Chapter 5
Plant Taxonomy and Metal Phytoremediation

Stanislaw W. Gawronski, Maria Greger, and Helena Gawronska

5.1 Introduction

Plants during 400 million years of evolution often were exposed to extreme environmental conditions. Plants, as organisms of sessile style of life, have developed unique defense mechanism(s) and strategies existing only in that group of organisms. As a result among all higher organisms only plants are able to survive in very polluted sites and tolerate high accumulation of toxic compounds in their tissues. They can thrive in soil, water and air contaminated to levels that are often orders of magnitude higher that can be accepted by other organisms. Nowadays pollution of soil, water and air environments is additionally raised as a side effect of antropopressure. At a certain point, the strength of the negative impact of human beings became so high that only the most resistant species are able to survive, very often at the cost of limited growth and development. Present state of knowledge and social awareness of negative anthropological impact on the environment lead to search for their elimination or at least lowering to permissible limits. Plants affect chemical, physical and biological processes in the environment and steer them in such a way as to change environmental conditions as close as possible to the optimum for plant growth. One of the spectacular example is the presence of the small crystals of pyromorphite in the rhizosphere of *Agrostis tenuis*, very tolerant to lead grass, nearby old lead mining site if soluble inorganic phosphate was present in the soil. Formation of the crystals in the surroundings of roots of *A. tenuis* indicates the plant's direct influence by release exudates or the impact on running this process by microbial community. Competence of plants for rock formation can be

S.W. Gawronski (✉) • H. Gawronska
Laboratory for Basic Research in Horticulture, Faculty of Horticulture and Landscape Architecture, Warsaw University of Life Sciences-SGGW, Warsaw, Poland
e-mail: stanislaw_gawronski@sggw.pl

M. Greger
Department of Botany, Stockholm University, Stockholm, Sweden

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recognized as a very intriguing phenomenon (Cotter-Howells and Caporn 1996). Lead, very common heavy metal polluting our environment, immobilization using phosphate amendments and shift from highly available to the most strongly insoluble form as pyromorphite is considered as worthy to work on and in some laboratories, research on the improvement and implementation of this process in practice take place (Miretzky and Fernandez-Cirelli 2008). This example very well highlights the plant's involvement in the process of "repairing of the environment" and underlines that plants were first in creating safe soil environment. Our duty is to find more species performing this activity or being more efficient.

Heavy metals (HM) are one of the most common pollutant and very dangerous for all living organisms. Toxic impact of the heavy metals on the plants and their responses was already recognized by Carl Linnaeus, the "Father" of taxonomy, who distinguished the leadwort plant family (Plumbaginaceae*)* represented by species very tolerant to lead. Sea Thrift (*Armeria maritima)*, Cape Leadwort (*Plumbago auriculata*) and some species from genus Limonium are the most common for cultivation in lead polluted sites.

Plants respond to toxic metals in different ways starting from avoiding strategies such as, for example, of ions uptake but, if already taken up they exploit tolerance strategies comprising several other mechanisms. For example, detoxification and/or deposition of toxicants in various cells or cell compartments (vacuoles, cell walls) or secreting back to the environment. Plants possess two systems of heavy metals detoxification. One is based on metalothioneins (Goldsbrough 2000) that are common for all living organisms and the second one on the synthesis of phytochelatins (Cobbett 2000; Rauser 1995), substances typical for plants. Nowadays, our knowledge on plant accumulation and detoxification has been expanded mainly as a result of the development of molecular tools (Verbruggen et al. 2008). Among higher living organisms plants are one of the most tolerant to pollution with high capabilities for heavy metal uptake, detoxification and accumulation in easy harvestable organs; these makes them very useful in new emerging environmental biotechnology – phytoremediation.

Phytoremediation is typical in situ technology and still under development. The process of phytoremediation usually takes few years and becomes completed when contaminants no longer impose danger to human beings and environment.

Most advanced in development is soil phytoremediation, covering three main areas:

1. Post-industrial polluted sites (brown field), which are usually highly polluted but with one or few pollutants such as heavy metals and with others pollutants though usually at lower level such as polycyclic aromatic hydrocarbons.
2. Urban area polluted sites characterized by lower level of pollution but most often as a rule with several pollutants.
3. Agricultural soil with elevated levels of various pollutants such as heavy metals, arsenic, pesticides and salinity.

On the post-industrial sites, a branch of phytoremediation called phytoextraction will be the most successful. Plants take up heavy metals from soil using root system and transport them to the above-ground parts, thus enabling the removal of heavy metals from soil. Therefore, plants take responsibility for the most difficult part of soil remediation. Increasing interest in this technology emerges from its economic viability and final effect, as soil after heavy metals removal is brought to the natural state or to the acceptable level of pollution. Phytoextraction on the brown fields is based mainly on annual plants, tolerant to pollutants, with good ability to transfer pollutants to upper parts and whose annual cultivation provides huge biomass and therefore high "pollutants yield."

On these sites also phytostabilization can be considered, which is based on storage of heavy metals in plant tissues or in soil in the form of complex with limited solubility (Babula et al. 2008; Cotter-Howells and Caporn 1996).

Phytovolatilization as a variant of phytoremediation is limited to elements such as Hg, As and Se. In practice it is attenuating them in atmosphere. In the case of Se, since there is deficiency of this essential element, its release can be considered as a positive process, but volatilization of Hg and As will be similar to throwing the pollutants elsewhere.

Urban area polluted sites possess different character. The citizens are spending part of their daily life in these places, e.g., during driving to the working place or even working at such places. At the polluted sites of urban areas, phytoremediation should be maintained as a continuous process in order to remove the pollutants on regular basis. Although the pollutants are in much lower level but from several groups, so far their synergistic or additive effect is not well recognized yet. Transportation vehicles are major emitters of pollutants to air, soil and also water flowing from lanes and pavements. Vehicles are emitting heavy metals and other pollutants including particulate matter (PM).The latter pollutants are nucleus for condensation of HM and finally, after several days, are falling down polluting soil and water.

On the agricultural sites, metals and organics can be efficiently removed by growing energy crops such as *Salix viminalis*. This will decrease the metal content in post-growing crops. This has successfully been shown for the Cd content in wheat grains, which decreases by 25% if cultivating Salix for 2–3 years in advance (Greger and Landberg, in prep). As mentioned, organics such as pesticides will also be most efficiently degraded by phytodegradation, rhizodegradation and phytostimulation. The efficiency of depends on the level of pollution, which in general in agricultural sites is rather slightly elevated but for food production is to high . The lower concentration of pollutants is in the soil the shorter time it takes to remove them by phytoremediation.

In the last years, one of the major areas of research in phytoremediation is improvement of pollutant uptake by plants, in the case of heavy metals limited by their bioavailability. Synthetic chelators such as EDTA (ethylene-diamine-tetraacetic acid) or NTA (nitriloacetate) are questionable and never used on large scale. They are expensive; moreover, some environmentalists treat them as additional man-made pollutants which create risk of leaching heavy metals to the ground water during heavy rain just after application. The process of heavy metals chelation intensifies metal uptake in nature. Hence, plants use low molecular weight organic acids such as citric, ferulic, maleic, oxalic and tartaric acids; utilization of this phenomenon is always attractive for implementation (Strobel 2001; Evangelou et al. 2006). This can be recommended as a simple tool available in our hands. Lowering of soil pH, which would increase metal solubility, can be obtained by application of strong acid fertilizers such as sulfuric salts or even elemental sulfur. Elemental sulfur, being slowly oxidized by bacteria, increases acidity as well (Kayser et al. 2000).

The availability and uptake of heavy metals into the plants depend not only on direct uptake but also on rhizosphere. Plants' life is tightly associated with microorganisms surrounding the plants' roots. In this respect mycorrhizal fungi appear to play a central modulating role. Among them arbuscular mycorrhizal (AM) fungi intensify few crucial processes such as water and nutrients uptake in the plants but simultaneously heavy metals are taken up more efficiently as well. Mycorrhizal fungi alleviate heavy metal stress on plants by detoxification via greater metallothioneins synthesis (Gonzalez-Guerrero et al. 2007) and consequently hold HMs in their tissue thus performing the role of a buffer between soil environment and plants (Hildebrandt et al. 2007; Ferrol et al. 2009). Mycorrhizal fungi express metallothioneins genes, but further steps, i.e., heavy metal transport to and accumulation in roots and upper parts of the plants are controversial. This is because both lowering and increasing of the level of metal pollutants in the plant tissue were recorded (Toler et al. 2005; Sell et al. 2005). Nevertheless, plants inoculation with mycorrhiza, even if it does not support phytoextraction, would allow plants to grow on polluted sites at concentration(s) that otherwise would be eliminated (if not mycorrhized) (Adriaensen et al. 2006). Moreover, it can be considered as an example of phytostimulation.

The above shows that the ability of plants to heavy metal uptake, translocation and accumulation in particular organs depends on environmental factors. However, some of the species, families or even orders have capability higher than others for heavy metal tolerance and uptake.

5.2 Species for Phytoremediation

Plant species useful for phytoremediation need to fulfill some requirements: (a) fast growth; (b) produce high biomass; (c) and be tolerant to pollution. In case of phytoextraction, pollutants additionally need to be translocated and accumulated in the easy harvestable part of plants. If phytoremediation of urban areas is considered, species tolerating trimming are desired. Species recommended for phytodegradation, which usually takes place in the roots, should possess large and dense root system. Root systems with enough large surface are also preferred for microbial communities running together with the plant process of phytostimulation (Pilon-Smits 2005). Three elements, As, Se and Hg, can be removed from the soil environment by phytovolatilization (Greger et al. 2005). However, in case of Hg the picture is not clear yet and requires further studies.

The technology of phytoremediation was inspired by the existence of a group of plant species called hyperaccumulators (Brooks 1998). These plant species, in majority, belong to the following taxonomical orders: Poales, Malpighiales, Fabales, Rosales, Brassicales, Caryophyllales, Solanales and Asterales (Bremer et al. 2009; Chase and Reveal 2009; Haston et al. 2009).

In some parts of world, there are places polluted with radionuclear elements such as cesium, strontium and uranium. Plant species from two taxonomic families and orders, Asteraceae from Asterales and Betaceae from Caryophyllales, are recognized as good phytoremediants of radionuclides with the former showing better performance (Tang and Willey 2003).

The presence, on specific sites, of species that belong to genera, families or orders known to have high tolerance to particular heavy metal(s) that may play a role of bioindicators suggests pollution of this site with given heavy metal(s).

5.2.1 Order: Poales

Among monocotyledons this order is dominating in the number of families with species possessing high capabilities for heavy metal uptake. Most distinguished among them is the Poaceae family with quite a long list of cultivated species such as cereals and high biomass producing grasses that could be considered as good phytoremediants.

5.2.1.1 Family: Poaceae

Grass family is one of the most important for phytoremediation of heavy metals and organic pollutants such as PAHs and petroleum hydrocarbons. The advantage of plants from this family is that after cutting and drying, the plant material is not breakable. They possess a rather shallow root system, but as very dense and well penetrating soil these plants are very effective in phytoextraction of upper soil levels. Tolerance in this family to heavy metals is widely known, e.g., *Leersia hexandra,* is the hyperaccumulator of chromium with potential for phytoremediation of Cr-contaminated soil (Zhang et al. 2007). The biggest biomass producer from this family is maize (*Zea mays*) which is tolerant to heavy metals and petroleum. Sometimes, among cereals the older long-stem cultivars of wheat (*Triticum aestivum*) and barley (*Hordeum vulgare*) are recommended for phytoremediation. When polluted sites also contain high levels of salt, barley, as the most tolerant to salinity among plants from this family (Orcutt and Nilsen 2000), would be the first choice for phytoremediation.

Among other grasses very tolerant to several pollutants are two genera: Lolium and Festuca; both grow as wild on the polluted road sides and there is also quite long list of cultivars that can be used for phytoremediation. Although as typical pasture/loan grasses they produce lower biomass, they are cut 2–3 times during the vegetation season and as a sum they produce a reasonably good yield of polluted biomass. Besides, pollutants deposited on foliage are collected before they are fully washed off by rain and replace pollution into the soil. From the Lolium genus, in Europe, there are two common perennial species: *L. perenne* and *L. multiflorum*. In case of Festuca genus, *F. rubra, F. arundinacea* and *F. ovina* can be utilized in phytoremediation. In this family, there is a highly resistant group of grass belonging to the genus Agrostis with two species, *A. tenuis* and *A. alba*. These grasses are characterized by very high levels of tolerance to heavy metals. Because plants of these two species accumulate heavy metals mostly in the roots, they can be recommended rather for phytostabilization. In fact, earlier described case of *A. tenuis* forming crystals of pyromorphite in the rhizosphere on sites highly polluted with lead whenever soluble inorganic phosphate was present in the soil is also a form of phytostabilization.

On the terrestrial polluted places, at temper zone, *Elytrigia repens,* can be found very often. Plants of this species are very tolerant to salinity and heavy metals with the latter being in high amounts accumulated in the underground rhizomes. Rhizomes can easily be mechanically pulled out from the soil.

Two other grasses cultivated in Europe as ornamental plants also possess high phytoremediation capabilities: *Deschampsia cespitosa* and *Vetiveria zizanioides*.

Grasses may also be used for water and sediments phytoremediation but since for these purposes they are growing in water or wet stands the plants must also tolerate such conditions. As a number one species for this purpose *Phragmites australis* is listed as the basic species used in constructed wetlands, highly tolerant to a wide range of pollutants including high salinity. Other species such as *Phalaris arundinacea* and *Miscantus* sp. are also good candidates but as they require higher temperatures for growth, they can be recommended for rather warmer regions. A very attractive candidate for phytoremediation is the perennial species *Miscanthus gigantheus* which accumulates very high amounts of biomass when aged more than 2 years. This species is more tolerant to frost and survives in countries of Central Europe.

It is noteworthy that all grasses are easily colonized by a wide range of species of mycorrhizal fungi from the Glomus genus, with *G. intraradices* being the most tolerant to heavy metals.

5.2.1.2 Family: Cyperaceae

Several species highly tolerant to pollution belong to this family and many species from this family are growing on very wet sites, just on the border between water and land. Therefore, they are unique for the application in the above described, very difficult, for phytoremediation conditions. At the temper and cooler zones of Europe, several species of Carex were found on polluted sites (Pawlowska et al. 1996) and one of them *C. hirta* very often is recommended as an ornamental plant. For more warmer, southern part of the continent and for Mediterranean, subtropical zone *Cyperus alternifolius* and *Cyperus papyrus*, respectively, can be considered. All species are easily propagated vegetatively by dividing the mother plants.

Another species from this family, *Eriophorum angustifolium*, is very tolerant to a wide range of pH and is therefore very suitable on acidic mine tailing impoundments, which if untreated are very acidic, down to 2.3, and if limed, can have a pH up to 11. This plant is useful in phytostabilization of metals in mine tailings by its property to stabilize the pH around 6 and thus can decrease the bioavailability of metals up to 98% (Stoltz and Greger 2002).

Growing in the South Africa river, sedge species *Bolboschoenus maritimus* is considered as a good bioindicator of sediments pollution with metals (Shuping et al. 2011). In North America, *Scirpus californicus* was tested for constructed wetland with Zn-contaminated water (Gillespie et al. 1999).

5.2.1.3 Family: Typhaceae

From this family, species from Typha genus are very common not only in Europe but also in other parts of the world. Two species are recommended for phytoremediation in many countries: *Typha angustifolia* (Demirezen and Aksoy 2004) and *T. latifolia* (Carranza-Alvarez et al. 2007). Both species very well accumulate heavy metals and can be recommended as an important component of plant community in constructed wetland. Maintained on the bigger area of the shallow water, they not only uptake pollutants but also accumulate enough big biomass for "green" energy production (Ciria et al. 2005). Usually for producing bigger biomass *T. angustifolia* is of first choice, but for obtaining greater biodiversity both the species can be cultivated. Typha, similar to Phragmites, colonizes no running water. Both of them are known as allelopathically active against algae; however, they become effective when plants cover more than 25% of the water surface. Typha phytoremediates heavy metals and agricultural pollutants such as N and pesticides flowing into the water reservoir from intensive conventional agriculture. Typha plants translocate pollutants to the upper part of the plants better than those of Phragmites, but it is much less tolerant to salinity.

5.2.1.4 Family: Juncaceae

Some species from rashes family show potential for heavy metal uptake. But only few species from this family are used as ornamentals. The fact that they accumulate not so big biomass makes them less attractive for phytoremediation. The first species *Juncus lutea* was recognized as a hyperaccumulator of nickel more than 50 years ago (Pichi Sermolli 1948 after Brooks 1998). Plants of other species such as *J. effuses* (Marian et al. 2009) and *J. articulatus* (Vardanyan and Ingole 2006) were also found growing at the polluted sites accumulating heavy metals.

5.2.2 Order: Malpighiales

5.2.2.1 Family: Salicaceae

It is the most common family with woody plants that are used in phytoremediation. Plants species belonging to this family are very fast growing, accumulate high amounts of biomass and uptake wide range of pollutants. These mean that they meet the requirements to be one of the best phytoremediants. Usually very fast growing trees are short living, but it is not a problem for this technology because the woody plants still grow for a decade. The willows species are especially recommended for phytoextraction of heavy metals such as Cd, Pb and Zn.

Within the genus Salix there is a big variation in uptake, translocation to the shoot and tolerance to a certain metal. This variation is found to a higher extent between clones of a species than between Salix species (Landberg and Greger 1996; Greger and Landberg 1999). This makes Salix unique because it is then possible to choose a certain clone for a certain phytoremediation purpose, e.g., stabilizing soils with Zn, decreasing the leakage of Zn from the soil by a clone with low uptake of Zn, or by removal of Cd and Cu by a clone that would translocate high amounts of these metals to the shoot. However, at least in the species *Salix viminalis*; it is found that most clones are excluders of heavy metals and it seems to be the most common way of coping with heavy metal toxicity. It is also shown that heavy metal uptake, tolerance and translocation to the shoot in various Salix species are not evolved in areas with high levels of heavy metals (Landberg and Greger 1996).

The property to have high accumulation of heavy metals is not correlated with the property to have high biomass production (Greger et al. 2001). From Salix genus, several species are utilized. From Salix genus, several species are utilized. *Salix viminalis* has the leading position when dealing with heavy metals phytoextraction of heavy metals, which simultaneously evolve biomass which can be utilized as a source of renewable energy (Greger and Landberg 1999). Significant differences between genotypes of *S. viminalis* are observed; thus, in practice, cultivars already checked for their phytoremediation ability need to be cultivated. Nurseries and breeding companies offer special cultivars of *S. viminalis* for phytoremediation with high ability for metal uptake. The advantage of this willow species is that it can be very easily vegetatively propagated by wooden cuttings. Individuals received via this propagation are known to grow much better on moist soils and positively respond to irrigation. Plantations survive more than 10 years but during the first 2–3 years, before the full establishment, they require protection against weeds' competition.

S. caprea, a shrub or small tree, is also known for good phytoremediation abilities but is less common in application because it is propagated by seeds, which is less convenient and not all plants inherit the desired character. In the last few years, *S. burjatica* is recommended as a good candidate species for phytoremediation (Pulford et al. 2002); it is obvious that because of the origin of this species it is tolerant to low temperatures.

Willows are easy to cross between species and many commercially offered cultivars are hybrids (Pulford et al. 2002). One of the oldest cross is *S. viminalis* and *S. caprea* known as *S. smithiana*. This very fast grown hybrid, accumulates high biomass, very well uptakes heavy metals and is easily propagated by wooden cuttings. *S. viminalis, S. daphnoides* and *S. pupurea* are also cultivated as ornamental species and, in urban areas polluted by heavy traffic, can be employed for phytoremediation of pollutants from the air. Organic pollutants such as PAHs, PCBs and dioxins are accumulated in the waxes covering leaves and stems. Raking the leaf litter in the autumn and cutting stems in the spring lead to partial removal of these carcinogenic pollutants from the cities' environment.

The genus of Populus is more universal and can be applied for phytoremediation of both heavy metals and organic pollutants such as TCE, TNT explosive. These plants with very deep root system (up to 20 m) and capabilities to uptake up to 200 L of water per day (by 5-year-old tree) are superior for some of the contaminated sites. In temper zone, poplars are one of the fastest growing species and accumulate big biomass. They are also easily propagated by wooden cuttings. Among poplars, the most successful are not species but interspecies hybrids. Since the poplars are easy in vitro (Lonardo et al. 2011) and vegetatively propagated, the advantages obtained on the basis of heterosis characters can be continuously maintained. The most common are crosses between European and American species: *P. nigra* var. *italica x P. deltoides*, in literature also known as *P. euroamericana,* and others such as *P. trichocarpa x P. deltoides* or *P. trichocarpa x P. maximowiczi*. During application of poplar for phytoremediation it should be kept in mind that very intensive growth of these plants requires high water availability. Poplar hybrids, growing up to 3 m per year, are free of competition with weeds even during the beginning of plantation.

Species from both genera Salix and Poplar are easily colonized by mycorrhizal fungi and they respond with better efficiency of phytoremediation (Sell et al. 2005).

5.2.2.2 Family: Violaceae

This family has some historical meaning for phytoremediation because the endemic metalophyte *Viola calaminaria*, now named hyperaccumulator, was discovered in the nineteenth century on the Belgian/Germany border (Baumann 1885). More common in Europe, closely related to the above-mentioned species and also tolerant to heavy metals is *V. lutea* (Hildebrandt et al. 2007). Although both species accumulate low biomass during vegetation season, they still are interesting from the mechanisms involved from the point of view of tolerance to heavy metals. In China, another hyperaccumulator has been discovered from this family, i.e., *V. baoshanensis* producing high biomass and over there it is considered as a candidate for phytoextraction (Zhuang et al. 2007).

5.2.3 Order: Fabales

5.2.3.1 Family: Fabaceae

Species from this family are very good phytoremediants of heavy metals. They also trap organic pollutants in waxes covering leaves and bark. Moreover, plants from this family stimulate growth of soil microbial community, which are capable of degrading PAHs and PCBs. Additional and very important advantages that plants from this family possess are: (a) self-sufficiency for nitrogen; (b) high tolerance to drought; and (c) capacity of some plant species to survive on very poor soil. Heavy metal uptake by herbaceous species such as *Lupinus* sp. and *Vicia* sp., *Sesbania exaltata* (Miller et al. 2008) was studied and well documented in several laboratories. All common species of *L. albus, L. luteus, L. angustifolius* and *L. hispanicus* show similar growth and accumulation of Mn, Pb, Cr (III), Cr(VI) and CH_3Hg (Pilar et al. 2001). In urban areas, high tolerance is also observed in ornamental species such as *L. polyphyllus* (Gawronski own study, not published). Attention can be directed also to the capabilities of metals including mercury uptake by genus Vicia (Sierra et al. 2008). List of legume species tolerant to pollutants is much wider and include tolerance to heavy metals recorded in *Medicago sativa* (Poniedzialek et al. 2005, Sherifi et al. 2009), to the metalloids arsenate shown by *Cytisus striatus* (Bleeker et al. 2003) and other elements, e.g., to selenium found in *Melilotus indica* (Guo and Wu 1998).

It should be underlined that in this family several hyperaccumulators of selenium were found with *Astragalus bisulcatus* as the first. According to Brooks (1998) along time, the number of species on the list of those tolerant to selenium increased up to 13.

In urban areas, ornamental trees and shrubs from this family such as *Robinia pseudoaccacia, Caragana arborescens* and *Amorpha fruticosa* are commonly cultivated. All these species easily uptake heavy metals and capture organic pollutants in the waxes. *R. pseudoaccacia*, in addition to the above, also exude to the soil high amounts of flavonoids, chemicals with six carbon rings with high similarity to PAHs. This stimulates the development of specific rhizobial microorganism community, which when overpopulated would starve and then start to degrade PAHs and PCBs using carbon skeletons as a source of energy for their living processes.

The above listed trees and shrubs very well re-grow after spring time trimming, which allows removing polluted plant materials for controlled utilization.

5.2.4 Order: Rosales

This is one of the most important order in human life, cultivated mainly for food and ornamental purpose.

5.2.4.1 Family: Rosaceae

Rosaceae is the biggest family in this order, possessing above average tolerance to pollution several species but generally not so high such as some of those described earlier. Tolerant species from this family are mainly ornamentals and often cultivated in polluted urban areas. Roses, tolerant to the pollution, are very often cultivated on the median strips dividing traffic directions with *Rosa rugosa, Rosa rugotida* and *Rosa nitida* recommended for such purpose. Roses not only uptake heavy metals but also create a kind of natural barrier for trespassing. *R. rugosa* is good bioindicator of pollution (Calzoni et al. 2007). Similarly successful in the biomonitoring of Cd, Pb and Zn is other ornamental shrub *Pyracantha coccinea* (Akguc et al. 2008). In many cities, new very decorative two shrubs *Sorbaria sorbifolia* and *Physocarpus opulifolius* are evaluated and they also appear as very promising with respect to tolerance to the pollution.

5.2.4.2 Family: Cannabaceae

Industrial crop *Cannabis sativa* seems to be very promising in the new role as phytoremediant. It is short day species and as the length of the day increases the plant will continue to grow vegetatively, sometimes even up to 4 m height accumulating huge amounts of biomass. The industrial hemp grows fast, does not need to use herbicides because hemp by itself, as being highly allelopathic active, keeps weeds away, probably by excreting some substance. High levels of metals are mostly found not only in the shoots but also in the leaves (Linger et al. 2005, Khan et al. 2008). This with a small root mass, together with the fact that the root system is poor and shallow, makes *C. sativa* interesting for phytoextraction (Greger et al. in prep). As annual plants, all biomass of the above ground part is completely harvested in the autumn. High biomass yield require supplementing nitrogen, calcium (sensitive to shortage of Ca) and water. This species is also known as very good phytoremediant of heavy metals and radionuclides with significant differences in phytoremediation capabilities between cultivars recorded. Due to the strong similarity to another species, the *Cannabis indica* a source of narcotics, in countries with strong anti-drug law there are formal difficulties to cultivate this crop.

5.2.5 Order: Brassicales

5.2.5.1 Family: Brassicaceae

Plant species belonging to this family are among the best accumulators of heavy metals, with a long list of the hyperaccumulators and with record levels of heavy metal concentrations in plant tissues. Most of the discovered hyperaccumulators from this family belong to the genera Alysum and Thlaspi (Brooks 1998). For phytoremediation, most often, species with known agronomical practises are proposed and in this taxonomic group most common is the Indian mustard (*Brassica juncea*)(Kumar et al. 1995). Selected lines of this species uptake heavy metals in very high amounts. The fact that plants of this species can be cultivated twice every growing season makes them very attractive as heavy metals phytoremediants. White mustard (*Sinapis alba)* – species commonly cultivated in Europe for a green manure – possesses slightly lower capacities for heavy metals phytoremediation (Winska-Krysiak and Gawronski 2002). Very valuable was the discovery that to this family belongs the species *Iberis intermedia* with capability to hyperaccumulate thallium, a very toxic element (Leblanc et al. 1999). Recently, in many countries, programs of renewable energy have started and acreage of rapeseed cultivation for biodiesel production is increasing. Industrial utilization of the rapeseed (*Brassica napus* L. var. *napus)* oil allows cultivating this crop on the polluted sites; thus, besides oil production simultaneous process of phytoremediation can be run. However, it needs to be remembered that rapeseed requires better soil to obtain good yield; so not all fields can be used for the combined purposes of oil production and heavy metals phytoremediation in case of this species.

There are two disadvantages of using plants from this family for phytoremediation: (a) necessity of plant protection against insects and (b) leaf blades after drying are fragile and are dropped off the stems. Therefore, in order to avoid secondary emission, plants must be harvested before full maturity and the vegetative parts must be utilized in a controlled manner. Additional disadvantage is also the lack of colonization with symbiotic mycorrhizal fungi, which if takes place leads not only to increased heavy metals uptake but also to increased tolerance.

Technology of phytomining can be applied for the highly valuable metals such as gold using *Brassica juncea* (Anderson et al. 1998) and nickel with domesticated hyperaccumulator *Alyssum murale* (Chaney et al. 2005).

5.2.6 Order: Caryophyllales

To this order belong several families with species tolerant to heavy metals and most of them are also tolerant to salinity.

5.2.6.1 Family: Plumbaginaceae

In leadwort family (Plumbaginaceae) there are species very tolerant to lead and usually they also are tolerant to other heavy metals. Most common on lead polluted sites is *Armeria maritima*, a plant commonly cultivated in gardens but this pioneer plant is successfully surviving on postindustrial sites (Dahmani-Muller et al. 2000) and even colonizing places as heap (Olko et al. 2008). The shrub *Plumbago auriculata* is one of the most popular blue color flower plant in gardens at warmer parts of the world. Not many of us know that this is one of the most tolerant species to lead and that in earlier times it was used as an antidote against lead poisoning. From the genus Limonium several species are cultivated as ornamental plants.

5.2.6.2 Family: Betaceae

Plants from this family are known as highly tolerant to salinity and can be recommended for phytoremediation of salt polluted sites. They are also recognized as efficient in uptaking heavy metals (Rosso et al. 2005). The most common from Betaceae family sugar beet, crop producing very high yield, is not used in phytoremediation because of the problem with utilization of obtained biomass due to high water content. Two other cultivated species accumulating high biomass, *Atriplex hortensis* and *Kochia scoparia,* can be recommended for this technology. Both species are ornamental plants, easily propagated from seeds with wide selection of cultivars available offered by seed companies. Most species from this family are not colonized by mycorrhizal fungi.

5.2.6.3 Family: Amaranthaceae

Amaranth (*Amaranthus* ssp.) is cultivated as an ornamental plant and lately also as an alternative edible crop. *A. blitoides* was found on widely known toxic spill from Aznalcollar mine in Spain (Rio et al. 2002) and another weedy species *A. hybridus* was tested for phytoextraction (Puschenreiter et al. 2001). Morphologically, plants belonging to this genus are very much differentiated; most of them are interspecies crosses. They possess several interesting characters for phytoremediation such as very high tolerance to salinity and capabilities of heavy metal uptake. Very fast growing and accumulating high biomass species/cultivars (some can growth up 2 m) can be recommended for phytoremediation of salt, heavy metal or both of these pollutants simultaneously.

5.2.6.4 Family: Caryophylaceae

Plant species from this taxonomic family very often appear on salt or heavy metal polluted sites such as, for example, *Agrostemma githago* (Pichtel et al. 2000), *Dianthus carthusianirum* (Baranowska-Morek and Wierzbicka 2004) and *Silene vulgaris* (Baroni et al. 2000). Since, similar to other ornamental plant species from this family, they accumulate low biomass, they are not employed in phytoremediation but they are good indicators of pollution with these two groups of contaminants. During visit to polluted sites when decision on application of phytoremediation is under consideration, the presence of the plants of species from this family well indicates the presence of pollutants in the soil and probably on the level which allows to cultivate tolerant plant species.

5.2.6.5 Family: Polygonaceae

Most of the species from this family are known to uptake salt and heavy metals from the soil and they occupy the banks of salty ponds and lakes (Vardanyan and Ingole 2006). Usually these are species from Polygonum genus such as *P. amphibium* and grow on more dry sites such as *P. aviculare*. For phytoremediation, however, much more interesting are species from Fagopyron genus and in practice the following species are used: *F. esculentum*, *F. tataricum* and *F. cymosum*. In fact, utilization of *F. esculentum* for cleaning up soil from heavy metals has been patented in the US (Tamura et al. 2010) and Europe (Sato et al. 2007).

5.2.6.6 Family: Tamaricaceae

Species from this family are among the most tolerant to dryness and salinity. They are typical steppe, semi-desert and desert, being present on and therefore are considered as maintaining sandy dunes. There are around 50 *Tamarix* species known and two of them *T. symyrnesis* (Manousaki et al. 2008) and *T. tetrandra* (Kalmuckov et al. 2009) were already evaluated for their phytoextraction capabilities.

It is commonly known that species from Tamarix genera are salt and metal excluders; so in practice they can be used for temporary phytostabilization.

5.2.7 Order: Solanales

5.2.7.1 Family: Solanaceae

This plant family contains several genera that are very important for humans as a source of food such as potato, tomato or even as condiments such as tobacco. A majority of the species from that family uptake heavy metals from soil very well. In phytoremediation technology, most advanced is the application of *Solanum nigrum* by increasing its efficiency by multiple harvesting (Wei et al. 2006), inoculation with microorganism (*Paecilomyces lilacinus*), intensifying plant microorganism chelates synergy or application of citric acid (Gao et al. 2010). *Datura inoxia* demonstrates interesting capabilities for heavy metal sequestration (Lin and Rayson 1998). It is well known that *Solanum tabacum* easily take up heavy metals from soil (Evangelou et al. 2006) but not all cigarette smokers are so oriented that they introduce to their lung considerable amounts of heavy metals. Several *Nicotiana* spp. are used as ornamental and can be cultivated in polluted sites of urban areas. To lower cost and limit contact with polluted soil for cultivation in such places, *N. silvestris* the perennial species is recommended.

5.2.8 Order: Asterales

5.2.8.1 Family: Asteraceae

Plant species from that family are used for remediation of heavy metals and radionuclides such as Sr, Cs and U. Two crop species *Helianthus annus* and perennial *Helianthus tuberosus* are used for phytoremediation of industrial polluted sites. The *H. annus* – sunflower is a common annual crop plant, accumulating big biomass up to 100 tons of fresh matter. It is tolerant to drought, exhibits strong allelopathic activity and high competitiveness against weeds. It is the best species in European conditions for phytoremediation, because of its good uptake of heavy metals including antimony, which during the last few years has become an increasing threat to the environment (Tschan et al. 2008). *Helianthus tuberosus* is perennial crop which is advantageous in cultivation because of lower cost and the polluted soil is not tilled. Although most of the hyperaccumulators accumulate small biomass, one of the exception is *Berkheya coddi* (Robinson et al. 2003). This species is one of the best in nickel uptake and is considered as a candidate for phytomining of this element and of cobalt as well (Robinson et al. 1999). This family is rich in ornamental species and some of them which accumulate high amounts of biomass can be recommended for phytoremediation of urban areas. Species from three genera can be considered: Solidago, Tanacetum and Rudbeckia. Ornamental species usually greatly differ in many characters but for phytoremediation, tall cultivars with big biomass are preferred even if they would not be the best in terms of aesthetic characters. Some of the species from this family also demonstrates high tolerance to salt, for example *Artemisia vulgaris*.

Above-described orders, families, genera and species do not cover all and the list is not complete. Along with further discoveries and our increasing general knowledge on plant kingdom, the list will be extended. A good example of this is the discovery of hyperaccumulating arsenic fern *Pteris vitata,* which can be utilized for phytoremediation of this dangerous environment polluting elements (Ma et al. 2001). One year later, the paper describing further study revealed that other species from Pteris genera such as *P. cretica*, *P. longifolia,* and *P. umbrosa* hyperaccumulate arsenic to the same extent as the first one (Zhao et al. 2002).

5.3 Conclusions

Among plant kingdom there are several families represented by relatively high number of species tolerant to heavy metals including hyperaccumulators.

There are already species which are recognized as good candidates for phytoremediation. It can be assumed that along with our increasing knowledge on plant biology new species tolerant to heavy metals and candidate good phytoremediants will be found.

Candidates for phytoremediants should be tolerant to heavy metals, uptake them in reasonably big amounts and accumulate in easily harvestable of high biomass organs, thus ensuring high "yield of pollution."

Depending on the site of phytoremediation, i.e., brown fields, urban areas or agricultural polluted sites, different requirements should be fulfilled by considered species.

Simple and low-cost methods of evaluation of plant tolerance (and their progeny) to heavy metals are strongly desired.

References

Adriaensen K, Vangronsveld J, Colpaert JV (2006) Zinc-tolerant *Suillus bovinus* improves growth of Zn-exposed *Pinus sylvestris* seedlings. Mycorrhiza 16:553–558

Akguc N, Ozyigit II, Yarci C (2008) Pyracanyha coccinea Roem. (Rosaceae) as a biomonitor for Cd, Pb and Zn in Mugla Province (Turkey). Pak J Bot 40:1767–1776

Anderson CWN, Brooks RR, Stewart RB, Simcock R (1998) Harvesting a crop of gold in plants. Nature 395:553–554

Babula P, Adam V, Opatrilova R, Zehnalek J, Havel L, Kizek R (2008) Uncommon heavy metals, metalloids and their plant toxicity: a review. Environ Chem Lett 6:189–213

Baranowska-Morek A, Wierzbicka M (2004) Localization of lead in root tip of *Dianthus carthusianirum*. Acta Biol Cracov 46:45–56

Baroni F, Boscagli A, Protano G, Riccobono F (2000) Antimony accumulation in *Achillea ageratum, Plantago lanceolata* and *Silene vulgaris* growing in an old Sb-mining area. Environ Pollut 109:347–352

Baumann A (1885) Das Verhalten von Zinksalzen gegen Pflanzen und im Boden. Landwirtschaftliche Versuchsstation 31:1–53

Bleeker PM, Schat H, Vooijs R, Verkleij JAC, Ernst WHO (2003) Mechanisms of arsenate tolerance in *Cytisus striatus*. New Phytol 157:33–38

Bremer B, Bremer K, Chase MW, Fay MF, Reveal JL, Soltis DE, Soltis PS, Stevens PF (2009) An update of the Angiosperm Phylogeny Group classification for the orders and families of flowering plants: APG III. Bot J Linn Soc 161:105–121

Brooks RR (1998) Plants that hyperaccumulate heavy metals. CAB International, University Press, Cambridge, p 380

Calzoni GL, Antognoni F, Pari E, Fonti P, Gnes A, Speranza A (2007) Active biomonitoring of heavy metal pollution using *Rosa rugosa* plants. Environ Pollut 149:239–245

Carranza-Alvarez C, Alonso-Castro AJ, Alfaro De La Torre M, Garcia-De La Cruz RF (2007) Accumulation and distribution of heavy metals in *Scirpus americanus* nad *Typha latifolia* from an artificial lagoon in San Luis Potosi, Mexico. Water Air Soil Pollut 188(1–4):297–309

Chaney RL, Angle JS, Wang AS, McIntosh MS, Broadhurst L, Reeves RD (2005) Phytoextraction of soil Cd, Ni and Zn using hyperaccumulator plants to alleviate risks of metal contaminated soils requiring remediation. International Workshop. Current developments in remediation of contaminated lands, Pulawy, Poland, p 39

Chase MW, Reveal JL (2009) A phylogenic classification of the land plants to accompany APG III. Bot J Linn Soc 161:122–127

Ciria MP, Solano ML, Soriano P (2005) Role of macrophyte *Typha latifolia* in a constructed wetland for wastewater treatment and assessment of its potential as a biomass fuel. Biosyst Eng 92(4):535–544

Cobbett CS (2000) Phytochelatins and their role in heavy metal detoxification. Plant Physiol 123:825–832

Cotter-Howells J, Caporn S (1996) Remediation of contaminated land by formation of heavy metal phosphates. Appl Geochem 11:335–342

Dahmani-Muller H, van Oort F, Gelie B, Balabane M (2000) Strategies of heavy metal uptake by three plant species growing near a metal smelter. Environ Pollut 109:231–238

Demirezen D, Aksoy A (2004) Accumulation of heavy metals in *Typha angustifolia* (L.) and *Potamogeton pectinatus* (L.) living in Sultan Marsh (Kayseri, Turkey). Chemosphere 56:685–696

Evangelou MWH, Ebel M, Schaeffer A (2006) Evaluation of the effect of small organic acids on phytoextraction of Cu and Pb from soil with tobacco *Nicotiana tabacum*. Chemosphere 63:996–1004

Ferrol N, Gonzalez-Guerrero M, Valderas A, Benabdellah K, Azcon-Aguilar C (2009) Survival strategies of arbuscular mycorrhizal fungi in Cu-polluted environments. Phytochem Rev 8 (3):551–559

Gao Y, Miao C, Mao L, Zhou P, Jin Z, Shi W (2010) Improvement of phytoextraction and antioxidative defense in *Solanum nigrum* L. under cadmium stress by application of cadmium-resistant strain and citric acid. J Hazard Mater 181:771–777

Gillespie WB, Hawkins WB, Rodgers JH, Cano ML, Dorn PB (1999) Transfers and transformations of zinc in flow-through wetland microcosms. Ecotoxicol Environ Saf 43: 126–132

Goldsbrough P (2000) Metal tolerance in plants: the role of phytochelatins and metallothioneins. In: Terry N, Banuelos G (eds) Phytoremediation of contaminated soil and water. Lewis Publishers, Boca Raton, pp 221–235, pp 408

Gonzalez-Guerrero M, Cano C, Azcon-Aguilar C, Ferrol N (2007) *GintMT1* encodes a functional metallothionein in *Glomus intraradices* that responds to oxidative stress. Mycorrhiza 17: 327–335

Greger M, Landberg T (1999) Use of willow in phytoextraction. Int J Phytoremediation 1:115–123

Greger M, Landberg T, Berg B (2001) Salix clones with different properties to accumulate heavy metals for production of biomass. Report to STEM. Akademitryck AB, Edsbruk

Greger M, Wang Y, Neuschütz C (2005) Absence of Hg transpiration by shoot after Hg uptake by roots of six terrestrial plant species. Environ Pollut 134:201–208

Guo X, Wu L (1998) Distribution of free seleno-amino acids in plant tissue of *Melilotus indica* L. grown in selenium-laden soils. Ecotoxicol Environ Saf 39:207–214

Haston E, Richardson JE, Stevens PF, Chase MW, Harris DJ (2009) The Linear Angiosperm Phylogeny Group (LAPG) III: a linear sequence of the families in APG III. Bot J Linn Soc 161:128–131

Hildebrandt U, Regvar M, Bothe H (2007) Arbuscular mycorrhiza and heavy metal tolerance. Phytochemistry 68:139–146

Kalmuckov K, Alexnardova E, Georgiev GI (2009) Copper accumulation capacity of tamarisk (*Tamarix tetrandra* L.) and white mulberry (*Morus alba* L.) depending on soil type. Gen Appl Plant Physiol 35:179–187

Kayser A, Vegner K, Keller A, Attinger W, Felix HR, Gupta SK, Schulin R (2000) Enhancement of phytoextraction of Zn, Cd and Cu from calcareous soil: the use NTA and sulfur amendments. Environ Sci Technol 34:1778–1783

Khan MA, Wajid A, Noor S, Khattak FK, Akhter S, Rahman IU (2008) Effect of soil contamination on some heavy metals content of *Cannabis sativa*. J Chem Soc Pak 30(6):805–809

Kumar PBAN, Dushenkov V, Motto H, Raskin I (1995) Phytoextraction: the use of plants to remove heavy metals from soils. Environ Sci Technol 29:1232–1238

Landberg T, Greger M (1996) Differences in uptake and tolerance to heavy metals in *Salix* from unpolluted and polluted areas. Appl Geochem 11:175–180

Leblanc M, Petit D, Deram A, Robinson BH, Brooks RR (1999) The phytomining and environmental significance of hyperaccumulation of thallium by *Iberis intermedia* from Southern France. Econ Geol 94:109–114

Lin S, Rayson GD (1998) Impact of surface modification on binding affinity distributions of *Datura innoxia* biomass to metal ions. Environ Sci Technol 32:1488–1493

Linger P, Ostwald A, Haensler J (2005) *Cannabis sativa* L. growing on heavy metal contaminated soil: growth, cadmium uptake and photosynthesis. Biol Plantarum 49(4):567–576

Lonardo SD, Capuana M, Armetoli M, Gabbrielli R, Gonnelli C (2011) Exploring the metal phytoremediation potential of three *Populus alba* L. clones using an in vitro screening. Environ Sci Pollut Res 18:82–90

Ma LQ, Komar KM, Tu C, Zhang W, Cai Y, Kennelley ED (2001) A fern that hyperaccumulates arsenic. Nature 409:579

Manousaki E, Kadukova J, Papadatonakis N, Kalograkis N (2008) Phytoextraction and phytoexcretion of Cd by the leaves of *Tamarix smyrnensis* growing on contaminated non-saline and saline soils. Environ Res 106:326–332

Marian M, Cozmuta LM, Varga C, Cozmuta AM, Nour E (2009) Vegetation dynamics depending on ecological particularities of Bozanta Mare (Maramures County – Romania) tailing pound: case study. Am J Environ Sci 5(1):116–123

Miller G, Begonia G, Begonia M, Ntoni J, Hundley O (2008) Assessment of efficacy of chelate – assisted phytoextraction of lead by coffeeweed (*Sesbania exaltata* Raf.). Int J Environ Res Public Health 5(5):428–435

Miretzky P, Fernandez-Cirelli A (2008) Phosphates for Pb immobilization in soils: a review. Environ Chem Lett 6:121–133

Olko A, Abratowska A, Żyłkowska J, Wierzbicka M, Tukendorf A (2008) *Armeria maritima* from calamine heap – initial studies on physiologic-metabolic adaptations to metal-enriched soil. Ecotoxicol Environ Saf 69:209–218

Orcutt DM, Nilsen ET (2000) The physiology of plants under stress. Wiley, New York, p 683

Pawlowska TE, Blaszkowski J, Ruhling A (1996) The mycorrhizal status of plants colonizing a calamine spoil mound in southern Poland. Mycorrhiza 6:499–505

Pichtel J, Kuroiwa K, Sawyerr HT (2000) Distribution of Pb, Cd and Ba in soils and plants of two contaminated sites. Environ Pollut 110:171–178

Pilar XE, Yolanda MA, Carmen C, Carmen C, Carmen B, Mercedes M (2001) Evaluation of lupinus species to accumulate heavy metals from waste waters. Int J Phytoremediation 4:369–379

Pilon-Smits E (2005) Phytoremediation. Annu Rev Plant Biol 56:15–39

Poniedzialek M, Sekara A, Ciura J, Jedrszczyk E (2005) Nickel and manganese accumulation and distribution in organs of nine crops. Folia Hort 17:11–22

Pulford ID, Riddell-Black D, Stewart C (2002) Heavy metal uptake by willow clones from sewage sludge-treated soil: the potential for phytoremediation. Int J Phytoremediation 4:59–72

Puschenreiter M, Stoger G, Lombi E, Horak O, Wenzel WW (2001) Phytoextraction of heavy metal contaminated soils with *Thlaspi goesingense* and *Amaranthus hybridus*: rhizosphere manipulation using EDTA and ammonium sulfate. J Plant Nutr Soil Sci 164:615–621

Rauser WE (1995) Phytochelatins and related peptides. Plant Physiol 109:1141–1149

Rio MD, Font R, Almela C, Velez D, Montoro R, Bailon DH (2002) Heavy metals and arsenic uptake by wild vegetation in the Guadiamar river area after the toxic spill of the Aznalcollar mine. J Biotechnol 98:125–137

Robinson BH, Brooks RR, Clothier BE (1999) Soil amendments affecting nickel and cobalt by *Berkheya coddii*: potential use for phytomining and phytoremediation. Ann Bot 84:689–694

Robinson BH, Lombi E, Zhao FJ, McGrath SP (2003) Uptake and distribution of nickel and other metals in the hyperaccumulator *Berkheya coddii*. New Phytol 158:279–285

Rosso PH, Pushnik JC, Lay M, Ustin SL (2005) Reflectance properties and physiological responses of *Salicornia virginica* to heavy metal and petroleum contamination. Environ Pollut 137:241–252

Sato T, Honda M, Tamura H (2007) Europatent no.: EP1795273 (A1)

Sell J, Kayser A, Schulin R, Brunner I (2005) Contribution of ectomycorrhizal fungi to cadmium uptake of poplar and willows from a heavily polluted soil. Plant Soil 277:245–253

Sherifi E, Bytyqi A, Lluga-Rizani K (2009) The concentration of Pb and Cd to *Medicago sativa* along Lipjan-Prizren Highway and their influence on biomass. J Eng Appl Sci 4(1):60–63

Shuping LS, Snyman RG, Odendaal JP, Ndakidemi PA (2011) Accumulation and distribution of metals in *Bolboschoenus maritimus* (Cyperaceae), from a South African river. Water Air Soil Pollut 216:319–328

Sierra MJ, Milan R, Esteban E, Cardona AI, Schmid T (2008) Evaluation of mercury uptake and distribution in *Vicia sativa* L. applying two different study scales: greenhouse condition and lysimeter experiments. J Geochem Explor 96:203–209

Stoltz E, Greger M (2002) Cottongrass effects on trace elements in submersed mine tailings. J Environ Qual 31:1477–1483

Strobel BW (2001) Influence of vegetation on low-molecular-weight carboxylic acids in soil solution – a review. Geoderma 99:169–198

Tamura H, Sato T, Honda M (2010) United States Patent no.: US 7,829,754 B2

Tang S, Willey NJ (2003) Uptake of ^{134}Cs by four species from Asteraceae and two varieties from the Chenopodiaceae grown in two types of Chinese soil. Plant Soil 250(1):75–81

Toler HD, Morton JB, Cumming JR (2005) Growth and metal accumulation of mycorrhizal sorghum exposed to elevated copper and zinc. Water Air Soil Pollut 164:155–172

Tschan M, Robinson B, Schulin R (2008) Antimony uptake by *Zea mays* (L.) and *Helianthus annus* (L.) from nutrient solution. Environ Geochem Health 30:187–191

Vardanyan LG, Ingole BS (2006) Studies on heavy metal accumulation in aquatic macrophytes from Sevan (Armenia) and Carambolim (India) lake system. Environ Int 32:208–218

Verbruggen N, Hermans C, Schat H (2008) Molecular mechanism of metal hyperaccumulation in plants. New Phytol 181(4):759–776

Wei S, Zhou Q, Koval PV (2006) Flowering stage characteristics of cadmium hyperaccumulator *Solanum nigrum* L. and their significance to phytoremediation. Sci Total Environ 369:441–446

Winska-Krysiak M, Gawronski SW (2002) Fizjologiczne aspekty tolerancji i hiperakumulacji ołowiu w wybranych genotypach *Brassica*. [Physiological aspects of lead tolerance and hyperaccumulationin *Brassica* species]. Zesz Prob Post Nauk Rol 481:605–613

Zhang X-H, Liu J, Huang H-T, Chen J, Zhu Y-N, Wang D-Q (2007) Chromium accumulation by the hyperaccumulator plant *Leersia hexandra* Swartz. Chemosphere 67:1138–1143

Zhao FJ, Dunham SJ, McGrath SP (2002) Arsenic hyperaccumulation by different fern species. New Phytol 156:27–31

Zhuang P, Yang QW, Wang HB, Shu WS (2007) Phytoextraction of heavy metals by eight plant species in the field. Water Air Soil Pollut 184:235–242