa, C. pseudocyperus, C. riparia, Cladium mariscus, Iris pseudacorus, I. sibirica, Ligularia sibirica, Poligonum amphibium, Ranunculus flammula, R. lingua, Sagittaria sagittifolia, Schoenoplectus lacustris, S. tabernaemontani, Sparganium erectum, Typha angustifolia, T. latifolia* and others. Coastal and aquatic species have a wider range of taxonomic diversity compared to aquatic species alone. Therefore, choosing the right species for landscaping coastal strips becomes much simpler (Danylyk, 2006).

As stated by reference [14], the vegetation found in quarries near aquatic areas is undergoing a transition from syngenetic to endoecogenetic succession. This process leads to an increase in ecological diversity among the species present, resulting in heightened competition for resources. Under the influence of the aquatic environment, the main belts of coastal and aquatic vegetation are formed, which correspond to a variety of vegetation development conditions: the underwater belt (*Phragmites communis, Typha angustifolia, Typha latifolia*); the belt of fluctuating water levels (*Carex acutiformis, Carex elata, Carex riparia, Sagittaria sagittifolia*); the belt with soils far from the water table. Here, perennial vegetation communities with a high intensity of seed and vegetative reproduction (*Tussilago farfara, Plantago lanceolata, Antennaria dioica, Lysimahia nummularia*) are prevalent. The coastal zone of the Rozdilska Reservoir (Lviv oblast, Ukraine) is represented by a significant number of multicomponent, largely cenotypically formed communities with an edificatory manifestation (*Calamagrostis epigeios, Phragmites australis*) [15].

The article [16] showcases the findings of research on the vegetation of Lake Holubove in the Khmelnytskyi region of Ukraine. The formation of this lake was a result of sand extraction by a dredger. It was determined that the lake's vegetation includes 11 associations belonging to 10 formations of true aquatic and coastal aquatic vegetation. Phytomelioration, or the use of plants to improve soil quality and environmental conditions, can indeed play a significant role in the coastal water zones of man-made reservoirs in mining areas by:

– Soil stabilization, the roots of certain plants can help stabilize soil along the coastal water zones, preventing erosion and sediment runoff into the reservoir. This is crucial in mining areas where soil disturbance and erosion are common [17, 18]. Also, it means the utilization the waste rocks mined during the mineral extraction [19, 20];

– Nutrient uptake, phytoremediation, a form of phytomelioration, involves using plants to remove contaminants from soil and water. Plants like water hyacinth, reeds, and cattails have been shown to absorb heavy metals and other pollutants from water, thereby improving water quality [18, 21];

– Habitat restoration by planting native vegetation along the coastal water zones helps restore habitat for aquatic and terrestrial wildlife. This can contribute to the overall ecological health of the reservoir and its surrounding areas [22, 23];

– Erosion control by using deep-rooted plants such as mangroves and certain grass species can help stabilize shorelines and prevent erosion, which is particularly important in coastal areas where wave action and storms can cause significant damage [18, 22, 24];

– Enhanced biodiversity by creating suitable habitats and improving water quality, phytomelioration efforts can promote the return of diverse plant and animal species to the coastal water zones [22, 25]. This enhances the resilience of the ecosystem and its ability to withstand disturbances.

– Aesthetic enhancement by planting native vegetation can also improve the aesthetic value of the coastal water zones, making them more appealing for recreation and tourism while also providing psychological benefits to nearby communities [22 26].

Implementing natural phytomelioration strategies in the coastal water zones of man-made reservoirs requires careful selection of appropriate plant species, consideration of local environmental conditions, and long-term monitoring to assess effectiveness [27]. Additionally, it's essential to integrate phytomelioration efforts with broader ecosystem management and restoration initiatives to achieve sustainable outcomes [26, 28].

Thus, based on the presented research, it can be concluded that the phytomelioration processes of the coastal-water zone of man-made reservoirs in mining areas are an important phenomenon of environmental safety that needs to be analysed and promoted.

2 Materials and methods

For the basis of our research, we utilized field tests. When conducting field studies for phytomelioration in coastal water zones of man-made reservoirs in mining areas, researchers typically employ a combination of methods to assess the effectiveness of plant-based interventions in improving soil quality and environmental conditions [29]. In our case, the work with materials is divided into several elements. Firstly, it is necessary to select appropriate plant species for phytomelioration, which is crucial. We examined the plants' ability to tolerate high levels of pollutants, such as heavy metals, and to thrive in aquatic or wetland environments. Common examples include water hyacinth (Eichhornia crassipes), reeds (Phragmites spp.), cattails (Typha spp.), and various grass species [30].

The second element involves using sampling and proper laboratory equipment. For collecting soil, water, and plant samples, tools such as soil corers, augers, sediment samplers, water quality meters, and plant harvesting equipment are used. Laboratory equipment is utilized for analysing soil and water samples for various parameters, including pH, nutrient content, heavy metal concentrations, and microbial activity [31]. At the final stage, instruments for collecting field data are employed. This includes GPS devices for mapping study sites, weather stations for monitoring environmental conditions, and light meters for assessing light availability in different habitats.

The research methodology comprised several steps aimed at obtaining accurate results. Initially, we identified suitable study sites within the coastal water zones of man-made reservoirs in mining areas, considering factors such as proximity to mining activities, historical pollution levels, and accessibility [32]. Subsequently, we conducted preliminary surveys to assess the existing soil and water quality, vegetation composition, and ecological characteristics of the study sites before implementing phytomelioration interventions. This provided a baseline for comparison with post-intervention data.

Following this, we designed controlled experiments or field trials to evaluate the effectiveness of various phytomelioration techniques, such as planting specific plant species, applying amendments like compost or biochar, or manipulating hydrological conditions. We collected soil, water, and plant samples at regular intervals during the study period and analyzed them for relevant parameters in the laboratory. This involved chemical analysis for pollutant concentrations, microbial assays for soil health assessments, and plant biomass measurements.

We then implemented long-term monitoring programs to track changes in soil quality, water quality, vegetation dynamics, and ecosystem function over time. This facilitated the assessment of the persistence and effectiveness of phytomelioration interventions and identification of any unintended consequences. Finally, we analyzed collected data using statistical methods to evaluate the significance of observed trends and relationships between variables, such as pollutant uptake by plants, changes in soil nutrient levels, and improvements in water quality.

By employing these methods and materials, we gained valuable insights into the efficacy of phytomelioration strategies for enhancing soil quality and environmental conditions in coastal water zones of man-made reservoirs in mining areas, ultimately contributing to more sustainable ecosystem management practices.

Field studies of coal mine waste heaps were carried out in 2021 – 2023 and are still ongoing. We opted to study the progress of coastal and aquatic flora by examining an abandoned waste dump from the Mezhyrichanska mine, which is in the Chervonohrad mining district of the Lviv-Volyn coal basin. Our analysis took into consideration the natural reservoir formed by the accumulation of wastewater at the base of this dump, as well as its proximity to the Rata and Western Bug rivers, both located in the Lviv region of Ukraine.

A schematic representation of the filling of man-made reservoirs with wastewater from waste heaps and atmospheric precipitation, as well as the development of coastal and aquatic vegetation belts, is shown in Fig. 1.

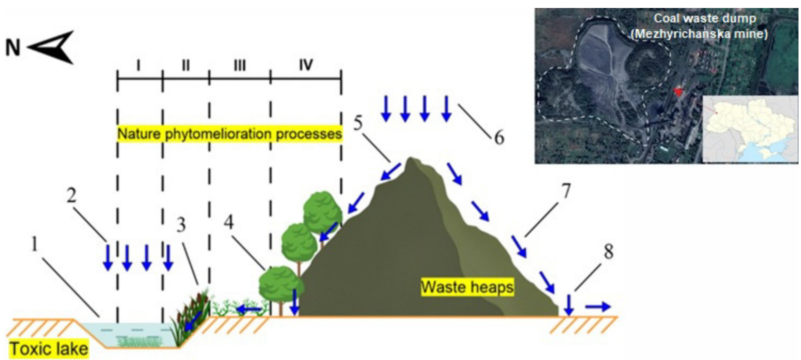

Fig. 1. The scheme of the process of filling man-made reservoirs due to precipitation and coastal water phytomelioration: I – belt of underwater vegetation; II – belt of vegetation of fluctuating water level; III – belt of shore vegetation; IV – belt of vegetation above the shore; 1 – man-made reservoir; 2, 6 – precipitation; 3 – flow channel of wastewater into the reservoir; 4 – foot of the waste heap; 5, 7 – flow channel of wastewater on the surface of the waste heap; 8 – flow channel of wastewater into the groundwater horizon.

The classification of the coastal and aquatic vegetation was carried out according to the German scientist H. Poyker, who identified the following zones in the coastal and aquatic vegetation: I – underwater vegetation, which is constantly covered with water (this also includes species with root system and stem constantly underwater, and leaf blade floating on the surface); II – vegetation of fluctuating water level; III – vegetation of the coastal zone, not covered by waves; IV – vegetation higher up the coastal zone, fed by precipitation [33]. The species composition of the vegetation was determined using a determinant [34].

3 Results and discussion

Field studies of the Rata River shoreline, flowing in the immediate vicinity at the foot of the waste heaps, revealed the growth of a significant number of vascular plant species that belong to the following families: Aster (*Asteraceae*), Bean (*Fabaceae*), Grasses (*Poaceae*), Rose (*Rosaceae*), Cattail (*Typhaceae*), Sedges (*Cyperaceae*), Horsetail (*Equisetaceae*), Sage (*Lamiaceae*), Willow (*Salicaceae*), Knotweed (*Polygonaceae*), Plantain (*Plantaginaceae*), Amaranth (*Chenopodiaceae*), Birch (*Betulaceae*), Rush (*Juncaceae*), Ginseng (*Araliaceae*), Crowfoot (*Ranunculaceae*), Pondweed (*Potamogetonaceae*), Primrose (*Primulaceae*), Water lilies (*Nymphaeaceae*), Arum (*Araceae*).

The distribution of species diversity belts of the coastal and aquatic vegetation of the study area by the taxonomic composition of families is as follows:

- Aster (*Asteraceae*) – shaggy hawkweed (*Hieracium villosum* Jacr.) – IV; field milk thistle (*Sonchus arvensis* L.) – IV; three-lobe beggarticks (*Bidens tripartita* L.) – II; narrowleaf hawksbeard (*Crepis tectorum* L.) – IV; yarrows (*Achillea micranta* Willd.) – IV;
- Bean (*Fabaceae*) – birdsfoot deervetch (*Lotus arvensis* Pers.) – IV; bird's-foot trefoils (*Lotus palustris* Pers.) – II;
- Grasses (*Poaceae*) – flattened meadow-grass (*Poa compressa* L.) – IV; wood small-reed (*Calamagrostis epigejos* L.) – IV; couch grass (*Elytrigia repens* L.) – IV; common reed (*Phragmites australis* (Cav.)) – II;
- Rose (*Rosaceae*) – silverweed (*Potentila anserina* L.) – IV;
- Cattail (*Typhaceae*) – lesser bulrush (*Typha angustifolia* L.) – II; broadleaf cattail (*Typha latifolia* L.) – II;
- Sedges (*Cyperaceae*) – greater pond sedge (*Carex riparia* Curt.) – II; wood clubrush (*Scirpus sylvaticus* L.) – II;
- Horsetail (*Equisetaceae*) – water horsetail (*Equisetum fluviate* L.) – IV; marsh horsetail (*Equisetum palustre* L.) – II;
- Sage (*Lamiaceae*) – gypsywort (*Lycopus europeus* L.) – II; water mint *(Mentha aquatica* L.) – II;
- Willow (*Salicaceae*) – white willow (*Salix alba* L.) – III;
- Knotweed (*Polygonaceae*) – lady's thumb (*Polygonum persicaria* L.) – III; great water dock (*Rumex hydrolapathum* Huds.) – II;
- Plantain (*Plantaginaceae*) – ribwort plantain (*Plantago lanceolata* L.) – IV;
- Amaranth (*Chenopodiaceae*) – goosefoot (*Chenopodium album* L.) – IV;
- Birch (*Betulaceae*) – common alder (*Alnus glutinosa* (L.)) – III; silver birch (*Betula pendula* Roth.) – III;
- Rush (*Juncaceae*) – bulbous rush (*Juncus bulbosus* L.) – II;
- Ginseng (*Araliaceae*) – arsh pennywort (*Hydrocotyle vulgaris* L.) – III;
- Crowfoot (*Ranunculaceae*) – common water-crowfoot (*Ranunculus aquatilis* L.) – I;
- Pondweed (*Potamogetonaceae*) – sharp-leaved pondweed (*Potamogeton acutifolius* Link ex Roem. & Schult.) – I; Fries' pondweed (*Potamogeton friesii* Rupr.) – I; hairlike pondweed (*Potamogeton trichoides* Cham. & Schltdl.) – I;
- Primrose (*Primulaceae*) – featherfoil (*Hottonia palustris* L.) – I;
- Water lilies (*Nymphaeaceae*) – spadderdock (*Nuphar lutea* (L.) Smith) – I;
- Arum (*Araceae*) – common duckweed (*Lemna minor* L.) – I; duckmeat (*Spirodela polyrhiza* (L.) Schleid) – I.

Representatives of the families *Asteraceae* (15%), *Poaceae* (11%), and *Potamogetonaceae* (8%) are involved in coastal and aquatic phytomelioration with the largest share. The detailed distribution of the family spectrum is shown in Fig. 2.

The analysis of species distribution among the coastal and aquatic phytomelioration belts of man-made waste heap reservoirs showed that the belt of fluctuating water level vegetation and the belt of vegetation higher up the coastal zone, which is fed by precipitation, account for the same proportion of 32% each. The belt of underwater vegetation that is permanently covered by water (including species with root systems and stems permanently underwater and leaf blades floating on the surface) accounts for 22%. Only 14% of the species composition belongs to the coastal zone vegetation belt, which is not affected by waves (Fig. 3).

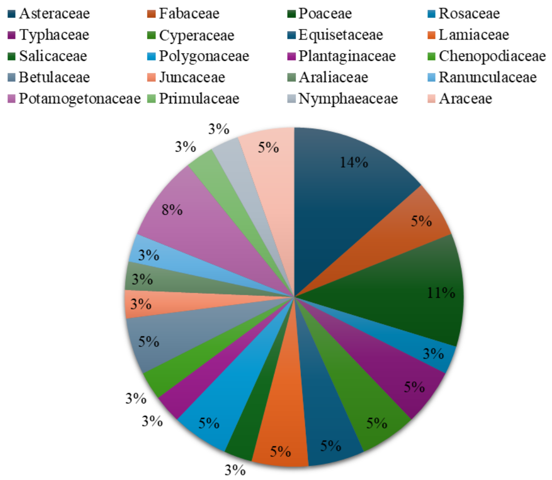

Fig. 2. Shares of families in the coastal-water phytomelioration of man-made waste heap reservoirs.

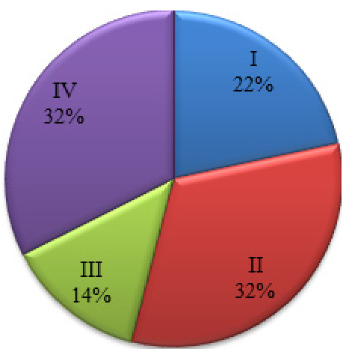

Fig. 3. Shares of coastal and aquatic vegetation depending on development zones.

The coastal and water areas in the waste heap influence zone benefit from the phytomelioration process, which involves 37 vegetation species from 20 families and 4 developmental zones.

4 Conclusions

The operation of coal mining enterprises poses a significant environmental threat to regions, leading to heightened levels of environmental danger and irreversible processes in the biosphere. In response to these challenges, efforts to explore natural coastal and water phytomelioration processes have been undertaken in the Lviv-Volyn coal basin. Through this exploration, researchers have identified four distinct development zones of vegetation: Zone I, comprising 22%; Zone II, 32%; Zone III, 14%; and Zone IV, 32%.

A closer examination reveals that the species composition is diverse, encompassing 37 species from 20 families. Among these families, the Asteraceae family holds the largest share at 15%, followed by Poaceae at 11%, and Potamogetonaceae at 8%. Understanding the species composition and the families involved in phytomelioration processes is crucial for effectively implementing environmental protection and ecological approaches aimed at enhancing the environmental quality of technogenically disturbed areas.

By comprehensively analyzing the species composition and family spectrum, researchers and environmental practitioners can devise tailored strategies for phytomelioration, leveraging the natural potential of various plant species to mitigate the adverse effects of coal mining activities. These efforts are vital for promoting sustainable development and safeguarding the delicate balance of ecosystems in coal mining regions.

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