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Detoxification of Heavy Metals

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Foreword

Many heavy metals are essential for all organisms, e.g. as active centres of enzymes. At higher than optimal concentrations, however, they become toxic. For non-essential metals, toxicity is observed above a range of tolerance. Because of the relevance of these phenomena for damage to nature in general and to humans in particular, heavy metal toxicity and mechanisms counteracting it in various ways are a subject of intensive research since many years (for a comprehensive recent review see, e.g. Küpper and Kroneck 2005).

Although I myself do not directly work on soil biology but on plant biology, I am writing this foreword because terrestrial plants certainly and heavily depend on the soil they are growing in. Thus, they suffer when this soil contains toxic compounds, such as excess levels of heavy metals. Such toxic heavy metal concentrations can have natural reasons; naturally heavy metal-rich soils are found in various locations around the world where metal ores come to the surface and decay due to weathering. A few examples of such locations are the Katangan copper belt in Kongo and Zaire (Duvigneaud 1958; Malaisse et al. 1999), nickel-rich serpentine soils in Cuba (Reeves et al. 1996), North America (Rajakaruna et al. 2009) as well as Sulawesi and New Caledonia (Proctor 2003) and some zinc and cadmium sites in Europe (Reeves and Brooks 1983). While these locations are usually not regarded as agriculturally relevant and usually no attempts are made to detoxify them (as it usually would be futile), the plants growing on them still have to detoxify the stream of nutrients they take up from such soils. This theme is dealt with in the Chaps. 3, 7, 8, 9, 10, 11, 15, 17 and 19 of this book and is also a theme of my own research for many years.

In terms of soil detoxification, sites that originally had low heavy metal levels but were contaminated by human activity are the main targets for soil detoxification as the main theme of this book, in particular when they are otherwise attractive for agriculture. Such contaminations can have various reasons and can be found in many countries of the world although a common misconception is that this would be mainly a problem for poor countries. The most obvious reason for anthropogenic heavy metal contamination of soils is the presence of ore-mining or -refining industry nearby, where emissions of dust particles and leakage of contaminated water (e.g. from dumps and storages) are the main causes of environmental pollution. Famous examples are Severonikel nickel–copper smelter at Monchegorsk in Russia (Barcan 2002), the Sudbury Area in Canada (Mandal et al. 2002) and the Cevennes region in France (Lombi et al. 2000). Heavy metal pollution of soils can also be a widespread and severe problem for countries that do not have a major metal-mining industry (any more). Again, industry may play a role, as metals are used in various processes, e.g. as catalysts, a famous case is the mercury poisoning in Minamata Bay, Japan (review by Harada 1995). But in many countries, like my home country Germany, the main source of heavy metal pollution of soils is the excessive use of metals in agriculture, as still many copper- and zinc-based pesticides are allowed, and especially copper is highly toxic for plants (much more than for most animals including humans). Copper concentrations in vineyard soil exceed legislative limits in the vast majority of studied vineyards (Komarek et al. 2010), and agricultural field runoff may reach micromolar levels (Gallagher et al. 2001), which is lethal for many sensitive plant species within days to weeks of exposure. In the USA, the metalloid arsenic became a problem in a similar way; arsenic compounds were used as insecticides in cotton industry (Osburn 1926) and caused severe contaminations of soils, surface water and groundwater in regions of intense cotton farming (Carbonell et al. 1998). Another way of heavy metal contamination by agriculture is the application of mineral fertilisers, as these often contain heavy metals and the metalloid arsenic as contaminants (McLaughlin et al. 1996; He et al. 2005). Sewage sludge is usually not a good fertiliser for the same reason (McBride et al. 1997). Another source of metal pollution in heavily industrialised countries like Germany is car traffic. The well-known case is lead that was banned from fuel many years ago and that was more toxic to animals than to plants (plants hardly take it up). Less known, but more toxic, is the release of cadmium from car tyres, which leads to significantly enhanced cadmium levels along busy roads (Lagerwerff and Specht 1970).

In all these cases of anthropogenic soil contamination with heavy metals, the highest heavy metal concentrations are found rather close to the surface, although not directly in the uppermost few millimetres to centimetres as these are leached by rain like in natural heavy metal sites (McBride et al. 2005; Mitani and Ogawa 1998). For this reason, decontamination of such areas is, in principle, possible in several ways. The classic way would be the removal of the topsoil and leaching of it in a chemical or microbial way in special facilities. Although this method is costly, this is the only realistic option for very small (and at the same time economically or socially very important) spots. For larger areas, decontamination by plants seems to be the most attractive option, as on fertile ground (which would be a most attractive kind of site for decontamination as it could be agriculturally valuable) plants will grow well without too much human effort. But it is hotly debated what kind of plants should be used for this task. In principle, three main strategies exist: (1) the use of naturally occurring metal hyperaccumulator plants, probably combined with classical breeding, (2) the use of high-biomass non-accumulator plants, (3) the transfer of genes from hyperaccumulator plants to turn originally non-accumulating high-biomass plants into high-biomass metal hyperaccumulators. While some of this is dealt with in more detail in chapters of this book, I would like to summarise work on these strategies from the perspective of my own work on metal metabolism in plants.

Many natural hyperaccumulators, i.e., plants that actively accumulate several percent of heavy metals in the dry mass of their above-ground parts, have a good potential to be used for phytoremediation, i.e., to extract and remove heavy metals from anthropogenically contaminated soils, which was first proposed by Chaney (1983). Some of them even allow for commercially profitable phytomining, i.e., the extraction of metals from naturally heavy metal-rich soils (that are not directly usable as metal ores) with subsequent burning of the plants, the ash of which can be used as a metal ore (first proposed by Baker and Brooks 1988). These applications of metal phytoextraction have been a subject to extensive research as reviewed, e.g. by Baker and Brooks (1989), Baker et al. (2000), McGrath et al. (1993), McGrath and Zhao (2003), Salt et al. (1995, 1998), Chaney (1983), Chaney et al. (2005, 2007) and Küpper and Kroneck (2005, 2007). For the metalloid arsenic, the fast-growing, high-biomass, As hyperaccumulating fern *Pteris vittata* and related species are very promising candidates for phytoremediating As-contaminated areas (Ma et al. 2001; Zhao et al. 2002; Meharg 2003). For cadmium, the Cd/Zn hyperaccumulator *T. caerulescens* seems to be the best known candidate for phytoremediation. Although it has a rather small biomass of 2–5 t ha^{-1} (Robinson et al. 1998; McGrath and Zhao 2003), the extreme bioaccumulation coefficient of its southern French ecotypes (Lombi et al. 2000; Zhao et al. 2003) yields Cd extraction rates high enough for cleaning up moderately Cd-contaminated soils within a few years as tested in the field by Robinson et al. (1998), Hammer and Keller (2003) and McGrath et al. (2006). The high copper sensitivity of *T. caerulescens*, however, may limit its use; copper concentrations that occur in multi-contaminated soils were found to strongly inhibit its growth (Walker and Bernal 2004). This might be alleviated by selection of copper-resistant individuals that occur in natural populations of this species (Mijovilovich et al. 2009). Nickel was the first metal for which the economic feasibility of phytomining was shown, and some nickel hyperaccumulators hyperaccumulate the even more valuable cobalt as well (Brooks and Robinson 1998; Robinson et al. 1999). Nicks and Chambers (1995) yielded a crop of nickel of equal value compared with an average crop of wheat by planting *Streptanthus polygaloides* on a metal-rich soil in California (USA). They furthermore showed that by burning these plants it is possible to yield, with low input of energy, a bio-ore (the plant ash) containing about 15% nickel. *Berkheya coddii* has been known as a high-biomass Ni hyperaccumulator since the work of Anderson et al. (1996). Robinson et al. (1999) carried out comprehensive studies of metal uptake and showed that fertilisation with sulfur and nitrogen greatly increased Ni and Co hyperaccumulation. Thus, their work has demonstrated that this species is a very promising candidate for both phytoremediation and phytomining. This has been confirmed by field trials in a recent study, which demonstrated that this species easily yields 110 kg of nickel per hectare and year (Brooks et al. 2001), and even 170 kg should be possible (Brooks et al. 1998). Similarly, *Alyssum bertolonii* has been shown to produce high enough nickel yields per hectare for phytomining (Robinson et al. 1997; Brooks and Robinson 1998; Brooks et al. 1998), which now has already been put into commercial operation (McGrath and Zhao 2003). For zinc, the Chinese plant *Sedum alfredii* may be the most promising candidate for phytoremediation and possibly even for commercial phytomining because of its correlation of high zinc accumulation with relatively high biomass (Long et al. 2002; Ye et al. 2003). In contrast, *Thlaspi caerulescens* has a rather low biomass and at high soil zinc concentrations also a low bioaccumulation coefficient (Robinson et al. 1998; Zhao et al. 2003), so that its use in zinc phytoremediation is generally limited to moderate levels of contamination. Indeed, while field trials on moderately contaminated soil by Baker et al. (1994) were successful, those on more heavily Zn-contaminated soil failed (Hammer and Keller 2003).

In addition to true hyperaccumulator plants, various other plants have been proposed for use in soil phytoremediation. One idea is to use high-biomass plants for absorbing the metals; it is argued that the much higher biomass will yield higher metal extraction per area of land compared with hyperaccumulators, despite the much lower metal content of non-accumulator plants (e.g. Salt et al. 1995, 1998; Pulford and Watson 2003). Those who argue for such an approach, however, mostly ignore that such a strategy would dilute the extracted metal in a much larger amount of toxic biomass compared with hyperaccumulator plants; this biomass would be too toxic for use as compost and would not contain enough metal to make a recycling of the phytoextracted metal feasible (discussed, e.g. by Chaney et al. 1997; Williams 2002). In addition, the bioaccumulation factor of metals in non-accumulator plants is usually so low that hundreds of crops would be required for phytoremediation of even a moderately contaminated soil (Baker et al. 1994; Chaney et al. 1997; McGrath and Zhao 2003). Those who argue for this approach because of the low biomass of many (not all, see above!) hyperaccumulators should also keep in mind the following facts.

(a) The biomass yield of non-accumulator plants on contaminated soils is reduced by phytotoxicity of the contaminating metal (Ebbs et al. 1997; Chaney et al. 1997).
(b) The biomass of hyperaccumulators can be rather easily improved by selecting suitable ecotypes and individuals within the natural population (Li et al. 2003; Schwartz et al. 2003), breeding (Brewer et al. 1999) and fertilisation (two to three times increase; Bennett et al. 1998; McGrath et al. 2000; Brooks et al. 2001; Li et al. 2003; Schwartz et al. 2003).
(c) The metal accumulation of hyperaccumulators can further be optimised by selection. Many recent studies pointed out more than 20-fold variation of bioaccumulation factors for the same metal between ecotypes/populations (e.g. Meerts and Van Isacker 1997; Bert et al. 2000, 2002; Escarré et al. 2000; Lombi et al. 2000; Macnair 2002; Roosens et al. 2003; Zhao et al. 2003). Furthermore, the accumulation efficiency is not directly correlated with the metal content of the habitat (Bert et al. 2002), and strong variation of metal bioaccumulation factors as well as metal resistance exists even within one population (Macnair 2002; Mijovilovich et al. 2009). Finally, accumulation is higher on the average moist agricultural land compared with their dry natural habitats (Angle et al. 2003), and fertilisation increases it further (Schwartz et al. 2003). In summary, presently it is not the phytoremediation

by hyperaccumulators that is a "hype," but the use of non-accumulating plants for this task. The only way that a non-hyperaccumulating plant species may become a better alternative would be by creating (by genetic engineering or traditional breeding) metal-accumulating cultivars.

It is often argued that instead of using natural hyperaccumulators for phytoremediation and phytomining, genetically engineered plants should be used. Looking at the results of classical selection breeding of hyperaccumulators vs. attempts to create transgenic hyperaccumulators, the former approach appears much more promising, for the following reasons. Research on the mechanisms of hyperaccumulation has revealed that this process involves many different steps in diverse parts of the plant, starting from enhanced uptake into the roots (e.g. Lasat et al. 1996) and continuing via enhanced xylem loading (e.g. Papoyan and Kochian 2004), translocation to the shoots possibly by transport ligands (e.g. Trampczynska et al. 2010), unloading from the veins and finally sequestration into vacuoles of usually epidermal storage cells (Küpper et al. 1999, 2001; Frey et al. 2000; Leitenmaier and Küpper 2011) – as reviewed e.g. by Küpper and Kroneck (2005, 2007) and Chaps. 3, 7, 8, 11 and 19 of this book. Furthermore, individual members of metal transport protein families display vastly different tissue-, age-, and metal nutrition-dependent regulation in the same plant (Küpper and Kochian 2010). Therefore, to re-create a hyperaccumulator by genetic engineering, one would have to modify the expression of many genes in a tissue-specific way and probably at particular stages of plant and leaf ontogenesis. This has not been achieved, not even in an approximation, in any study so far (review, e.g. by Chaney et al. 2007). Therefore, it is not surprising that in all attempts of creating hyperaccumulators by genetic engineering at best a few times enhancement of metal accumulation compared with the original non-accumulator wildtype was achieved, while true (natural) hyperaccumulators usually have hundreds of times higher metal bioaccumulation coefficients than those non-accumulators (Küpper and Kroneck 2005, 2007; Chaney et al. 2007). And such transgenics are not useful to apply, for the same reasons as explained for wildtype non-accumulators. Unless someone finds a general "switch gene" that leads to the changed expression pattern of all the other genes involved in hyperaccumulation, transgenic plants that really accumulate as much metal as hyperaccumulators will remain a science fiction.

In contrast, field trials have shown that the biomass of natural hyperaccumulators can be dramatically increased by addition of fertiliser, natural selection and classical breeding to reach levels that are economically attractive (reviewed by Chaney et al. 2005). As a source for selecting species that are suitable for a specific phytoextraction tasks, conservation of metallophyte biodiversity is of prime importance (Whiting et al. 2004).

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Preface

The volume Soil Heavy Metals duly edited by Irena Sherameti and Ajit Varma, published in 2010, was a success story. This was nicely celebrated in typical German style in the house of Professor Dr. Ralf Oelmüller, Institute of General Botany and Plant Physiology, University of Jena. Over a glass of wine I proposed to Irena to edit a volume on detoxification of heavy metals in soil. After a short discussion, we agreed to work together on this volume.

This volume summarises the ongoing scientific activities in the field of detoxification of heavy metals in soils, plants and microorganisms. The chapters are arranged in such a way that first we get an introduction about the art of detoxification of heavy metals and the heavy metal plants. The second group of chapters deals with the phytoremediation in general and phytoremediation of special ions. The next section describes several aspects of plant responses to heavy metals and the responses of special organisms/groups to heavy metals. At last different methodologies for detoxification of heavy metals in soils and plants are discussed.

Soil, one of the most important natural resources, is becoming degraded due to anthropogenic activities such as mining, agricultural activities, sewage sludge, fossil fuel combustion, metallurgical and chemical industries and electronics. As described in Chap. 1 written by Jyoti Agrawal, Irena Sherameti and Ajit Varma each source of contamination has its own damaging effects to plants, animals and humans, but the pollution from heavy metals is of serious concern and a big potential threat to the environment and human health. This chapter gives a general overview of some of the sources of heavy metal contaminants in soil, soil–plant relationships regarding heavy metals and heavy metal tolerance mechanism(s) in plants. In Chap. 2, Hermann Bothe directs us to the heavy metal soils and heavy metal plants (Metallophytes) of Central Europe showing that the adaptations of these metallophytes to the adverse conditions of heavy metal soils differ from one plant species to the next. Further we get introduced to some strategies employed by the metallophytes to cope with high concentrations of heavy metals at the whole plant level and gene expressions upon heavy metal stress in plants. Functional significance of metal ligands in hyperaccumulating plants is analysed by Marjana Regvar and Katarina Vogel-Mikuš in Chap. 3. This chapter focuses on ligands (organic acids, histidine, metallothioneins, low-molecular-weight thiols, etc.) that have roles in the immobilisation, transport and/or storage of accumulated metals in plant organs, tissues and cells.

Chapter 4, written by Shao Hongbo, Chu Liye, Xu Gang, Yan Kun, Zhang Lihua and Sun Junna is a progress in phytoremediating heavy metal-contaminated soils, that introduces the latest development in the field of phytoremediation as one of the main methods for removing hazardous heavy metal from contaminated soils. Using plants and microbes is preferred because of its cost-effectiveness, environmental friendliness and fewer side effects. So far all plant species recognised as useful for phytoremediation belong to angiosperm phylogeny group that is classified into 63 orders and 413 families. The authors of Chap. 5, Stanislaw W. Gawronski, Maria Greger and Helena Gawronska, show that among all only species from 8 orders and 18 families are identified as well-tolerating pollutants and useful for phytoremediation having advantages and limitations in their usefulness as phytoremediants. The authors of Chap. 6, Dora M. Carmona, Raúl Zornoza, Ángel Faz, Silvia Martínez-Martínez and Jose A. Acosta, describe the environmental impacts of mining activities in Southeast Spain. A field trial was established and experimental plots were designed, using marble wastes, pig manure and sewage sludge as amendments to reclaim the mine soils. The authors monitored the dynamics of heavy metals, soil properties and vegetation along 5 years after reclamation.

Zinc is an essential micronutrient with various cellular functions, but excess Zn in plants is toxic and causes chlorosis and growth disorders. To ensure Zn homeostasis the transport machinery is responsible for uptake and export of Zn that includes members of the metal tolerance protein (MTP), ZRT1/IRT1-like protein (ZIP) and heavy metal ATPase (HMA) families. Their roles in the acquisition, distribution, homeostasis and signalling of Zn are described in Chap. 7 by Miki Kawachi, Yoshihiro Kobae, Rie Tomioka and Masayoshi Maeshima. Copper, trace amounts of which are required to sustain plant life (so-called essential elements), in high concentrations causes plant death. Discussing current methods and approaches used for quantification of apoplastic and symplastic copper pools has a significant place in Chap. 8 written by Valentina P. Kholodova, Elena M. Ivanova and Vladimir V. Kuznetsov. The role of arbuscular mycorrhizal fungi producing an extraradical mycelium in metal ion immobilisation is also considered in this chapter. Arsenic is a ubiquitously distributed and an extremely toxic metalloid affecting the health of many people in more than 23 countries. On land arsenic is relatively immovable through binding of soil particle; however, most arsenic can readily dissolve in water and in soluble form may leach into surface and ground waters. Chapter 9, written by Dharmendra K. Gupta, Sudhakar Srivastava, H.G. Huang, Maria C. Romero-Puertas and Luisamaria M. Sandalio, focuses on arsenic contamination, accumulation, tolerance and detoxification mechanisms in plants. Chapter 10 of Kavita Shah presents an overview of the research information on sources and effects of cadmium metal on plants in particular. The knowledge of metal hyperaccumulation physiology and the molecular and genetic basis of Cd tolerance and detoxification in plants forms a major part of this chapter. The prospects and the future applications of hyperaccumulators in phytoremediation of Cd metal are also discussed. Dieter Rehder deals in Chap. 11 with the transport, accumulation and physiological effects of vanadium. Industrial and volcanic exhalation of vanadium oxides can cause locally a vanadium overload in soil surface areas. Soil bacteria such as *Geobacter metallireducens* and *Shewanella oneidensis* reduce vanadate to insoluble and comparatively harmless vanadium (IV) hydroxide. The remobilization of vanadium (IV) can occur by strong chelators excreted by other bacteria such as Azotobacter. Tapan Jyoti Purakayastha deals in Chap. 12 with the remediation of arsenic-contaminated soil. The use of engineered microbes as selective biosorbents is an attractive green cure technology for the low-cost and efficient removal of arsenic from soil. Fate of cadmium in calcareous soils under salinity conditions is discussed in Chap. 13 by Ali Khanmirzaei. The chemistry of calcareous and saline soils, the application of fractionation and speciation analysis for investigating the mobility and environmental ecotoxicity of this element in calcareous soils and some examples on Cd detoxification in carbonate rich soils are outlined in this chapter.

The current status of organellar proteomics as a high-throughput approach for obtaining a better understanding of heavy metal accumulation and detoxification in plants is analysed in detail in Chap. 14 by Nagib Ahsan, Byung-Hyun Lee and Setsuko Komatsu. To identify the proteins involved in organ-specific heavy metal response pathways is a fundamental step in the process of understanding the molecular mechanisms leading to accumulation and detoxification of toxic heavy metals in plant cells. Chapter 15, written by Laura A. Hardulak, Mary L. Preuss and Joseph M. Jez, provides an overview of sulfur metabolism in plants, how it plays a critical role in heavy metal tolerance and how efforts to engineer these pathways may improve bioremediation efforts. Metabolically, sulfur metabolism is a core pathway for the synthesis of molecules required for heavy metal tolerance in plants. Etsuro Yoshimura in Chap. 16 discusses Cd(II)-activated synthesis of phytochelatins. Phytochelatins are implicated in heavy metal tolerance in higher plants, algae, and a fungal species. Synthesis of the peptides is mediated by an enzyme designated as PC synthase (PCS) from the tripeptide glutathione (GSH).

Elsholtzia splendens has been proven to be a Cu-tolerant plant and can remarkably influence the behaviour of Cu in root–soil interface by root exudates, rhizosphere bacteria and arbuscular mycorrhizal fungi. *E. splendens* has evolved a series of defensive strategies against Cu stress such as Cu compartmentation and speciation transformation, which are discussed in detail in Chap. 17 by Yingxu Chen, Mingge Yu and Dechao Duan.

The role of aquatic macrophytes in biogeochemical cycling of heavy metals, the relevance to soil-sediment continuum detoxification and ecosystem health is presented in Chap. 18 by Przemysław Malec, Beata Mysliwa-Kurdziel, M.N.V. Prasad, Andrzej Waloszek and Kazimierz Strzałka. The wetland sediments and soils of flood plains play an important role in the biogeocycling of heavy metals. The role of both photosynthetic activity and competitive/synergistic effects of the elements available to aquatic macrophytes in the circulation and deposition of metals are discussed in terms of the functioning of wetland ecosystems and phytoremediation. To stimulate phytoremediation, fast growing plants with high metal uptake and high biomass are required. Alternatively, soil microorganisms such as fungi and bacteria are used in heavy metal detoxification. The recent advances in effect and significance of fungi and rhizobacteria in heavy metal detoxification is reviewed in Chap. 19 by Sema Camci Cetin, Ayten Karaca, Ridvan Kizilkaya and Oguz Can Turgay. The same group of authors contributed Chap. 21 in which the detoxification of heavy metals using earthworms is discussed. Earthworms can effect either available or total metal concentrations in soil because of their capability for accumulating heavy metals in their tissues and hence reduce their involvement in soil food chain. D.V. Yadav, Radha Jain and R.K. Rai, authors of Chap. 20, deal with the phytoremediation/detoxification of heavy metals from soils through sugar crops, especially sugar cane, sugar beet and sweet sorghum. The potential of these sugar crops is presented. At Chap. 22, Roberto Terzano and Matteo Spagnuolo discuss the stabilisation of heavy metals by promoting zeolite synthesis in soil which can be easily done at low temperatures by adding Si- and Al-containing materials in alkaline conditions. This methodology is a promising one and in combination with other physico-chemical or biological remediation processes can effectively stabilise heavy metals in polluted sites.

This volume promises to be useful for researchers, students and other academicians involved in understanding the basics of detoxification of heavy metals in soils.

We are very thankful to all authors for contributing to this volume and we hope that their contribution will stimulate further high-quality teaching and research. It has been a pleasure to edit this book, primarily due to the stimulating cooperation of the contributors.

We wish to thank Hanna G. Hensler-Fritton, Editorial Director Life Sciences/Biomedicine Europe II, Jutta Lindenborn and Dieter Czeschlik (former Life science Head, Springer Heidelberg) for generous assistance and patience in finalising the volume. A special thanks goes to our families.

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Jena, Germany Irena Sherameti
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Chapter 1
Detoxification of Heavy Metals: State of Art

Jyoti Agrawal, Irena Sherameti, and Ajit Varma

1.1 Introduction

Land and water are precious natural resources on which rely the sustainability of agriculture and the civilization of mankind. Unfortunately, they have been subjected to maximum exploitation and are severely degraded or polluted due to anthropogenic activities. The pollution includes point sources such as emission, effluents, and solid discharge from industries, vehicle exhaustion, and metals from smelting and mining, and nonpoint sources such as soluble salts (natural and artificial), use of insecticides/pesticides, disposal of industrial and municipal wastes in agriculture, and excessive use of fertilizers (McGrath et al. 2001; Nriagu and Pacyna 1988; Schalscha and Ahumada 1998). Each source of contamination has its own damaging effects to plants, animals, and ultimately to human health, but those that add heavy metals to soil and water are of serious concern due to their persistence in the environment and carcinogenicity to human beings. They cannot be destroyed biologically but are only transformed from one oxidation state or organic complex to another (Garbisu and Alkorta 2001; Gisbert et al. 2003). Therefore, heavy metal pollution poses a great potential threat to the environment and human health.

In order to maintain good quality of soil and water and keep them free from contamination, continuous efforts have been made to develop technologies that are easy to use, sustainable, and economically feasible. Physicochemical approaches

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