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Phytoremediation of technogenically disturbed soils of coal mines

Svetlana Ivanova [1,2*], Anna Vesnina [3], Nataly Fotina [4], Alexander Prosekov [5]

[1]*Institute of NBICS-technologies, Kemerovo State University, 6 Krasnaya str., Kemerovo, 650043, Russia*

[2]*Department of TNSMD Theory and Methods, Kemerovo State University, 6 Krasnaya str., Kemerovo 650043, Russia*

[3]*Natural Nutraceutical Biotesting Laboratory, Kemerovo State University, 6 Krasnaya str., Kemerovo, 650043, Russia*

[4]*Phytoremediation of Technogenically Disturbed Ecosystems Laboratory, Kemerovo State University, 6 Krasnaya str., Kemerovo, 650043, Russia*

[5]*Laboratory of Biocatalysis, Kemerovo State University, 6 Krasnaya str., Kemerovo 650043, Russia*

Abstract

The use of joint planting of tree species with different life strategies, annual growth rates, but with a complementary reaction to co-growth in reclamation sites makes it possible to more effectively use ecological niches and ensure the formation of species-rich forest communities with higher biological productivity. At each age stage of planting, a certain category of woody plants "works" on carbon accumulation, which generally provides an increased deposition effect compared to single-species plantations. Modern recommendations on forest reclamation are focused on the creation of monocultures that are insufficiently stable, do not create a nature-like structure of plant communities and are not sustainable for a long period of time. Currently, technologies have been developed taking into account the sustainability of forest plantations on landfills.

Keywords: Coal mine, biorecultivation, phytoremediation, environmental pollution, carbon footprint

Full length article **Corresponding Author*, e-mail: pavvm2000@mail.ru Doi # https://doi.org/10.62877/70-IJCBS-24-25-19-70

1. Introduction

Industrially developed Kuzbass (Kemerovo region, Russia) is not only the planet's source of raw materials, but also a producer of ferrous and non-ferrous metals and chemical products. Since the 1990s, the "lungs of the planets" — the Siberian taiga — have been actively cut down, mining and processing enterprises have been built. Most of the territory of Kuzbass is subject to strong man-made impacts. The irreversible process of destruction and degradation of the soil under industrial waste dumps from open-pit coal mining, pollution of groundwater and surface waters, pollution of the atmosphere by industrial emissions result in the disappearance of natural flora and fauna, as well as a catastrophic threat to the health of people living in the region. Only 30% of the territory of the region, where 5-10% of the population lives, meets satisfactory environmental requirements. The 20th century brought mankind a lot of benefits associated with the rapid development of science and industry. However, it also put the Earth on the brink of an environmental disaster. The intensification of the extraction and use of natural resources, urbanization and huge amounts of harmful emissions are changing nature. Their widespread use has led to such an interaction between nature and man, when the anthropogenic load exceeds the ecological capabilities of a given territory, mainly due to the potential of its natural resources and the general stability of natural landscapes to the effects of human activity [1].

The theoretical purpose of the reclamation of technogenically disturbed territories is the restoration of land use to the condition before the start of mining in the mine/mine sites [2-4]. In each case, it is necessary to restore the structure, functions of the ecosystem and the original terrain at least approximately. The concept of restoration/reclamation of disturbed territories covers a whole range of technical solutions. To understand the issue, these solutions can be divided into three main groups: restoration, rehabilitation and replacement [5]. The following stages of reclamation of degraded mine sites are distinguished [6-9]: (1) preliminary environmental assessment; (2) planning of the final state of the site; (3) detailed environmental assessment of the nature and extent of the negative impact; (4) identification of criteria for purification from pollutants; (5)

development of a recovery plan; (6) final verification and monitoring of the resulting condition. The effectiveness of such a restoration concept has been confirmed by long-term practices of its application [7-12].

The planned resulting state of the site affects all stages of the reclamation strategy, since the goals of the resulting state affect the cleaning criteria and determine the scale of necessary measures. Upon completion of the restoration plan, the terrain should be modified to obtain morphological, topographic and scenic effects (Figure 1) compatible with the intended end use of the site [13]. Often, landscape creation measures include backfilling, contouring rock piles, as well as replacing overburden and topsoil, both to restore contours and natural landforms, and to restore fertility. The main areas of use of the restored territories of mine coal dumps are agriculture, forestry, the formation of reservoirs and habitats of wild animals, etc. At the same time, the realization of any of these land-use opportunities is driven by technical, economic, social and environmental aspects [5].

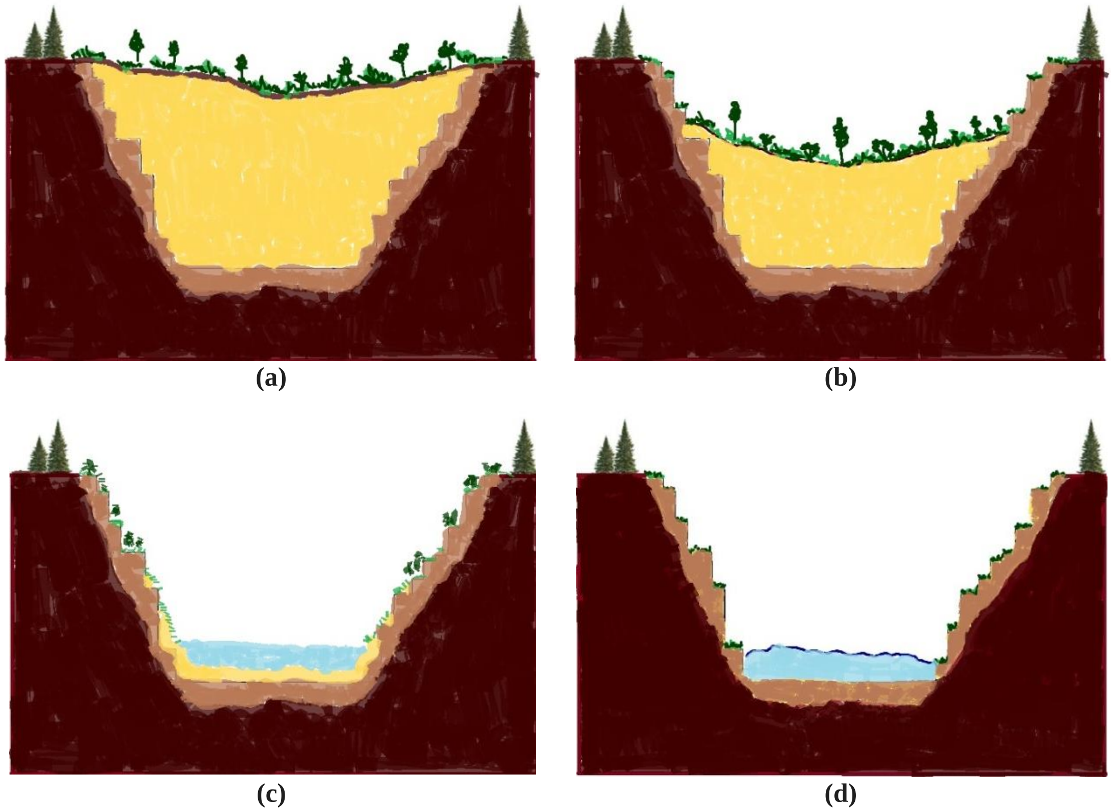

Figure 1. Schematic representation of the reclamation of an open pit, including various forms of landscape restoration: (a) complete backfilling to restore the original uses in agroforestry or the introduction of new uses; (b) partial backfilling to restore previous uses before the development or introduction of new uses; (c) minimal selective backfilling and surface treatment of rocks, tops and embankments for replacement activities; and (d) maintaining the morphological characteristics of an open pit with vegetation laying or some improvement actions for spontaneous ecological succession.
Source: Illustration by authors, the scheme idea by [5].

Technologies for the restoration of disturbed areas that combine physical, chemical and biological approaches are usually classified as “passive" or “active" [14-16]. A more effective treatment strategy is considered to be based on biological activity - biological strategies [17]. Within the framework of these processes, some of them can be considered active, while the other can be considered passive. For both approaches to the cultivation of territories, the main goal is to restore the qualitative characteristics of soils (decrease in acidity, decrease in the concentration of toxic metals, decrease in the concentration of sulfates, etc.) [16]. Active processing methods take up less space and are more reliable than passive systems, but generally require high capital costs and high ongoing operation and maintenance costs due to regular maintenance fees for continuous operation [14, 16, 18, 19]. Active systems include chemical neutralization, aeration, autonomous sulfidogenic bioreactors, etc. The main advantages of passive processing methods are low creation costs, ease of operation and maintenance. Despite the economic attractiveness, passive methods have significant limitations. They require a large area and are best suited for cleaning mine effluents with low acidity and low costs [16]. Passive systems include open limestone channels, oxygen-free limestone drains, dispersed alkaline substrate, aerobic wetlands, anaerobic “wetlands”/composting reactors, sequential alkali production systems, permeable reactive barriers, iron oxidation bioreactors with a compacted layer, etc. [14,15,20,21]. In practice, passive methods are used either individually or in combination, depending on soil characteristics and processing requirements. In general, alkaline materials are used to neutralize acidity, organic substrates are used to create a reducing medium, and bacteria are used to catalyze reactions and accelerate deposition processes [14]. It can be considered that passive processing methods resemble similar physical, chemical and biological processes that occur in natural wetlands [14]. In these systems, the acidity and pH of the water to be treated change, which leads to the neutralization of the level of active acidity in favor of the formation of insoluble chemical compounds that deposit and retain heavy metals. At the same time, there are old, abandoned mines in the world, without any plans for environmental restoration or reclamation. Some of these mine sites are currently overgrown with wild vegetation. This spontaneous process of colonization and rooting of species on degraded or disturbed lands (spontaneous ecological succession) helps to reduce the risks of pollution from old abandoned mines. In this context, spontaneous ecological succession can be considered as a natural way to restore degraded areas. Therefore, when it is impossible to provide technical reclamation in an economically feasible way, the regeneration process by natural restoration (spontaneous succession) can be considered an acceptable solution, especially in cases of small mines. Quite often, passive restoration leads to the desired result of reclamation [22-25].

This process of natural recovery can be controlled by increasing efficiency and accelerating the effects necessary for spontaneous ecological succession [10, 25-27]. The existing natural vegetation cover in abandoned mines can be multiplied by large-scale plantings and the maintenance of native species for several years. It is possible to expand the uniform distribution of seeds obtained from wild plants in the territory. Eventually, it is possible to change the artificial habitat and make it more suitable for subsequent plant communities [28]. The potential of local vegetation species to restore soils is quite attractive, since local wild species do not require frequent irrigation, fertilization and pesticide treatment, while at the same time a plant community comparable to the existing one can be created. An alternative strategy is the gradual reclamation of the territories of existing mines at separate stages, where ore extraction is completed. To implement such a phased approach, a mining plan is needed, adjusted to take into account the landscape restoration plan. The stages of gradual restoration can be the following: removal and storage of soil and overburden for use in reclamation works; research to ensure optimal restoration of vegetation and the results of reclamation; sowing and creation of forage crops (grasses, shrubs and trees) for subsequent restoration of vegetation [29,30]. Agricultural use is a suitable and economically sound solution for rural areas. The creation of crops can be achieved at a lower cost than with other possible uses such as forestry, and with higher and immediate economic profitability. The options for using the restored territories of coal mines in agriculture are described in [31-33]. Even deep mines can be adapted for agriculture, they can be used to store agricultural products or build wine cellars, providing the advantages of constant temperature and high humidity. The characteristics of the destroyed section of the mine determine the options for their subsequent use. For the operation of agricultural machinery, a relatively flat slope and the presence of a soil layer satisfying the following conditions are necessary: a minimum thickness of 40 ; a surface horizon rich in humus, not mixed with other horizons, without compaction; backfilling compatible with effective drainage; soil restoration above the groundwater level, the necessary provision of soil quality characteristics after extraction [30,34,35]. Failure to meet all these conditions sets a different direction for the use of the restored territories, for example, forestry. Forestry use of land after mining is also suitable for rural areas and is the best solution for poor, rocky soils and areas with steep terrain. The reclaimed lands of coal dumps of mines are often used for forestry purposes [30,36-38]. In technogenically disturbed lands of mine dumps, the soil is deficient in nutrients, it has high levels of toxic metals, low pH values and substrate compaction, which can limit vegetation growth. At the same time, the choice of plant species depends on the thickness of the available soil and the objectives of reclamation measures, i.e. the selection of suitable species and ensuring the availability of water in the soil, satisfactory permeability and drainage conditions, protection from pests are necessary measures to ensure the best prospects for successful forest management. The reproduction of forest lands after mining can be considered the optimal resulting state of land management. The restoration to the resulting state of forest management of the lands of worked-out or abandoned mines provides an aesthetic landscape, a natural habitat and economic benefits, for example, from wood products, resin and other products of forest processing [39]. Forestry use after reclamation has other advantages: nutrition and protection of wildlife, prevention of erosion and creation of recreation areas.

Despite the artificial nature of open-pit mining, the topographic relief created as a result of mining operations may contain elements identical to the diverse topographic characteristics of the natural landscape [5]. Thus, dams of reservoirs and artificial lakes formed during the flooding of quarries may be important for the survival of animal and plant species in areas with water scarcity, determining the diversification and conservation of ecosystems in inland regions. Usually, underground mine galleries and open-pit mines are flooded by natural groundwater and surface water inflow and/or through human intervention [30,40,41]. Sometimes mine galleries are intentionally flooded to prevent and/or mitigate the oxidation of pyrite formations. At the same time, flooded mines can be used as strategic reservoirs for storing water, which can be used for various purposes: (irrigation, domestic and/or industrial water supply, hydraulic fracturing, aquifer recharge, fire fighting, etc.). On the other hand, flooded quarries can form a habitat for wild waterfowl and animals [5]. In modern society, various physico-chemical methods of reclamation of soils contaminated by mines are being avoided due to the increased risk of re-contamination through wastewater treatment plants and high cost [28]. Increasingly, preference is being given to in situ methods that are less destructive to the environment and more economical. In this sense, phytoremediation methods become a suitable alternative [42].

The purpose of this work was to study the potential of phytoremediation approaches that reduce the carbon footprint in the territories of technogenically disturbed landscapes.

2. Methods

2.1. Objects of research

Biological methods and technologies for reducing the carbon footprint on technogenically disturbed lands by coal enterprises were the main object of the study.

2.2. Research methods

A bibliographic search and subsequent analysis of scientific manuscripts and online resources devoted to biological approaches to reclamation were carried out as part of our research. Materials from open sources and the Scopus citation database were used. The depth of the search was limited mainly by the last five years, taking into account the relevance of the topic of biological remediation and carbon footprint. The need to cite earlier works on specific issues of phytoremediation and reduction of anthropogenic impact on technogenically disturbed lands was determined by the uniqueness of the results presented in them.

3. Results and Discussions

Phytoremediation is understood as the use of trees, shrubs, herbs and aquatic plants and related microorganisms to remove, decompose or isolate toxic substances from the environment [47]. Figure 2 shows the general scheme of the phytoremediation process.

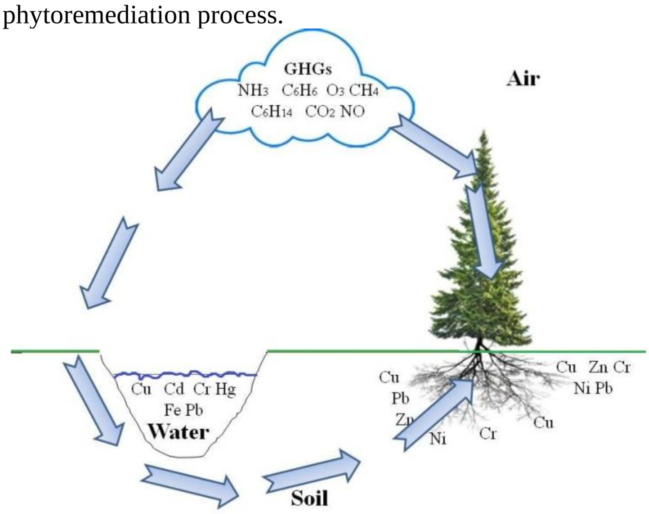

Figure 2. Schematic drawing showing phytoremediation in air, soil and water

Source: Illustration by authors, the scheme idea by previous study [44].

Depending on the chemical nature and properties of the contaminant, phytoremediation of contaminated sites can be performed by various methods and combinations thereof [45-46]: phytodegradation/phytotransformation, phytostabilization/phytoimmobilization, phytofiber, phytoextraction, phytofiltration and phytostimulation. Hydraulic barriers, vegetation cover, created wetlands and phyto desalination, which some authors refer to as independent methods of phytoremediation, are essentially a combination of previously defined ones. The basic idea that vegetation can be used to restore soil, air and water is primitive [47]. However, the scientific approach and the interdisciplinarity of the conducted research led to the expansion of these ideas to a global method of restoring the ecological environment [48]. Phytoremediation of inorganic pollutants, i.e. the use of plants for the destruction, decomposition and/or stabilization of organic substances in the environment, is now a promising, profitable and environmentally friendly method of bioremediation [49-55]. In addition to the removal of pollutants, phytoremediation has extra advantages such as improving soil quality, soil carbon sequestration, biomass production and aesthetic effect [50]. Various pollutants (heavy metals, organic compounds, pesticides and xenobiotics) can be effectively eliminated by plants [56].

The creation of vegetation cover is a common method of restoration during the reclamation of mine sites. Vegetation restoration can cover the entire area or part selectively, in accordance with the intended subsequent use of the site. As a rule, the physico-chemical properties of soils in the mine area interfere with soil-forming processes and plant growth [28]. In addition to increased concentrations of metals, there are other adverse factors (lack of topsoil, erosion, drought, compaction, significant temperature fluctuations, lack of fine materials forming the soil, lack of essential nutrients) [57-58]. Technogenically disturbed soils of mines usually have low concentrations of important nutrients such as N, P and K [59]. Toxic metals and substances negatively affect the abundance, diversity and activity of soil organisms, suppressing the processes of decomposition of soil organic matter and nitrogen mineralization [60]. The pH of the substrate affects plant growth mainly through its effect on the solubility of chemicals, including toxic metals and nutrients. The application of additives (inorganic and organic fertilizers) is a common practice to promote the restoration of vegetation on degraded or polluted soils. The application of organic fertilizers (compost, manure, bio-solids) provides an effective way to recycle waste [61,62]. It is a common practice to select drought-resistant fast-growing crops and/or forage plants that can grow on soils contaminated with metals or on soils with nutrient deficiencies [28]. When using this approach, degraded and/or polluted soil is covered with vegetation resistant to adverse soil conditions, which limits further soil erosion and leaching of pollutants into groundwater [63]. Grasses, shrubs or trees growing on man-made disturbed soils or tailings ponds are used to minimize the penetration of rainwater and contain the spread of pollutants. Roots enhance soil aeration, promoting biodegradation, evaporation and transpiration [28,64-68]. The creation of vegetation cover can help achieve the goals of stabilization, pollution mitigation and visual improvement. Such vegetation covers are often integrated with classical engineering technologies such as fencing, insulation or encapsulation of hazardous waste from mines. A broader perspective which includes various groups of plant species that perform various functional roles in the reclamation process, is attractive for soil restoration in mines [28]. Thus, the use of legumes can enrich the nutrient content, and the combined use of perennial and annual plants can provide a significant contribution in terms of organic matter and nutrient recycling, making a significant contribution to soil development [62,69,70]. However, this approach requires additional information about plant communities growing on degraded mine soils in order to accurately understand their potential for remediation of polluted/degraded soils in abandoned mines [28].

The creation of vegetation on technogenically disturbed lands of mines requires the use of special methods depending on the state of the soil and the general environment; interaction between abiotic and biotic factors; knowledge in the field of plant biology; morphology of the area; methods of sowing and planting, vegetation and forestry [71-74]. It has been established that the use of fibrous crops (for example, miscanthus, vetiver and saccharum) in phytoremediation helps to eliminate pollutants accumulating in various parts of plants. These crops are also used to produce biofuels and green energy [75]. Planting fiber crops will also improve the scenic beauty of the area, providing nesting and breeding grounds for various birds and small organisms, which restores the ecosystem and supports biodiversity. It is known that plants are carbon storages and support soil flora [76,77]. Carbon sequestration reduces the carbon burden in the environment and can help mitigate the effects of global warming and climate change [78]. But the fabrics of fibrous crops grown in contaminated sites must be strictly checked for safe human use, so products made from them, such as baskets, mats, handmade products, decorative materials and reinforcing materials, must also be checked for safe contamination limits.

However, the entire positive potential of phytoremediation is determined not only by plants, since the synergistic effect of the joint action of plants with microbes in phyto- and bioremediation is always better than any of the individual processes. In most cases, metallophytic plants already contain various heavy metal-resistant microbes that stimulate plant growth and help plants extract metals [79]. In fact, plants constantly interact with microorganisms present near the roots, called the rhizosphere, many of which form close, stable and mutualistic associations with plants. The most important examples of such symbiosis are arbuscular mycorrhizal fungi, which trigger mutualism or symbiosis with terrestrial plants [80], and nitrogen-fixing rhizobia, which establish symbiosis with legumes [81]. Both of these symbioses enhance phytoremediation. It has recently been discovered that plant endophytic microorganisms that live inside plant tissues play a crucial role in plant health, contribute to plant protection from pathogens and pollutants [82]. Although plant growth in the territories of coal dumps is very limited due to harsh environmental conditions, phytoremediation can stabilize tailings ponds, providing vegetation cover that prevents the spread of potentially toxic elements [49,83,84]. Microbial communities have the ability to deposit pollutants inside soils and can stimulate plant growth on soils of mines and tailings ponds [8385]. Their combination in the process of phytoremediation forms approaches to more sustainable, efficient and environmentally friendly technologies [85-87]. Similarly, symbiotic nitrogen-fixing bacteria such as *Rhizobium* retain atmospheric nitrogen and improve legume growth [88-89]. The use of metagenomics, metaproteomics, etc. approaches in combination with traditional methods (physiological research and isolation) allows to gain more knowledge about the mechanisms of interaction between prokaryotic and eukaryotic microbial communities in the conditions of mining [90-92]. The use of microorganisms instead of chemicals in plant bioaugmentation is another promising alternative, since microbial metabolites are biodegradable and less toxic, can be synthesized in the rhizosphere and they will improve the absorption of metals and their bioavailability [93-94].

Several extensive reviews on these topics have been published [95,96] and options for interaction between plants and bacteria (bioremediation) for the restoration of hydrocarbon-contaminated soil have been proposed [97,98]. A detailed report on the rhizosphere control of associations between plants and microorganisms, the effects on biodegradation and bioavailability of organic and metalloid pollutants, as well as the prospects for manipulating the rhizosphere for control during phytoremediation of soils is provided in [99]. According to the author of this work, multi-polluted soils are complex and heterogeneous, which requires an integrated rhizosphere management process, in which a combinatorial approach using hydrocarbon and/or coal-mining microbes, joint cultivation of crops and phytoextraction of pollutants is used to achieve the desired results of soil and land management. Thus, for soils containing excessive amounts of nickel, it is promising to use the following plants during biological reclamation: *Salix schwerinii* E. L. Wolf, *A. retroflexus* L., and microorganisms - *Pleurotus ostreatus, Pseudomonas frederiksbergensis* 158. For soils containing arsenic: *Solanum nigrum* L.; *Klebsiella pneumoniae microorganisms.* For soils containing cadmium: *Pinus sylvestris* Lour., *Solanum nigrum* L., *Brassica juncea* (L.) Coss; *Klebsiella pneumonia*, *Cupriavidus taiwanesis, Pseudomonas putida, Azotobacter chroococcum, Rhizobium leguminosarum bv. trifolii, Enterobacter hormaechei* 146, *Aspergillus niger*, *Aspergillus fumigatus* and *Penicillium rubens microorganisms.*To increase soil fertility, the use of biodegradable (which includes natural fibers) geotextile material is promising [100]. Geotextile is able to create optimal conditions for seed germination, the development of soil microflora, because it contains a number of nutrients, is able to accumulate the optimal amount of moisture, and is the optimal means of combating soil erosion [101].

So, to reduce the content of heavy metals, measures using plants and microorganisms capable of accumulating these substances are effective. There are known works [102-107] in which it was found that strains of microorganisms effective in the bioconversion of coal have a stimulating effect on plant growth due to the production of organic acids [108]. Ultimately, interactions between plants and bacteria can lead to the creation of candidate strains for the development of a biological treatment process, stabilization, and even restoration of disturbed soils [109]. To normalize the pH and increase soil fertility, the application of biochar is a promising measure. Biochar (charcoal) is a product of pyrolysis of plant biomass in oxygen–free conditions, consisting of carbon and ash [110]. Studies show that the application of biochar contributes to an increase in low soil pH values, affects the processes of nitrification and ammonification, increases the C/N ratio, is a source of phosphorus; increases the capacity of soil cation exchange, which leads to a decrease in leaching due to nutrient retention. This contributes to the development of microorganisms even in soil with a low content of organic substances [111-114].

Liming (lime of organic origin was used – sugar beet lime) and the introduction of composted solid biological substances into the topsoil proved to be effective in reducing soil acidity; data on the reclamation of a copper mine (Poderosa deposit, Spain) [115].

To reduce the alkaline pH to a neutral value of soils, gypsuming and acidification of soils are used. During gypsuming (application of gypsum, various industrial wastes, for example, phosphogypsum – waste from the production of mineral fertilizers, phosphoric acid and phosphoric fertilizers, into the soil) [116], sodium is replaced with calcium, resulting in a decrease in alkalinity. During acidification, soil acidification occurs due to the introduction of sulfur, sodium disulfate, etc. [117]. In [118], the use of phosphogypsum as a mineral carrier for beneficial groups of microorganisms in bioprocess detoxification of environmental components, including technogenically disturbed lands of coal dumps, is considered as one of the directions of utilization of phosphogypsum. For the detoxification of heavy metals, measures for the use of humic preparations are promising. Humic preparations are liquid, pasty and solid substances of natural origin obtained from brown and oxidized hard coals with alkaline treatment, used for detoxification and soil reclamation [119,120]. It is known that humic preparations are able to bind metals, reducing their solubility, bioavailability, and mobility [121].

Alternatively, on-site production of humic substances from coal production waste by specialized microorganisms. Under aerobic conditions, coal is oxidized by both biotic and abiotic processes to a weathered material rich in humic substances [122]. Under anaerobic conditions, a sequence of primary and secondary bacterial enzymes depolymerizes and metabolizes coal, providing a wide range of short-chain organic acids and alcohols [123]. These low molecular weight organic compounds serve as substrates for other consortia of microorganisms, such as acetogens and methanogens [124-127]. In [128], fungal coal was obtained on the weathered coals of mines in South Africa by the introduction of fungi with specific characteristics, which was planned to be used to restore the lands of waste areas both as a source of humic material and in the form of biofertilizers [129,130].

4. Conclusions

Modern research considers phytoremediation not only as the use of green plants to remove or neutralize environmental pollutants, but also as a tool of green biotechnology, in which plants create a rich microenvironment that provides conditions for the reproduction and activity of microorganisms thanks to organic materials, nutrients and oxygen, for the implementation of sustainable practices for the restoration of technogenically disturbed lands of coal enterprises. It is generally recognized that plants enrich the microenvironment not only by releasing organic substances, nutrients and supplying oxygen to stimulate the growth and activity of soil microbes, but also by absorbing carbon from soil, water and air.

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