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MINI-REVIEW

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Phytoremediation: an overview of metallic ion decontamination from soil

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Abstract In recent years, phytoremediation has emerged as a promising ecoremediation technology, particularly for soil and water cleanup of large volumes of contaminated sites. The exploitation of plants to remediate soils contaminated with trace elements could provide a cheap and sustainable technology for bioremediation. Many modern tools and analytical devices have provided insight into the selection and optimization of the remediation process by plant species. This review describes certain factors for the phytoremediation of metal ion decontamination and various aspects of plant metabolism during metallic decontamination. Metal-hyperaccumulating plants, desirable for heavily polluted environments, can be developed by the introduction of novel traits into high biomass plants in a transgenic approach, which is a promising strategy for the development of effective phytoremediation technology. The genetic manipulation of a phytoremediator plant needs a number of optimization processes, including mobilization of trace elements/metal ions, their uptake into the root, stem and other viable parts of the plant and their detoxification and allocation within the plant. This upcoming science is expanding as technology continues to offer new, low-cost remediation options.

Introduction

Phytoremediation is an emerging technology, which uses plants and their associated rhizospheric microorganisms to remove various pollutants from contaminated soils, sediments, groundwater and surfacewater. Global industrialization has resulted in the release of large amounts of potentially toxic compounds into the biosphere, among which are trace elements, like cadmium, mercury, lead, arsenic, zinc and nickel, which are commonly addressed as heavy metals (Lasat et al. 1998). Over the past five decades, the worldwide release of heavy metals reached 22,000 t for cadmium, 939,000 t for copper, 783,000 t for lead and 1,350,000 t for zinc. Toxic heavy metals cause DNA damage and their carcinogenic effects in animals and humans are probably caused by their mutagenic ability (Knasmuller et al. 1998; Baudouin et al. 2002). Various physical, chemical and biological processes are already being used to remediate metal-contaminated soils. The cleanup of most of these soils is mandatory in order to reclaim the area and to minimize the entry of potentially toxic elements into the food chain. There are certain plants which can be used to treat many classes of contaminants, including petroleum hydrocarbons, chlorinated solvents, pesticides, metals, radionuclides, explosives and excess nutrients. Phytoremediation is a solar-driven and aesthetically pleasing technique that takes advantage of plants' natural abilities to take up, accumulate and/or degrade constituents of their soil and water environment. It includes a variety of remediation techniques, summarized in Table 1, and indicates that phytoremediation is actually a broad class of remediation techniques, which includes many treatment strategies.

Phytoremediation for metallic decontamination

The plants used in phytoremediation/phytodegradation are generally selected on the basis of their growth rate and biomass, the depth of their root zone, their potential to evapotranspirate groundwater and their ability to tolerate and bioaccumulate particular contaminants (Lasat et al. 1998; Meagher 2000). Grasses are more suitable for inorganic and organic heavy metal remediation, due to their growth habitat and adaptability to a wide range of edaphic and climatic conditions. Plants can break down and metabolize certain organics and stabilize various metal ion contaminants, by acting as filters or traps (Burken et al. 2000; Krämer and Chardonnens 2001). The uptake and accumulation of contaminants varies from

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Table 1 Mechanisms for the removal of toxic contaminants from the environment and the techniques used in phytoremediation

Phytoremediation techniques	Mechanism	Media
Rhizodegradation	Uptake of contaminants in plant roots	Surfacewater and water pumped through roots
Phytotransformation	Plant uptake of organic contaminants and degradation	Surface- and groundwater
Plant-assisted bioremediation (microbial)	Microbial degradation in the rhizosphere region	Groundwater within the rhizosphere and soil
Phytoextraction	Direct uptake of contaminants in plant tissues with subsequent removal of the plants	Soil
Phytostabilization	Roots exudates cause metals to precipitate and biomass becomes less bioavailable	Groundwater, soil, mine tailings
Phytovolatilization	Plants evaporate certain metal ions and volatile organics	Soil, groundwater
Removal of aerial contaminants	Uptake of various volatile organics by leaves	Air

plant to plant and also from species to species within a genus. Some species act as powerful remediators of the primary chemical contaminants and some remediate only the chemical species of the primary contaminants (Krämer and Chardonnens 2001).

Hyperaccumulation of metallic ions by plants

Plants use photosynthetic energy to extract ions from the soil and concentrate them in their biomass, as per their nutritional requirements. When present at elevated levels in soil or water, non-essential elements/heavy metals are able to enter plants through the nutrient transport systems by virtue of their chemical similarity to nutrient ions. Some naturally occurring plants, termed metallic hyperaccumulator plants, can accumulate 10–500 times higher levels of elements than crops. These plants occur on metal-rich soils and accumulate metals in their above-ground tissues to concentrations between one and three orders of magnitude higher than the surrounding *normal* plants grown at the same site (Baker and Brooks 1989; Krämer and Chardonnens 2001). These plant parts can then be harvested and the incinerated plant ash of these parts can be recycled and decomposed into modified green manure or disposed of as hazardous matter in specialized dumps. In highly contaminated sites, where removal of pollutant elements is impossible, tolerant plants can be grown to reduce the spread of contaminants through wind-erosion, run-off or leaching (Hursthouse 2001). Hyperaccumulators like *Thlaspi caerulescens* provide a marvelous model system for elucidating the fundamental mechanisms and ultimately the genes that control metal hyperaccumulation (Pence et al. 2000). These genes govern processes that can increase both the solubility of metals in the soil surrounding the roots and the transport proteins that move metals into the root cells and further through the plant vascular system to other parts of the plant.

Strategies for the hyperaccumulation of metals by plants include binding of metals by root exudates and the possible involvement of the plasma membrane, either by reducing the uptake of heavy metals or by stimulating the efflux pumping of metals that have entered the cytosol. Hyperaccumulators exhibit enhanced translocation of the absorbed metal to the shoot. In the protoplast, various other potential mechanisms also exist, e.g. for the repair of stress-damaged proteins involving heat-shock proteins or metallothioneins and for the chelation of metals by organic acids, amino acids or peptides, or their compartmentation away from metabolic processes by transport into the vacuole (Hall 2002).

Uptake and biotransformation of metallic ions in plants

There are various processes involved in phytoremediation (Table 1) and each process involves various mechanisms for the total decontamination of metal ions from the environment. All such processes either *decontaminate* the soil or *stabilize* the pollutant within it (Fig. 1). Specifically, two processes are involved. First is phytoextraction, in which high-biomass, metal-accumulating plants and appropriate soil amendments are used to transport and concentrate metals from the soil into the harvestable part of roots and above-ground shoots, which are harvested with conventional agricultural methods (Schmoger et al. 2000; Lasat 2002). The other is rhizofiltration, in which plant roots grown in water absorb, concentrate and precipitate toxic metals and organics from polluted effluents (Schmoger et al. 2000).

Soil factors influencing plant uptake of metals

Soil metal concentration

Soil represents the major repository of trace elements over geologic time. There is considerable variability in the trace metal concentrations of soils from different climatic regions. Trace element levels in soils may increase by the deposition of fly ash from coal combustion plants. In addition, metallic ions may enter soil indirectly as a result of industrial activity and directly in municipal wastes, fertilizers or other soil additives (Petrangeli et al. 2001; Pagnanelli et al. 2002). Several such sources can increase the local concentration of these elements in soils.

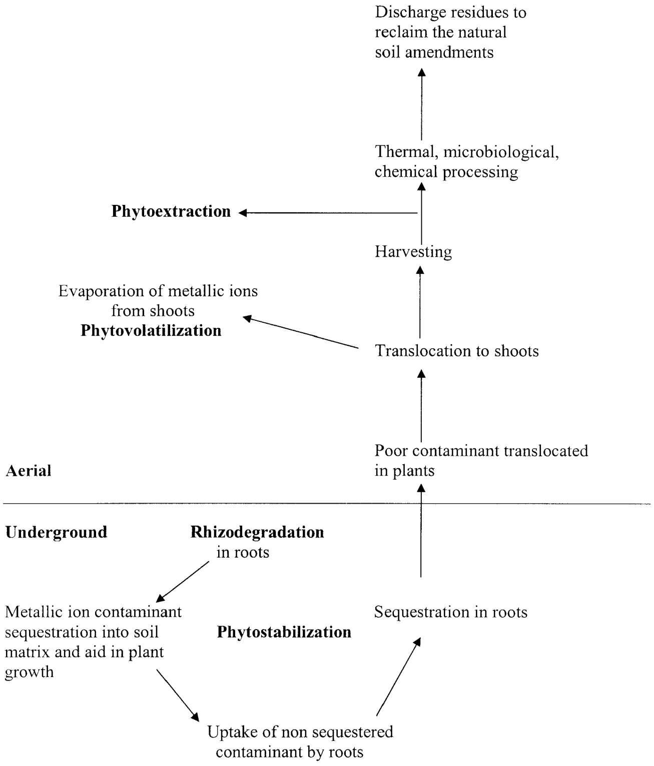

Fig. 1 Scheme of metallic ion decontamination in natural phytoremediation processes

Soil processes and properties

The major factors governing the availability of metallic ions to plants are the solubility and the thermodynamic activity of the uncomplexed ion (Petrangeli et al. 2001) since, in order for root uptake to occur, a soluble species must exist adjacent to the root membrane for some finite period. The solubility of metallic ions depends on various soil physiochemical factors, such as the pH, type and density of the charge on soil colloids and the reactive surface area (Magnuson et al. 2001). All such phenomena are dependent upon soil properties, including metal concentration and form, particle size distribution, quantity and reactivity of hydrous oxides, mineralogy, degree of aeration and microbial activity (Magnuson et al. 2001; Petrangeli et al. 2001). Hence, it is clear that the soil factors influencing the concentration, form and plant availability of metals are highly complex.

Plant factors influencing metal uptake

Plant–microbe interactions in the rhizosphere

Plant and soil physical factors determine the efficiency with which plants harvest both essential nutrients and non-nutrients from soil. The supply of ions is controlled by the kinetics of solubilization of ions adsorbed to the solid phase of soil (Chaney et al. 1997). The limited bioavailability of various metallic ions, due to their low solubility in water and strong binding to soil particles, restricts their uptake/accumulation by plants. However, root-colonizing bacteria and mycorrhiza can significantly increase the bioavailability of various heavy metal ions for uptake. The process of plant root intrusion into the soil provides an extensive rhizosphere for ion absorption. Plant–microbe symbiotic processes are ubiquitous in natural and in most anthropogenically influenced soils (Ehlke and Kirchner 2002). Certain soil microorganisms have been shown to significantly enhance Zn accumulation in the shoot of the hyperaccumulator *T. caerulescens* by facilitating an increase in the solubility of non-labile Zn in the soil and thus enhancing its bioavailability to this plant (Whiting et al. 2001).

Metabolism of metal ions in plants

The apparent tolerance of plants to increasing levels of toxic elements can result from the exclusion of toxic elements or their metabolic tolerance to specific elements. The major mechanism in tolerant species of plants appears to be compartmentalization of metal ions, i.e. sequestration in the vacuolar compartment, which excludes them from cellular sites where processes such as cell division and respiration occur, thus providing an effective protective mechanism (Chaney et al. 1997; Hall 2002). Members of the cation diffusion facilitator (CDF) [also known as cation efflux (CE)] family are probably involved in metal transport into the vacuole. For instance, the metal tolerance proteins TgMTP1s from the Ni hyperaccumulator *T. goesingense* have been suggested to be responsible for metal ion accumulation in the shoot vacuoles of this plant (Persans et al. 2001). Similarly, ZAT1 [a member of the ZRT, IRT-like proteins (ZIP) family] has been implicated in the vacuolar sequestration of Zn (van der Zaal et al.1999). Complexation with metal-binding peptides, metallothioneins and phytochelatins may also serve to alleviate the toxicity of heavy metals in plants.

Metals are mobilized by being captured by root cells from soil particles, bound by the cell wall and then transported across the plasma membrane, driven by ATP-dependent proton pumps that catalyze H^+ extrusion across the membrane. Along with cationic nutrients, plant transporters are also involved in shuttling potentially toxic cations across plant membranes (Mäser et al. 2001). Several other heavy metal transport protein families, such as CPx-ATPases, CDF/CE, natural resistance-associated macrophage proteins (Nramp), ZIP, the Ni^{2+}–Co^{2+} transporter and the cyclic nucleotide gated channel have been identified and studied (Guerinot 2000; Krämer and Chardonnens 2001; Mäser et al. 2001; Clemens et al. 2002). Cpx-ATPases, such as PAA1 and RAN1 from *Arabidopsis*, which are heavy metal ATPases, may have a role in heavy metal transport and trafficking, although no direct evidence is available (Williams et al. 2000). Nramp proteins are a family of highly conserved proteins present in bacteria, yeast, insects, humans and plants and have been suggested to play a role in divalent metal ion transport (Belouchi et al. 1997; Williams et al. 2000). CDF proteins are also implicated in the transport of the heavy metals Zn, Co and Cu and have been identified in bacteria, archea and eukaryotes. Some members of this family are thought to be involved in heavy metal uptake, some catalyze metal efflux (Paulsen and Saier 1997) and others play a role in sequestration (van der Zaal et al. 1999). A Fe-phytosiderophore transporter (ys1) which mediates Fe uptake was recently identified in maize and such ys1-like sequences have also been found in the *Arabidopsis* genome (Curie et al. 2001).

There are three major processes which govern the movement of metals from the root into the xylem, i.e. sequestration of metal inside root cells, symplastic transport into the stele and release of metallic ions into the xylem. The transportation of ions into the xylem is tightly governed and controlled by membrane transport proteins (Gaymard et al. 1998). Transition metals can then reach the apoplast of leaves in the xylem sap, from where they have to be scavenged by leaf cells. Pumps such as P-type ATPases and metallochaperones such as CCH1 are assumed to be involved in these processes (Himelblau et al. 1998; Clemens et al. 2002). Chelation with certain ligands also routes metals to the xylem, e.g. chelation with histidine (which chelates Ni^{2+}) results in a 50-fold increase in the rate of transport of Ni into the xylem of *Alyssum montanum* (Krämer et al. 1996).

Monitoring of metal contaminants by plants

Plants can serve as indicators of incremental increases of metallic ions. The sedentary nature of plants is a major advantage for plant-based assays monitoring toxic chemicals in the environment (Grant 1999). Several tests have been proposed in this regard, including the *Allium cepa* chromosome aberration, micronucleus tests (Fiskesjo 1988) and the *Tradescantia* tests (Steinkellner et al. 1998), which have been applied to study the genetic effects of heavy metals. However, at the molecular level, these tests provide limited information on the effects of toxic metals, due to their low sensitivity and mobility. Transgenic plants carrying a recombination- or mutation-reporter transfer allow direct scoring of DNA damage in a known but nonessential target sequence. Such plants have been reported to carry disabled versions of the *GUS* genes and have been used to monitor the mutagenic effects of ionizing or UV radiation (Kovalchuk et al. 2000). Recently, a few systems have been developed for monitoring the genotoxic effects of heavy metals at the molecular level (Kovalchuk et al. 2000; Andolfi et al. 2002). Thus, for specific sites with local pollution sources, plants may be useful for monitoring increases in metal concentrations.

Detoxification of metal ion contaminants

Three major strategies are involved during the detoxification of metallic ions: (1) phytovolatilization and/or chemical transformation, (2) binding or chelation of trace elements and (3) efflux from the cytoplasm.

Phytovolatilization

The chemical conversion of toxic elements into less toxic and volatile compounds is a very effective strategy for detoxification, resulting in the removal of harmful elements from plant tissues. In Hg-contaminated soils and sediments, microbial activity converts the highly toxic Hg(II) into organomercurials and, under optimum conditions, elemental Hg (which is far less toxic) enters the global biogeochemical cycle upon volatilization (Bizily et al. 2000).

Chelation: role of metallothioneins and phytochelatins

Metallothioneins (MTs) are low-molecular-weight, cysteine-rich proteins that have high affinity for binding metal cations, such as Cd, Cu and Zn (Cobbett and Goldsbrough 2002). MTs from animal sources can be introduced in plants for a transgenic approach that can reduce metal accumulation in shoots by trapping the metal in roots. Expression of MTs under the control of root- or shoot-specific promoters might help to tailor their overexpression according to the requirements of a specific application. The overexpression of MTs can increase plant tolerance to specific metals, for example Cd or Cu. Phytochelatins (PCs) are also a family of metal-complexing peptides which are rapidly induced on overexposure to metals or metalloids in plants, animals and some yeasts (Vatamaniuk et al. 2001). PCs can bind metals possessing a high affinity to sulfhydryl groups, for example As and Cd (Schmoger et al. 2000; Cobbett and Goldsbrough 2002). However, a clear role for both MTs and PCs remains to be established in heavy metal detoxification in plants (Hall 2002).

Metal efflux

A number of genes and gene families with a putative role in intracellular compartmentalization, for example in the vacuole or tonoplast, or in the cellular efflux of trace elements have been identified, including CPx-type ATPases (Williams et al. 2000), members of the Nramp family, members of the CDF/CE family (Paulsen and Saier 1997), ATP-binding cassette transporters (Rea 1999) and divalent cation/proton antiporters, like the *Arabidopsis CAX* genes and AtMHX1 (Hirschi et al. 1996; Shaul et al. 1999). Several P-type ATPase genes in the *Arabidopsis* genome encode pumps of unknown specificity which resemble the bacterial pumps transport-

Table 2 Genetically manipulated plants with their respective sources of genes and products for metallic ion decontamination

Genetically manipulated plant	Genetic source	Genes and respective product	Metallic ion hyperaccumulation/tolerance/volatilization
Arabidopsis thaliana	*A. thaliana*	*ZAT1*: Zn transporter	Zn tolerance
Bacillus juncea	*Escherichia coli*	*Gsh1*: γ-Glu-Cys synthase	Cd hyperaccumulator
B. juncea	*E. coli*	*Gsh2*: GSH synthase	Cd hyperaccumulator
B. juncea	*A. thaliana*	*APS1*: ATP sulfurylase	Se hyperaccumulator
B. oleracea	*Saccharomyces cerevisiae*	*CUP-1*: metallothionein	Cd tolerance
Nicotiana tobacum	Mouse	*MT-1*: metallothionein	Cd tolerance
N. tobacum, *Liriodendron tulipifera*	Gram-negative bacteria	*MerA*: Hg(II) reductase	Hg tolerance and hypervolatilization
A. thaliana	Gram-negative bacteria	*MerA*: Hg(II)reductase; *MerB*: organomercurial lyase	Hg tolerance and hypervolatilization

ing heavy metals such as Ag, Zn, Co, Cd and Pb (Axelsen and Palmgren 2001; Clemens et al. 2002), suggesting a similar role for these proteins in metal transport. Recently, Li et al. (2002) identified a detoxifying efflux carrier, AtDX1, in the plasma membrane of *A. thaliana* which could efflux the heavy metal Cd^{2+} in addition to other toxic compounds.

Molecular approaches for metallic ion removal

The modern approach of biotechnology is targeted towards the development of phytoremediation plants for the complete decontamination of hazardous metallic ions from the environment. Traditional plant breeding can only use the available genetic diversity within a species to combine the characteristics needed for successful phytoremediation. Many metal-hyperaccumulating plants are low-biomass-producing and slow-growing, which limits their usefulness for large-scale applications. However, the relevant genes from these hyperaccumulators can be introduced into higher-biomass-producing non-accumulators for an improved phytoremediation potential, making it a commercially viable technology. A few successful reports have come to light about the introduction of a modified bacterial mercuric ion-reductase gene into yellow poplar and *Nicotiana tabacum* (Rugh et al. 1998; Nies 1999; Bizily et al. 2000; Meagher 2000). The bacterial gene *merA* was successfully modified (Rugh et al. 1996) and introduced into higher-biomass plants. Tobacco transformants expressing the modified *merA* gene were able to develop and flower on soils containing up to 500 ppm Hg(II) (Heaton et al. 1998). Hg volatilization was found to be much higher in *merA*-expressing transgenic yellow poplar plantlets, compared with wild-type plantlets (Rugh et al. 1998). Expression of *merA* and *merB* in *A. thaliana* seedlings enabled them to develop on methyl Hg concentrations more than 40-fold higher than the maximum tolerated by wild-type seedlings (Bizily et al. 2000).

In an attempt to obtain Al-tolerant plants by enhancing the production of citrate [a metal chelator which complexes with Al(III)], a citrate synthase gene from *Pseudomonas aeruginosa* was introduced into *N. tabacum* and *Carica papaya* for expression under the control of a constitutive (35S) promoter (De La Fuente et al. 1997). These plants secreted large quantities of citrate which blocked Al(III) uptake, thus providing resistance to Al(III) toxicity. Other examples include transgenic tobacco plants expressing two ferric reductase genes, *FRE1* and *FRE2*, from *Saccharomyces cerevisiae* under the control of a constitutive (35S) promoter (Samuelsen et al. 1998), tobacco seedlings with increased tolerance to Ni as a result of overexpression of NtCBP4 (Arazi et al. 1999), *A. thaliana* plants overexpressing *ZAT1* (encoding a putative Zn transporter in the CDF family of membrane transporters), which accumulated higher Zn concentrations in their roots than did the control plants (van der Zaal et al. 1999), and transgenic tobacco plants ectopically overexpressing the *A. thaliana* vacuolar Mg^{2+}/H^{+} antiporter, ATMHX1, under the control of the 35S promoter with hypersensitivity to Mg^{2+} and Zn^{2+} (Shaul et al. 1999). A heavy metal transporter cDNA, *ZNT-1*, a member of the *ZIP* gene family, was cloned from *Thlaspi caerulescens* through functional complementation in yeast and was shown to mediate both high-affinity Zn^{2+} uptake and low-affinity Cd^{2+} uptake (Pence et al. 2000). The use of tissue-specific promoters is likely to be of key importance in advanced transgenic phytoremediation approaches. Thus, plants have been genetically engineered to address the most widespread metallic contaminants. The most effective genetically modified plants with their respective genes are summarized in Table 2.

In the past few years, several cation transporters have been identified with the help of molecular techniques, in particular complementation studies using *S. cerevisiae* mutants. Unraveling the genomes of *A. thaliana* and *S. cerevisiae* has revealed information about genes that are potentially involved in heavy metal tolerance, homeostasis, transport and detoxification. Homologues of some of the proteins involved in heavy metal trafficking and transport in yeast have been found in *Arabidopsis*, which may provide an insight into these processes in higher plants. Studies in yeast are providing important information about the regulation and metabolism of metals that can be directly applied to plants. These studies have shown that most of the transporters are broad-range metal ion transporters which allow even nonessential metals like

Table 3 Advantages and limitations of phytoremediation

Advantages	Limitations
Solar driven	Mass transfer limitations associated with other biotreatments
In situ	Limited to shallow soil, streams and groundwater
Passive	Hyperaccumulation of hazardous contaminants might be toxic for plants
Public acceptance	Bioavailability and toxicity of degradative products is not known
Costs 10–20% of mechanical treatments	Slower than mechanical treatments
Transfer is more rapid than natural attenuation	Effective only for moderately hydrophobic contaminants
Fewer secondary wastes	Potential for contaminants to enter food chain through animal consumption
Fewer air and water emissions	Contaminants may be mobilized into the groundwater
Soils remain in place and are usable following treatment	Unfamiliar to many regulators

Cd to enter cells. For example, IRT1 expression rescued Fe^{2+}, Mn^{2+} and Zn^{2+} uptake-deficient *S. cerevisiae* strains and caused Cd^{2+} hypersensitivity (Korshunova et al. 1999). *AtNramp1* and *OsNramp1* were able to complement a yeast mutant defective in Fe uptake and *AtNramp* was also shown to transport Cd in addition to Fe (Thomine et al. 2000). Heterologous yeast expression of the metal-tolerance proteins, TgMTP1t1 and TgMTP1t2, from *T. goesingense* complemented the metal (Cd, Co, Ni) sensitivity of yeast mutants lacking functional vacuolar metal ion transport proteins, suggesting the involvement of TgMTP1s in the transport of metal ions (Persans et al. 2001). A putative Cu-influx protein COPT1 identified from *Arabidopsis* is believed to be homologous in function to the yeast CTR1 Cu transporter (Williams et al. 2000).

Advantages and limitations of phytoremediation

Phytoremediation has made tremendous gains in market acceptance in recent years. Early research indicates that phytoremediation technology is a promising cleanup solution for a wide variety of metal-contaminated sites, although it has its limitations. Plants make soil contaminants nontoxic and this process is often also referred to as bioremediation, botanical bioremediation or green remediation. Table 3, summarizing the advantages and limitations, reveals that many of phytoremediation's limitations and advantages are a direct result of the biological aspect of this type of treatment system. Plant-based remediation technology can function with minimal maintenance once it is established, but it is not always the best solution to a contamination problem. The use of phytoremediation is limited by the climatic and geologic conditions of the site to be cleaned, the temperature, altitude, soil type and the accessibility for agricultural equipment (Salt and Krämer 2000; Schmoger et al. 2000). On the one hand, phytoremediation is far less disruptive to the environment, with a high probability of public acceptance, avoids the excavation of heavy traffic and has the potential versatility to treat a diverse range of hazardous materials. But, on the other hand, it takes longer than other technologies, contaminants can accumulate in fuel wood, contaminants collected in leaves can be released again into the environment during litter fall and the formation of vegetation may be limited by extremes of environmental toxicity (Macek et al. 2000; Schmoger et al. 2000). One way to summarize many of the limitations of phytoremediation is that the metals must be bioavailable to a plant and its root system. Following critical consideration of these factors and the much lower cost expected for phytoremediation, it appears that it can be used in cleanup operations on a much larger scale than other methods (Macek et al. 2000).

Conclusion

Phytoremediation is recognized as a fast-growing and cost-effective technology to remediate hazardous toxic metals from contaminated sites. However, delivering a remediation system that is applicable to specific contaminated soils is a relatively recent focus. There is a significant need to pursue both fundamental and applied research at the primary level and it is important to determine the factors which can increase the uptake, translocation and tolerance of soil contaminants by plants. Molecular genetics has greatly advanced our understanding of metal homeostasis in recent years, especially in bacteria and yeasts and also in plants and humans. In the past, a number of effective novel genes involved in the acquisition, allocation and detoxification of metallic ions have been identified and characterized from a variety of organisms. The potentialities of such genetic factors until now have not been explored fully in the field of phytoremediation. Limited numbers of transgenic plants have been engineered to contain large amounts of recombinant proteins with possible roles in chelation, assimilation or membrane transport of trace elements. A number of field studies have been carried out for phytoremediation for the decontamination of metallic ions and for obtaining credible and scientifically valid cost estimates of phytoremediation in the market. Basic research is still needed by plant biologists for a deeper understanding of plant decontamination processes. The concept of genetically modified transgenic plants and their innovative genes that regulate toxic metal uptake is today's cutting-edge research. Many routinely used agricultural techniques for cultivating, harvesting and processing plants have now been adopted for phytoremediation, which makes it a novel approach, due to its technical and economical advantages over conventional approaches.

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