Integrating Ecosystem Services in Historically Polluted Areas: Bioremediation Techniques for Soils Contaminated by Heavy Metals

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Abstract

Bioremediation of soils contaminated by heavy metals is based on the use of specially selected plants able to reduce the hazards of toxic metals. Depending on the mode of action on the heavy metals existing in the soil and the place where the action takes place, the following mechanisms for soil phytoremediation are distinguished: phytostabilization, phytoextraction, phytoimobilization, rhizofiltration, or evapotranspiration. These mechanisms are complex and include the plant ability to reduce the mobility and bioavailability of heavy metals and other pollutants, to extract large amounts of heavy metals from the soil or to evaporate water together with various pollutants already reached in the rhizosphere. Decontamination of polluted soils by using bioaccumulative plants is proposed as an environmental-friendly alternative to the traditional physicochemical methods, being a sustainable method with a great potential in the terms of environmental protection and cost management.

Keywords: contaminated sites, hyperaccumulators, phytoextraction, phytoremediation, phytomining, soil contamination

1. Introduction

Pollution has become a worldwide concern because its effects can lead to ecological imbalances, affecting flora, fauna, and the health of people living in the vicinity of the contaminated sites. Soil pollution with heavy metals is as old as human ability to melt and process ores. Each stage of cultural development of humanity left behind its pollution with metals, mainly stored in soil, sediments, and ice [1].

Heavy metal pollution is a major public health concern, and although efforts have been made to limit the population exposure, the problem persists due to the accumulation of these substances in the environment [2]. Especially long-term industrial and mining activities are the preponderent sources for heavy metal environmental contamination worldwide. Unlike other pollutants (organic compounds and radionuclides), heavy metals are considered to be the most persistent contaminants in soil because these elements tend to accumulate in the soil and then, through the plant and animal food chain, the population is exposed to their toxic effects [3, 4].

Heavy metals are defined as elements with metallic properties (conductivity, ductility, cation stability), atomic number greater than 20, and density greater than 5 kg/dm^3 [5, 6]. Recently, the term "heavy metal" is used as a general term for those metals and semi-metals with toxic potential on the human body or the environment [7]. The most common elements in heavy metal contamination of environment are Cd, Cr, Cu, Hg, Pb, and Zn. They occur naturally in the soil in relatively small concentrations but can occur in much higher quantities as a result of human activities.

Some heavy metals, in small amounts, have a physiologically beneficial role for plants or in the human body (e.g., Zn, Mn, and Se), and others are potentially toxic to organisms and humans regardless the concentration [8].

Expansion of areas affected by mining and industrial activities contaminating the environment with heavy metals makes the application of traditional technologies inappropriate due to the high costs associated with soil remediation. The majority of conventional methods such as incineration, vitrification, or land replacement are extremely expensive. Also, the potential impact on the environment must be considered, in particular the change of agricultural soil properties and damage to the landscape [9]. In historically polluted areas, the challenge is to decontaminate soils in order to resume agricultural practices and protect the population health. Thus, in addition to soil remediation, it is necessary to remedy the water or wastewater used for crop irrigation [10].

The importance of biodiversity, both below and above ground, is currently increasing for the cleaning of metal-contaminated ecosystems [11]. The concept of ecosystem services may be integrated in this field, having implications for the practice of soil remediation [12, 13]. There is a close connection between soil, plants, and other ecosystem components. In fact, ecosystem services include the services provided by air, water, soil, and biota. Of these, the soil functions are important for the ecosystem good functioning and refer to some valuable properties: the capacity of storing, filtering, or transforming nutrients, substances, and water; biomass production (crops and forestry); host of biodiversity (habitats, species, etc.); source of raw materials; physical and cultural environment for humans; and human activities [14]. Ecological consequences of soil pollution apply not only to soil functions, such as its biological activity, but have also negative effects on soil-crop-animal-human system [5]. On the other hand, plants and microorganisms play a crucial role in restoring the specific soil functions and also other ecosystem components, being considered as ecological or ecosystem engineers [15].

A wide range of biodegradation processes of soil contaminants are currently available, an advantage of these biological treatments being their potential to be cost-effective [16–18]. Initially, research is focused on bacteria, taking into account catabolic reactions mediated by bacterial enzymes. The first investigations into phytoremediation have been confronted with some opinions that if a contaminant cannot be degraded by bacteria that have a wide range of catabolic enzymes, it can certainly not be by plants [19]. Plant remediation features include three common strategies for "treating" heavy metal-contaminated soils: immobilization, removal, and destruction [20].

Phytoremediation, also known as green remediation or agro-remediation, uses vegetation to remove pollutant substances such as heavy metals, organic compounds, and radioactive compounds from the soil, sediments, or water [21]. Phytoextraction, one of the most important phytoremediation techniques, is defined as the extraction of contaminants from soils by plants and is known as a mild, ecological remediation method. It uses the plants to take pollutants from the soil through the roots, with their subsequent accumulation on the upper part of plant, generally followed by the harvesting and elimination of plant biomass [22].

The applicability of phytoremediation depends on the possibility of identifying plants that have the ability to tolerate high concentrations of heavy metals, to extract and accumulate important quantities of heavy metals from the soil, or to immobilize contaminants at the soil-root interface, thus reducing the possibility of groundwater contamination.

2. Soil pollution in industrial and mining areas

Soil is the most important compartment for all terrestrial ecosystems, providing essential nutrients for plant growth, plant degradation, and transport of biomass. A significant role of the soil is also as natural buffer within the transport of chemical elements and substances in the atmosphere, hydrosphere, and biota [3].

The persistence of contaminants in soil is much higher than in other compartments of the biosphere, and soil pollution by heavy metals appears to be permanent in soils [23]. Heavy metals are native components of the earth crust, existing in different concentrations in all ecosystems [24].

The period of existence of metals in soil in temperate climatic conditions can be estimated for the metal elements, as follows: Cd between 75 and 380 years, Hg between 500 and 1000 years, and between 1000 and 3000 years for Ag, Cu, Ni, Pb, Se, and Zn [3, 25].

The sources of heavy metals in the environment are very diverse and can be of both natural and anthropogenic origins. The main natural sources are rocks and soils [26], and the anthropogenic sources are represented by socioeconomic activities; some of these are illustrated in **Table 1**. The problem of this type of pollution derives in particular from the exploitation of minerals and the use of metals by the human population.

Historically contaminated areas by heavy metals are found all over the world, especially caused by mining and ore processing activities. Consequently, the metal pollution is not

Source	As	Cd	Cr	Cu	Pb	Hg	Ni	Zn
Mining and processing of ores	√	√		√	√	√		√
Metallurgy	√	√	√	√	√	√	√	√
Chemical industry	√	√	√	√	√	√		√
Alloy industry					√			
Paint industry		√	√		√			√
Glass industry	√				√	√		
Paper industry			√	√	√	√	√	
Textile industry	√		√			√		√
Chemical fertilizer industry	√	√		√	√	√	√	√
Petroleum industry	√	√	√	√	√	√		√
Burning of coals	√	√	√	√	√	√	√	

Table 1. Industrial sources of the most important heavy metals in the soil [27].

attributable exclusively to mining activities, although these are preponderent in many regions [28–30]. Most of these activities are currently closed, remaining behind enormous quantities of heavy metals that have been deposited in the soil. The volume of tailing dumps discharged has exceeded 10 billion tonnes per year [31]. Usually, these mine tailings are not covered by vegetation caused by a poorly structured soil, being potential sources of heavy metal spreading through water infiltration or wind [32].

3. Phytoremediation: a green technology to remove heavy metals from the soil

Many remediation techniques have been used to respond to the growing number of soils contaminated with heavy metals [33–35].

Decontamination methods currently applied in the majority of sites are mainly characterized by the manipulation of enormous quantities of soil or heavy metal extraction by using chemical reagents. These practices are very expensive and also lead to the loss of soil fertility by changing its physicochemical properties (structure, cationic exchange capacity, etc.), destroying at the same time the microorganisms from the soil and, ultimately, the humus layer [36]. In this situation, other less brutal methods for heavy metal extraction were searched and developed. Bioremediation and phytoremediation in particular are such “mild” remediation methods that maintain or even restore the natural soil fertility [21].

Thus, methods by which plants, natural or genetically modified, alone or in the presence of auxiliary substances cause polluted soils to become less dangerous for humans have been developed [37, 38].

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Phytoremediation is defined as a phenomenon of polluting substances extraction by using plants. With all these, there are many types of phytoremediation, so we can state that phytoremediation represents a much broader defined term [39, 40]. Phytoremediation of soils, waters, and sediments is not a new concept; for decades it has been found that some plants can degrade or extract heavy metals and other pollutants from these environmental compartments. Plants have been used for the decontamination of wastewater about 300 years ago. *Thlaspi caerulescens* and *Viola calaminaria* were the first species of plants used in the nineteenth century and found to accumulate large concentrations of metals [4].

A strong motivation to apply phytoremediation in historically contaminated sites, in addition to other advantages, is the particularly low cost of this method compared to conventional ones. **Table 2** highlights the costs of different soil remediation techniques. Nevertheless, the most frequently applied remediation techniques for contaminated soil in Europe include land excavation or disposal [41].

3.1. Phytoremediation process and techniques

The metal extraction or accumulation by plants involves a variety of biological mechanisms and requires direct knowledge of plant physiology and soil science.

Through the rhizosphere (the interface between plant roots and soil), the water is absorbed by the roots to replace the evaporated water from the leaves. The metals in the soil solution (free ions or organometallic complexes) can move together with water (by convection or mass transfer) as the plant absorbs the water needed for vital processes. Absorption of water from the rhizosphere creates a hydraulic gradient directly from the ground to the surface of the roots. This concentration gradient or hydraulic control ensures the diffusion of ions from the soil particles to the deficient layer surrounding the roots [45, 46].

The elimination by plants of exudates and metabolites play an important role in the phytoremediation process. Thus, enzymes such as dehydrogenase, hydrolase, peroxidase, and phosphatase are released at the plant-soil interface and contribute to the degradation of

Remediation method	Remediation costs (in US dollars/m^3 soil)
Excavation and disposal	140–720
Vitrification	360–1.370
Soil washing, ex situ	80–860
Soil washing, in situ	20–270
Solidification and stabilization	40–200
Electrokinetic methods	30–290
Bioremediation	10–310
Phytoremediation	1–150

Table 2. Costs of different soil remediation methods [42–44].

some soil compounds [47]. Plant enzymes named metallothioneins and phytochelatins bind the heavy metals increasing the extraction of these elements [48, 49].

In fact, phytoremediation is based on the extension of already existing processes in different ecosystems, with other processes that occur under different conditions, different degrees of contamination, different pollutants, and plant species.

Depending on the mode of action on the pollutants and the place where the action takes place, the following phytoremediation mechanisms and biological processes are distinguished: phytoextraction, phytostabilization, phytoimobilization, evapotranspiration, rhizodegradation, rhizofiltration, phytodegradation, and phytovolatilization [35, 50, 51].

Heavy metals in the soil are only suitable for phytoextraction, evapotranspiration, phytostabilization, and phytoimobilization [35, 52]. Phytoextraction is by far the most studied and applied method. Phytodegradation and rhizodegradation processes, as well as phytovolatilization, are specific to organic pollutants; the major difference between these and other processes applicable to metals is the complete mineralization of the pollutant after degradation.

From the point of view of the place where the remediation takes place, this procedure is exclusively in situ, without excavation of contaminated site, in all types of phytoremediation [52, 53]. Also, from the point of view of the processes that occur, they can be either in plant, by the absorption of the metals in the plant (phytoextraction, rhizofiltration, phytovolatilization), or ex plant due to the action of the excreted enzymes by the plants or the microorganisms associated with the plants (phytoimobilization), either combined (in the case of phytostabilization).

Phytoextraction is based on the cultivation of large biomass plants and the ability to extract large amounts of heavy metals from the soil, accumulating them in the plant tissues. These plants are harvested using conventional farming methods and then dried and incinerated, the resulting ash being stored [54].

Starting from the necessity of finding solutions for the decontamination of areas polluted with heavy metals of anthropogenic origin, the concept of “heavy metal phytoextraction” was introduced for the first time by Baker and Brooks in 1983 [55].

Phytostabilization refers to plant ability to stabilize pollutants, thereby reducing their mobility and bioavailability. In the case of nonagricultural land, especially those with a high degree of pollution, a method of mitigating the risk of pollution can be the reduction of the possibility of moving heavy metals into the soil [56].

From the point of view of the area where the pollutant fixation takes place, phytostabilization can take place in the rhizosphere, on the root membranes, or in the root cells. This method applies especially to tailings dumps, but the main disadvantage of this technique is that the metals remain in the soil.

Phytostabilization research is still in the laboratory phase, with very few applications in the field. These include the use of plants as *Brassica juncea* for the stabilization of lead and cadmium from both mine and tailing dumps; *Rubus ulmifolius* to stabilize arsenic, lead, and nickel; or lemon grass to stabilize copper in mine tailings [49, 57, 58].

Phytoimobilization represents a combination of phytoextraction (heavy metals are extracted from the soil by perennial plants, but they are not harvested) and phytostabilization (fallen leaves are collected, the soil being treated to immobilize heavy metals). This technique uses tolerant species to the target pollutant which will form a "vegetal carpet" in areas where natural vegetation is absent due to the high concentration of pollutants. The method is already successfully used in the case of tailing dumps from the mining industry [59].

Evapotranspiration – plants also have the ability to influence local hydrogeological conditions. Thus, plants are capable of intercepting a significant amount of rain on the surface of their leaves. This intercepted water is evaporated directly into the atmosphere, not reaching the ground. Simultaneously, infiltrations are reduced, so the method can also be used to limit the accumulation of water in the ground.

The presence of vegetation above a groundwater body has the effect of a "pump," on the one hand reducing the amount of water in the area of the rhizosphere; on the other hand, extracting the heavy metals the groundwater may have lower heavy metal concentrations [60]. The presence of plants at the surface of the soil also prevents its erosion.

Rhizodegradation, also called photosynthesis or plant-assisted degradation, represents the transformation of existing organic contaminants into the soil due to the bioactivity in the rhizosphere. Plants metabolize organic pollutants (including with the help of associated micro-organisms) at the level of the roots, turning them into less or no toxic compounds. A symbiotic relationship is established between plants and microorganisms in the soil. Plants increase the pH of the soil and provide the nutrients needed for the microorganisms. These contribute to soil clean-up, thus providing the rhizosphere more conducive to the development of the roots [61]. Many pollutants can be degraded into harmless products or can be transformed into energy and feed sources for plants or soil organisms. But then, natural substances removed from plant roots (e.g., sugars, alcohols, phenols, carbohydrates, and acids) contain organic carbon that feeds soil microorganisms, stimulating their biological activities.

Rhizofiltration is based on the property of plant roots that grow in well-aerated water to precipitate and concentrate toxic metals from the pollutant effluents.

Phytodegradation, also known as phytotransformation, refers to the absorption of organic pollutants from soil, sediments, and water and their subsequent transformation by plants. Depending on the concentration and composition, as well as the plant species and local conditions, an organic pollutant may be able to pass through the protective barrier of the rhizosphere. In this case, it may suffer a transformation process inside the plant. The transforming mechanisms are very diverse, the resulting products being stored in vacuoles or embedded in plant tissues [50].

In order to be absorbed by the plant through the roots, an organic pollutant must be soluble in the soil solution. Once the pollutant has reached the plant, it can be stored and/or biotransformed in the plant biomass through lignification (binding the pollutant or its byproducts within the plant lignin) or can be further metabolized to carbon dioxide and water (mineralization) [35]. Plants capable of causing pollutant degradation are the phreatophytes (species of *Populus*, *Salix*) or grains (rye, *Sorghum*) [62, 63].

Phytovolatilization is applied exclusively for the treatment of soils contaminated with As, Hg, or Se, metals that may exist in the gaseous phase. This method uses plants capable of extracting these metals from the soil and volatilizing them in the atmosphere [64]. Plants extract volatile compounds from soil, including metals, and evaporate them through the leaves. Due to the particular toxicity of these metals, which once released can no longer be controlled, the method is still subject of controversy.

3.2. Metal accumulative plant species

The ability of plants to accumulate extraordinarily high levels of some metals and other pollutants has reached an increase interest over the past few years.

In general, heavy metals are phytotoxic to plants, but there are plants capable of absorbing and storing metals in their various tissues (roots, leaves), used successfully in soils rich in heavy metals and known as hyperaccumulative plants. Brooks and his colleagues used this term for the first time in 1977 to describe plants that are able to accumulate more than 0.1% Ni (>1000 μg/g) in their leaves. Hyperaccumulative plants (hyperaccumulators or metallophytes) are those plants capable of accumulating 100 times larger quantities of metal than common plants considered non-accumulating [65, 66].

Hyperaccumulative plants are spread all over the world, although they are very rare plants and are found only in certain areas. The approximately known number for these plants is about 500 species belonging to a number of plant families. The majority are "obligate metallophytes," species that occur only on metalliferous soils; a smaller, but increasing number of plant species are "facultative hyperaccumulators" that hyperaccumulate heavy metals when occurring on metalliferous soils, although they commonly grow on normal, non-metalliferous soils [67].

To be considered a hyperaccumulator, the concentration of heavy metal should be 2–3 times greater than in leaves of most species growing on normal soils and at least one order higher than the usual range found in plants from metalliferous soils. The proposed threshold criteria (in g metal per g of dry leaf tissue) are 100 for Cd, Se, and Tl; 300 for Co, Cr, and Cu; 1000 for As, Ni, and Pb; 3000 for Zn; and 10,000 for Mn [68].

The growth of certain plants on soils contaminated by heavy metals leads to their adaptation to the pollution conditions and the assimilation of toxic elements into the vegetal organism. Of course, not all plants are resistant to the action of pollutants, as not all are able to accumulate significant amounts of toxic elements. The vast majority of plants are able to overaccumulate only one heavy metal from the soil, even if the soil is polluted with several such elements. Special abilities for the simultaneous bioaccumulation of several heavy metals have been proven by *Thlaspi caerulescens* for zinc, cadmium, and copper and *Brassica juncea* (Indian mustard) for lead and cadmium [49, 66]. Other hyperaccumulative plant species are shown in **Table 3**.

Thlaspi caerulescens has been extensively studied and is used in most studies as a model plant for assessment the mechanisms of metal translocation, accumulation, and tolerance and for investigating the physiological and biochemical mechanisms of metal accumulation in plants [72].

Hyperaccumulators	Heavy metal	References
Thlaspi caerulescens	Zn, Cd, Cu	[66, 69]
Brassica juncea	Pb, Cd, Ni	[49, 70]
Arabidopsis halleri	Cd, Zn	[71, 72]
Phytolacca acinosa	Mn	[73]
Alyssum bracteatum	Ni	[55, 74]
Brassica napus	Zn	[75]
Sedum alfredii	Zn	[76]

Table 3. Examples of hyperaccumulative plants and the targeted heavy metal/heavy metals.

3.3. Factors that are influencing the phytoremediation process

The success of extensive application of phytoextraction depends on several key factors: the soil physicochemical properties, the degree of soil contamination, the possibility that the metal is absorbed in the roots, and the ability of plants to accumulate metals and then translocate them into the air [77, 78]. The soil properties affecting the bioavailability of heavy metals to plants include soil pH, redox potential, organic matter, clay content, and cation exchange capacity [79].

The low bioavailability of metals in the soil represents a major factor that is limiting the potential for the use of phytoextraction in the case of many heavy metals [77, 80, 81]. A major objective of the phytoremediation studies in historical areas contaminated by heavy metals is to increase the availability of metals to be absorbed from the soil by plants. On the other hand, in the case of phytostabilization, it is preferable to reduce the heavy metal availability in soils.

Particularly, the mobility of metals in soil is directly influenced by their chemical species. The chemical characterization of metals determines their behavior and toxicity in the environment [82]. The metal species represent the specific forms of an element including isotopic composition, electron or oxidative state, and complex or molecular structure [3]. Several chemical forms of metals include free metal ions, metal complexes dissolved in solutions and adsorbed on solid surfaces, and metal species coprecipitating in their own solids or in other metals with much higher concentrations. The metal species modify both toxicity and certain processes such as volatilization, photolysis, adsorption, atmospheric deposition, acid-base balance, polymerization, electron transfer reactions, solubility and precipitation equilibrium, microorganism transformations, and diffusion [82, 83].

There are also plant-related factors contributing to the efficiency of phytoremediation: rapid growth and high biomass producers, the presence of an extensive root system capable of exploring large soil volumes, a good tolerance for high metal concentrations, a high transfer factor (TF > 1), and adaptability to polluted areas under different climatic conditions [82–87].

The availability or retention of a metal in soil and plants can be expressed by several indices [88, 89]:

- *The modified distribution coefficient (Kmd)*, defined as the ratio between the metal concentration in the soil and its concentration in the soil solution.

- *The bioavailability factor (BF)*, defined as the ratio between the metal content in mobile phase and the total metal concentration in the soil. This value indicates the fraction of the total metal concentration in the soil that is considered available for plants.
- *The retention factor (RF)*, the ratio between the amount of metal in the residual fraction (after mineralization and then sequential extraction) and the total amount of metal in the soil. Its value reflects the amount of metal retained in the solid phase. Normally, the retention factor is lower in soils with low pH and low clay content.
- *The transfer factor (TF) or bioaccumulation factor*, the ratio between the metal content of certain plant tissues and the total amount of metal in soil. It expresses the degree to which a plant absorbs the metal in the roots and other tissues, usually having much higher values for roots than for stem or seeds. Currently, the accumulation factor in the edible parts of the plants is of maximum interest.

3.4. Other bioremediation techniques

Phytoremediation can be used in combination with other remediation techniques: chelate-assisted remediation, microbial-assisted remediation, and the use of transgenic plants [90, 91].

The 1990 EPA Manual on In situ Treatment of Contaminated Soils mentions the remediation term or ecological restauration, limiting the definition to the physicochemical methods of immobilizing or extracting heavy metals from the soil [92].

The purpose of the biological remediation process is to degrade contaminants and transform them into harmless intermediates and byproducts. The last step is to complete the mineralization of contaminants to carbon dioxide, water, and simple, inorganic compounds. Microorganisms in the rhizosphere can symbiotically interact with roots to increase the absorption of metals from soil or to biodegrade or immobilize certain toxic compounds for plants [93, 94].

The low solubility of heavy metals in the soil solution is an important impediment to their extraction by plants. In order to make the phytoextraction process more efficient, it is necessary to find methods to solubilize the heavy metals, increasing their bioavailability and therefore the ability to be extracted from plants, preferably with accumulation in the aerial parts, easy to remove by harvesting. Until now, besides soil pH reduction, the only viable solution for increasing the mobility of heavy metals in soil is the addition of substances that form soluble compounds with heavy metals existing in the soil in different forms, thus increasing their bioavailability. The use of chelators for soil remediation has started from the finding that these heavy metal complexes are more soluble in aqueous solutions than other combinations. Applying some ligands to the soil, such as EDTA, citrate, or tartrate, results an increased heavy metal mobility, an immediate increase of the mobile fraction amount in the soil and then in the roots and aerial parts of the plants [95, 96].

The use of amendments and fertilizers is also useful to increase the phytoextraction capacity of plants. Adding organic amendments such as compost, green fertilizer, and biosolids is playing an important role in metal mobility and plant growth [97, 98].

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4. Future developments

Phytoremediation requires a greater effort than simply plant cultivation with minimal maintenance, assuming that the concentration of heavy metals in the soil will decrease. In addition, phytoextraction also refers to phytomining. A limited definition of the term "phytomining" is the possibility to use the crop plants to achieve economical production of metals, both from contaminated soils and also from soils that naturally have a high concentration of metals [66]. This extraction for commercial purposes of heavy metals from crop plants is not widely used. Several plant species are used by geologists for mineral prospecting, as indicator plants for the presence of different metals in soils: *Equisetum arvense* (horsetail) for gold, *Alyssum bertolonii* and *Thlaspi* L. for nickel, *Viola calaminaria* for zinc, and *Pteridium aquilinum* for arsenic [99, 100].

Another method of improving the cost-benefit of phytoremediation is to extract active principles from plants and used before plant processing. Obviously, if any useful substances (metals or oils) are recovered from the plants or by using the harvested plants for biofuel production, this practice can reduce the related costs of phytoremediation [101, 102].

Recent research in the phytoremediation application includes the use of transgenic plants and removal of metallic nanoparticles from soils [37, 103]. The challenge is to identify genes coding the specific heavy metal hyperaccumulation in plants.

5. Conclusions

The goal of phytoremediation is to improve the functioning of ecosystems. Plants are considered veritable "ecosystem engineers," and bioremediation by using plants is appreciated as a special applied form of ecosystem services. Assessment of the bioremediation applicability and effectiveness may be required for specific ecosystems, at least until the technology becomes firmly demonstrated and established. Extensive studies of field conditions are required in order to implement this technique in historically heavy metal-contaminated areas.

Thus, further research is still needed before implementing this technique in a large scale. Before becoming a commercially widely applicable process, phytoremediation requires a commitment to resident population and to local authorities in polluted regions, as well as financial and time resources. At the same time, it has the potential to offer low costs for its application and is considered a green alternative to conventional technologies for soil remediation.

Decontamination of polluted soils by using bioaccumulative plants is proposed as an environmental-friendly alternative to the traditional physicochemical methods, being a sustainable method with a great potential in the terms of environmental protection and cost management.

Conflict of interest

The authors declare no conflict of interest.

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