23

Exploitation of Weeds and Ornamentals for Bioremediation of Metalliferous Substrates in the Era of Climate Change

M.N.V. Prasad

Abstract

Weeds not only adversely affect the plant productivity but many of them also cause health hazards in human beings and animals. They are also known to seriously affect the biodiversity. Apart from this negative side, many weeds are known to have beneficial properties in one way or the other and have immense potential as food and fodder, medicinal, aromatic, phytoremediation, industrial, soil and water conservation resources, etc. A very little information is available on the use of weeds for such beneficial purposes. Therefore, this subject of research needs to be explored and expanded. Several of the weeds are utilized for (a) soil and water conservation, (b) alternative livelihood opportunities, and (c) industrial uses. Survey of published literature indicates that there is great scope for application of weeds in bioremediation. More research efforts are required for utilizing weeds for bioremediation of different type of pollutants from air, water, and soil. Ornamental plants have an added advantage of enhancing the environmental esthetics besides cleaning the environment. This approach has several advantages for environmental moderation, cleanup, and generation of revenue. Therefore, this approach will add a new dimension to the field of bioremediation of contaminated aquatic and terrestrial environments.

Keywords

Weeds • Ornamentals • Phytostabilization • Phytoremediation • Metalliferous substrates • Biocontrol

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M.N.V. Prasad (✉)
Department of Plant Sciences, University of Hyderabad,
Prof. C.R. Rao Road, Gachibowli,
Central University P.O., Hyderabad, AP 500 046, India
e-mail: mnvsl@uohyd.ernet.in; prasad_mnv@yahoo.com

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1 Introduction

Bioremediation is an emerging and an effective technology for treatment of a wide variety of contaminants. This technology includes plant- and microbe-mediated processes (phytoremediation andrhizoremediation,respectively).Bioremediation approach is currently applied to contain contaminants in soil, groundwater, surface water, or sediments including air. These technologies have become attractive alternatives to conventional cleanup technologies due to relatively low capital costs and the inherently esthetic nature (Fig. 23.1). Quite a variety of plants, natural, transgenic, and/or associated with rhizosphere micro-organisms are extraordinarily active in these biological interventions for cleaning up pollutants by removing or immobilizing (Ma et al. 2011). Climate change will affect the ability of ecological systems that provide a range of essential ecological goods and services, such as food and fiber production; provision of clean and sufficient water maintenance of biodiversity; maintenance of human health; and storage and cycling of carbon, nitrogen, and phosphorus.

Technogenic and anthropogenic sources of metals is subject of importance not only to human health but also in general to the field of biogeochemistry, environment, and medicine (Figs. 23.2–23.4). Smelting and mining processes are the point source of a contamination of metals causing environmental contamination and pollution. Consequently, these pollutants get dispersed in natural resources (soil, water, and air) and ultimately enter the food chain. Physical stabilization (covering the metalliferous waste with geotextiles/geomembranes, etc.) and chemical stabilization (use of chemical binding agents) to reduce wind and water erosion are not a feasible proposition for large areas. However, phytostabilization – use of a specific type of vegetation is far more desirable than physical and chemical stabilization (Prasad 2006; Tordoff et al. 2000). Phytostabilization is an effective process of phytoremediation technology.

In order to cleanup large areas contaminated with toxic metals, plants producing very high biomass with limited inputs and simplistic management are desirable. It is a general belief that climate change promotes explosion of weeds in addition to other phenomena (Fig. 23.5).

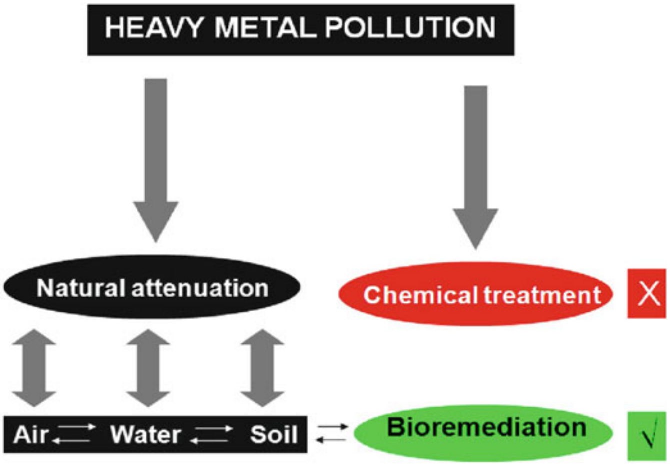

Fig. 23.1 Bioremediation, a schematic presentation. Bioremediaiton is based on use of the ecosystem services provided by its biotic compartment. Some examples of its application include the reduction and control of pollution through wetland systems, restoration of degraded natural systems or establishment of Eco-industrial parks, carbon sinks and ameliorating the effects and impacts of climate change

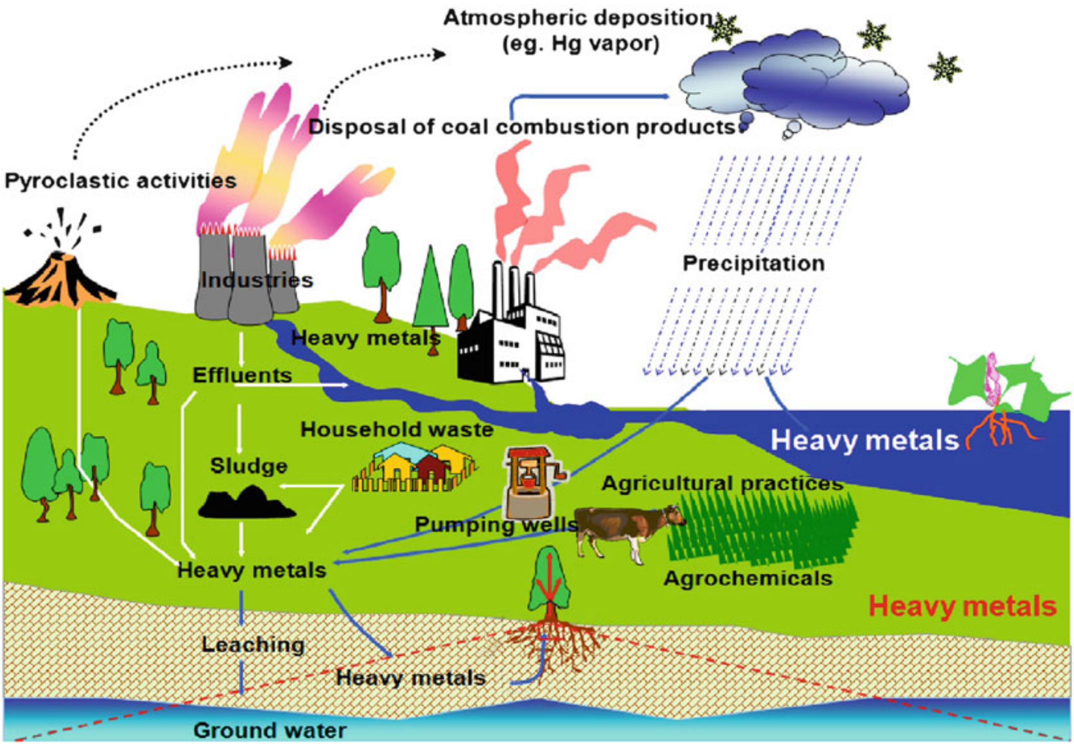

Fig. 23.2 Biogeochemical cycling of heavy metals in a generalized ecosystem

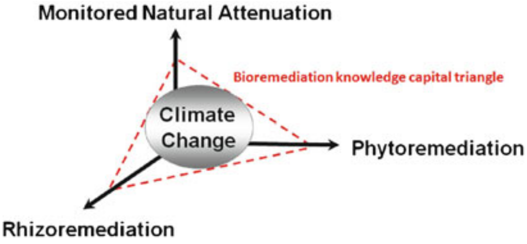

Fig. 23.3 Bioremediation knowledge capital triangle

Non-alien plants when they grow outside their niche become invasive. Invasives are widely distributed in a variety of ecosystems throughout the world. Many invasive alien species support farming and forestry systems positively in a big way. However, some of the alien species become invasive when they are introduced deliberately or unintentionally outside their natural habitats into new areas where they express the capability to establish, invade, and outcompete native species. According to International Union for Conservation of Nature and Natural Resources (IUCN), alien invasive species means, an exotic species which becomes established in natural or seminatural ecosystems or habitat, an agent of undesirable change which threatens the native biological diversity. Invasive species are therefore considered to be a serious hindrance to conservation and profitable use of biodiversity, with significant undesirable impacts on the services provided by ecosystems. Alien invasive species are supposed to have huge requirement and destructive modes of resource acquisition and consumption that would ultimately bring change in soil structure and nutrient composition, its profile, decomposition, moisture availability, etc.

Trace metal contamination and pollution in the environment is increasing due to technogenic and geogenic sources. The flux of trace metals deteriorates the quality of the environment since these are considered to be cytotoxic, mutagenic, and carcinogenic. In order to be healthy, physically and mentally, clean soil, water, and air are

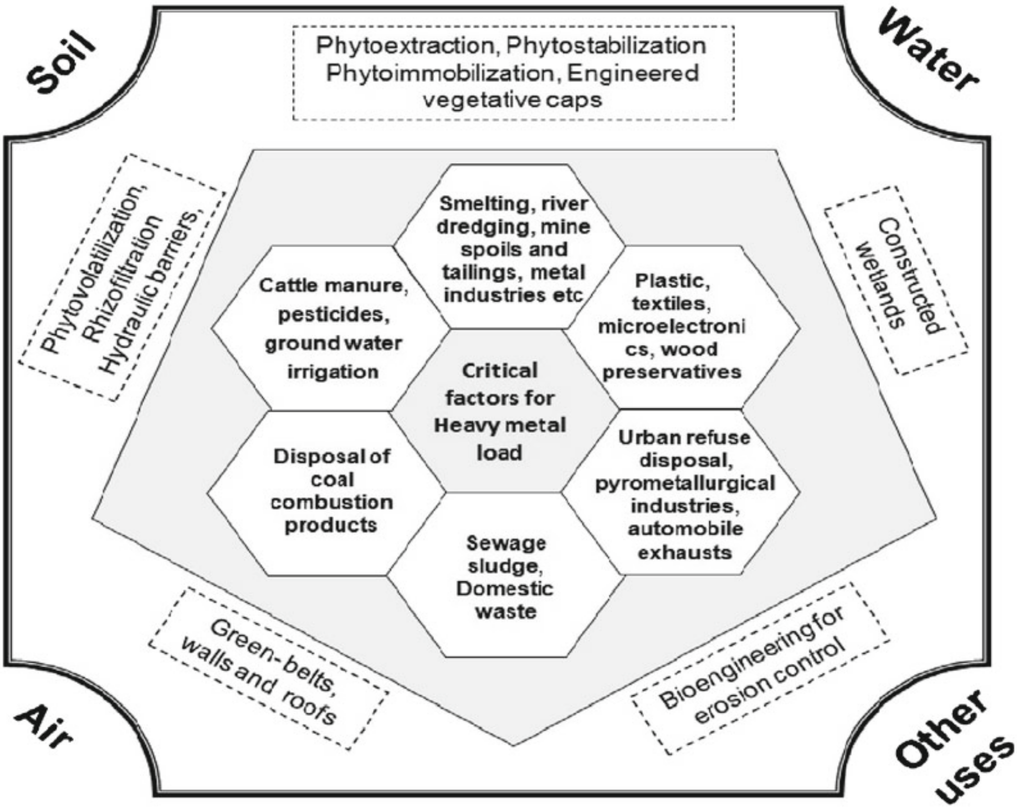

Fig. 23.4 Sources of heavy metals in the environment and various applications of bioremediation for treatment of natural resources and for miscellaneous applications

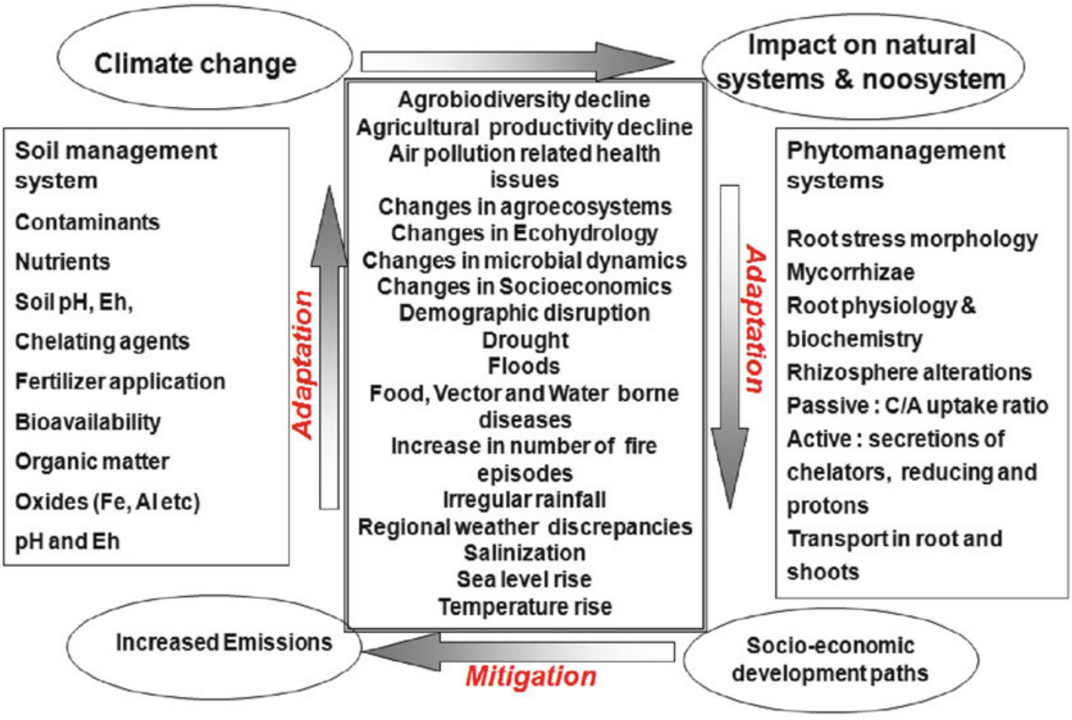

Fig. 23.5 Climate change induced adaptations and mitigation processes

prerequisites. Trace metal contamination and pollution would exert direct and indirect harmful effects that would eventually deteriorate biodiversity and economic wealth. In developed nations, trace metal contamination or pollution is often highly localized and the pressure to use such contaminated land and water for agricultural food production is minimal. In contrast, the technogenic/geogenic pollution and contamination is widespread in many Asian and eastern European countries and is dramatically increasing in Southeast Asia, India, and China (Cheng 2003; Meharg 2004). In order to contain trace metal pollution in soil, water, and air, phytoremediation is being considered as a low cost solution and a globally recognized technology (Garbisu and Alkorta 2001; Garbisu et al. 2002; McCutcheon and Schnoor 2003; Prasad and Freitas 2003; Macek et al. 2004; Gratão et al. 2005). Ornamental foliage plants have been suggested for the removal of arsenic (Alkorta et al. 2004). Therefore, this approach of involving weeds for bioremediation of metalliferous substrates in the era of climate change would yield desirable results with limited efforts and investments (Lorenzini et al. 2006; Prasad and Freitas 2003).

2 Grasses: Ideal for Phytostabilization

Grasses are tolerant to toxic metals and have played a convincing role in phytostabilization (Prasad 2006; Lai and Chen 2006; Li et al. 2009; Néel et al. 2007; Redondo-Gómez et al. 2011; Shu et al. 2002; Vernay et al. 2007; Wang et al. 2005; Zhang et al. 2010; Atabayeva et al. 2010). Abandoned mine soils and estuarine sediments are phytostabilized against erosion by grass species (Cambrollé et al. 2008; Comino et al. 2009; Mateos-Naranjo et al. 2008). Soil amendments and biosolids accelerate phytostabilization process (Santibáñez et al. 2008; Zhou et al. 2007). Grasses possess thickets of adventitious roots, unique root morphology (Li et al. 2009), high bioproductivity (Liu et al. 2009), therefore have an added advantage for application in phytostabilization. Further, grasses are often associated with mycorrhizal and endophytic fungi (Chen et al. 2008; Deram et al. 2007, 2008; Kuldau and Bacon 2008; Ortega-Larrocea et al. 2010; Punamiya et al. 2010). Grasses together with legume association have helped in situ stabilization of chemical waste (Hartley et al. 2009; Hartley and Lepp 2008). In climate constrained and carbon dioxide enriched era, grasses have physiological advantage (majority being C_4) of producing/increasing their biomass. Hence, grasses perform well in phytostabilization process (Wu et al. 2009). In view of their advantageous metabolic processes, hydroponic grass system based on plate or fabric is considered for the treatment of aquacultural wastewater (Pan et al. 2007).

2.1 *Lolium perenne* (Ryegrass)

It is a perennial exhibits luxuriant growth and produces large amounts of aboveground biomass. It has been used for phytostabilization of abandoned uranium mine (Abrutiga, Portugal) (Fig. 23.6).

2.2 *Panicum virgatum* (Switchgrass)

It is one of the perennial rhizomatous grasses being developed for the purpose of biomass production. It is a perennial C_4 grass propagated by seed that can be established at low cost and requires very low inputs while giving high biomass yields even on marginal soils. Attributes of switchgrass desirable for bioenergy cropping include its demonstrated high productivity across many environments, suitability for marginal and erosive land, relatively low water and nutrient requirements, and positive environmental benefits. There is need to examine its (a) adaptability across a range of contaminated sites, (b) fresh and dry matter yields.

2.3 *Prosopis juliflora* (Velvet Mesquite)

It is an evergreen phreatophyte, fast growing, drought resistant, widely distributed not only in

Fig. 23.6 *Lolium perenne* – phytostabilization of abandoned mine and soil profile

India but also in other arid and semiarid tropical countries. It is the only exotic species capable of growing on a wide variety of soils and climatic conditions. It is a valued tree for shade, timber, and forage. It is a thorny, deciduous, large crowned and deep rooted bush or tree which grows up to 10-m height or more, depending on the variety and climatic conditions. It is also widely distributed in the dry tropical and subtropical regions of Central America and Northern South America.

P. juliflora is an ideal species for stabilizing the pegmatitic tailings of mica mines in Nellore district of Andhra Pradesh, India (Nagaraju and Prasad 1998). It is also helpful for reclamation of copper, tungsten, marble, dolomite mine tailings and is a green solution to heavy metal contaminated soils (Varun et al. 2011). It is an appropriate species for rehabilitation of gypsum mine spoil in arid zone and restoration of sodic soils. It outperformed all other tree species in sand dune stabilization (Kailappan et al. 2000; Rai et al. 2003; Senthilkumar et al. 2005). Mycorrhizae are reported to greatly improve the growth of *P. juliflora* on high pH soils. *P. juliflora* was able to grow satisfactorily without amendments up to pH 9. Arbuscular mycorrhizal inocula isolated from its rhizosphere (low cost agro-technology) were found to accelerate the growth of other agroforestry and social forestry legumes in perturbed ecosystems (Gardea-Torresdey et al. 2005; Siddhu and Behl 1997; Singh 1995).

3 Ornamentals for Environmental Moderation and Toxic Trace Metal Cleanup

Several ornamental plants have successfully been applied in environmental toxic cleanup. (Belmonth and Metcalfe 2003; Chintakovid et al. 2007; Davies et al. 2001; Madejon et al. 2003; Mazen 2004; McIntyre 2003; Mungur et al. 1995; Murillo et al. 1999; Negri and Hinchman 2000; Niu et al. 2007; Wei et al. 2009, 2010a, b)

Lemon-scented geraniums (*Pelargonium* sp. "Frensham," or scented geranium) accumulated large amounts of Cd, Pb, Ni, and Cu from soil in greenhouse experiments (Dan et al. 2000). Biotechnological interventions through hairy root regenerants are useful in floriculture (Giri and Narasu 2000; Giovanni et al. 1997). Pellegrineschi et al. (1994) improved the ornamental quality of scented *Pelargonium* spp. This plant has pleasant odor that adds scent to the toxic metal contaminated soil.

Vetiveria zizanioides (Vetiver grass): It is known to have multiple uses. This plant had several popular names such as "the miracle grass," "a wonder grass," "a magic grass," "an unique plant," "an essential grass," "an amazing plant," "an amazing grass," "a versatile plant," "a living barrier," "a living dam," "a living nail," "a living wall," "an eco-friendly grass." This extraordinary grass is adaptable to multiple environmental conditions and it is globally recognized as an easy and economical alternative to control soil erosion and to solve a variety of environmental problems. It has been used for restoration, conservation, and protection of land disrupted by man activities like agriculture, mining, construction sites, oil exploration and extraction, infrastructure corridors, as well as used for water conservation in watershed management, disaster mitigation, and treatment of contaminated water and soil. Research at the global level has proved the relevance of vetiver in multiple applications. In Australia, *V. zizanioides* has been successfully used to stabilize mining overburden and highly saline, sodic, magnesic, and alkaline (pH 9.5) tailings of coalmines, as well as highly acidic (pH 2.7) arsenic tailings of gold mines. In China, it has been demonstrated that *V. zizanioides* is one of the best choices for revegetation of Pb/Zn mine tailings due to its high metal tolerance (Chen et al. 2004a, b; Chiu et al. 2005, 2006; Chong and Chu 2007; Rotkittikhun et al. 2007; Makris et al. 2007; Pang et al. 2003; Singh et al. 2008; Truong 2000; Wilde et al. 2005).

(a) *Hydrocotyle umbellata* (Pennywort): It is a wetland/marshy plant commonly found in many tropical countries. The plant grows very rapidly and serves as an ornamental and decorative purpose. It is reported to remove trace metals from aquatic systems.

(b) *Alternanthera philoxeroides* (Alligator weed): It is one of the most common aquatic weed in contaminated/polluted ecosystem. This is native to South America and naturalized in India (Naqvi and Rizvi 2000). Several Amaranthaceae produce large biomass and are suitable for environmental remediation and toxic metal cleanup (for e.g., *Amaranthaceae retrflexus*, Prasad 2001) (Table 23.1).

(c) *Talinum cuneifolium* (Portulacaceae): It is a succulent shrub of about 60-cm height with cuneate to obovate leaves, flowers in terminal panicles and purple colored corolla. It flowers and fruits throughout the year. It is widely distributed in India, Arabia, and Africa. Cuttings are a ready means of propagation of these plants. *T. cuneifolium* is and has been reported to accumulate high levels of copper in its leaves. These plants showed absorption barriers at high soil copper concentrations, indicating limits to uptake of the metal (Tiagi and Aery 1986; Adeniyi 1996).

4 Ornamental Hydrophytes for Phytoremediation

Several ecotechnological opportunities are available for aquatic plants (Lakshman 1987; Outridge and Noller 1991). The use of aquatic plants in water quality assessment has been in practice for centuries. The occurrence of aquatic macrophytes is unambiguously related to water chemistry and using these plant species or communities as indicators or biomonitors has been well recognized and established for in situ bioremediation (Deng et al. 2004). The noable examples are: *Azolla filiculoides*, *A. philoxeroides*, *Bacopa monnieri*, *Canna flaccida*, *Carex juncell*, *Carex pedula*, *Carex rostrata*, *Carex Sp.*, *Ceratophyllum demersum*, *Chara*, *Nitella*, *Cladium jamaicense*, *Cyperus eragrostis*, *Distichlis spicata*, *Eichhornia crassipes*, *Elodea canadensis*, *Elodea densa*, *E. crassipes*, *Eriocaulon septangulare*, *Euryale ferox*, *Elodea nuttallia*, *E. canadensis*, *Eloea sptangulare*, *Eriophorum angustifolium*, *Eriophorum scheuchzeri*, *Glyceria fluitans*, *Hydrilla verticillata*, *Hygrophila onogaria*, *Isoetes lacustris*, *Lemna minor*, *L. trisulca*, *L. gibba*, *L. palustris*, *H. umbellata*, *Ipomea aquatica*, *Juncus articulatus*, *L. minor*, *Littorella uniflora*, *Ludwigia natans*, *Lysimachia nummularia*, *Myriophyllum spicatum*,

Table 23.1 *Alternanthera philoxeroides* (Mart.) Griseb: Potential for environmental remediation and cleanup

Tolerant to cadmium stress	Ding et al. (2007)
Responds rapidly to shoot removal	Wilson et al. (2007)
Accumulate Cd, Pb, and Zn from constructed wetlands	Liu et al. (2007a, b)
Herbivory, mowing, and herbicides differently affect production and nutrient allocation	Schooler et al. (2007)
Distribution and bioaccumulation of microcystins in water columns: a systematic investigation into the environmental fate and the associated risks with microcystins	Song et al. (2007)
Lead and zinc accumulation and tolerance in populations	Deng et al. (2006)
Exhibit phenotypic plasticity in relation to different water availability	Geng et al. (2006)
Differently respond to biological control	Li and Ye (2006)
Abiotic stress and phenotypic plasticity influenced riparian zone population	Pan et al. (2006)
Growth and reproduction simulated herbivory	Schooler et al. (2006)
Removes Ni(II), Zn(II), and Cr(VI) from aqueous solution	Wang and Qin (2006)
Genetic diversity has been established in *Alternanthera philoxeroides* in China	Wang et al. (2005)
Suitable for phytoremediation of small-scale oil spills in fresh marsh environments: a mesocosm simulation	Dowty et al. (2001)
Biologically controlled with fungi	Barreto et al. (2000)
Its extract had antiviral effect on epidemic hemorrhagic fever virus in vivo	Peng et al. (1997)
Contain phytochemicals, viz., alternanthin, A C-glycosylated flavonoid	Zhou et al. (1988)
Accumulate monosodium methanearsonate (MSMA)	Anderson et al. (1980)
The economics of its biological control	Andres (1977)
Insects as agents for biological control	Bennett (1977)
The biological control in the USA	Spencer and Coulson (1976)
Water hyacinths and alligator weeds for removal of lead, mercury, silver, cobalt, and strontium from polluted waters	Wolverton and McDonlad (1975a, b)

This is not an exhaustive

M. alterniflorum, *Melilotus indica*, *Mentha aquatica*, *Miscanthus floridulus*, *Miscanthus sacchariflorus*, *Mougeotia*, *Najas marina*, *Nasturtium officinale*, *Nuphar lutea*, *Nymphaea alba*, *Nymphaea violacea*, *Nymphoides germinate*, *Potamogeton natans*, *P. attenuatum*, *P. communis*, *Potamogeton crispus*, *P. filiformis*, *P. lapathifoilum*, *P. orientalis*, *P. pectinatus*, *P. perfoliatus*, *P. richardsonii*, *P. subsessiles*, *Phragmites karka*, *Pistia stratiotes*, *Ranunculus aquatilis*, *Ruppia maritima*, *Sagittaria latifolia*, *Salvinia acutes*, *Salvinia molesta*, *Scapania uliginosa*, *Schoenoplectus lacustris*, *Scirpus validus*, *Spartina alterniflora*, *Spirodela oligorrhiza*, *Sporobolus virginicus*, *Typha domingensis*, *Typha latifolia*, *Vallisneria americana*, *Vallisneria spiralis*, *Wolffia globosa, and Zizania aquatica* (Prasad 2007; McCutcheon and Schnoor 2003; Keskinkan et al. 2004; Peles et al. 2002; Hattink et al. 2000; Sheppard and Motycka 1997).

Aquatic plants have been frequently used to remove suspended solids, nutrients, trace metals, toxic organics and bacteria from acid mine drainage (AMD), agricultural landfill, and urban storm-water runoff. In addition, considerable research has been focused on determining the usefulness of macrophytes, as biomonitors of polluted environments and as bioremediative agents in waste water treatments. The response of an organism to deficient or excess levels of metal (i.e., bioassays) can be used to estimate metal impact. Such studies done under defined experimental conditions can provide results that can be extrapolated to natural environment. There are multifold advantages in using an aquatic macrophyte as a study material. Macrophytes are cost-effective, universally available with their ability to survive adverse conditions and high colonization rates and are excellent tools for studies of phytoremediation. Rooted macrophytes especially

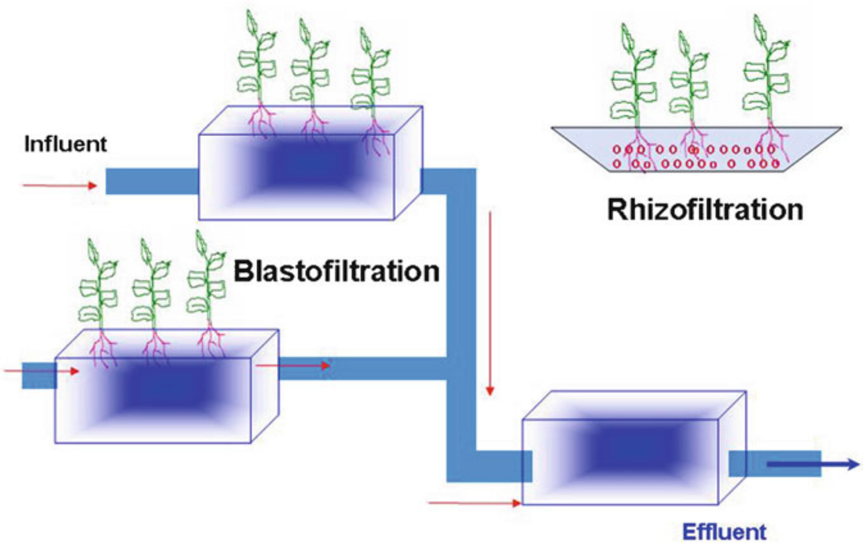

Fig. 23.7 Cascade model for removal of xenobiotics and treatment of waste streams. Most commonly employed species are *Spartina alterniflora*, Cord grass; *Sporolobus virginicus*, Coastal dropseed; *Salicornia virginica*, Perennial glasswort; *Cladium jamaicense*, Sawgrass; *Salicornia alterniflora*, Vermillon cordgrass; *Scirpus validus*, Great bulrush. A cascade model of treatment system was suggested for removal of radionuclides by rhizofiltration Dushenkov et al. 1995; 1997a, b; 2002 and blastofiltration (seedlings), e.g., sunflower

play an important role in metal bioavailability through rhizospheric processes. Macrophytes (floating, emergent, and submersed) readily take up metals in their reduced form from sediments, which exist in anaerobic situations due to lack of oxygen and oxidize them in the plant tissues making them immobile and bioconcentrate them in their tissues, thus reduced the toxic trace metal bioavailability in the interstitial waters. Rooted and emergent macrophytes make them particularly effective as bioindicator of metal pollution, as they represent real levels present at that site.

In the past research with macrophytes has centered mainly on determining effective eradication techniques for nuisance growth of several species such as *Elodea canadensis*, *Eichhornia crassipes*, *Ceratophyllum demersum*, etc. Scientific literature exists for the use of a wide diversity of macrophytes in toxicity tests designed to evaluate the hazard of potential pollutants. Estuarine and marine plant species are being used considerably less than freshwater species in toxicity tests conducted for regulatory reasons. *Lemna*, *Myriophyllum*, *Potamogeton*, *Ceratophyllu*, *Elodea*, *E. crassipes* have been exhaustively used in phytotoxicity investigations. Duckweeds have received the greatest attention for toxicity tests as they are relevant to many aquatic environments, including lakes, streams, and effluents.

The most important role of plants in wetlands is that they increase the residence time of water, which means that they reduce the velocity and thereby increase the sedimentation of particles and associated pollutants. Thus, they are indirectly involved in water cleaning. Plants also add oxygen providing a physical site of microbial attachment to the roots generating positive conditions for microbes and bioremediation.

Constructed and engineered wetlands (including naturalvwetlands) are in use for centuries for waste water treatment containing organic matter, nitrogen, phosphorus, (Kadlec and Knight 1996) (Figs. 23.7 and 23.8).

Aquatic macrophytes have paramount significance in the monitoring of metals in aquatic ecosystems (e.g., *L. minor*, *E. crassipes*, *Azolla pinnata*). Aquatic plants are important in nutrient cycling, control of water quality, sediment stabilization, and provision of habitat for aquatic organisms. The use of aquatic macrophytes in water quality assessment has been a common practice employing in situ biomonitors (Sobolewski 1999). The submerged aquatic

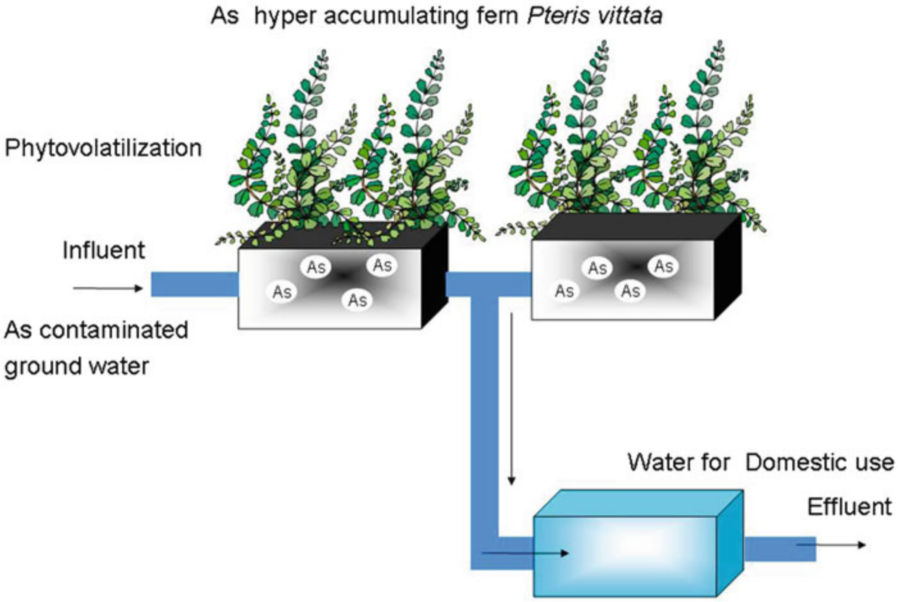

Fig. 23.8 Use of arsenic hyperaccumulator ferns and wetland vegetation (Carbonell-Barrachina et al. 1998; Rahman and Hasegawa 2011; Ma et al. 2001) for arsenic removal from water (Elless et al. 2005)

macrophytes have very thin cuticle and therefore readily take up metals from water through the entire surface. Macrophytes with their ability to survive adverse conditions and high colonization rate are excellent tools for phytoremediation. Further they redistribute metals from sediments to water and finally take up in the plant tissues and hence maintain circulation. Benthic rooted macrophytes (both submerged and emergent) play an important role in metal bioavailability from sediments through rhizosphere exchanges and other carrier chelates. This naturally facilitates metal uptake by other floating and emergent forms of macrophytes. Macrophytes readily take up metals in their reduced form from sediments, which exist in anaerobic situations due to lack of oxygen and oxidize them in the plant tissues making them immobile and thus get bioconcentrated in their tissues (Okurut et al. 1999).

A special group of plants may reduce element leakage from mine tailings by phytostabilization. Plants that are tolerant to elements of high concentrations have been found useful for reclamation of dry mine tailings containing elevated levels of metals and other elements. Mine tailings rich in sulfides, e.g., pyrite, can form AMD if it reacts with atmospheric oxygen and water, which may also promote the release of metals and As. To prevent AMD formation, mine tailings rich in sulfides may be saturated with water to reduce the penetration of atmospheric oxygen. An organic layer with plants on top of the mine tailings would consume oxygen, as would plant roots through respiration. Thus, phytostabilization on water-covered mine tailings may further reduce the oxygen penetration into the mine tailings and prevent the release of elevated levels of elements into the surroundings. Metal tolerance can be evolutionarily developed while some plant species seem to have an inherent tolerance to trace metals. Since, some wetland plant species have been found with the latter property, for example, *T. latifolia*, *G. fluitans,* and *Phragmites australis*, wetland communities may easily establish on submerged mine tailings, without prior development of metal tolerance. Some plant species have mechanisms that make it possible to cope with high external levels of elements. Low accumulators are plants that can reduce the uptake when the substrate has high element concentrations or have a high net efflux of the element in question, thus the plant tissue concentration of the element is low even though the concentration in the substrate is high (Williams 2002; Wood and Mcatamney 1994; Woulds and Ngwenya 2004; Ye et al. 2001).

5 Utilization of Water Weeds for Bioremediation of Metalliferous Substrates

Weeds cannot be eradicated, hence there is a need to find appropriate and sustainable solutions. (Ji et al. 2011; Lin and Liu 2003); Liphadzi et al. 2003) Several of the wetland plants not only effectively purify metal contaminated water effectively (Horne 2000), Zhang et al. 2007 but also establish a dense vegetative cover (Ye et al. 2003).

For successful phytoremediation, plants chosen should have the following attributes:

(a) Adaptive and tolerance mechanisms.
(b) Fast growing with high bioproductivity such as duck weeds (Fig. 23.9) *Typha latifolia* (Cattail) and *Phragmites australis* (Ye et al. 1997a, b), *Eichhornia crassipes* (water hyacinth), *Alternanthera philoxeroides* (alligator weed), *Pistia stratiotes* (water lettuce), and *Potamogeton crispus*. The biomass production of these plants often exceeds the yield of most productive agricultural crops.

Further, the dried biomass of many of these aquatic macrophytes is an excellent biosorbent for removal of Cr(III), Ni(II), Cu(II), Zn(II), Cd(II), and Pb(II) (Andre et al. 1999). Wetland plants (water weeds) accelerate the sedimentation in constructed wetland and this being principal process for the removal of heavy metals from wastewater. Also wetland plants act as sites for metal precipitation (Mays and Edwards 2001). Water weeds for treatment of waste water are enumerated in Table 23.2

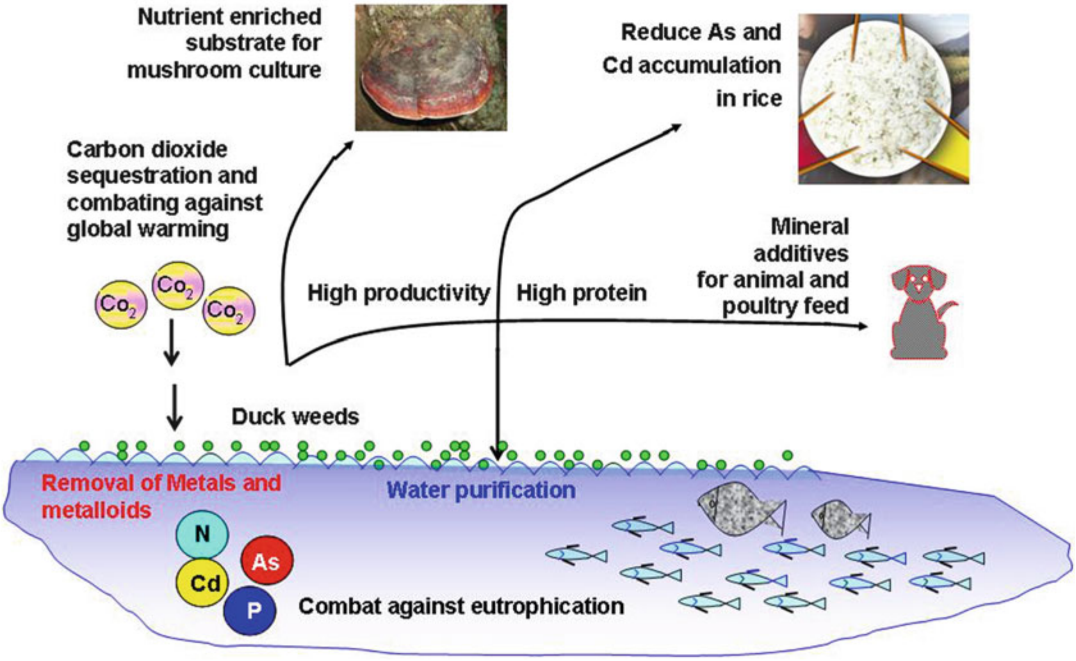

Fig. 23.9 Duck weeds for waste water treatment and for phytoproducts

Table 23.2 Water weeds for treatment of waste water: Lab, field, and pilot-scale experiments (not exhaustive)

Uptake of Zn, Cu, and Cd in metal loaded *Elodea canadensis*	Nyquist and Greger (2007)
Tolerance and phytoaccumulation of chromium by three *Azolla* species	Arora et al. (2006)
Tolerance and accumulation of copper and chromium in two duckweed species: *Lemna minor* L and *Lemna gibba* L	Ater et al. (2006)
Phytoremediation of chromium by model constructed wetland	Mant et al. (2006)
Wetland grasses for phytoremediation	Czako et al. (2005)
Accumulation of As in *Lemna gibba* (duckweed) in tailing waters of two abandoned uranium mining sites in Saxony, Germany	Mkandawire and Dudel (2005)
Potential of *Azolla caroliniana* for the removal of Pb and Cd from wastewaters	Stepniewska et al. (2005)
Lead accumulation in the aquatic fern *Azolla filiculoides*	Benaroya et al. (2004)
The ability of *Azolla caroliniana* to remove heavy metals such as Hg^{2+}, Cr^{3+}, Cr^{6+} from municipal wastewater	Bennicelli et al. (2004)
Responses induced by high concentration of cadmium in *Phragmites australis* roots	Ederli et al. (2004)
Capacity of *Salvinia minima* to tolerate and accumulate As and Pb	Hoffmann et al. (2004)
Phytoaccumulation of heavy metals by aquatic plants	Kamal et al. (2004)
Bioaccumulation of copper from contaminated wastewaters by using *Lemna minor* (aquatic green plants)	Kara (2004)
Heavy metal adsorption properties of a submerged aquatic plant (*Ceratophyllum demersum*)	Keskinkan et al. (2004)
Capacity of *Lemna gibba* (duckweed) for uranium and arsenic phytoremediation in mine tailing waters	Mkandwire et al. (2004)
Accumulation of trace elements by *Pistia stratiotes*: implications for phytoremediation	Odjegba and Fasidi (2004)
Metal uptake transport and release by wetland plants: implications for phytoremediation and restoration	Weis and Weis (2004)
Lead and nickel removal using *Microspora* and *Lemna*	Axtell et al. (2003)
Removal of heavy metals from aqueous solution by water hyacinth (*Eichhornia crassipes*)	Ingole and Bhole (2003)
Removal by marsh macrophytes *Spartina alterniflora* (cordgrass) and *Phragmites australis* (common reed)	Windham et al. (2003)
Phytoaccumulation and phytotoxicity of Cd and Cr in *Wolffia globosa*	Boonyapookana et al. (2002)
Chromium removal from tannery effluents by aquatic plants	Sinha et al. (2002)
Biosorption of cadmium and chromium in duckweed *Wolffia globosa*	Upatham et al. (2002)
Chromium phytoaccumulation from solution by selected hydrophytes	Zurayk et al. (2001)

5.1 *Ipomoea aquatica*

Ipomoea aquatica is a fast growing aquatic plant and has been applied widely to purify eutrophic water. It is a metal accumulator and metal removal potential depends upon levels of metal contamination in the water body in which they were growing. Water is regarded as a limited and susceptible resource, essential for life. It is widely distributed throughout tropical and warm climate regions in the world, especially in China and India. It is a fast-growing herbaceous vine commonly found in creeping on muddy stream banks or floating in freshwater marshes and ponds. Moreover, its leaves have high nutritive value and eaten as vegetables by human beings as well as fish and other grazing animals, and possess medicinal importance. In addition, in recent years, it is also used widely to purify wastewater (Gothberg et al. 2002, 2004; Cao et al. 2006; Hu et al. 2007). Rai et al. (1995) reported the toxic metals Pb, Cd, and Cr in *I. aquatica* accumulated highly from water resources of Eastern Ghats of India.

6 Biocontrol of Invasives Applied in Phytoremediation

Classical biocontrol agents or mycoherbicides are known for biocontrol of the following water weeds (Barreto et al. 2000): *Azolla xliculoides*, *Echinochloa polystachya*, *Eichhornia azurea*, *E. crassipes*, *Egeria densa*, *Myriophyllum aquaticum*, *Paspalum repens*, *Pistia stratiotes*, *Polygonum spectabile*, *Salvinia auriculata*, *S. molesta,* and *Typha domingensis*.

A triad approach of lab, pilot, and field studies are necessary for understanding the limitations and scope of bioremediation potential of weeds (Figs. 23.10 and 23.11).

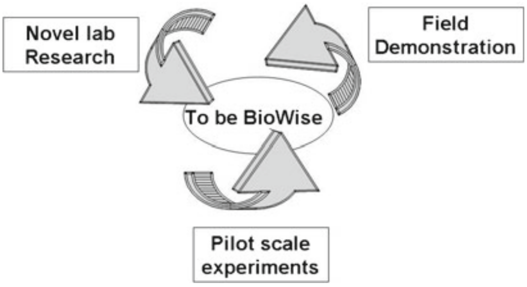

Fig. 23.10 The triad approach for successful bioremediation

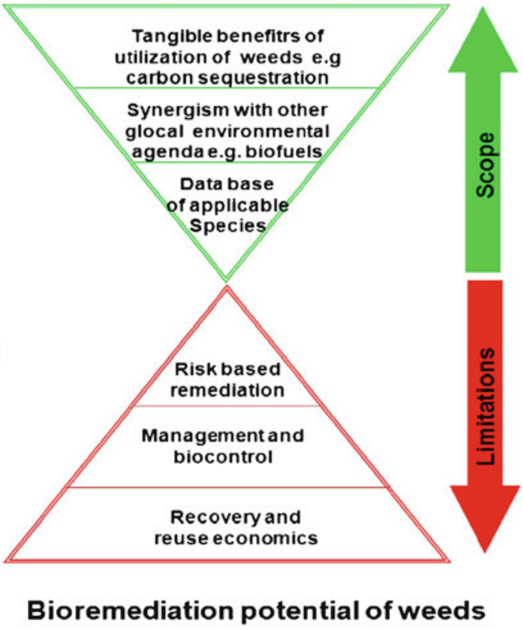

Fig. 23.11 Scope and limitations of weed application for bioremediation of heavy metals

7 Conclusions and Future Perspective

Screening of weeds and ornamentals capable of accumulating and hyperaccumulating metals for bioremediation of metalliferous substrates in the era of climate change has sufficient scope. Weeds, ornamentals, and grasses possess such properties. Some of these are extensively adaptive in capacity. Compared with crop, they possess adaptive and antistress properties which make them exceptional to grow in metalliferous substrates. With these characteristics, it is possible that weeds exhibit strong tolerance and exceptional functions to heavy metals. Identification of appropriate soil amendments that can enhance biomass production need to be investigated. Selected examples of weeds that might be useful for polishing soils contaminated with metals are *Solanum nigrum*, *Rorippa globosa*, *Bidens pilosa*, *Taraxacum mongolicum*, *Conyza canadensis,* and *Kalimeris integrifolia* (Wei and Zhou 2004a, b, 2008a, b; Wei et al. 2005, 2006, 2008a, b, 2009, 2010a, b). *Chromolaena odorata* (L) King & Robinson, (Asterceae), an invasive weed has the capability to phytoremediate soil contaminated with crude oil in the presence of metals (Atagana 2011; Tanhan et al. 2007). Critical functions of weeds for potential applications in cleanup of metalliferous substrates are:

(a) Translocation property: the contents of heavy metals in shoots should be higher than those in its roots, i.e., TF (transport factor) > 1.
(b) Enrichment factor: the concentration ratio in plant shoots to soils should be higher than 1 (EF > 1).
(c) Use of soil amendments for enhancing the biomass production for removal of metals.

Several potential and promising options for this emerging technology are forging ahead for environmental management., yet certain bottlenecks are to be investigated for wider applications such as (a) many tested plants have bioconcentration factor (BCF) less than 1, (b) usage of soil amendments and chelators may be necessary for achieving the hyperaccumulation and BCF > 10.

The regulatory bodies and environmental safety agencies are concerned about chelate and amendment assisted cleanup, as this approach would rapidly mobilize contaminant and increase the area of contamination including leaching of the toxic trace metals into ground water. Costs of the chelate applications need to be assessed. Arsenic hyperaccumulating fern, *Pteris vittata* (an important foliage ornamental), was used in the pilot-scale demonstration phytofiltration project to produce drinking quality water from arsenic contaminated ground water in New Mexico, a classic example of service to mankind (Elless et al. 2005).

The compost generated from the plants used in remediation serves as a compost and can be reused as growing media for production of ornamentals (Abad et al. 2001; Benito et al. 2006; Hernandez-Apaolaza et al. 2005; Hicklenton et al. 2001; Ingelmo et al. 1998) (Table 23.3). These questions have been satisfactorily answered for fostering phytoremediation using ornamentals. Phytoremediation technologies today have reached the site from lab to pilot-scale trials and field applications using aquatic, terrestrial (Prasad 2003, 2004a, b, 2007; Prasad and Freitas 2003) including space ecology (Kozyrovska et al. 2004, 2006). The debris generated from the ornamentals containing the toxic metal residues need to be treated as the biomass would be relatively less in view of high water contents and an appropriate

Table 23.3 Ornamentals for environmental cleanup and ecosystem service

Ornamental for environmental moderation and remediation	References
Calendula officinalis and *Althaea rosea* exhibited higher tolerance to Cd and Pb contamination and could effectively accumulate these metals	Liu et al. (2007a, b)
Ni(II) biosorption by *Cassia fistula* (its common names are Amaltas, Canafistula, Golden Shower, and Indian Laburnum)	Hanif et al. (2007)
Flindersia schottiana is a tree species used in the ornamental horticulture industry. Urea formaldehyde resin foam (UFRF) product used as a soil amendment. It is proposed to improve the physicochemical properties (viz., water relations and aeration) of the plant root zone. UFRFs are a relatively new class of soil amendment compared with hydro gels. Under plant nursery conditions, incorporation of 30% (v/v) Hydrocell™ into composted pine bark media and also into sand and loam soils led to limited, but significant ($P \leq 0.05$) growth benefits (e.g., increased leaflet number) for potted	Chan and Joyce (2007)
Biodegradable chelating agents, [*S*,*S*]-ethylenediaminedisuccinic acid (EDDS) and methylglycinediacetic acid (MGDA) assisted. Trace metals phytoextraction was demonstrated in *Mirabilis jalapa* including the growth of the associated bacterial population	Cao et al. (2007)
Phytoextraction trace metals with *Mirabilis jalapa*, combinatorial effect of biodegradable chelating agents and on its associated bacteria	Cao et al. (2007)
Crassula portulacea (Crassulaceae), *Hydrangea macrophylla* (*Hydrangeaceae*), *Cymbidium* Golden Elf (Orchidaceae), *Ficus microcarpa var. fuyuensis* (Moraceae), *Dendranthema morifolium* (Asteraceae), *Citrus medica var. sarcodactylis* (Rutaceae), *Dieffenbachia amoena cv. Tropic Snow* (Araceae), *Spathiphyllum Supreme* (Araceae), *Nephrolepis exaltata cv. Bostoniensis* (Davalliaceae), and *Dracaena deremensis cv. Variegata* (Dracaenaceae) had greatest capacity to remove benzene from indoor air	Liu et al. (2007a, b)
African marigold (*Tagetes erecta*), scarlet sage (*Salvia splendens*), and sweet hibiscus (*Abelmoschus manihot*) were investigated. According to the tolerant indexes, sweet hibiscus (*A. manihot*) was the most tolerance while scarlet sage (*S. splendens*) was the least and African marigold (*Tagetes erecta*) is in between	Wang and Zhou (2005)
Different compensatory mechanisms in two metal-accumulating aquatic macrophytes exposed to acute cadmium stress in outdoor artificial lakes	di Toppi et al. (2007)

(continued)

Table 23.3 (continued)

Ornamental for environmental moderation and remediation	References
Ficus microcarpa can provide useful information about the spatial variations of Ba, Cu, Fe, and Mg contents assuming the spatial differences are high enough. Temporal variations are evident for Al, Cu, Fe, Mg, Pb, V, and Zn. *F. microcarpa* foliage is not considered as a reliable biomonitor for Pb, Zn, and V in the urban areas	Oliva and Rautio (2005)
Tagetes patula and ornamental arum (*Syngonia* sp.) as phytoremediators of arsenic	Huq et al. (2005)
Araucaria angustifolia (Brazilian pine). The species is valuable for its wood, edible seeds, and ornamental use, and is today listed as a threatened species. This tree species establishes associations with arbuscular mycorrhizal fungus *Glomus clarum*, *Araucaria angustifolia* seedlings inoculated with *G. clarum* had a high degree of mycorrhizal colonization of their roots (81%). The inoculated seedlings grew significantly more (312% mass increase) than the controls	Zandavalli et al. (2004)
Cyperus papyrus and *Miscanthidium violaceum*-based constructed wetlands for wastewater treatment in a tropical country – a comparative study	Kyambadde et al. (2004)
Anorthosite is a poor support of the marigold growth, hence bacterial residents of alumino-silicate rocks to leach the plant essential ions from a substrate and therefore improved plant development and identified pioneer plants for a lunar base	Kozyrovska et al. (2004, 2006)
Ipomoea aquatica (water spinach, Morning glory, Convolvulace), is common in Southeast Asia. *I. aquatica* significantly accumulated toxic metals (such as cadmium, copper, and lead) in the roots, stems, and leaves	Costa-Pierce (1998), Kashem and Singh (2002), Gothberg et al. (2004)
Ornamental hydrophytes, viz., *Acorus gramineus* Soland and *Iris japonica* L., *Acorus calamus* L., *Lythrum salicaria* L., are suitable for sewage treatment. Performance of *Canna indica* on domestic sewage was better than *Phragmites communis*	Liu et al. (2003), Zhao et al. (2003)
Phosphate enhanced arsenic uptake by *Lolium perenne*, *Urtica dioica,* and *P. vittata*. Thus to alleviate arsenic toxicity, phosphate condition has to be managed	Otte et al. (1990), Cao et al. (2003)
Uptake and translocation of plutonium in two plant species using hydroponics. Comparative uptake of plutonium from soils by *Helianthus annuus*	Lee et al. (2002a, b)
Transgenic hairy roots in ornamentals: recent trends and applications	Giri and Narasu (2000)
Reed beds for water treatment	Lienard et al. (1995)
Nutrient removal from aquaculture wastewater using a constructed wetlands system	Lin et al. (2002)

techno-economic feasible options based on integrated model systems was recently suggested for the appropriate use of *E. crassipes* (water hyacinth) (Malik 2007). Similar solutions need to be worked out for the ornamental plants proposed for toxic metal cleanup, since each ornamental plant is a nonpolluting chemical factory producing a wide range of bioresource for the welfare of the mankind in addition to their ecosystem service, viz., environmental remediation and enhancing the beauty with esthetics and fragrance (Table 23.3).

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