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# Hydroponics and Environmental Clean-Up

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## 1. Introduction

Water pollution refers to any chemical, physical or biological change in the quality of water that is detrimental to human, plant, or animal health. Water pollution affects all the major water bodies of the world such as lakes, rivers, oceans and groundwater. Polluted water is unfit for drinking and for other consumption processes. It may also be not suitable for agricultural and industrial use.

### 1.1 Types of water pollution

#### 1.1.1 Toxic substances

The greatest contributors to toxic pollution are oil spills, herbicides, pesticides, industrial compounds and heavy metals such as mercury (Hg), cadmium (Cd), chromium (Cr), nickel (Ni), lead (Pb) arsenic (As), copper (Cu), zinc (Zn), among others. Organic pollution occurs when an excess of organic matter, such as manure or sewage, enters the water. When organic matter increases in a water body, the number of decomposers will increase. These microorganisms grow rapidly and use a great deal of oxygen during their growth. This leads to a depletion of oxygen as the decomposition process occurs and consequently limits oxygen availability to aquatic organisms.

As the aquatic organisms die, they are broken down by decomposers which lead to further depletion of the oxygen levels. A type of organic pollution can occur when inorganic pollutants such as nitrogen and phosphates accumulate in aquatic ecosystems. High levels of these nutrients cause an overgrowth of plants and algae. The enormous decay of this algae and plant matter become organic material in the water and lowers the oxygen level causing suffocation of fish and other organism in a water body. This overall process is known as eutrophication.

#### 1.1.2 Thermal pollution

Thermal pollution can occur when water is used as a coolant near a power or industrial plant and then is returned to the aquatic environment at a higher/cooler temperature than it was originally. Thermal pollution can have a disastrous effect on life in an aquatic ecosystem as temperature increases/decrease the amount of oxygen in the water, thereby reducing the aquatic life presence.

### 1.1.3 Natural pollution

Also called Ecological pollution, takes place when chemical pollution, organic pollution or thermal pollution is caused by nature rather than by human activity. An example of natural pollution would be an increased rate of siltation of a waterway after a landslide which would increase the amount of sediments in runoff water. Another example would be when a large animal, such as a deer, drowns in a flood and a large amount of organic material is added to the water as a result. Major geological events such as a volcano eruption might also be sources of ecological pollution.

### 1.2 Sources of water pollution

The most important sources of water pollution are domestic wastes, industrial effluents and agricultural wastes. Other sources include oil spills, atmospheric deposition, marine dumping, radioactive waste and eutrophication.

- *Domestic sewage:* is wastewater generated from the household activities. It contains organic and inorganic materials such as phosphates, nitrates, heavy metal-containing wastes. Organic materials are food and vegetable waste, whereas inorganic materials come from soaps and detergents.
- *Industrial Effluents:* Manufacturing and processing industry wastes contain organic pollutants and other toxic chemicals. Some of the pollutants from industrial source include Cd, Pb, Hg, As, asbestos, nitrates, phosphates, oils, etc. Wastewater from food and chemical processing industries contribute more to water pollution than the other industries such as distilleries, leather processing industries and thermal power plants. Also dye industries generate wastewater which changes the water quality especially water color. Many of the big industries have come up with wastewater treatment plants.

However, it is not the case with small-scale industries. Water can also become contaminated with toxic or radioactive materials from industry, mine sites and abandoned hazardous waste sites. For instance, in 1932, the Minamata disease in which nearly 1,800 people died and many more suffered occurred due to consumption of fish containing high amounts of methyl mercury. It was caused by release of methyl mercury from Chisso Corporation's chemical factory.

Additionally, an indirect effect by industrial activity is when acid precipitation is caused as burning fossil fuels emit sulfur dioxide into the atmosphere. The sulfur dioxide reacts with the water in the atmosphere, creating rainfall which contains sulfuric acid. As acid precipitation falls into lakes, streams and ponds it can lower the overall pH of the waterway, affecting plant life, and subsequently the whole food chain. It can also leach heavy metals from the soil into the water, killing fish and other aquatic organisms. Because of this, air pollution is potentially one of the most threatening forms of pollution to aquatic ecosystems.

- *Agricultural Waste:* includes manure, slurries and runoffs. Farms often use large amounts of herbicides and pesticides, both of which are toxic pollutants. These substances are particularly dangerous to life in rivers, streams and lakes, where toxic substances can build up over a period of time. The runoffs from these agricultural fields

cause water pollution to the nearby water sources. The seepage of fertilizers and pesticides causes groundwater pollution, which is commonly known as leaching. Fertilizers can increase the amounts of nitrates and phosphates in the water, which can lead to eutrophication. Allowing livestock to graze near water sources often results in organic waste products being washed into the waterways and can also lead to eutrophication.

### 1.3 Heavy metal pollution in water

Heavy metal pollution of freshwater environments is a serious environmental problem in the industrial areas. Water pollution by heavy metals (elements with an atomic density greater than  $6 \text{ g cm}^{-3}$ ) has become therefore a global issue that need considerable attention towards combating. The common heavy metals that have been identified in polluted water include As, Cu, Cd, Pb, Cr, Ni, Hg and Zn. The release of these metals without proper treatment poses a significant threat to public health because of their persistence, *biomagnification* and accumulation in food chain. Their presence in water is due to discharges from residential dwellings, groundwater infiltration and industrial discharges. Their occurrence and accumulation in the environment is a result of direct or indirect human activities, such as rapid industrialization, urbanization and anthropogenic sources.

Severe toxic effects of heavy metal intake include reduced growth and development, cancer, organ damage, nervous system damage, and in extreme cases, death. The danger of heavy metal pollutants in water lies in two aspects of their impact. Firstly, heavy metals have the ability to persist in natural ecosystems for an extended period. Secondly, they have the ability to accumulate in successive levels of the biological chain, thereby causing acute and chronic diseases.

### 1.4 Water treatment for heavy metal removal

Several methods of removing heavy metals from water based on chemical and microbiological processes have been developed with a degree of success. Control over the quality and composition of industrial waste, including the removal of heavy metals, may take advantage principally of physicochemical methods based on chemical precipitation and coagulation (flocculation) followed by sedimentation, flotation, ionic exchange, reverse osmosis, extraction, microfiltration, adsorption on activated carbon, etc. However, these techniques are associated with high costs if large volumes, low metal concentrations, and high clean-up standards are involved. The insufficient effectiveness of the traditional heavy metal removal from water techniques has led to the search for more economical and simple procedures for the primary and (or) final removal of heavy metals from wastewater (Salt et al. 1995). Among these promising techniques is the phytoremediation of industrial wastewater, which involves the removal of heavy metals by adsorption, accumulation, or precipitation using higher aquatic and terrestrial plants, and the subsequent processing, utilization or burial of the contaminated biomass in special areas.

## 2. Phytoremediation

The term phytoremediation ("*phyto*" meaning plant, and the Latin suffix "*remedium*" meaning to restore) actually refers to a diverse collection of emerging plant-based technologies that

use either naturally occurring or genetically engineered plants for cleaning contaminated environments (Sarma, 2011). The primary motivation behind the development of phytoremediative technologies is the potential for low-cost remediation (Garbisu & Alkorta, 2001). Phytoremediation use plants to remove, reduce, degrade, or immobilize environmental contaminants, primarily those of anthropogenic origin, with the objective of restoring area sites to functional conditions for private or public applications. Research on phytoremediation has focused on the use of plants to: 1) accelerate degradation of organic contaminants, usually in concert with root rhizosphere microorganisms, or 2) remove/extract hazardous heavy metals from soils or water. Phytoremediation of contaminated sites is appealing because it is relatively inexpensive and aesthetically pleasing to the public compared to traditional remediation strategies.

## 2.1 Response of plants to metal pollution

The general response of plants growing on a metal contaminated soil is categorized into the following:

- *Hyperaccumulators*: These are species of plants that absorb and concentrate high levels of heavy metals either in their roots, shoots and/or leaves. By definition, a hyperaccumulator must accumulate at least 100 mg g<sup>-1</sup> (0.01 % dry weight), Cd, As and some other trace metals, 1,000 mg g<sup>-1</sup> (0.1 dry weight.) cobalt (Co), Cu, Cr, Ni and Pb and 10,000 mg g<sup>-1</sup> (1 % dry weight.) (Reeves & Baker, 2000). Hyperaccumulators take up high amounts of a toxic substance, usually a metal or metalloids in their shoots during normal growth and reproduction (Baker & Whiting, 2002). Hyperaccumulators are found in 45 different families with the highest among the Brassicaceae (Reeves & Baker, 2000). One such hyperaccumulator, *Thlaspi caerulescens* is a well-known Zn hyperaccumulator able to accumulate close to 30,000 and 10,000 mg kg<sup>-1</sup> Zn and Cd respectively in the shoot dry matter without growth reduction (Milner & Kochian, 2008).
- *Metal Excluders (tolerant)*: This category of plant species can grow on soil with concentration of a particular elements that are toxic to most other plants by means of preventing metals from entering their aerial parts and so maintain constant metal concentration in the soil around their roots (Ghosh & Singh, 2005).
- *Metal Indicators*: In this plants, the extent of metal accumulation reflects metal concentration in the rhizospheric soil/water. Indicator species have been reported for mine prospecting studies to find new ore bodies (Chaney et al., 2007). In general, shows poor control over metal uptake and transport processes.

## 2.2 Types of phytoremediation

Depending on the underlying processes, polluted matrix, applicability, and nature of the contaminant, phytoremediation can be broadly categorized as:

### 2.2.1 Phytodegradation

Also called phytotransformation, is the breakdown of organic contaminants taken up by plants through metabolic processes within the plant, or the breakdown of contaminants surrounding the plant through the effect of compounds (such as enzymes) produced by the

plants. Complex organic pollutants are degraded into simpler molecules and are incorporated into the plant tissues to help the plant grow faster. Plants contain enzymes (complex chemical proteins) that catalyse and accelerate chemical reactions. Some enzymes break down and convert ammunition wastes, others degrade chlorinated solvents such as trichloroethylene (TCE) and others degrade herbicides.

### **2.2.2 Phytostimulation**

Also called rhizostimulation or plant-assisted bioremediation/degradation, is the breakdown of organic contaminants in the rhizosphere area (water/soil surrounding the roots of plants) through microbial activity and enhanced by the presence of plant roots. This process is generally slower than phytodegradation. Microorganisms (bacteria, fungi) consume and digest organic substances for nutrition and energy. In this way, certain microorganisms can digest organic pollutants such as hydrocarbons, pesticides or solvents and break them down into harmless products in a process called biodegradation. Natural substances released by the plant roots (exudates) – sugars, acids and alcohols – contain organic carbon that provides food, attract microorganisms to the rhizosphere and enhance their activity.

### **2.2.3 Phytovolatilization**

Is the uptake and transpiration of a contaminant by a plant (e.g. poplars), with release of the contaminant (mainly organic) or a modified form of the contaminant to the atmosphere. Phytovolatilization occurs as growing trees and other plants take up water and the contaminants. Some of these contaminants can pass through the plants to the leaves and evaporate, or volatilize, into the atmosphere.

### **2.2.4 Phytoextraction**

Also called phytoaccumulation, refers to the uptake of metals from soil by plant roots into above-ground portions of plants. Certain plants, i.e. hyperaccumulators, absorb unusually large amounts of metals in comparison to other plants. After the plants are allowed to grow for some time, they are harvested and either incinerated or composted to recycle the metals. This procedure may be repeated as necessary to bring soil contaminant levels down to allowable limits. If plants are incinerated, the ash must be disposed of in a hazardous waste landfill, but the volume of ash will be less than 10% of the volume that would be created if the contaminated soil itself were dug up for treatment. Metals such as Ni, Zn and Cu are the best candidates for removal by phytoextraction because the majority of the approximately 400 known plants that absorb unusually large amounts of metals have a high affinity for accumulating these metals (Reeves & Baker, 2000).

### **2.2.5 Phytostabilization**

Is the use of certain plant species to immobilize inorganic contaminants in the groundwater and soil through adsorption onto roots, absorption and accumulation by roots, or rhizosphere-mediated precipitation. This process is intended to reduce the mobility of the contaminant and prevent migration to the groundwater or atmosphere, with a consequent reduction of the pollutant bioavailability (Grimaldo & López-Chuken, 2011). This technique



can be used to revegetate sites where natural vegetation is lacking due to high metal concentrations in surface soils. Metal-tolerant species can be used to restore vegetation to the sites, thereby decreasing the potential migration of contamination through wind erosion and transport of exposed surface soils and leaching of soil contamination to groundwater.

### 2.2.6 Phytofiltration

More commonly called rhizofiltration is the use of roots to uptake also store contaminants from an aqueous growth matrix. The description of this hydroponic-based technology is expanded in the next section.

## 3. Rhizofiltration

### 3.1 Background

Because heavy metal pollution affects the quality of drinking water supply and wastewater discharge, great efforts have been made in the last two decades to reduce pollution in water resources to reach environmental sustainability (Goal 7 of the Millennium Development Goals). This section is therefore aimed at giving a general overview of rhizofiltration – an hydroponic-based environmental biotechnology - as a cost-effective and sustainable alternative for the remediation of heavy metals pollutants in drinking water and wastewater treatment systems.

As mentioned previously, metal pollutants in wastewater, superficial water and groundwater are most commonly removed by chemical precipitation or flocculation, followed by sedimentation and disposal of the resulting sludge (Ensley, 2000). A promising alternative to these conventional clean-up methods is rhizofiltration (*'rhizo'* means root), a plant-based technique designed for the removal of metals in aquatic environments. In rhizofiltration plant roots grown in water absorb, concentrate and precipitate toxic metals and organic chemicals from polluted effluents (Vallini et al., 2005). The plants can be used as filters in constructed wetlands (Kang, 2011) or in a hydroponic setup (Candelario-Torres et al., 2009).

### 3.2 Rhizofiltration technology

Rhizofiltration is primarily used to remediate extracted groundwater, surface water, and wastewater with low contaminant concentrations. It is defined as the use of plants, both terrestrial and aquatic, to absorb, concentrate, and precipitate contaminants from polluted aqueous sources in their roots. Rhizofiltration can be used for Pb, Cd, Cu, Ni, Zn, and Cr, which are primarily retained within the roots. The plants to be used for rhizofiltration clean-up are raised in greenhouses with their roots in water. Contaminated water is either collected from a waste site or the plants are planted in the contaminated area allowing an in-situ treatment, minimizing disturbance to the environment, where the roots then take up the water and the metal contaminants dissolved in it. As the roots become saturated with contaminants, they are harvested.

During this hydroponic process, plants can adsorb or precipitate onto roots (or absorb into the roots) the metal contaminants that are in solution surrounding the root zone (Dushenkov et al., 1995). Changes in rhizosphere pH and root exudates may also cause

metals to precipitate near root surfaces. As roots become saturated with the metal contaminants, plants can be harvested for disposal or reutilization (Sas-Nowosielska et al., 2004). Dushenkov et al. (1995), suggested that that plants used for rhizofiltration should preferably accumulate metals only in the roots since the translocation of metals from roots to shoots would decrease the cost-effectiveness of rhizofiltration by increasing the amount of contaminated plant residue needing disposal. In contrast, Straczek et al. (2009) suggest that the capacity for rhizofiltration can be increased by using plants with an enhanced ability to translocate metals within the plant. Despite this difference in opinion, it is apparent that proper plant selection should be based in the total amount of metal removed from the polluted water indistinctly whether metal is accumulated in roots or shoots (Figure 1).

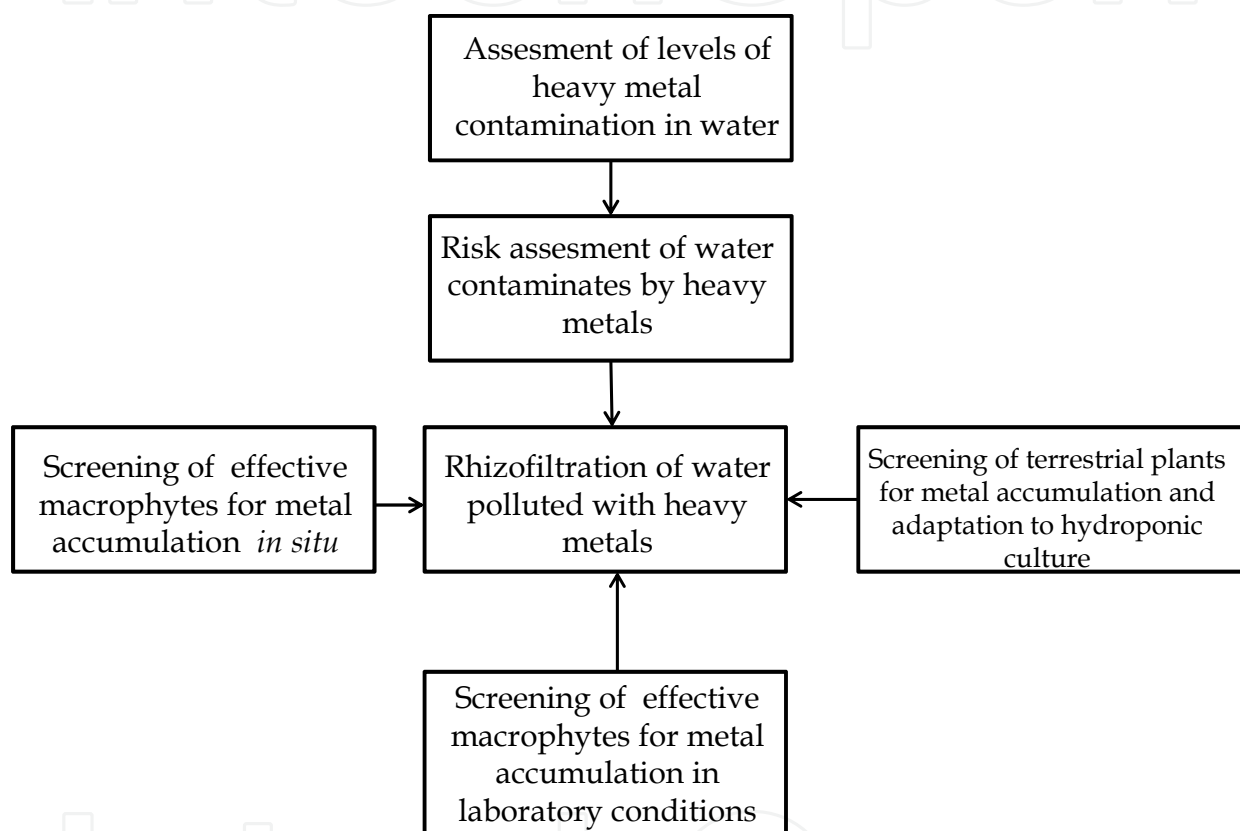


Fig. 1. Scheme of phytoremediation process for water contaminated by heavy metals. Modified from Galiulin et al. (2001).

### 3.3 Plant species for rhizofiltration

Dushenkov & Kapulnik (2000) described the model characteristics of plants used for rhizofiltration. Plants should be able to tolerate and accumulate significant amounts of the target metals in conjunction with easy handling, low maintenance cost, and a minimum of secondary waste requiring disposal. It is also desirable plants to produce significant amounts of root biomass or root surface area and high evapotranspiration rates. Several aquatic species have shown the capacity to remove heavy metals from water, for instance, water hyacinth (*Eichhornia crassipes*, Mahmood et al., 2010), pennywort (*Hydrocotyle umbellata*, Khilji & Bareen, 2008), and duckweed (*Lemna minor*, Hou et al., 2007). However, these plants have shown limited potential for rhizofiltration, because they are not efficient at



metal removal, a result of their small, slow-growing root system (Dushenkov et al., 1995). These authors also point out that the high water content of aquatic plants make difficult their drying, composting, or incineration.

Despite limitations, Mahmood et al. (2010) indicated that water hyacinth is effective in removing trace elements in waste streams. For example, Mahmood et al. (2010) demonstrated that water hyacinth would remove silver from industrial wastewater for subsequent recovery with high efficiency in a fairly short time. The accumulation of some other heavy metals and trace elements in many species of wetland plants has also been demonstrated (Romero-Núñez et al., 2011). Water hyacinth has been used successfully in wastewater treatment systems to improve the quality of water by reducing the levels of organic and inorganic nutrients, and readily reducing the level of heavy metals in acid mine drainage water.

Trace element removal by wetland vegetation can be greatly enhanced by selection of appropriate wetland plant species. The selection is based on the types of elements to be remediated, the geographic location, microclimate, hydrologic conditions, soil properties, and known accumulation capacities of the species. Knowledge of the capabilities of different wetland plant species to absorb and transport trace elements under different conditions is important to know. One such plant is the vascular aquatic plant water hyacinth which is commonly found in tropical and subtropical regions of the world. Water hyacinth is a fast growing, floating plant with a reasonably well-developed fibrous root system and large biomass and it adapts easily to various aquatic conditions.

Hydroponic system involves aeration and therefore is not limited to aquatic species; it often makes use of terrestrial species with large roots and good capacity to accumulate inorganics (Dushenkov & Kapulnik, 2000).

### 3.4 Rhizofiltration using terrestrial plants

The advantages associated with rhizofiltration are the ability to use both terrestrial and aquatic plants for either *in situ* or *ex situ* applications. Terrestrial plants are thought to be more suitable for rhizofiltration because they produce longer, more substantial, often fibrous root systems with large surface areas for metal sorption (López-Chuken & Young, 2010). Another advantage is that contaminants do not have to be translocated to the shoots. Sunflower (*Helianthus annuus*), Indian mustard (*Brassica juncea*), spinach (*Spinacia oleracea*), corn (*Zea mays*) and tobacco (*Nicotiana tabacum*) are among the most promising terrestrial candidates for metal removal in water. The roots of *B. juncea* are effective in the removal of Cd, Cr, Cu, Ni, Pb, and Zn (Dushenkov et al. 1995), sunflower removes Pb (Dushenkov et al. 1995), U (Dushenkov et al. 1997a), <sup>137</sup>Cs, and <sup>90</sup>Sr (Dushenkov et al. 1997b) and tobacco removes Cd, Ni, Pb, Cr, Zn, Cu, Hg and As (Candelario-Torres et al., 2009) from hydroponic solutions. Similarly, López-Chuken & Young (2010) and López-Chuken et al. (2010) observed that roots of hydroponically grown terrestrial plants such as *B. juncea* and *Z. mays* effectively removed Cd from aqueous solutions. Candelario-Torres et al. (2009) shown that *N. tabacum* plants effectively remove toxic metals, such as Pb, Cd and Cr from polluted solutions.

Perhaps, the best example of a successful rhizofiltration remediation program occurred at Chernobyl, Ukraine, where, sunflowers were successfully used to remediate radioactive

uranium from pond water. Tobacco has been shown to develop long and hairy root systems when grown in nutrient solution, which create an extremely high surface area.

### 3.5 Rhizofiltration: Recent advances

Arthur et al., (2008) published an remarkable and extensive review of the use of rhizofiltration technologies applied to removal and further recovery of metals. While the extensive review of literature reported by the authors, only a few representative examples will be provided here. Rhizofiltration of metal-contaminated water was early investigated by Schulman et al. (1999). They developed a screening method to look for mutants of *Brassica juncea* that had enhanced Cd or Pb accumulation capabilities. The authors found that cell-wall binding and precipitation are the primary mechanisms of Pb accumulation in plants, thus the authors concluded that the hyperaccumulating characteristic of the mutant was due to the increased cell wall per unit of root weight. The ability to remove and recover heavy metals, including Pb, Cr, Zn, Cu and Ni from aqueous solutions was shown in experiments with *Medicago sativa* (alfalfa). Optimum binding was in aqueous solutions at pH 5, and tests showed that binding to alfalfa shoots occurred within five minutes. Similar results were reported by López-Chuken & Young (2010), where a rapid initial reduction of Cd concentration in a hydroponic solution was observed after an initial 3 hours of exposition to maize plants. This was thought to signify a rapid equilibration between the root system and Cd in solution rather than true absorption into roots. Alfalfa biomass is also reported as an effective species for recovering Au(III) from aqueous solutions (Gamez et al., 2003). Recovery of valuable metals by plants is called “*phytomining*”.

Rhizofiltration of uranium (U) by terrestrial plants has been investigated by Dushenkov et al. (1997a). They found that certain sunflower species had a high affinity for U and could concentrate it from water into the roots. Phytofiltration of chromium-contaminated water has been studied (Candelario-Torres et al., 2009), and it has been found that several plant species can uptake the toxic Cr(VI) species and reduce the pollutant to the nontoxic form, Cr(III). Water hyacinth supplied with Cr(VI) in nutrient culture accumulated Cr(III) in root and shoot tissues. Reduction to the nontoxic form appeared to occur in the fine lateral roots (Lytle et al., 1998). Phytofiltration of As from potable water has being evaluated using the brake fern (*Pteris vittata*). This plant species is known to tolerate high concentrations of As (Elless et al., 2003).

While some plants may have desirable characteristics for rhizofiltration of toxic metals from the environment, it is critical to better understand the mechanisms behind these capabilities before they can be exploited to the fullest extent for phytoremediation programs (Arthur et al., 2008). Recently, much research has being conducted to elucidate the chemical and physiological interactions involved in metal adsorption and accumulation.

To improve the potential of candidate plants for rhizofiltration, several research studies have been undertaken to select lines and improve plants by breeding. Recently, research using genetically modified (GM) plants has been spreading. Some transgenic plants are designed to be dwarf species. In this way, most of the biomass goes to leaves, and the rest to produce a short stem, similar approach as in the 1960s ‘Green Revolution’ for food production. Under this circumstances, when the native plants compete with them, do not allow them to develop (Gressel and Al-Ahmad, 2005).

However, according to Gressel and Al-Ahmad (2005), there are some considerations of the use of GM plants in field studies: The presence of wild relatives in the same area; harvesting time; the possibility that the plant become a weed; the possibility of gene flux and plant surviving on its own. Additionally, consideration to leave a fallow zone of about 8-18 m. There is also recommended that no food production at site be allowed during the next growing season. In general, whether GM plants or not, a problem for species used for phytoextraction should be considered: The risk that they can displace native species.

## 4. Challenges of hydroponic phytotechnologies

### 4.1 Plant development and variability

One of the main problems encountered by rhizofiltration research at laboratory level is the large variability in heavy metals content measured between plants exposed to the same treatment solutions. López-Chuken (2005) made several attempts to minimise this variation. For example, growing a large excess of seedlings in order to select uniform plants prior to treatment application, increase nutrient solution volume and nutrient concentration to reduce minor variation in conditions during the exposure period, validate digestion and analysis procedures against standard reference materials. In addition, it was shown that for an hydroponic trial using *Z. mays* which showed apparently erratic trends with Cd treatments (López-Chuken et al., 2010) there was, nevertheless, a good correlation between root and shoot analysis for individual plants which seems to suggest that the variability in response observed lay with individual plants rather than being caused by a methodical source of error. In general, plant variability in the hydroponic trials followed the qualitative trend: maize > Indian mustard > tobacco (Candelario-Torres et al., 2009; López-Chuken & Young, 2010; López-Chuken et al., 2010).

To date, hydroponic experiments dealing heavy metal uptake, generally involve the use of plants at early steps of development, for example an experiment used young seedlings (wheat harvested 6 days after sowing) with short exposure times to the treated solution ranging between 0 and 200 minutes (Berkelaar & Hale, 2003). In general, seeds from the Fam. Gramineae normally contain high nutrient reserves. Therefore, for short-term trials at early seedling stage, these plants may be still partially absorbing energy from the endosperm, and not completely reflecting nutrient conditions from solution. It is therefore recommended that hydroponic trials dealing with metal uptake, should preferably use plants as mature as possible (at least 6 weeks), and with enough metal exposure time ( $\geq 10$  days) (López-Chuken, 2005). This would allow the study of more mature plants and also minimised any short-term effects arising from the transition from nutrient to treatment solutions.

Berkelaar & Hale (2003) suggested the use of short-term metal accumulation experiments to maintain aseptic conditions and avoid biodegradation when using organic ligands as a reservoir of chelated metal in solution. However, it has been demonstrated an initial rapid sorption of metals from treatment solutions which does not necessarily reflect the normal uptake rate of the plants growing under steady state conditions in the treatment solutions (López-Chuken & Young, 2010). This effect was concluded to be a rapid approach to a pseudo-equilibrium state between root surface sorption sites and nutrient solutions. Furthermore, even when aseptic conditions are not strictly controlled, little effect in metal speciation was observed due to the presence of organic matter in solution of long-term trials (6-8 weeks) (López-Chuken & Young, 2010).

#### 4.2 Can rhizofiltration effectiveness be extrapolated to soil pollution?

One of the main advantages of the hydroponic-based experiments is that the solution chemistry in contact with plant root surfaces can be unequivocally designed and controlled during uptake trials. This represents a significant advantage over the uncertainties intrinsic to contaminated soil studies. Furthermore, (arguably) reliable morphological and chemical analysis of roots is only possible when using hydroponic growth media. However, the disadvantages of altered plant physiology and short exposure time in hydroponic studies are also well recognised. The choice of soil or hydroponic systems for the study of metal uptake must be dictated by the intention of the study but will always remain a compromise between the desire for control over experimental conditions and the unrealistic side effects of using any medium other than a naturally contaminated soil with a field sown plant allowed to follow its full span of physiological development. Chaney et al., (2005) suggested that the best media to test accumulator capacity by plants is the naturally contaminated soil (long-term), preferably in situ since it represents realistic conditions.

One problem associated with metal uptake trials with hydroponic systems, and other artificial media, is that such studies often seem to adopt very high 'unrealistic' metal concentrations. Recent research has shown that ordinary plants can even reach the metal hyperaccumulator "definition", for example  $\text{Cd} > 100 \text{ mg kg}^{-1}$  (Baker et al., 2000) under artificial media conditions (de la Rosa et al., 2004).

In a set of soil-based and hydroponic experiments using maize and Indian mustard plants (López-Chuken, 2006; López-Chuken & Young, 2010; López-Chuken et al., 2010) it has been shown that the ratio of Cd concentrations ( $\text{Cd}_{\text{shoot}}:\text{Cd}_{\text{root}}$ ) for different maize species ranged between 0.09 and 0.43 (mean = 0.24; SD = 0.11) throughout the trials. These results indicated that for all treatments, whether in soil or nutrient solution and even using different maize varieties (hybrid W23/L317; salt tolerant 2001-196-1; mays PI596543 and Cameron), Cd concentrations in roots were consistently larger than in shoots. However, when *B. juncea* plants were used, the ratio of concentrations ( $\text{Cd}_{\text{shoot}}:\text{Cd}_{\text{root}}$ ) showed large differences between soil (1.63 - 2.65; mean = 2.18; SD = 0.51) and nutrient solution (0.02 - 0.05; mean = 0.03; SD = 0.01) trials, despite using the same variety of Indian mustard (var. G32192). These results may suggest that perhaps not all plants are suitable for hydroponic experiments because plants show different physiological Cd uptake responses when growing in soil or dissimilar artificial media conditions. In the case of *B. juncea* the rapid root-to-shoot transfer observed for soil trials was virtually suspended in solution culture. Thus, under hydroponic conditions some factor (or a combination of factors) controlling Cd accumulation by roots and translocation to shoots may be affected.

#### 4.3 Importance of root surface area in expressing metal uptake

Hydroponic trials also offer some advantages over soil experiments where there is a particular interest in the role of the root morphology as a control over metal uptake rates. Although the morphology of roots grown in nutrient solutions will differ from those generated in soils, the entire root can be extracted without physical damage or contamination from soil particulates.

López-Chuken & Young (2010) in a Cd rhizofiltration trial using *Z. mays* observed that the dataset was effectively 'normalised' when including root morphological parameters to



express Cd uptake rates by plants. In all cases the root surface area (RSA) was the morphological characteristic that best explained changes in Cd uptake by plants. However, other measured root characteristics, (i.e. volume, length, root projected area) were so strongly correlated ( $R = 0.88-1.00$ ) with the RSA that the differences between expressing Cd uptake rates using these parameters were minimal. Furthermore, Berkelaar & Hale, (2000) in a nutrient solution trial growing wheat, expressed Cd uptake rates per unit root length or 'number of tips' with similar efficiency to that of RSA. It would be hence interesting to include, as future work, the use of rooting hormones on single varieties to investigate the potential enhancement of metal uptake rates by plants. A recent research (in hydroponics) has shown that adding the growth phytohormone IAA (indole-3-acetic acid) in combination with EDTA, increased Pb accumulation in leaves by about 2800% and by 600%, as compared to Pb content in leaves of lucerne plants exposed to Pb alone and with Pb/EDTA, respectively (López et al., 2005).

#### 4.4 Utilization of phytoremediation by-products

One of the main concerns about the use of plants with high metal phytoaccumulation characteristics is their post-harvest disposal. Rhizofiltration technologies applied to metal removal generally involve repeated cropping of plants in contaminated water, until the metal concentration drops to acceptable level. The ability of the plants to account for the decrease in water metal concentrations as a function of metal uptake and biomass production plays an important role in achieving regulatory acceptance (Ghosh & Singh, 2005). Although this may sound simple, several factors make it challenging in the field. One of the difficulties for commercial implementation of rhizofiltration has been the disposal of contaminated plant material (Ghosh & Singh, 2005). After each cropping, the plant is removed from the site; leading to accumulation of huge amounts of hazardous biomass waste that needs to be stored or disposed appropriately so that it does not pose any risk to the environment.

Composting and compaction has been proposed as post-harvest biomass treatment by some authors (Blaylock & Huang, 2000) however, leachates generated by composted or compacted biomass will need to be collected and treated appropriately. It has been also reported that plant material may be dried, burned and disposed of in landfill as ash (Keller et al, 2005). Another promising route to utilize biomass produces by phytoremediation in an integrated manner is through thermochemical conversion process (Keller et al, 2005). If rhizofiltration could be combined with biomass generation and its commercial utilization as an energy source, then it can be turned into profit making operation and the remaining ash can be used as bio-ore, the basic principle of phytomining.

Thermochemical energy conversion best suits the rhizofiltration biomass waste because it cannot be utilized in any other way as fodder and fertilizers. Combustion is a rudimentary method of burning the biomass and should be applied only under controlled conditions, whereby volume is reduced to 2-5 %. This method of plant matter disposal has to be carefully evaluated as burning the metal bearing hazardous waste in open will releases the gases and particulates to the environment.

Another alternative is the process called "*gasification*" through which biomass material can be subjected to series of chemical changes to yield clean and combustive gas at high thermal

efficiencies. This mixture of gases called as producer gas and/or pyro-gas that can be combusted for generating thermal and electrical energy. The process of gasification of biomass in a gasifier is a complex phenomenon; it involves drying, heating, thermal decomposition (pyrolysis) and gasification, and combustion chemical reactions, which occurs simultaneously and it may be possible to recycle the metal residue from the ash.

## 5. Cost estimates using rhizofiltration

Rhizofiltration is a cost-competitive technology in the treatment of large volumes of water containing low, but environmental significant concentrations of heavy metals such as Cr, Pb, and Zn (Candelario-Torres et al., 2009). The commercialization of rhizofiltration systems need to be driven by cost-effectiveness as well as by such technological advantages as applicability to many real conditions, ability to treat high volumes, lesser needed for chemicals, reduced volume of secondary waste, possibility of recycling and the almost secure likelihood of regulatory and public acceptance (Dushenkov et al. 1995).

This hydroponic-based phytotechnology has worked effectively at test sites near the Chernobyl nuclear plant in Ukraine. It has been estimated that the cost to remove radionuclides from water using sunflowers would be between \$2 and \$6 per 1,000 gallons, including disposal costs. On the other hand, a standard treatment of microfiltration and precipitation would cost nearly \$80 per 1,000 gallons (EPA, 2000). Glass (1999) estimated that depending on the pollutant, substrate, and alternative remediation methods available, phytoremediation could be typically 2–10-fold cheaper than conventional remediation methods.

Despite obvious advantages, the application of this plant-based technology may be more challenging and susceptible to failure than other methods of similar cost. The production of hydroponically grown plants and the maintenance of successful hydroponic systems in the field will require the qualified personnel, and the facilities and specialized equipment required could exceed the original estimated cost. Perhaps the fundamental benefit of this remediation method is related to positive public perception. Using plants at a site where contamination exists conveys the idea of cleanliness in an area that would have normally been perceived as polluted.

## 6. Rhizofiltration and sustainable development

Contaminated water in the urban environments and rural areas represents a major environmental and human health problem in the world. As shown above, some plants possess pronounced capacity and ability for the metabolism and degradation of many contaminants and are regarded as “green livers” acting as a sink for environmentally harmful contaminants. It has been reported that green space programmes are conducted in most countries to check the increasing levels of carbon dioxide which causes global warming. But when properly managed and handled through the use of some plants that have phytoremediation property, green space would not only clean the atmosphere of its excess carbon dioxide but also the soil and water from its contaminants.

Developing cost effective and environmentally friendly technologies for the remediation of soils and wastewaters polluted with toxic substances is a topic of global interest.



The Millennium Development Goals-MDGs agreed by the international community includes “environmental basic sanitation” as a critical target (IRC- International Water and Sanitation Centre, 2004). The necessity in decontaminating polluted sites is recognised worldwide, both socially and politically, because of the increasing importance placed on environmental protection and human health. Based on the success recorded by various studies on phytoremediation, rhizofiltration could represent a good alternative to contribute to achieve the above-mentioned goals.

## 7. Conclusions

Metals and other inorganic contaminants are among the most prevalent forms of contamination found at waste sites and the high cost of existing clean-up technologies has led to the search for new clean-up strategies that have the potential to be low-cost, low-impact, visually benign, and environmentally sound. Rhizofiltration as an emerging new clean-up concept needs to be promoted and emphasized and expanded mainly in developing countries due to its low cost and potential to be applicable to a variety of contaminated sites. Selection of the appropriate plant species is a critical process for the success of this technology. Fast growing plants, adapted to hydroponic conditions, with high biomass and good metal uptake ability are needed.

An extra important advantage of rhizofiltration is that both terrestrial and aquatic plants can be used (Prasad & Oliveira, 2003). Although terrestrial plants require physical support, they generally remove more contaminants than aquatic plants. This system can be either in situ (floating rafts on ponds) or ex situ (an engineered tank system). However, rhizofiltration has some intrinsic limitations (Prasad & Oliveira, 2003) a) pH of the polluted water has to be continually adjusted to obtain optimum metals uptake. b) chemical speciation and interaction of all metallic species in the influent has to be understood (López-Chuken et al., 2010), c) An engineered system is required to control influent flow rate, d) plants may have to be grown in greenhouse, e) periodic harvesting and plant disposal are needed, and f) metal uptake results from laboratory studies might be overestimated and not be achievable under real conditions.

In general, phytoremediation is a multi- and inter-disciplinary technology that will benefit from research in many different areas. Much still remains to be discovered about the chemical and biological processes that underlie a plant's ability to detoxify and accumulate pollutants. Better knowledge of the biochemical mechanisms involved may lead to: a) the identification of novel genes and the subsequent development of transgenic plants with enhanced remediation capacities, and b) a better understanding of the ecological interactions involved (e.g. plant-microbe interactions in the rhizosphere) among others. This knowledge will help improve risk assessment during the design of rhizofiltration programs as well as alleviation of the associated risks during remediation. Adapting each rhizofiltration system to the specifics of polluted water will become more feasible as more information becomes available; for example to select a combination of plant species with different remediation capabilities to clean up sites containing a mix of contaminants. Preferentially, native plant species will be used in order to promote ecosystem restoration during the cleanup process.

An interesting perspective for phytoremediation could be the adoption of an integrated approach both for research and commercial purposes. Currently, most plant-based

remediation research is carried out by scientists with expertise in only certain fields e.g. plant molecular biology, plant biochemistry, plant physiology, plant biochemistry, plant physiology, ecology, toxicology or microbiology but phytoremediation would be benefited more by a team of multidisciplinary researchers. Commercially to improve public acceptance phytoremediation could be integrated with landscape architecture with an attractive design so that the area may be used as a park or some other recreational place by the public after the remediation process (Pilon-Smits, 2005).

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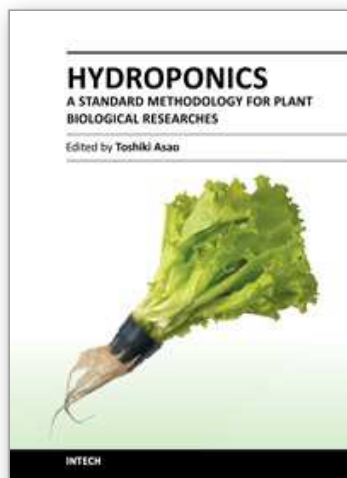
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## Hydroponics - A Standard Methodology for Plant Biological Researches

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Hydroponics-A standard methodology for plant biological researches provides useful information on the requirements and techniques needs to be considered in order to grow crops successfully in hydroponics. The main focuses of this book are preparation of hydroponic nutrient solution, use of this technique for studying biological aspects and environmental controls, and production of vegetables and ornamentals hydroponically. The first chapter of this book takes a general description of nutrient solution used for hydroponics followed by an outline of in vitro hydroponic culture system for vegetables. Detailed descriptions on use of hydroponics in the context of scientific research into plants responses and tolerance to abiotic stresses and on the problems associated with the reuse of culture solution and means to overcome it are included. Some chapters provides information on the role of hydroponic technique in studying plant-microbe-environment interaction and in various aspects of plant biological research, and also understanding of root uptake of nutrients and thereof role of hydroponics in environmental clean-up of toxic and polluting agents. The last two chapters outlined the hydroponic production of cactus and fruit tree seedlings. Leading research works from around the world are brought together in this book to produce a valuable source of reference for teachers, researcher, and advanced students of biological science and crop production.

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