Biotechnology and Bioprocess Engineering 18: 431-439 (2013)
DOI 10.1007/s12257-013-0193-8

REVIEW PAPER

An Overview of Phytoremediation as a Potentially Promising Technology for Environmental Pollution Control

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Received: 25 March 2013/ Accepted: 27 March 2013

Abstract Phytoremediation is the use of plants for the removal of pollutants from contaminated soil or water. Phytoremediation is an environmentally friendly and cost-effective alternative to current remediation technologies. This review article outlines general aspects of phytoremediation, along with discussions about its advantages and limitations. It further reviews various phytoremediation processes in detail: phytoextraction, rhizofiltration, phytostabilization, phytodegradation, and phytovolatilization. Unlike previous review articles available in various journals, this paper presents a more comprehensive view of this issue, and deals with a much wider range of its applications to environmental pollution control. These include the treatment of wastewaters, removal of heavy metals and metalloids (*e.g.* lead and arsenic), phytoremediation of organic pollutants, such as 2,4,6-trinitrotoluene (TNT) and polychlorinated biphenyls (PCBs), and cleanup of soil and water contaminated with radionuclides, such as cesium (^{137}Cs) and strontium (^{90}Sr). This paper also describes recent developments of transgenic plants for improving phytoremediation. Along the way, the present status of phytoremediation research in Korea is briefly introduced. Finally, the article concludes with suggestions for future research.

Keywords: phytoremediation, hyperaccumulator, heavy metals, radionuclides, organic xenobiotics, transgenic plants

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1. Introduction

Contamination of soil and water with organic or inorganic waste poses major environmental and human health problems [1]. Over the last two decades, plant-based environmental remediation (*i.e.* phytoremediation) has been widely pursued as a favorable clean-up technology, and is an area of intensive scientific investigation [2]. Phytoremediation is defined as the use of green plants to remove pollutants from the environment, or to render them harmless [3-5]. Excellent review articles on this subject are available in the literature [1,3,5-10].

Phytoremediation may be carried out by using hyperaccumulators. These are plants that can absorb high levels of contaminants with their roots. In general, plants are involved in the uptake, translocation, sequestration, and degradation of pollutants. Subsequently, the plants can be harvested, and processed by drying, ashing or composting. Some metals can be reclaimed from the ash [1]. The hyperaccumulators can accumulate 50 ~ 100 times more metals that normal plants [8,9]. The degree of accumulation of metals in these plants often reaches 1 ~ 5% of the dry weight. Examples include species of *Thlaspi*, which can accumulate more than 3% Zn, 0.5% Pb, and 0.1% Cd in their shoots [9]. Currently about 400 species of meta l hyperaccumulators are identified [3,11]. The best hyperaccumulators should have the following traits: an ability to accumulate high levels of contaminants; a fast growth rate; high biomass production; and resistance to diseases and pests [12].

An alternative to the use of hyperaccumulators, is the use of normal plants together with the manipulation of soil conditions, either to increase the bioavailability, or the stabilization of metals [9]. As metallic contaminants are usually present in insoluble and unavailable forms, the use of plants to remediate contaminants can be aided by the proper use of soil amendments [11]. The most successful amendments have been the addition of chelates, such as ethylenediaminetetraacetic acid (EDTA, henceforth) for lead, ethyleneglycoltetraacetic acid (EGTA) for cadmium, and possibly citrate for uranium [3]. Certain chelating agents can increase the ambient soil solution levels of certain heavy metals greater than 1,000-fold [7], and these agents greatly facilitate metal uptake by soil-grown plants [1]. For example, the accumulation of Pb in the shoots of plants such as *Zea mays* and *Brassica juncea* was enhanced through the application of EDTA [13,14]. For chelate-assisted phytoremediation (*viz*. induced phytoextraction), EDTA is added to the soil, shortly before plant harvesting [3]. In contrast, metal-inactivating soil additives, such as coal fly ash or zeolites, strongly reduce the availability of metals to plant uptake, and limit eventual toxicity to plants [15]. In addition, other factors, such as soil conditions (*e.g.* pH, pKa, organic and water content, texture) and plant physiology, may also influence the bioavailability and uptake of target compounds [3].

Phytoremediation has several advantages, compared to conventional physico-chemical methods, as can be seen below [10,16]:

- It is an aesthetically pleasing, environmentally-friendly technology.
- It is an inexpensive technology (50 ~ 80% of the cost of current methods, or even less). In most cases, engineering costs are minimal [9], and this technology can be applied both *in situ* and *ex situ*.
- It is useful for treating a broad range of environmental contaminants.
- There is minimal disruption of the environment.
- There is the possibility of the recovery and re-use of valuable metals after harvesting processes. The harvested biomass can be reduced in volume and/or weight, by thermal, microbial, or chemical means [7].

On the other hand, phytoremediation has a number of limitations. The disadvantages of phytoremediation are:

- Phytoremediation is most effective only at sites with shallow contaminated soils and water (< 5 m depth).
- It is a time-consuming process, and climate or seasonal conditions may interfere with or inhibit plant growth.
- Organic and inorganic contaminants may be toxic to plants, and thus the survival of the plants may be affected by the toxicity of the contaminants.
- Plants that absorb toxic contaminants may pose potential risks of transferring contaminants to the food chain.

Although phytoremediation has the limitations described above, phytoremediation is increasingly recognized as a developing technology that promises effective and inexpensive cleanup of contaminated sites. As a result, phytoremediation is currently used for removing pollutants from contaminated soil and water in the United States and EU countries [12,15,20]. Although there are several review articles on phytoremediation [1,3,5-9,18,31,53,56,68-73], most individual articles deal with only a very specific application of phytoremediation, and are rather limited in suggesting the values of phytoremediation. Unlike other researchers, therefore, the author attempts in the present article to present a much more comprehensive view of its applications to various forms of environmental pollution control. These include the treatment of wastewaters, removal of heavy metals and metalloids (*e.g.* lead and arsenic), phytoremediation of organic pollutants, such as 2,4,6-trinitrotoluene (TNT) and polychlorinated biphenyls (PCBs), and cleanup of soil and water contaminated with radionuclides, such as cesium (^{137}Cs) and strontium (^{90}Sr).

It is expected that bioprocess and environmental engineers would provide significant contributions to commercial development of phytoremediation processes. Nevertheless, no review article regarding phytoremediation has been published to date by the Biotechnology and Bioprocess Engineering Journal. The aim of the present study is to give a broad overview of phytoremediation, and its application to environmental pollution control. To begin with, various phytoremediation processes will be briefly introduced in section 2. Then, its applications to various environmental pollution controls will be summarized in section 3. In addition, recent development of transgenic plants for enhanced phytoremediation of toxic metals and organic xenobiotics will be outlined in section 4. Finally, the present status of phytoremediation research in Korea will be presented in section 5, and conclusions drawn in section 6.

2. Various Phytoremediation Processes

Phytoremediation is divided into a number of processes: Phytoextraction, rhizofiltration, phytostabilization, phytodegradation, and phytovolatiliization [3,9]. In fact, these phytoremediation processes operate simultaneously, to some extent. Fig. 1 shows the processes of the five main subgroups involved in phytoremediation [1,3,4,8,10,17]:

• *Phytoextraction*

The use of pollutant-accumulating plants to remove metals (*e.g.* Cd, Pb, Zn, Ni, Cr, Co), metalloids (*e.g.* As, Se), and radionuclides (*e.g.* ^{90}Sr, ^{137}Cs, ^{238}U) from soil by concentrating them in the harvestable parts of root and above-ground shoots. The plant biomass is then followed

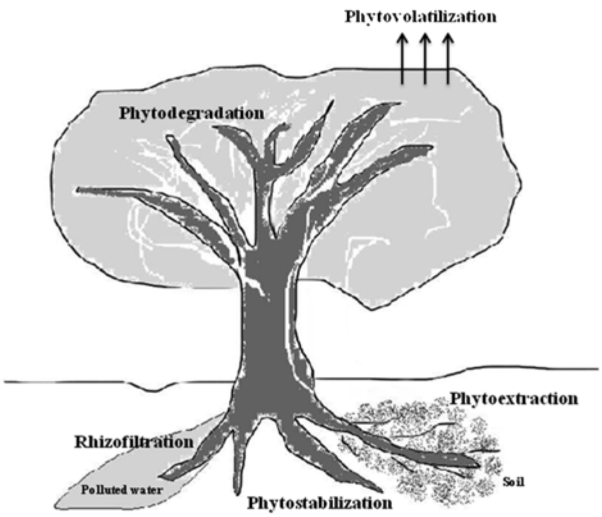

Fig. 1. The processes involved in phytoremediation, illustrating phytoextracion, rhizofiltration, phytostabilization, phytodegradation, and phytovolatilization.

by ultimate disposal. The phytoextraction of heavy metals and radionuclides represents one of the largest economic opportunities for hytoremediation [1]. Popular species for phytoextraction include Indian mustard (*Brassica juncea*) and sunflower (*Helianthus annuus*), because of their fast growth, high biomass, and high tolerance of heavy metals [10].

• ***Rhizofiltration***
The use of plant roots to absorb, precipitate, and concentrate pollutants from surface water and aqueous waste streams. An ideal plant for rhizofiltration should have rapidly growing roots, with the ability to remove toxic metals from solution [1]. Rhizofiltration will be a particularly cost-effective technology in the treatment of surface and ground water containing relatively low concentration of toxic metals [18]. Therefore, this process may be particularly applicable to radionuclide contaminated water.

• ***Phytostabilization***
The use of plants to immobilize or stabilize contaminants in the soil, thereby reducing the bioavailability of pollutants in the environment, and reducing the risk of further environmental degradation by leaching into the water or by airborne spread. This process is not to degrade, but to reduce the mobility of the contaminants; and prevents migration to deeper soil or ground water [16]. Unlike phytoextraction, phytostabilization focuses mainly on sequestering pollutants in soil near the root, but not in plant tissues. Phytostabilization of heavy metal-polluted soils is already a proven technology in Europe. One of the most successful examples was the use of beringite, for treating a site heavily contaminated with Zn and Cd, in Belgium [15]. However, phytostabilization is a less-developed area of phytoremediation research [1].

• ***Phytodegradation***
The use of plants with associated microorganisms to degrade organic pollutants, such as 2,4,6-trinitrotoluene (TNT) and polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), herbicides, pesticides, and inorganic nutrients. For example, hybrid poplars are capable of degrading trichloroethylene (TCE), which is one of the most common pollutants [19]. Plants produce enzymes (*e.g.* dehalogenase, peroxidase, nitroreductase, laccase, nitrilase), which help degrade pollutants [6,16,20]. Phytodegradation is the uptake and degradation of contaminants within the plant, or the degradation of contaminants in the soil, ground water, or surface water, by enzymes. Phytodegradation is most suited for moderately hydrophobic organic chemicals (octanol-water partition coefficients, log K_{ow} = 0.5 ~ 3.0) [3,6]. These include most BTEX (benzene, toluene, ethylbenzene, and xylene) chemicals, chlorinated solvents, and short-chain aliphatic chemicals [6]. If organics are too hydrophilic (log K_{ow} < 0.5), they cannot pass membranes, and never get into the plants. In contrast, hydrophobic chemicals (log K_{ow} > 3.0) are bound so strongly to the surface of roots, that they cannot easily be translocated within the plant [6].

• ***Phytovolatilization***
The use of plants to extract contaminants, which are then dispersed into the atmosphere by volatilization from leaf surfaces. Toxic metals, such as Se, As, and Hg, can be biomethylated to form volatile molecules, which can then be lost to the atmosphere [1]. For example, Se volatilization in the form of methyl selenate was reported as a major mechanism of Se removal by plants [21,22]. Once volatilized, the molecules may be degraded further in the atmosphere, or stay as air pollutants. Therefore, risk assessment studies may be necessary, so that this process will become accepted by regulators, and the public [3].

3. Examples of Applications

3.1. *Wastewater treatment*

Various plants have been employed in the treatment of wastewaters. Biddlestone *et al.* used reed (*Phragmites australis*) bed systems to reduce dairy waste with a BOD_5 value of 1,006 mg/L, down to 57 mg/L [23]. Sub-surface constructed wetlands with *Phragmites australis* for wastewater treatment have been intensively studied in the Czech Republic, for several decades [24]. The size of these wetlands was in the range of 18 ~ 4,500 m^2, and the treatment efficiency was found to be excellent (*i.e.* 88% reduction in BOD_5, and 84% for suspended solids). Similar results were also obtained with *Typha latifolia* and *Salix atrocinerea* in Spain, for municipal wastewater treatment [25]. In addition, a comparative study of *Cyperus papyrus* (papyrus) and *Miscanthidium violaceum*-planted wetlands for wastewater treatment in Uganda revealed that papyrus was the more efficient for removing nutrients (ammonium-nitrogen and total reactive phosphorus) [26].

Recent work by Bodini *et al.* showed that *Cupressus sempervirens* and *Quercus ilex* proved tolerant to six-month olive mill wastewater, followed by six-month water irrigation [27]. The olive mill wastewater is characterized by low pH, high BOD_5 and COD loads, and phytotoxic levels of phenolic compounds, and thus has been a waste management problem in olive oil producing countries. It is interesting to note that phytoremediation of textile effluent with *Glandularia pulchella* was tested to decolorize structurally different dyes. Differential patterns of enzyme induction, with respect to time, were obtained for lignin peroxidase, tyrosinase and dichlorophenolindophenol reductase, during the decolorization of dye mixture [28].

3.2. Phytoremediation of toxic elemental pollutants such as heavy metals

Microbial bioremediation has been successful, to some extent, in the degradation of certain organic contaminants. However, it is ineffective for toxic metal contaminants. In general, organic molecules can be degraded, but toxic metals can only be remediated by removal from soil [1]. Removal of toxic heavy metals is one of the major targets for phytoremediation [1,3]. Phytoextraction, together with rhizofiltration, are the best-developed subgroups of toxic metal phytoremediation. All plants have an ability to accumulate heavy metals, which are essential for their growth and development [18]. These metals include Fe, Mn, Zn, Cu, Mg, Mo, and Ni. On the other hand, certain plants also have the ability to accumulate other heavy metals (*e.g.* Cd, Cr, Pb, Co, Ag, Se, and Hg), which have no known biological function [18]. Inorganics are usually present as charged cations or anions, and thus are hydrophilic [10].

Some plants are capable of accumulating exceptionally high concentrations of phytotoxic metals, such as Zn, Ni, Cd, Mn, Cu, and Co, in their harvestable biomass [7]. For example, a number of the *Brassica* family, *Thlaspi caerulescens*, can accumulate up to 4% zinc in its tissue, without apparent damage [5]. Another example of Ni hyperaccumulator is *Alyssum bertolonii*, which has been successfully used for phytoremediation in practice [10]. The ecological role of metal hyperaccumulation is still not clear, but it has been suggested that metal accumulation provides protection against fungal and insect attack [1,3]. Table 1 includes some applications of phytoextraction for toxic elemental pollutants. Examples of well-known hyperaccumulators are *Pteris vittata* and Indian mustard (*Brassica juncea*), which accumulate arsenic and lead, respectively. Mercury has been removed from soils by transgenic plants expressing a modified bacterial gene [29,30]. It was reported that *Thlaspi caerulescens* has a high resistance to the toxic effects of both Zn and Ni in its shoots [18].

3.3. Phytoremediation of organic pollutants

Organic pollutants in the environment are mostly manmade, and xenobiotic to the plant. Organic pollutants are released into the environment *via* spill (fuel, solvents), military activities (explosives, chemical weapons), agriculture (pesticides, herbicides), industry (chemical, petrochemical), wood treatment, *etc.* [10]. Unlike inorganic pollutants, organic pollutants can be degraded to stable intermediates, or even mineralized to inorganic compounds (*e.g.* CO_2, H_2O, and Cl_2) by some plants and their associated enzymes. This process is called phytodegradation. Several plant degradative enzymes (*e.g.* dehalogenase, peroxidase, nitroreductase, laccase, and nitrilase) have been identified in previous studies [6,16,20]. Until now, soil amendments that can induce the uptake and accumulation of organics in plants are mostly not known.

Plants can facilitate biodegradation of organic pollutants by microbes in their rhizosphere (root-soil interface). This is called phytostimulation, or rhizodegradation [10]. Phytosti-

Table 1. Examples of the phytoextraction of toxic elemental pollutants

Chemical element (s)	Description	Plant	Effect	Reference
Zinc (Zn) and nickel (Ni)	Transition metal	*Thlaspi caerulescens*	2.9 mg/g dry weight for Zn and 8.4 mg/g dry weight for Ni in roots	[18]
Selenium (Se)	Non-metal	*Brassica oleracea*	-	[22]
Arsenic (As)	Metalloid	*Pteris vittata*	Removal of 3.5 ~ 11.4% of the total soil As	[60]
Cadmium (Cd)	Transition metal	*Solanum nigrum*	-	[61]
Lead (Pb)	Metal	*Brassica juncea*	108 mg of Pb/g dry weight in roots	[62]
Mercury (Hg)	Transition metal	Transgenic *Arabidopsis thaliana*	Conversion of toxic Hg^{2+} to less toxic Hg^0	[29]

mulation is used for hydrophobic organics (*e.g.* PCBs, PAHs and other hydrocarbons, log $K_{ow} > 3.0$) that cannot be taken up by plants, but that can be degraded by microbes. Plants release organic compounds in the rhizosphere, which can serve as carbon sources for bacteria and fungi. Densities of microbes in the rhizosphere can be as much as two to four orders of magnitude greater than populations in the surrounding soils, and these microbes are able to degrade a number of recalcitrant xenobiotics, such as polychlorinated biphenyls (PCBs), and polycyclic aromatic hydrocarbons (PAHs) [3].

Organic pollutants removed by phytodegradation include explosives, such as 2,4,6-trinitrotoluene (TNT) [31-33], and solvents, such as trichloroethylene (TCE) [19]. The removal of TNT from contaminated wetlands, and TCE from ground water using poplar trees, has been successfully applied in America [20]. While nitroreductase and laccase break down TNT, dehalogenase helps reduce chlorinated solvents, such as TCE, to chloride ion, carbon dioxide, and water [6]. Others examples include pesticides [34,35], as well as herbicides [36]. In contrast, phytostimulation works particularly well for some organics. Examples are polychlorinated biphenyls (PCBs) [37-39], polycyclic aromatic hydrocarbons (PAHs), such as naphthalene [40-43], and petroleum hydrocarbons, such as diesel [44-47], and ethylene glycol [48].

3.4. Cleanup of soil and water contaminated with radionuclides

Radionuclide contamination represents another major opportunity for phytoremediation [18]. Contamination of soil and water by radionuclides occurs due to natural processes, nuclear weapon testing, discharges from nuclear installations, disposal of nuclear waste, and occasional nuclear accidents, such as Chernobyl in 1986, and Fukushima in 2011 [49]. After the Chernobyl nuclear accident in the Ukraine, the so-called Chernobyl sunflower project began in 1994 [50]. The sunflower (*Helianthus annuus*) preferentially absorbed cesium (^{137}Cs) and strontium (^{90}Sr) from a mixture of metals. The plants did not metabolize the radionuclides, but the cesium stayed in the roots, and most of the strontium moved to the shoots. It was reported that *Brassica juncea* also was able to accumulate ^{90}Sr [18]. Similar results were obtained using a giant milky weed (*Caltropis gigantean*), and the plant was found to be a potential candidate plant for phytoremediation of ^{137}Cs and ^{90}Sr [49]. It seems that the same plant-driven approach can also be applied to decontaminating the Fukushima nuclear accident that occurred in Japan.

On the other hand, it was found that a common reed (*Phragmites australis*), grown in uranium-contaminated soils, accumulated uranium (^{238}U) in the roots, and translocated to the shoots, in limited amounts [51]. The plant could be useful for phytoremediation of mine waters in uranium mining areas. In addition, Saleh investigated water hyacinth (*Eichhornia crassipes*) for phytoremediation of cesium (^{137}Cs) and cobalt (^{60}Co) [52]. Cesium (^{137}Cs) and cobalt (^{60}Co) are known to be dominant radionuclides among fission products, and release of these radionulides may arise from low-level radioactive disposal facilities [52]. Table 2 shows various radionuclides, which were removed from radionuclide-contaminated soil and water by using plants, such as birch and sunflower (*Helianthus annuus*). It appears that rhizofiltration is a practical way to treat radionuclide-contaminated water, and will become an important process for environmental management of large areas contaminated with radionuclides [53].

4. Transgenic Plants for Enhanced Phytoremediation

As plants are autotrophs, they do not use organic compounds for their carbon and energy sources. Therefore, plants usually lack the catabolic enzymes necessary to achieve full mineralization of organic molecules to carbon dioxide and water. Thus, the idea to enhance phytoremediation through biotechnology was explored in recent years [17]. The obvious approach is the application of recombinant DNA technology, to express specific genes from organisms, such as bacteria and mammals, to increase plant tolerance and metabolism of organic chemicals or heavy metals [54]. Excellent articles regarding various transgenic plants for enhanced phytoremediation have been published. Examples are applications for organic xenobiotics [55], toxic metals [56], and toxic explosives [31,57].

Arabidopsis thaliana has 150 different cation transporters

Table 2. Radionuclides removed from soil and water by phytoremediation

Radionuclide (s)	Plant	Process	Medium	Reference
Strontium (^{90}Sr) and Cesium (^{137}Cs)	Birch	Phytoextraction	Soil	[63]
Strontium (^{90}Sr) and Cesium (^{137}Cs)	Sunflower	Rhizofiltration	Groundwater	[50]
Strontium (^{90}Sr) and Cesium (^{137}Cs)	Giant milky weed	Rhizofiltration	Groundwater	[49]
Uranium (^{238}U)	Common reed	Phytoextraction	Soil	[51]
Cesium (^{137}Cs) and/or cobalt (^{60}Co)	Water hyacinth	Rhizofiltration	Radioactive waste solution	[52]

Table 3. Selected examples of transgenic plants for enhanced phytoremediation

Gene transferred	Origin	Target plant	Effect	Reference
Pentaerythritol tetranitrate reductase	Bacteria	Tobacco	Degradation of explosives	[33]
Metallothionein II	Human	*Brassica napus* and *Nicotiana tabacum*	Cadmium (Cd) tolerance	[64]
Mecuric reductase *(merA)*	Bacteria	Yellow poplar (*Liriodendron tullpifera*)	Remediation of mercury pollution	[30]
Phytochelatin synthetase	Wheat	*Nicotiana glauca*	Lead (Pb) accumulation	[65]
Cytochrome P450	Human	Poplar (*Populus*)	Remediation of trichloroethylene (TCE)	[17]
Nitroreductase	*Escherichia coli*	*Arabidopsis thaliana*	Degradation of 2,4,6-trinitrotoluene (TNT)	[57]
Mercuric reductase (*merA*) Organomercurial lyase (*merB*)	Bacteria	*Arabidopsis thaliana*	Detoxification of methylmercury	[66]

[10]. A transgenic approach that may be used to alter the uptake of inorganic pollutants is overexpression or knockdown of membrane transporter proteins. This approach was successfully employed to enhance Zn accumulation in *Arabidopsis thaliana* [58]. In Table 3, selected examples of transgenic plants for enhancing phytoremediation are summarized. It was evident that these transgenics showed improved metal tolerance, as well as metal accumulation, and remarkable improvement of degradation of organic xenobiotics.

5. The Present Status of Phytoremediation in Korea

In Korea, phytoremediation research has been carried out since the late 1990s. Most research has been performed at government-sponsored institutes, such as KRIBB (Korea Research Institute of Bioscience and Biotechnology), and universities, such as POSTECH (Pohang University of Science and Technology), and GIST (Gwangju Institute of Science and Technology). Phytoremediation research has also been funded by the Ministry of Environment, and the Ministry of Education, Science and Technology. The target of the research was the phytoremediation of toxic metals, and development of transgenic plants [74-78]. A group headed by Lee at POSTECH inserted the yeast *YFC1* gene, which was found to be responsible for Cd detoxification, into *Arabidopsis thaliana*. The transgenic plants showed enhanced tolerance of Pb and Cd [78]. On the other hand, researchers at GIST studied phytoremediation of soil contaminated with heavy metals using *Brassica napus,* and tried to link phytoremediation to biodiesel production [83]. In fact, they have developed expertise in the remediation of arsenic [67]. There are several phytoremediation companies in Korea. For example, PHYGEN Inc. (www.phygen.co.kr) specializes in the removal of heavy metals, and bioenergy production.

Since there are more than 2,000 abandoned mines on the Korean peninsula, phytoremediation has arguably become one of the most important technologies in Korea. The release of acidic drainage streams, containing relatively high concentrations of dissolved metals and metalloids from the abandoned mines, has been causing significant environmental problems. Thus, it is likely that in the foreseeable future, phytoremediation will become the technology of choice, for a partial solution to environmental contamination problems.

6. Conclusion

Phytoremediation is increasingly being acknowledged as a cost-effective and environment-friendly alternative to traditional methods of environmental cleanup [20]. In this review article, basic processes and some applications of phytoremediation were briefly summarized. Currently, toxic heavy metal and organic pollutants are the major targets for phytoremediation. Many phytoremediation projects have been successfully undertaken [6,59] and phytoremediation has been widely implemented on a global level (especially in the US, and EU countries).

The research on phytoremediation is still in its infancy. For further improvement of phytoremediation efficiency, further research is needed to find more efficient hyperaccumulators, which show fast growth, high biomass, high tolerance, and accumulation of metals and other inorganics. Existing plants could also be improved, through the use of conventional breeding techniques, and genetic engineering approaches [11]. Long-term improvements in phytoremediation are likely to result from the introduction of genes responsible for metal tolerance, or the metabolism of organic chemicals. In addition, more sophisticated knowledge of plant-microbe interactions is needed, to more efficiently design phytoremediation processes, such as phytostimulation [79,80].

Both plant physiologists and microbiologists will play a key role in this line of research. In addition, there is a need for more pilot and field studies to demonstrate the effectiveness of phytoremediation technology, and increase its acceptance [10]. It is noteworthy that researchers tend to link phytoremediation to biomass production, from an economic point of view [81,83]. For example, Witters *et al.* examined bioenergy production and carbon dioxide abatement through the use of phytoremediation crops [81]. An additional focus on biomass energy, feedstock for pyrolysis, biofortified products, and carbon sequestration may be necessary, for the advancement of research on, and practical applications of, phytoremediation [82]. Multidisciplinary teams of researchers from different backgrounds (*e.g.* plant physiologists, agronomists, soil scientists, molecular biologists, microbiologists, chemists, environmental engineers, bioprocess engineers and government regulators) could accomplish these aforementioned tasks, for further improvements in phytoremediation [10,18]. As phytoremediation is still in its initial stages of research and development, more well-designed and well-documented demonstration projects are necessary, to promote phytoremediation as an environmentally friendly and cost-effective technology [9].

Acknowledgement

This research was supported by a grant from the Korea University of Technology and Education.

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