Review Articles

Phytoremediation: European and American Trends

Successes, Obstacles and Needs

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Abstract. Phytoremediation is an emerging technology based on the use of green plants to remove, contain, inactivate or destroy harmful environmental pollutants. Recent developments in Europe and the USA show that the approach is somewhat different on both sides of the Atlantic. In Europe, phytoremediation has more basically been research driven and, based on the outcomes, applications have been envisaged. By contrast, the approach in the USA is more application and experience driven. In spite of a growing track record of commercial success, more demonstration projects are needed to prove that phytoremediation is effective in order to rigorously measure its underlying economics, and to expand its applications. More fundamental research is also required to better understand the complex interactions between pollutants, soil, plant roots and micro-organisms at the rhizosphere level, to increase the bioavailability of pollutants, to fully exploit the metabolic diversity of plants and, thus, to successfully implement this new green technology.

Keywords: Constructed wetlands; organic pollutants; phytoextraction; phytodegradation; phytoremediation; phytostabilization; phytostimulation; radionuclides; toxic metals

1 Introduction

Phytoremediation has a strong potential as a natural, solar-energy driven remediation approach for the treatment of sites, groundwater and wastewaters contaminated with heavy metals, organic xenobiotics and radionuclides [1–4]. Due to the low cost of the technique, the *in situ* treatment, a high probability of public acceptance and the fact that it is easy to handle, research and development in this area has increased over the last decade. However, large-scale application of phytoremediation presently faces a number of obstacles. These include the time required for remediation and the levels of pollutants tolerated by the plants employed. Furthermore, soil treatment is often limited to the bioavailable fraction of the contaminants.

1.1 Increase or decrease in the bioavailability of pollutants?

The bioavailable fraction should be considered as the most important from ecological, toxicological and health standpoints, and is determined not only by its speciation, but also by soil characteristics and ageing processes. Therefore, a good knowledge of chemical species and a prediction of changes in equilibrium after exhaustion of the bioavailable fraction are important. However, present environmental regulations are mainly based on total pollutants concentrations, so that the successful application of phytoremediation to soil contaminants should require adaptation of the regulations to a risk-based approach [5]. An example of a risk-based concept is the use of metal-inactivating soil additives combined with revegetation. As a consequence of soil amendments, the availability to plants, the uptake and eventual toxicity of heavy metals can be strongly decreased, thereby allowing for a revegetation of heavily contaminated sites. The subsequent establishment of a vegetation cover prevents the dispersal of polluted dusts from formerly bare sites through wind and water erosion, and markedly decreases the leaching to groundwater [6–9]. To monitor the sustainability of the immobilization, there is a prerequisite for rapid, cost-effective biological screening methods. A whole cell biosensor concept, referred to as BIOMET [10,11], has emerged as a very promising screening tool. The test showed a good correlation with other, more time consuming and expensive tests based on plants and invertebrates.

Ageing decreases bioavailability, while depressed redox potential and organic material could decrease the persistence of a substance in soil [5]. Bioavailability can be increased by artificial surfactants, biosurfactants or soluble organic matter produced by microbes and plants. In contrast to synthetic additives, substances excreted by bacteria and plants are continuously produced *in situ* and are often non-toxic [12]. In the case of plants, exudates are localized and coupled with absorption. However, an increased bioavailability may be risky, since it can result in a progressive leaching of the pollutant, and surrounding soil or groundwater might become contaminated. Therefore, a risk assessment should be included before using surfactants or other mobilizing agents on a large scale.

1.2 Towards the use of transgenic plants?

To broaden the applicability of phytoremediation, plants with significantly improved performance will be required, especially for metal phytoextraction, where increased biomass production, enhanced uptake and translocation capacities are some of the topics to be addressed. An increased degradation potential towards organic pollutants may also be needed. Since classical plant breeding might be unsuccessful in achieving these objectives, the use of genetically modified organisms (GMO) should be envisaged. Work has been done in this area for both metal uptake and transformation, and for the enhanced degradation capacity of organic pollutants [13–18]. However, before transgenic plants can be applied in phytoremediation, public concerns on their application must be addressed. This should include issues on safety of the modified plants, the potential risk of transferring genes across natural and cultivated species, the possible transfer of contaminants to the food chain, and an environmental impact assessment. Another strategy to improve phytoremediation could be based on the exploration and exploitation of natural plant diversity, and of interactions between plant roots and their associated micro-organisms [19–21]. The use of endophytic bacteria possessing improved capacities for metal accumulation and/or degradation of organic pollutants also deserves to be explored [22].

1.3 Economics vs ecology?

Phytoremediation must become an economically feasible approach to increase its acceptance as a remediation concept [1]. The economics of phytoremediation of organic compounds is generally favourable, but cost is an acute problem for metal phytoremediation, which can in principle be overcome by several strategies. One option is the use of plants that, in addition to their role in phytoremediation, produce biomass with an added value. For example, the biomass of fibres, oil or fragrance producing plants could be used to recover these valuable products. Trees used for groundwater cleanup can be harvested and used for paper production. Another option is based on the selective recovery of heavy metals from plant residuals after combustion, which could provide an economically valuable recycled product, depending on the type and concentration of the heavy metal.

The success of phytoremediation depends on many biological, physical and chemical parameters: an approach involving plant physiologists, agronomists, soil scientists and engineers is thus required. This needs funding opportunities that stimulate the creation of such multidisciplinary project teams.

2 Research Funding Opportunities

At present, the two largest markets for phytoremediation are in the USA and Europe, and it is therefore not surprising that significant research funding has been allocated to phytoremediation [1]. However, it seems that the driving forces differ on both sides of the Atlantic. In our opinion the major contrast is that phytoremediation in Europe has generally been more basic research driven and, based on the outcomes, applications are envisaged. By contrast, the approach in the USA is more application and experience driven. To some degree, this may reflect the existence of a culture that supports entrepreneurship and risk-taking in business ventures, thereby accounting for the fact that there is a larger, more mature phytoremediation industry, and a greater emphasis on applied research even within academia. Another explanation could be differences in the type of prevalent funding opportunities.

2.1 European trends

In Europe, the major financial support for phytoremediation emphasized basic and explorative research, although a tendency exists for more application-driven research, as shown in several research projects on phytoremediation presently supported by the European Commission (EC) 5th Framework Programme. Phytoremediation also received some support during the previous Framework Programme, but these projects were oriented to basic research. Another important evolution is a stronger involvement of small and medium-sized enterprises as partners in the projects presently sponsored, which might reflect a general tendency towards more application-driven research. Another striking point is that EC funded phytoremediation research is mostly aimed at heavy metals, despite the fact that soil and groundwater contamination with organic pollutants forms a much more serious problem. Much of the long-term ongoing work on phytodegradation of xenobiotics started in Europe as very general research, with national funding, and was only recently directed to phytoremediation due to support opportunities. Industrial funding for phytoremediation research has been very limited in Europe, but this is changing (**Table 1**).

A successful network and fruitful coordination of national phytoremediation efforts have been established in the framework of COST Action 837 (http://lbewww.epfl.ch/COST837), a unique European initiative established at the end of 1998. Several American programmes foster cooperation of various kinds, but they often lack the interdisciplinary approach that COST has assembled. In fact, a common complaint in the USA among remediation professionals and researchers alike is that engineers with remediation expertise and experience do not always communicate with scientists who understand the underlying basis of the remedial approach. The ability of COST Action 837 to bring together researchers with different backgrounds is unique in this respect.

2.2 American trends

In the USA, the early research on phytoremediation of organic contaminants started in the laboratories of J.L. Schnoor at the University of Iowa [3], and M.P. Gordon at the University of Washington [23]. Entrepreneurial companies like Ecolotree (http://www.ecolotree.com), Phytokinetics, Verdant Technologies and Applied Natural Sciences quickly

Table 1: Some European phytoremediation field projects

Site Name (Location)	Institution	Plant Species	Contaminant
Czechowice oil refinery (Katowice, Poland)	Phytotech, Florida State University, IETU	*B. juncea*	Pb, Cd
Former landfill (Switzerland)	Swiss Federal Institute of Technology	*Salix viminalis* (willow)	Zn, Cd
Sewage disposal site (United Kingdom)	University of Glasgow	Salix species	Ni, Cu, Zn, Cd
Zinc waste landfill (Hlemyzdi, Czech Republic)	International Graduate School Zittau	*H. annuus, Z. mays,* C. *halleri*	Zn
Zinc/Copper contaminated site (Dornach, Switzerland)	Several	Improved tobacco plants	Cu, Cd, Zn
Zinc smelter site (Lommel, Belgium)	Limburgs University	Grasses for phytostabilization	Zn, Cd, Pb, Cu
Contaminated playing ground (Overpelt, Belgium)	Limburgs University	Grasses for phytostabilization	Zn, Cd, Pb, Cu
Zinc/cadmium contaminated soil (Balen, Belgium)	Limburgs University	*B. napus* for phytoextraction	Zn, Cd, Pb
Guadiamar river area, Donana National Park (Aznalcollar mine, Spain)	Several	Various	Pb, Cu, Zn, Cd, Ti, Sb, As
Oil well blow-out (Trecate, Italy)	Battelle Europe	Alfalfa, clover, corn, rye, sorghum	Petroleum hydrocarbons
BTEX contaminated groundwater (Genk, Belgium)	Limburgs University	*Populus x canadensis* (poplar)	BTEX
Old gasworks site (Husarviken, Sweden)	Stockholm University	Various	PAHs, heavy metals
Eka Chemicals site (Bohus, Sweden)	Stockholm University	Various	Chlorinated organics, mercury
Old gas filling station (Axelved, Denmark)	Technical University of Denmark	Poplar and willow	Gasoline and diesel compounds
Former municipal gaswork site (Holte, Denmark)	Technical University of Denmark	Poplar and willow	Cyanide, BTEX, PAHs and oil
Resort pollution by pesticides stored in bunkers (Niedwiady, Poland)	Polish Academy of Sciences, Kornik ISTEA-CNR, Bologna	Poplars	Pesticides

From [1, 26–28, 56, 57, 75, 76]

emerged based on the preliminary work coming from those laboratories. Some early applications-oriented research were also conducted and funded by the US Environmental Protection Agency (EPA; http://es.epa.gov). Metal phytoremediation did not reach its current level of establishment either until the mid-1990s founding of Phytotech Inc., in spite of the long years of pioneering basic research on metal hyperaccumulation done at Rutgers University and the USDA.

However, significant phytoremediation research in the USA is also government funded, either traditional Federal support of academic research, 'small business' grants to companies for applied research, or government funding of remediation projects. As is the case with most academic research in the USA, basic phytoremediation research is most commonly funded by individual competitive grants awarded by any of several government agencies, including the EPA, the US Department of Agriculture and the Department of Energy (DOE; http://www.em.doe.gov). Individual research projects more specific to a given remediation problem or scenario, often site-specific, might also be funded by these agencies, or by the various armed services within the Department of Defence (DOD). Several programmes within or between these agencies, such as the DOD Environmental Security Technology Certification Program (ESTCP) and the DOD/DOE/EPA Strategic Environmental Research and Development Program (SERDP; http://www.serdp.org) have been very active in funding phytoremediation laboratory and field projects. These research grants are generally part of each agency's ongoing programme of funding basic or applied research across many different fields or disciplines, or encompassing different remediation technologies, and have not been part of focused programmes dedicated to phytoremediation. Because the funding has come from divisions of these agencies devoted to solving real-world environmental problems, the projects are more application-focused.

There have been a limited number of larger-scale funding programmes in the USA more focused on phytoremediation. For example, the EPA has funded studies at the Great Plains/Rocky Mountain Hazardous Substance Research Center (HSRC; http://maven.gtri.gatech.edu/hsrc) for about ten years. Although this programme was based at Kansas State University (http://www.engg.ksu.edu/HSRC), the funds have been distributed to a total of fourteen different US universities. Most recently, EPA has funded a new HSRC based at Purdue University, where the main focus is phytoremediation. This new centre is also based on a multi-university approach. In the DOE, the Savannah River site is most active in promoting phytoremediation as a low cost, natural remediation strategy.

There is some industrially or privately funded phytoremediation work, and while it is certainly larger than what is seen in Europe, it is probably not as large as one might imagine. We are not aware of any published figures quantifying the relative amounts of spending on phytoremediation research by the public and private sectors, and information on amounts of industrial funding is often confidential and hard to come by. However, of the more than two hundred field phytoremediation projects undertaken in the USA, many have been conducted at sites owned by private companies, either as pilot research projects or as part of actual remediation efforts.

3 Progress and Trends in Research and Applications

3.1 Heavy metals

Phytostabilization of heavy metal polluted soils, with or without the addition of soil additives, is a proven technology, as indicated by successful studies performed in both Europe and the USA. In Europe, one of the most successful examples is a large-scale heavy metal inactivation plus revegetation trial at Maatheide (Belgium). The treatment of this site heavily contaminated with Zn and Cd started with the addition of beringite, a coalmine refuse [6–8]. Unfortunately, this additive is no longer available, and, at present, several studies aim to come forward with alternatives. Since physical, chemical and ecological parameters were all evaluated during the last decade, this site provides an excellent example for the sustainability of heavy metal immobilization combined with revegetation [10,11]. Similar experiments have been done near a copper rod company in Prescot, UK [24]. Such initiatives are strongly supported by regional and national governments, indicating the willingness to accept *in situ* immobilization as a remediation strategy. In the USA, work has been strongly supported by the EPA using bio-solids as amendments for mining sites in Colorado, Missouri and Idaho, with promising results in all three sites (http://es.epa.gov).

Phytoextraction has been applied mostly in the USA [25]. The example that received most publicity, even if not the most successful, was the phytoextraction by Phytotech Inc. (now part of Edenspace Corporation; http://www.Edenspace.com) of lead at a Superfund Site in New Jersey, a facility formerly operated by a battery manufacturer, but known as the Magic Marker site. Phytotech has also demonstrated the applicability of phytoremediation at a lead contaminated site in Bayonne, NJ, and a residential site in Dorchester, MA. The accident of the Aznalcollar mine, in April 1998 in the proximity of the Donana National Park (southern Spain), led to the contamination of the Guadiamar river and the adjacent agricultural areas [26–28]. After physically removing the sediments, the soils have remained polluted by heavy metals such as Pb, Cu, Zn, Cd, Ti, Sb and metalloids like As. A multidisciplinary research project on phytoremediation aims to use plants and micro-organisms as bioindicators of toxic metal contamination, to identify plant species growing in heavily contaminated areas, to evaluate the tolerance to toxic metals in crops and wild species, to develop phytoextraction protocols, to isolate and characterize rhizospheric bacteria and their effect on plant growth, tolerance to toxic metals and their ability to accumulate them, and to characterize plant responses to toxic metals at the molecular level, with special emphasis on metal absorption, translocation and accumulation, and synthesis of stress metabolites (i.e. secondary metabolites, antioxidants).

An ideal plant for metal phytoextraction should possess the following characteristics: (a) tolerance to the metal concentrations accumulated, (b) fast growth and highly effective metal accumulating biomass, (c) accumulation of metal in the above ground parts, (d) easy harvest. A limiting factor of naturally occurring Zn, Cd and Pb hyperaccumulators is often their slow growth and low biomass production [29–31]. Genetic engineering in the improvement of plants opens up new possibilities for phytoremediation of metal-polluted soils [13–16]. However, this approach can be fully exploited only when the mechanisms of metal tolerance, accumulation and translocation are better understood. The genome of *Arabidopsis thaliana* is a useful source of genes involved in metal uptake and translocation and is an important tool for a better understanding of the regulation of these processes, and simultaneously a potential source of genes for construction of high biomass producing hyperaccumulators. Moreover, several metal transporter genes from the hyperaccumulator *Thlaspi caerulescens* have already been reported. Transfer to other high biomass-producing members of the Brassicaceae may be possible. Another possibility is the introduction of genes (often bacterial) into plants which encode enzymes able to detoxify metals by changing their redox state or serve to chemically convert them into a less hazardous compound [16]. However, the use of GMO in the field may be problematic in terms of public acceptance.

Successful phytoextraction also mostly depends on plant availability of the metals in soils. Application of chemical chelators, like Ethylene-Diamine-Tetra-Acetic acid (EDTA), Nitrilo-Tri-Acetic acid (NTA), or citric acid, increasing the metal bioavailability, uptake and translocation in the plants has been proposed to overcome this problem [32–37]. The use of these chelators raised some general questions about mass balances, to confirm that the metals were not leached to the groundwater. Furthermore, the addition of synthetic chemicals like EDTA is questionable from an environmental standpoint [34,37]. On the other hand, the capacity of a plant to chelate and accumulate relatively large amounts of heavy metals often depends on its capacity to produce chelating compounds such as phytochelatins. The induction and an increased activity of enzymes involved in their biosynthesis should thus be of considerable importance in the enhancement of heavy metal accumulation by plants [38]. In addition, biotic interactions between bacteria, mycorrhizal fungi and plants seem to play a key role to decrease the phytotoxicity of heavy metals. However, microbial protection of plants against phytotoxic concentrations of heavy metals is often based on an exclusion of heavy metals or decrease of stress ethylene levels [20,39]. One can therefore wonder whether such a concept could be applicable to improve phytoremediation. Although it might be successful in the case of phytostabilization, a different approach will be needed to improve phytoextraction. Since certain plant-associated micro-organisms are known to naturally produce heavy metal-chelating agents, such as siderophores, this field should be further exploited to define new phytoextraction concepts based on optimal combinations of plants and associated, chelate-producing micro-organisms.

A new development is the **phytomining** of nickel, thallium and gold, whose primary aim is cost-efficient mining instead of decontamination [40,41]. The advantage of these metals is due to high value on the world market, as compared to that of other metals such Cd, Zn and Pb.

3.2 Organic pollutants

Phytoremediation of soils and groundwater contaminated with organic xenobiotics is becoming increasingly popular as a cost-effective remediation strategy, and is enjoying considerable commercial use and success, mostly in the USA [1]. The systems established seem to fulfil their task properly and remove pollutants from various matrices with good efficiency and at a comparatively low cost. However, these successes have been achieved against a background of limited formalised knowledge of the mechanisms involved and a more systematic approach to the selection of plants and optimisation of remediation is urgently required.

On the other hand, many scientific teams are involved in basic research, which aim to understand plant metabolism of xenobiotics. Higher plants are equipped with a complex and versatile array of enzymes that protects them from the phytotoxic actions of natural products and man-made chemicals. The structure and function of many detoxification enzymes have been revealed by a combination of classical biochemistry and modern molecular biology techniques [23,42–48]. Detoxified xenobiotics are then stored as water-soluble metabolites in the vacuole or fixed as bound residues in the extra-cellular matrix and cell wall [49–51]. Many valuable results have been published, but they seem far away from the remediation of contaminated sites and wastewaters. The challenge is now to use the basic scientific knowledge to solve actual pollution problems.

However, with soil based contaminants as opposed to groundwater organic pollutants, the limiting factor is often neither the intensity of metabolism nor enzyme activities, but the penetration of pollutants into the plant, which depends on the properties and bioavailability of the xenobiotic, as well as on the size and shape of the root system [52]. Organic pollutants under consideration are often hydrophobic and bound to soil components, causing a severe problem to the uptake of the compound by plant roots. Once in the rhizosphere, the pollutants have to migrate into the root, then become translocated into other tissues and organs of the plant, where detoxification and metabolism will eventually take place. These uptake and translocation processes, that involve plants as well as their associated bacteria and mycorrhiza, are not yet well known and should be more carefully investigated [2,19,53].

One of the most striking features of many plants used in phytoremediation is the extensive evapo-transpiration of water through the stomata. This high consumption of water, that may almost equal the amount of water added to an area via precipitation, prevents wash out of pollutants and slows down the possible migration in the soil and into the groundwater. Furthermore, upward movement of water will also transport soluble organic pollutants into the plants [52].

In many cases, the associated microflora plays an important, if not the decisive, role in the treatment of sites polluted with hydrophobic xenobiotics, i.e. those defined as having a log Kow >4. Hence, stimulation of micro-organisms by plant exudates and leachates, and by fluctuating oxygen regimes has also to be considered [19,53]. This is the proposed pathway for the degradation of polychlorinated biphenyls (PCB) and polycyclic aromatic hydrocarbons (PAH) in the rhizosphere [54,55]. Plant roots may excrete not only enzymes like peroxidases (favouring the formation of residues bound to the humic part of the soil), but also small soluble organic molecules, acting as biosurfactants, thus able to enhance the bioavailability and uptake of pollutants. Although rhizosphere micro-organisms can certainly improve phytoremediation of hydrophobic compounds, such as PAH, recent results suggest that numerous compounds enter the xylem faster than the soil microflora can degrade them, even if the rhizosphere is enriched with degrader bacteria [56]. This observation led to the European ENDEGRADE project, supported by the EC, where endophytic bacteria are used to improve the *in planta* degradation of these compounds.

A phytoremediation study on hydrocarbon-polluted agricultural soils was conducted successfully in northern Italy [57]. The soil, contaminated following the blow out of a land-based oil well, underwent on site treatment in a biopile prior to being replaced in its original location. For a couple of years, the study compared the ability of eleven agricultural plants to facilitate hydrocarbon removal (via microbial degradation and/or plant uptake) with that of land farming and natural attenuation. Soil PAH and total petroleum hydrocarbon concentrations decreased in land farmed parcels and weedy areas, but much less than in planted parcels, most notably in those planted with corn and sorghum (**Figs. 1 and 2**). Other field projects on hydrocarbons are going on in Europe, particularly in Den-

Fig. 1: Aerial view of the site contaminated with petroleum hydrocarbons at the beginning of the phytoremediation trial (Trecate, Italy)

Fig. 2: Phytoremediation with sorghum growing on a parcel contaminated with petroleum hydrocarbons (Trecate, Italy)

mark [56]. In the USA, studies on the phytoremediation of hydrocarbon-polluted soils are being co-ordinated by the EPA Research Technology Department Forum (RTDF; http://www.rtdf.org/public/phyto). Through this organisation, multiple universities and companies are running comparative trials throughout the country to determine the best plants and soil amendments to be added under a variety of agricultural and climatic conditions.

Most examples on the successful application of phytoremediation of groundwater-based xenobiotics are found in the USA. Although many organic pollutants are metabolised in plants, xenobiotics – or their metabolites – can be toxic to plants, and this could limit the applicability of phytoremediation. Alternatively, in the case of volatile pollutants, plants can release the compounds, or their metabolites, through the stomata, which could question the merits of phytoremediation. This seems to be the case for the removal of benzene, toluene, ethylbenzene and xylene (BTEX), using hybrid poplar trees. In the case of solvents such as trichloroethylene (TCE), although preliminary work suggested phytovolatilisation was the primary way plants deal with the compound, field studies showed that the majority of TCE is metabolised within the plant [58,59]. It is not yet known if trees would have similar degradation rates with compounds such as BTEX.

A special phytoremediation concept is the use of constructed wetlands for cleanup of effluents and drainage waters. For example, a constructed wetland has been successfully operated and monitored in Portugal for the last seven years to treat industrial effluents containing nitrogenous aromatic compounds from an aniline and nitrobenzene production plant. Using reed beds on a total planted area of 10,000m^2, reductions in aromatic compounds up to 100% were obtained, depending on the acclimatization period for inlet effluent composition of 10–300 mg/L aniline, 10–100 mg/L nitrobenzene and 10–30 mg/L nitrophenols [60].

Other successful examples include nitro-aromatics [61,62]. The US Army Corps of Engineers, through its Waterways Experiment Station in Vicksburg, MS, is developing a wetlands system to treat groundwater contaminated with 1 mg/L 2,4-6-trinitrotoluene (TNT) and up to 13 mg/L hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX). Laboratory studies led to the selection of three aquatic species: coontail (*Ceratophyllum demersum*), pondweed (*Potamogeton nodosus*), and emergent arrowhead (*Sagittaria latifolia*), which reduced TNT levels by 95%, and, when used with a microbial consortium, reduced RDX levels by 80%. It was estimated that the tested plants could remove approximately 0.02 mg/L TNT per day and 0.13 to 0.29 mg/L RDX per day at 25°C. It is believed that these species were accomplishing remediation mainly by endogenous enzymes (nitroreductase, dioxygenases and laccase). After completion of laboratory work, a full-scale trial, involving the aquatic plants and poplars, was begun (http://www.wes.army.mil/el/phyto).

Most of the plants used in the phytoremediation of xenobiotics are crops or weeds selected by agronomical practices. However, exploring and exploiting the natural biodiversity are important issues in the choice of appropriate species among agricultural plants (cultivation well known), hybrid poplars or willows (high water use), or wild plants growing in contaminated areas [63]. Plant taxonomy and phytochemistry should be the first steps in the adequate use of the huge biochemical potential of plant species, with very specific metabolism: plants often produce natural chemicals whose structure is close to xenobiotic compounds [19]. Whereas natural biodiversity is not yet fully exploited, the use of transgenic plants is therefore not the only solution to improve the efficiency of phytoremediation.

Large root absorption area, big root tip mass, high enzyme activity, increase of bioavailability using exudates are critical factors to the successful implementation of phytoremediation of soil-based organic pollutants. Important tools to improve the removal of these pollutants could also be root biotechnology (using rhizogenic *Agrobacterium* to induce root proliferation), plant hairy-root technology and rhizosphere biotechnology [64].

3.3 Radionuclides

The phytoremediation of radionuclides is less documented [65–73], but a few trials should be mentioned. Laboratory and greenhouse studies have been conducted to determine the potential of plants to remove low levels of ^{137}Cs soil contamination at a former waste disposal site at an Argonne National Laboratory's facility (http://www.anl.gov). Willow, *Kochia scoparia* (a weedy plant) and *Brassica napus* (colza) were tested on spiked soil, and these plants were capable of 40–60% removal of the ^{137}Cs under greenhouse conditions. Additives were not effective in improving the rates of uptake. Field tests were planned, although the greenhouse results led to extrapolations that 4 to 7 years would be needed for field remediation. Other trials indicate that redroot pigweed (*Amaranthus retroflexus* L.) and other plant species were able to accumulate ^{137}Cs [65–68]. However, significant improvements are necessary to make phytoremediation technology a feasible option for restoration of ^{137}Cs (and also ^{90}Sr) contaminated soils [65,68]. In contrast, Phytotech conducted a field trial on surface water from the Chernobyl, Ukraine nuclear disaster, contaminated with ^{137}Cs and ^{90}Sr, using sunflowers grown on rafts in a contaminated pond, and showed a dramatic reduction in the levels of these radionuclides in the water within a 4–8 week period [1].

Phytotech conducted another field trial of rhizofiltration of uranium-contaminated process water, using sunflowers in a greenhouse-based hydroponic reactor, and found that uranium-contaminated water with concentrations as high as 350 mg/L could see reductions of 95% within 24 hours. Limited information is available on screening and selection of terrestrial plants for uptake and translocation of uranium from soil [69–72]. It seems that uranium extraction efficiency decreases sharply across hydroponic, sandy and organic soil systems, indicating that soil organic matter sequesters uranium, rendering it largely unavailable for plant uptake: plant behaviour in hydroponic systems does not correlate well with that in soil systems. Only one plant species, Juniper (*Juniperus monosperma*), exhibits consistent uranium extraction efficiencies and biological absorption coefficient in both sandy and organic soils, suggesting unique uranium extraction capabilities [71]. Further research is required for the development of an effective phytoremediation strategy for uranium as well as for plutonium-contaminated soils [70–73].

4 Outlooks

- Like any other new technology, phytoremediation will only become accepted if its success has been demonstrated [74]. Key success factors of phytoremediation are low cost and aesthetical aspects, making it very suitable for the remediation of large contaminated areas or sites in the proximity of habitation. Credits for the positive image of phytoremediation should in the first place go to a number of American players, who were pioneers in the demonstration of phytoremediation as a remediation concept, including companies such as Phytotech, Ecolotree, Verdant Technologies and Applied Natural Sciences. This is in contrast with a more conservative attitude in Europe as was shown in the past. Consequently, only few well-documented, successful or ongoing demonstration projects are available in Europe, although at present this is changing (Table 1).
- The dissemination of results, public awareness and acceptance of the technology is another major issue. The most significant initiatives are the Phytonet discussion group (http://www.dsa.unipr.it/phytonet) and the Citizen's Guide to Phytoremediation published by the US EPA (http://clu-in.org/products/citguide/phyto2.htm). A general information site on phytoremediation is hosted by the Missouri Botanical Garden (http://www.mobot.org/jwcross/phytoremediation), whereas the HSRC at Kansas State University has sponsored a Phytoremediation Discussion Group (http://www.engg.ksu.edu/HSRC/phytorem). Most of these actions address in the first place members of the scientific community, rather than the general public, and aim at creating discussions amongst scientists from different disciplines. However, a detailed technical report by the Interstate Technology and Regulatory Cooperation (ITRC) Working Group has been published, which explains phytoremediation and its applications primarily for the benefit of state and local regulators (http://www.itrcweb.org). The ITRC is now conducting seminars and workshops around the USA to educate regulators and site owners about the potential of phytoremediation.

5 Needs

- A large amount of knowledge is now available on the biochemical processes involved in the detoxification of pollutants inside plant cells. One of the most important challenges is to use this basic scientific information to improve the efficiency of phytoremediation in the field.
- Another important task is to better understand and control the uptake and translocation of organic pollutants in green plants. Numerous pollutants are very hydrophobic, showing log K_{ow} values above 4. This characteristic and high chemical stability explains why such pollutants are persistent in the environment. A major limiting factor for phytoremediation of recalcitrant organic pollutants is often their low bioavailability. Therefore, there is an urgent need for research aiming at a better understanding of the subtle and complex interactions between pollutants, soil material, plant roots and micro-organisms in the rhizospheric zone. Of particular interest are the roles of root exudates, mycorrhizal fungi and rhizospheric bacteria in the modification of the ability of plants to remove pollutants from contaminated soils. An extended knowledge of these mechanisms will contribute to optimise the phytoremediation process and make it more attractive in the near future.
- More demonstration projects are also urgently required to provide recommendations and convince regulators, decision-makers and the general public of the applicability of a green approach for the treatment of soils, brownfields, groundwater and wastewater contaminated by toxic metals, organic pollutants and radionuclides.

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