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# The microorganism-plant system for remediation of soil exposed to coal mining

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**Abstract:**
*Introduction*. Coal mining causes a radical transformation of the soil cover. Research is required into modern methods and complementary technologies for monitoring technogenic landscapes and their remediation. Our study aimed to assess soil and rhizosphere microorganisms and their potential uses for the remediation of technogenic soils in Russian coal regions.
*Study objects and methods*. We reviewed scientific articles published over the past five years, as well as those cited in Scopus and Web of Science.
*Results and discussion*. Areas lying in the vicinity of coal mines and coal transportation lines are exposed to heavy metal contamination. We studied the application of soil remediation technologies that use sorbents from environmentally friendly natural materials as immobilizers of toxic elements and compounds. Mycorrhizal symbionts are used for soil decontamination, such as arbuscular mycorrhiza with characteristic morphological structures in root cortex cells and some mycotallia in the form of arbuscules or vesicles. Highly important are Gram-negative proteobacteria (*Agrobacterium*, *Azospirillum*, *Azotobacter*, *Burkholderia*, *Bradyrizobium*, *Enterobacter*, *Pseudomonas*, *Klebsiella*, *Rizobium*), Gram-positive bacteria (*Bacillus*, *Brevibacillus*, *Paenibacillus*), and Gram-positive actinomycetes (*Rhodococcus*, *Streptomyces*, *Arhtrobacter*). They produce phytohormones, vitamins, and bioactive substances, stimulating plant growth. Also, they reduce the phytopathogenicity of dangerous diseases and harmfulness of insects. Finally, they increase the soil's tolerance to salinity, drought, and oxidative stress. Mycorrhizal chains enable the transport and exchange of various substances, including mineral forms of nitrogen, phosphorus, and organic forms of C3 and C4 plants. Microorganisms contribute to the removal of toxic elements by absorbing, precipitating or accumulating them both inside the cells and in the extracellular space.
*Conclusion*. Our review of scientific literature identified the sources of pollution of natural, agrogenic, and technogenic landscapes. We revealed the effects of toxic pollutants on the state and functioning of living systems: plants, animals, and microorganisms. Finally, we gave examples of modern methods used to remediate degraded landscapes and reclaim disturbed lands, including the latest technologies based on the integration of plants and microorganisms.

**Keywords:** Technogenic landscapes, heavy metals, pollutants, phytoremediation, remediation, mycorrhizal fungi, rhizogenic microorganisms

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## INTRODUCTION

Areas of anthropogenically transformed soils continue to expand throughout the world. Soil transformation is caused by degradation or complete destruction of topsoil as a result of deforestation, wind and water erosion, pesticide pollution, mining, industrial and civil construction, and growing urbanization [1–6].

Russia accounts for 15% of coal production and export in the world [7]. One of its regions, Kemerovo Oblast-Kuzbass, has about 100 coal mines, of which half are open-pit mines. In the first half of 2021, it produced 116.84 million tons of high-quality coal, up 8% from the previous year.

Extraction of coal and other minerals transforms topsoil drastically, especially in case of opencast mining.

Drilling and blasting are accompanied by enormous dust emissions that contain toxic pollutants, including heavy metals and carcinogenic gas (benzo(a)pyrene) [8–15]. Large amounts of methane and carbon dioxide released into the atmosphere have a greenhouse effect and change the thermal regime, vegetation, and topsoil of the area. All this exacerbates health problems, such as a growth in oncological and cardiovascular diseases, as well as congenital malformations [16].

Active mining causes a serious ecological imbalance. In particular, it transforms or destroys natural landscapes and creates new anthropogenic forms with different physical, chemical, and biological properties. According to Rosprirodnadzor (Russia's environmental watchdog), the country had 194 225 hectares of disturbed lands by 2019. Back in 2015, the Center for Hygiene and Epidemiology in Kemerovo Oblast and the Kemerovo Center for Hydrometeorology and Environmental Monitoring confirmed a strong correlation between increased coal mining, industrial production, and total emission of pollutants into the air. They identified eight ecologically vulnerable districts: Yaysky, Topkinsky, Tisulsky, Leninsk-Kuznetsky, Guryevsky, Prokopyevsky, Novokuznetsky, and Mezhdurechensky.

The above factors call for research that applies modern methods to monitor technogenic landscapes and introduce the latest complementary technologies for their remediation [17–21]. This can be done by using living systems: plants and soil animals and microorganisms. Of great importance are plant-microbial complexes: arbuscular ecto- and endomycorrhizae, symbiotic associations of plants and nitrogen-fixing prokaryotes, as well as rhizobial and cyanobacterial symbioses.

Our aim was to assess the use of soil and rhizosphere microorganisms for remediating technogenic soils in Russia's coal-mining regions.

## STUDY OBJECT AND METHODS

We studied the scientific articles published over the past five years, as well as those cited in Scopus and Web of Science.

## RESULTS AND DISCUSSION

The Institute of Soil Science and Agrochemistry (Siberian Branch of the Russian Academy of Sciences) has developed theoretical and practical foundations for improving the methods of recultivating technogenic soils [3]. Unfortunately, the geobotanical approach to disturbed territories still prevails, with reclamation of dumps by pine trees or perennial grasses [22]. Along with that, it is important to scientifically substantiate the latest reclamation technologies, taking into account the biosystems of undisturbed soils in a particular geographical zone.

Until 2000, external dumps had been selectively formed during the exploitation of coal deposits. Overburden was selectively placed into the body of the dump. This method of reclamation was used to ensure the rational use of the area's land and develop a harmonious anthropogenic landscape that met the ecological, socioeconomic, and sanitary requirements by using the fertile soil layer and potentially fertile species.

Today, this method is not as common. The biological stage of forest and agricultural reclamation is not effective due to the water regime and, consequently, insufficient moisture supply to the biota. Low moisture in the root layer and the presence of highly toxic heavy metals and other pollutants result in poor survival among trees and poor germination of perennial grass seeds.

Irreversible soil degradation caused by technogenesis may have severe consequences for living systems. Of great concern is chemical pollution of landscapes, especially with heavy metals that are deposited and adsorbed in soil [23–27]. When the contents of metals exceed the ecological capacity or change the redox potential (pH), pollutants are released. The human body contains 81 out of 92 elements found in nature, of which 15 are vital (Fe, I, Cu, Zn, Co, Cr, Mo, Ni, V, Se, Mn, As, F, Si, and Li) and four are conditionally essential (Cd, Pb, Sn, and Rb). They were found in low concentrations in plant and animal tissues, but they are highly dangerous for human health even in the smallest amounts [28]. Almost all regions of the world have a chemically "aggressive" environment. However, biochemical anomalies are more common in the zones of industrial development of natural landscapes, during mineral extraction, and in urban industrial agglomerations. Agrogenic lands are polluted through excessive use of pesticides [29].

According to Li *et al*., mining operations in China resulted in increased copper and cadmium contents in the soil used to grow rice. The environmental load changed in decreasing order from lead to chromium: Pb > Cd > Ni > As > Zn > Cu > Cr [30]. Moreover, lead, chromium, and cadmium exceeded the maximum permissible concentrations in crop production 2–8 times [31, 32]. Lead has the longest period of clearance from the soil-plant system. Plants receive its excessive quantities from soil. As a result, lead inhibits their respiration, suppresses photosynthesis, and sometimes increases the amount cadmium, while decreasing the intake of zinc, calcium, phosphorus, and sulfur.

It has also been found that during coal transportation, many pollutants are deposited on the transport routes along with dust. Heavy metals accumulate in soils for a long time. Their excessive amounts affect plant growth, metabolism, physiology, and aging. Plants have stress control mechanisms responsible for maintaining homeostasis of the basic metals that they require. These mechanisms make plants tolerant to metal contamination by forming less toxic metal complexes with active metabolites excreted through the root system. Other mechanisms are triggered by specific stress [31].

Arsenic is the most dangerous inorganic substance. It does not immediately cause symptoms of poisoning in animals, but its concentrations in their blood, hair, hooves, and urine remain high in contaminated areas. It belongs to a special group of conditionally essential elements since it acts at the ionic level or as part of nonspecific molecules or ions that penetrate the organism of living systems.

Heavy metals in soil have a detrimental effect on living organisms as a result of bioaccumulation and biomagnification [33]. Due to their impact on physiological and biochemical processes, most pollutants are toxic to plants [34]. The extent of toxicity depends on their content in soil, which can vary from 1 to 100 000 mg/kg [35, 36]. Heavy metals are also dangerous because they can replace the ions of the main metals that living systems and humans need [37, 38]. This disturbs metabolic processes and biochemical reactions during food consumption and removes metabolites from the body. Excessive accumulation of heavy metals causes protein compounds to break down at the molecular level, ruptures peptide bonds, increases free radicals, and severely damages vulnerable organs (brain, kidneys, liver, and blood vessels).

Phytoremediation is a well-known method of cleaning contaminated soil by extracting pollutants through the roots of trees, shrubs, and herbaceous plants [17, 39]. The results depend on the plants' tolerance to pollutants, the volume of biomass, and the efficiency of pollutant transportation from roots to shoots. Absorbed by the root system of plants, toxic elements accumulate in their tissues and are subsequently decomposed or converted into safer forms [40].

Russian and foreign researchers have recently developed efficient technologies to improve soil by physical and chemical methods [10–14]. For example, scientists in Kemerovo Oblast have proposed combining a bioorganic remediation agent from industrial waste with a technical agent to improve soil physicochemically and obtain a pollutant-free biomass of perennial grasses [41]. In another study, Altunina *et al.* developed a land reclamation method based on biocryogels. They have high porosity, good mechanical strength, stability in any biotechnological environment, and thermal resistance. Plants in cryostructured soil develop a good root system and do not inhibit soil microflora (www.ipc.tsc.ru).

Soil can also be remediated by sorbents produced from environmentally friendly materials, such as humic acids from naturally oxidized coals [25]. The cleaning mechanism is based on the introduction of reaction centers into the composition of humic acids to bind with metal ions.

A mixture of dry lime and sapropel (5:1) can be used as an active natural sorbent. It is applied evenly to the surface of soil contaminated with heavy metals in an amount of 0.5–1.5 t/ha in early spring. The sorbent improves the redox potential (pH) and the soil's absorbing capacity. Increased amounts of mineral and organomineral colloids contributes to active accumulation and long-term immobilization (3–5 years) of toxicants in the humus horizon, preventing the migration of heavy metals to other ecosystem components (patent RU 2655215C1).

Many studies report using groups of microorganisms with different biological functions to remove heavy metals, radionuclides, and organic compounds from soils. Microbiota used to clean soils, wastewater, bottom sediments, and overburden from pollution are able to extract elements and compounds from adjacent environments, convert them into less hazardous waste products or transport them to plant tissues as nutrition. The most efficient groups of microorganisms are those with high symbiotic activity in relation to plants of different classes, families, genera, and species.

Structurally largest is a group of arbuscular mycorrhiza with characteristic morphological structures in the cells of the root cortex and some mycotallia in the form of arbuscules or vesicles [12]. It has been established that by interacting with arbuscular mycorrhiza, host plants are often actively nourished with nitrogen and phosphorus [11, 13]. Just as important are groups of proteobacteria from the genera *Agrobacterium*, *Azospirillum*, *Azotobacter*, *Burkholderia*, *Bradyrizobium*, *Enterobacter*, *Pseudomonas*, *Klebsiella*, *Rizobium* (Gram-negative), *Bacillus*, *Brevibacillus*, *Paenibacillus* (Gram-positive), as well as Gram-positive actinomycetes (*Rhodococcus*, *Streptomyces*, *Arhtrobacter*).

Mycorrhizal chains can form in soil to transport and exchange various substances, including mineral forms of nitrogen, phosphorus, and organic forms of C3 and C4 plants. Many representatives of the above genera produce phytohormones, vitamins, and bioactive substances that stimulate plant growth, inhibit phytopathogenic diseases and harm from insects, and increase the tolerance to soil salinity, air and soil drought, and oxidative stress [12–16, 22–26]. Mycorrhizal chains are also involved in the removal of toxic elements by precipitating or accumulating them both inside cells and in the extracellular space. The activity of mycorrhizal networks is strongly influenced by soil animals: mites, amoeba, collembola, lumbricids, and others [42, 43].

Mycorrhiza can be identified in plant groups and communities in any ecological zone of the world. Their development depends on abiotic and biotic factors, such as moisture and heat supply of the soil and atmosphere, altitudes above sea level, atmospheric pressure, variety of vegetation, and the presence of phytopathogenic infection or harmful animals (invertebrates and vertebrates). These factors are interdependent and can exert varying degrees of environmental pressure on the development of mycorrhizal networks in the rhizoplane of plants. Mycorrhiza has been identified in 44% of bryophytes, 52% of ferns, 100% of gymnosperms, and 85% of flowering plants. However, it has not been

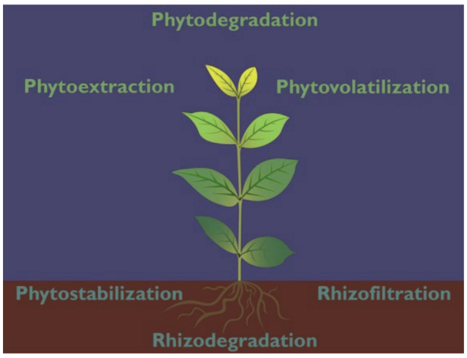


**Figure 1** Basic phytoremediation processes [44–50]

found in the families *Caryophyllaceae*, *Cyperaceae*, *Brassicaceae*, *Chenopodiaceae*, and others.

Well studied is the interaction of plants and nitrogen-fixing prokaryotes at the level of symbiotic, associative, and non-symbiotic nitrogen fixation. Lack of nitrogen in the soil limits the bioproductivity of many plant species. Plants absorb nitrogen from the soil in the form of nitrates, ammonium, and amino acids that are available to them as a result of the microbiological destruction of organic litter (leaves, branches, fruits, etc.) or nitrogen fixation. Symbiotic nitrogen fixation occurs in specialized structures of plants. Associative nitrogen fixation takes place in the rhizoplane or rhizosphere of roots and on the surface of leaves. Non-symbiotic nitrogen fixation occurs through external sources of organic matter or photosynthesis in cyanobacteria.

The type of rhizobial symbiosis is associated with prokaryotes of the order *Rhizobiales* and plants from the *Fabaceae* family and *Ulmaceae* family (*Parasponia* ssp.). Thanks to the short-lived nitrogen-fixing nodules on the plant roots, they are able to collect up to 450–550 kg/ha of nitrogen per year. These bacteria are active in wide pH ranges (5.0–8.5). In Siberia, active nitrogen-fixing nodules can be found on many species of clover, astragalus and other plants.

Actinorhizas of the order *Frankia* come into symbiosis with over 200 species of dicotyledonous plants, including woody ones. These long-lived root nodules collect up to 225 kg/ha of nitrogen per year. They can grow on pioneer substrates and easily function even in acidic boggy soils.

Cyanobacteria are mainly of the *Nostoc* genus and sometimes of the *Anabaena* genus. They are localized in the *Azolla* L. cavity, in intercellular spaces of cycad bark, on plant stems, and leaf petioles. Moisture and heat are the main conditions for their activation. Maximum nitrogen fixation is up to 720 kg/ha in Australia and much less in the boreal zone.

Actinorhizal plants are of the families *Betulaceae*, *Elaefgnaceae*, *Rozaceae*, *Datiscaceae*, *Ramnaceae* and other species. Flowering plants that come into symbiosis with cyanobacteria belong to the *Gunneraceae* genus and are common for the southern hemisphere. Cyanobacteria function mainly under aerobic conditions and can use their own photosynthesis or sources of organic matter.

Any type of symbiosis between plants and microorganisms can be used to clean the soil from pollutants. Figure 1 shows the main soil phytoremediation processes using microorganisms as plant symbionts.

Table 1 shows the main stages and processes in the plant during the transformation of toxicants [35, 44–49].

Plants and microorganisms can be mutually beneficial, which gives them an advantage in surviving critical conditions. Microorganisms stimulate the plant's growth and, at the same time, transform soil pollutants into a more accessible form.

Pollutant-resistant bacteria and fungi can be isolated from the rhizosphere of pollution-resistant plants [51]. They are of particular value for biotechnologies to remediate lands contaminated with heavy metals and toxic organic compounds [52]. Table 2 shows strains of microorganisms that are currently of practical interest in the rehabilitation of lands contaminated by active industrial development and are of strategic importance for the economic development of Russian regions [16, 53–67].

In addition to the strains listed in Table 2, more active consortia can be created to produce new soil varieties that are effective and safe for the biota of microbial communities, plants, and soil animals. Such

**Table 1** Pollutant transformation processes in plants

| Stages | Process description |
|---|---|
| Rhizofiltration | Pollutants are adsorbed by plant roots with a developed fibrous system. Plants secrete special organic compounds in order to attract microbial communities [44]. |
| Rhizodegradation | Harmful substances are decomposed by various microorganisms, including bacteria, fungi, and yeast, which live in the plant's root system. This process removes such contaminants as pesticides, oil, and PCBs [45, 46]. |
| Phytostabilization | Harmful substances are immobilized in the soil and prevented from entering groundwater and then the food chain. Stabilization is enabled by pollutants sorption in the plant's rhizosphere [47]. |
| Phytovolatilization | Plants convert pollutants into volatile forms that enter the atmosphere [48]. |
| Phytodegradation | Organic substances are biodegraded in the plant under the action of various enzymes such as peroxidase, dehalogenase, nitroreductase, and others [35, 49]. |
| Phytoextraction | The plant's roots accumulate toxicants which then enter its aerial parts [35]. |

**Table 2** Microorganisms for remediation of transformed soils

| Microorganisms | Source of extraction | Positive effect on the plant | Reference |
|---|---|---|---|
| Rhizobacteria: | | | |
| *Cellulosimicrobium* 60I1 and *Pseudomonas* 42P4 | *Capsicum annuum* L. | Increased growth rate, protection against abiotic stress | [53] |
| *Pseudomonas stutzeri* Pr7 and *Bacillus toyonensis* Pr8 | *Prunus domestica* L. | Increased growth rate, antifungal activity, impro-ved disease resistance | [54] |
| *Brevibacterium frigoritolerans* (AIS-3), *Alcaligenes faecalis* subsp. *Phenolicus* (AIS-8) and *Bacillus aryabhattai* (AIS-10) | *Crocus sativus* L. | Increased growth rate, antifungal activity | [55] |
| *Pseudomonas alcaliphila* and *Pseudomonas hunanensis* | *Ocimum basilicum* L. | Improved growth | [56] |
| *B. aryabhattai* MS3 | Rice root zone | Resistance to salt stress and iron restriction | [57] |
| *Pseudomonas toyotomiensis* ND1 (E), *Microbacterium resistens* ND2 (G), and *Bacillus pumilus.* train ND3 (I) | *Lepironia articulata* L. | Biodegradation of polycyclic aromatic hydrocarbons | [58] |
| *Aeromonas taiwanensis* isolate 5E, *Bcillus* sp. isolate 7G, *Bacillus cereus* isolate 8H and 3Ca, *Bacillus velezensis* isolate 9I, *Bacillus proteolyticus* isolate 4D, *Bacillus stratosphericus* isolate 14N, *Bacillus megaterium* isolate 11K, *Pseudomonas* sp. isolate 12L, *Enterobacter cloacae* | *Scirpus grossus* L. | Improved disease resistance | [59] |
| Pseudomonas aeruginosa | Arable land exposed to industrial effluent | Resistance to oxidative stress, increased chlorophyll content, improved growth, zinc resistance | [60] |
| *Enterobacter ludwigii* (HG2) and *Klebsiella pneumoniae* | Rhizosphere of plants from contaminated areas | Improved growth, resistance to mercury-caused oxidative stress | [61] |
| Consortium of cyanobacteria: *Calothrix* sp. and *Anabaena cylindrica* and rhizobacteria: *Chryseobacterium balustinum*, *Pseudomonas simiae*, and *Pseudomonas fluorescens* | Irrigated field horizon | Improved growth | [62] |
| Rhizobia: | | | |
| alpha proteobacteria from the genera *Rhizobium* and *Ensifer* | *Mimosa* spp. | Nitrogen fixation | [63] |
| Sinorhizobium medicae | *Medicago sativa* L. | Nitrogen fixation | [64] |
| *Rhizobium leguminosarum* bv. *Trifolii* | *Trifollium* spp. | Nitrogen fixation | [64] |
| Mycorrhizal fungi: | | | |
| 42 genera of endophytic fungi, with a prevalence of *Chaetomium* spp. and *Fusarium* spp. | Blueberry | Improved growth | [65] |
| *Glomus versiforme* and *Rhizophagus intraradices* | *Zea mays* L. | Resistance to cadmium-caused oxidative stress | [66 |
| *Funneliformis mosseae*, *R. intraradices* | *Trifolium repens* L. | Improved growth, resistance to copper-caused oxidative stress | [67] |

consortia improve the soil's bioactivity and ecological functions.

**Soil bioremediation by plants.** All plants assimilate very small quantities of copper, manganese, iron, nickel, and zinc. Along with this, there are plants that are capable of absorbing highly toxic heavy metals, such as cadmium, arsenic, lead, mercury, and others, without serious damage to their growth. They are called hyperaccumulators and are able to accumulate pollutants in large quantities without signs of phytotoxicity in the aerial parts of plants. Metal hyperaccumulators absorb at least 100 mg/kg of arsenic and cadmium and 1000 mg/kg of cobalt, copper, chromium, manganese, nickel, and lead. These plants include *Pteris vittata*, *Bidens pilosa*, *Jatropha curcas*, and *Helianthus annuus* [68–71]. They can resist the harmful effects of heavy metals by accumulating and suppressing them inside cells.

Exposure to toxicants changes the expression of genes responsible for the synthesis of transporter proteins that capture and transfer metals [72]. In Siberia, and Kemerovo Oblast in particular, *H. annuus* is the most available plant of those listed. There are several families of genes responsible for metal transport. These include macrophage proteins (Nramps), heavy metal ATPases, cation diffusion catalysts (CDFS), cationic antiporters, Zn-regulated transporter (ZRT), and the ZIP family [73].

Pollutants are adsorbed by plants in two ways – by symplastic and apoplastic transport. In the case of symplastic transport, heavy metals diffuse into the roots' endothermal cells through the plasma membrane. Ions can be transported by such carriers as proteins or organic acids, e.g., oxalic acid in combination with aluminum. In the case of apoplastic transport, metals are located in the free space between cells in non-cationic forms [39]. Special carrier proteins help pollutants to diffuse across the plasma membrane. There are special carriers for iron, zinc, and other metals [72, 74]. Various substances produced by plants, such as metallothioneins, glutathione, and phytochelatins, bind metal ions and are transported to vacuoles or shoots [74].

In hyperaccumulator plants, chelates are transported to shoots by membrane proteins: MATE, ATPase, and oligopeptide carrier proteins [72]. There, they are stored in vacuoles of parenchymal and epidermal leaf cells, which occupy 60 to 95% of the cell volume [75].

The problem with toxicant absorption by plants is that not all metals are absorbed in equal amounts. Cadmium and zinc are more readily available, which depends on the mobility of metal ions. Therefore, for better assimilation of elements, the soil conditions need to be adjusted, namely redox potential (pH) and temperature. In addition to these factors, plants themselves create conditions for better absorption of heavy metals. In particular, they secrete phytosiderophores and carboxylates, as well as acidify the rhizosphere for better release of ions from the soil [73].

**Soil bioremediation by microorganisms.** Microorganisms use various mechanisms for the transformation of pollutants. To survive in toxic environments, they transform compounds into safer substances. Thus, toxicants can be removed both inside and outside the plant's cells and tissues. To neutralize pollutants, microorganisms generate substances that are released into the environment and enhance the processes of cleaning soil from pollutants [76].

Some bacteria (*P. aeruginosa*, *P. fluorescens*, *Haemophilus* spp.) use various cellular enzymes (laccases, peroxidases, phosphatases, nitrilases, nitro-reductases, etc.) and are therefore effective in soil remediation [77].

Soil contaminants can be retained through their attachment to the membrane of a microorganism or absorption by inclusions in the form of bodies [78, 79]. At the intra- and extracellular level, toxic chemical compounds can be immobilized through the formation of minerals.

Another important mechanism for soil remediation is using microorganisms to generate exopolymer substances. For example, polysaccharides bind pollutants and they can be simultaneously removed from polluted environments during flocculation. The composition and properties of such polymers depend on the factors listed above, as well as the availability of various useful substances and the contents of salts and heavy metals in the soil [80].

**Interaction between plants and microorganisms for bioremediation.** An effective mechanism for cleaning transformed landscapes is to use micro-organisms that promote plant growth in a polluted environment. They help capture nitrogen and create phytohormones, as well as produce antibiotics for plant protection. For example, introducing *Sinorhizonium meliloti* in the zone of plant roots increases the level of photosynthetic proteins.

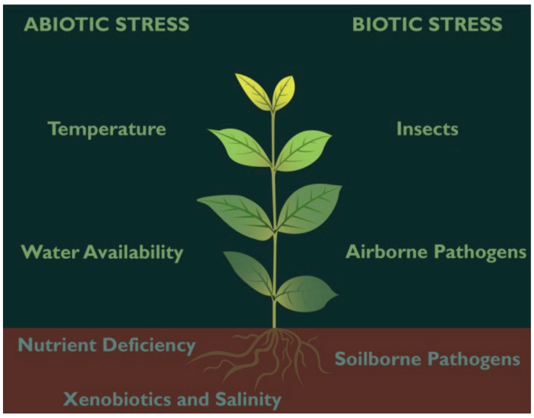


**Figure 2** Interaction of plants with biotic and abiotic factors

Figure 2 shows the influence of biotic and abiotic factors on plants.

Bacteria help plants survive under stress conditions (drought, nutritional deficiencies, toxicants). Their survival is facilitated by metabolites such as amino acids, isoflavonoids, flavonoids, and fatty acids. Bacteria can reproduce in mycorrhizal and non-mycorrhizal roots. In a stressful environment, they stimulate the production of special transport proteins and chaperones by plants. For example, the GroEL and DnaK proteins benefit the body under such stress conditions as temperature, drought, and exposure to toxicants [51].

Intensive plant growth is due to bacteria's ability to produce substances such as auxin, cytokinin, gibberellin, hydrogen cyanide, siderophores, indo-leacetic acid, and others [81]. In addition, rhizobacteria are able to prevent the effects of unwanted pathogens and insects [79]. Host plants help these bacteria reproduce by providing them with bioactive substances (flavonoids, glycosides, fatty acids, and others) [82].

**Prospects for using the microorganism-plant system for soil decontamination.** The benefit of the microorganism-plant system is in reducing the anthropogenic impact on both industrially transformed landscapes and agrogenic soils.

Heavy metals pose a great danger to human and animal health. Pinter *et al.* found that phytoremediation was enhanced by a combined use of As-resistant grapevine species and microorganisms such as *Bacillus licheniformis*, *Micrococcus luteus* and *P. fluorescens*. This activated siderophore production, phosphate solubilization, and nitrogen fixation [83].

In another study, Jiang *et al.* isolated microorganisms that improve plant adaptation to the environment from the rhizosphere of plants growing in polluted areas of chemical and oil refineries. In particular, they isolated *Pseudomonas*, *Cupriavidus*, and *Bacillus* from the rhizosphere of *Boehmeria nivea*. These bacteria are resistant to $Pb^{2+} > Zn^{2+} > Cu^{2+} > Cd^{2+}$ and therefore help plants survive in the soil with high concentrations of heavy metals [84].

Jiang *et al.* studied the effect of arbuscular mycorrhizal fungi *G. versiforme* and *R. intraradices* on the growth, Cd absorption, and antioxidant properties of Japanese honeysuckle (*Lonicera japonica* L.). They found a decreased concentration of cadmium in the plant's shoots and roots. Mycorrhizal fungi increased the biomass of shoots and roots, contributed to the accumulation of phosphorus, and activated such enzymes as catalase (CAT), ascorbate peroxidase (APX), glutathione reductase (GR), and others [85].

A promising symbiosis for soil remediation is between hyperaccumulators, grain crops, and mycorrhizal fungi. Studies by Yang *et al.* showed that a combined use of rice crops, hyperaccumulator *Solanum nigrum* L., and arbuscular mycorrhiza lowered the concentration of cadmium in this strategic culture to 64.5%. Low bioaccumulation was also due to decreased expression of the *Nramp5* gene and decreased activation of the *HMA3* gene in rice roots. In addition, a decline in pH was observed in the plant's rhizosphere. These studies are promising for agricultural production [86].

In another study, pepper (*C. annuum* L.) was inoculated with arbuscular mycorrhizal fungi *F. mosseae* and *R. intraradices* in the soil that contained copper (8 mM). It resulted in a high accumulation of dry biomass and a large leaf area (30 and 50%, respectively) [67].

The presence of arsenic in groundwater can have negative consequences. Mallick *et al.* identified a microbial consortium of resistant halophilic strains *Kocuria flava* AB402 and *Bacillus vietnamensis* AB403 from the rhizosphere of mangrove thickets. These microorganisms were resistant to arsenic concentrations from 20 to 35 mM. Also, the consortium adsorbed arsenic both inside cells and on the surface of biofilms. The strains facilitated better germination of rice seedlings and reduced toxicity [87].

Lyubun and Chernyshova studied the influence of *Aeromonas* sp. MG3, *Alcaligenes* sp. P2, *Acinetobacter* sp. K7, and *Azospirillum brasilense* Sp245 on the growth of, and arsenic absorption by, various plants. In particular, they selected sugar sorghum (*Sorghum saccharatum* L.), Sudan grass (*Sorghum sudanense* L.) and sunflower (*H. annuus* L.). The addition of arsenic had a negative effect of the plants' growth and development, reducing their biomass and height by 30–50%. However, their bioproductivity was restored by the rhizobacteria introduced into the soil. In particular, the use of *A. brasilense* Sp245 and *Acinetobacter* sp. K7 reduced the level of arsenic in the sunflower biomass [88].

Well studied is the positive effect of legumes and rhizobia on plant resistance to pollutants. Current studies are looking for new combinations with rhizobacteria. For example, a combined use of *P. mucilaginosus* rhizobacteria and *S. meliloti* rhizobia resulted in the absorption of copper by alfalfa. The microorganisms decreased lipid peroxidation and radicals accumulation, improving the plant's antioxidant properties and survival rate. In addition, the consortium enhanced the biochemical properties of the soil, contributing to increased contents of nitrogen, available phosphorus, and organic matter. Finally, the rhizosphere microorganisms became more diverse [89].

Shen *et al.*, who used *M. sativa* L. together with rhizobia and urea (nitrogen source) observed the plant's resistance to copper. Nitrogen content was the dominant factor of the pollutant's absorption. The scientists concluded that the combination of rhizobia with urea had a beneficial effect on soil remediation. As a result, copper consumption was 89.3% higher in the shoots and 1.5 times as high in the roots, compared to the control. In addition, rhizobia improved the plant's tolerance to oxidative stress, activated catalase, superoxide dismutase, and peroxidase in the roots and shoots, and increased the content of chlorophyll in the green organs [90].

In another study, castor bean was cultivated on a substrate saturated with lead and zinc, which resulted in a significantly smaller root surface area. The plant's inoculation with a bacterial mix, including phosphate-solubilizing *Actinobacteria*, contributed to its growth and good development of the root system, regardless of the presence of lead or zinc [91].

An association of arbuscular mycorrhizal fungi can also be effective in the phytoremediation of soil contaminated with hexavalent chromium [92]. Kullu *et al.* have found that *Rhizophagus irregularis* promotes the bioaccumulation of chromium by *Brachiaria mutica* (paragrass or buffalo grass). Fungal inoculation decreased the degree of soil contamination and made the pollutant more bioavailable for the plant. Mycorrhiza has a positive effect on plants growing in the soil contaminated with 60 mg/kg of hexavalent chromium. The experiment by Kullu *et al.* showed increased contents of carotenoids, chlorophyll, proline, protein, and protein-enzymes (ascorbate peroxidase, catalase, and glutathione peroxidase). In addition, the plant had improved electron transfer and photosynthetic characteristics. The scientists concluded that *R. irregularis* was compatible with the *B. mutica* population [93].

Islam and Yasmeen evaluated the effect of *P. aeruginosa* on wheat's resistance to oxidative stress caused by 1500 mg/kg of zinc. The study showed that adding the rhizobacteria to the plant's rhizosphere increased the content of antioxidant enzymes, phenolic compounds, and ascorbic acid. This reduced the pollutant's adverse effect on wheat biomass [60].

Another experiment determined the reaction of a consortium of *E. ludwigii* (HG 2) and *K. pneumoniae* (HG 3) to soil contamination with 75 μM of mercury.

This resulted in increased biomass and relative water content in wheat, compared to the control [61].

The above studies have shown the benefits of microbiological associations in remediating natural, agrogenic, and industrial lands destroyed or contaminated with heavy metals and organic toxicants.

## CONCLUSION

Anthropogenic impact in industrially developed regions leads to complete transformation of natural landscapes. This has a negative effect on all living systems (plants, animals, and microbocenoses) and causes medical and social problems associated with an increased incidence of all diseases, including the most severe ones.

Our review of scientific literature revealed a variety of methods for soil reclamation and remediation. The most promising and accessible methods are those involving plant communities. Plants can utilize toxicants, convert them into less stable compounds or transfer them to mineral complexes.

Another promising method is to introduce consortia of various microorganisms into the plant's rhizoplane. This approach is effective due to symbiotic interaction. On the one hand, microorganisms convert hard-to-reach minerals and heavy metals into other forms digestible for plants. On the other hand, they actively use plant metabolites for their own life support.

Examples from scientific literature show that consortia can develop bioactive substances, vitamins, and phytohormones for living systems to increase their stress resistance to biotic and abiotic environmental factors.

Rhizobacteria, rhizobia, mycorrhizal fungi, and their consortia have proved to be the most efficient in technogenic land remediation.

## CONTRIBUTION

The authors were equally involved in writing the manuscript and are equally responsible for plagiarism.

## CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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