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Review

Phytoremediation and Its Mechanisms: A Review

E. E. Etim

Department of Chemistry, University of Uyo, Uyo, Nigeria

* Author to whom correspondence should be addressed; E-Mail: emmaetim@gmail.com.

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Abstract: Since the dawn of the Industrial Revolution, mankind has been introducing numerous hazardous compounds into the environment at an exponential rate. These hazardous pollutants consist of a variety of organic compounds and heavy metals, which pose serious risks to human health. The problem of environmental pollution has assumed an unprecedented proportion in many parts of the world. Many methods and processes of preventing, removing and correcting the negative effects of pollutants released into the environments exist, but their application for this purpose has either been poorly implemented or not at all, a situation that is worsening owing probably to claims of lack of virile regulatory bodies. The use of plants to reduce contaminant levels in soil is a cost-effective method of reducing the risk to human and ecosystem health posed by contaminated soil sites. The objective of this review is to discuss the different phytoremediation mechanisms and their potentials as remediation techniques that utilize the age long inherent abilities of living plants to remove pollutants from the environment but which are yet to become a commercially available technology in many parts of the world especially the developing countries.

Keywords: environment, explosive, heavy metal, mechanism, oil pesticide, phytoremediation, pollution.

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1. Introduction

The generic term ‘phytoremediation’ consists of the Greek prefix *phyto* (plant), attached to the Latin root *remedium* (to correct or remove an evil) (Cunningham *et al.*, 1996). Phytoremediation is an alternative or complimentary technology that can be used along with or, in some cases in place of mechanical conventional clean-up technologies that often require high capital inputs and are labor and energy intensive. Phytoremediation is an *in situ* remediation technology that utilizes the inherent abilities of living plants. It is also an ecologically friendly, solar-energy driven clean-up technology, based on the concept of using nature to cleanse nature (UNEP, Undated). Contamination of soil by oil spills is a wide spread environmental problem that often requires cleaning up of the contaminated sites (Bundy *et al*., 2002).

Phytoremediation is a broad term that has been used since 1991 to describe the use of plants to reduce the volume, mobility, or toxicity of contaminants in soil, groundwater, or other contaminated media (USEPA, 2000). Phytoremediation uses plants to clean up pollution in the environment. Plants can help clean up many kinds of pollution including metals, pesticides, explosives, and oil. The plants also help prevent wind, rain, and groundwater from carrying pollutants away from sites to other areas. Phytoremediation is a non-destructive and cost effective *in situ* technology that can be used for the cleanup of contaminated soils. The potential for this technology in the tropics is high due to the prevailing climatic conditions which favors plant growth and stimulates microbial activity (Zhang *et al*., 2010).

For at least 300 years, the ability of plants to remove contaminants from the environment has been recognized and taken advantage of in applications such as land farming of waste. Over time, this use of plants has evolved to the construction of treatment wetlands or even the planting of trees to counteract air pollution. In more recent years, as recognition grew of the damage resulting around the world from decades of an industrial economy and extensive use of chemicals, so did interest in finding technologies that could address the residual contamination, among them phytoremediation (USEPA, 2000).

Research into and application of phytoremediation has flourished over the last 15 years. Phytoremediation has been implemented as a component of the selected remedy at 18 Superfund sites in the United States (Wuana *et al.,* 2010). Since 2001, the International Journal of Phytoremediation has been published quarterly. An international conference devoted to phytoremediation work has been convened seven times. In this same time period, public and private dollars have been funneled into research at the laboratory, greenhouse, and field scale to understand both the mechanisms by which plants address existing contamination and to establish the actual remediation performance of various plant species in different media and contaminants (Tanee and Akonye, 2009). The objective of this review is to discuss the different phytoremediation mechanisms and their potentials as remediation techniques that utilize the age long inherent abilities of living plants to remove pollutants from the environment but which are yet to become a commercially available technology in many parts of the world especially the developing countries.

2. Mechanisms of Phytoremediation

The mechanisms and efficiency of phytoremediation depend on the type of contaminant, bioavailability and soil properties (Cunningham and Ow, 1996). There are several ways by which plants clean up or remediate contaminated sites. The uptake of contaminants in plants occurs primarily through the root system, in which the principal mechanisms for preventing toxicity are found. The root system provides an enormous surface area that absorbs and accumulates water and nutrients essential for growth along with other non-essential contaminants (Raskin and Ensley, 2000).

This review has identified seven mechanisms by which plants can affect contaminant mass in soil, sediments, and water. Although overlap or similarities can be observed between some of these mechanisms, and the nomenclature varies, this report makes reference to seven phytoremediation mechanisms, each explained in detail below. Each of these mechanisms will have an effect on the volume, mobility, or toxicity of contaminants, as the application of phytoremediation is intended to do (EPA, 2000).

2.1. Phytoextraction

This also called phytoaccumulation, it refers to the uptake and translocation of metal contaminants in the soil by plant roots into the above ground portions of the plants. Phytoextraction is primarily used for the treatment of contaminated soils (USEPA, 200). To remove contamination from the soil, this approach uses plants to absorb, concentrate, and precipitate toxic metals from contaminated soils into the above ground biomass (shoots, leaves, etc.) (Fig. 1). Discovery of metal hyperaccumulator species demonstrates that plants have the potential to remove metals from contaminated soils (Raskin and Ensley, 2000). A hyperaccumulator is a plant species capable of accumulating 100 times more metal than a common non-accumulating plant (UNEP, Undated). Metals such as nickel, zinc and copper are the best candidates for removal by phytoextraction because it has been shown that they are preferred by a majority of plants (approximately 400) that uptake and absorb unusually large amounts of metals.

There are several advantages of phytoextraction. The cost of phytoextraction is fairly inexpensive when compared to conventional methods. Another benefit is that the contaminant is permanently removed from the soil. In addition, the amount of waste material that must be disposed of is substantially decreased (up to 95%) (USEPA, 2000) and in some cases, the contaminant can be recycled from the contaminated plant biomass.

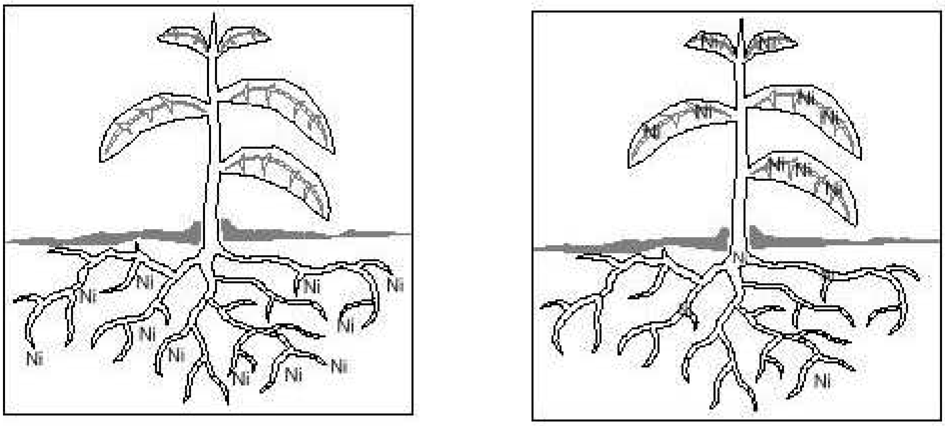

Figure 1. Phytoextraction of Ni from contaminated soil.

The use of hyperaccumulator species is limited by slow growth, shallow root system, and small biomass production. In addition, the plant biomass must also be harvested and disposed of properly, complying with standards (Raskin and Ensley, 2000). There are several factors limiting the extent of metal phytoextraction including:

• Metal bioavailability within the rhizosphere
• Rate of metal uptake by roots
• Proportion of metal "fixed" within the roots
• Rate of xylem loading/translocation to shoots
• Cellular tolerance to toxic metals

The method is also usually limited to metals and other inorganic compounds in soil or sediment (EPA, 2000).

In order for this clean-up method to be feasible, the plants must (1) extract large concentrations of heavy metals into their roots, (2) translocate the heavy metal into the surface biomass, and (3) produce a large quantity of plant biomass. In addition, remediative plants must have mechanisms to detoxify and/or tolerate high metal concentrations accumulated in their shoots (Brennan and Shelley, 1999).

2.2. Rhizofiltration

This is primarily used to remediate extracted groundwater, surface water, and wastewater with low contaminant concentrations. It is the adsorption or precipitation onto plant roots or absorption of contaminants in the solution surrounding the root zone. Rhizofiltration is typically exploited in groundwater (either in situ or extracted), surface water, or wastewater for removal of metals or other inorganic compounds (EPA, 2000). Rhizofiltration can be used for Pb, Cd, Cu, Ni, Zn, and Cr, which are primarily retained within the roots (USEPA, 2000). An illustration of this method is shown in Fig. 2. Rhizofiltration is similar to phytoextraction, but the plants are used primarily to address contaminated ground water rather than soil. The plants to be used for cleanup are raised in greenhouses with their roots in water rather than in soil. To acclimatize the plants, once a large root system has been developed, contaminated water is collected from a waste site and brought to the plants where it is substituted for their water source. The plants are then planted in the contaminated area where the roots take up the water and the contaminants along with it. As the roots become saturated with contaminants, they are harvested. Sunflower, Indian mustard, tobacco, rye, spinach, and corn have been studied for their ability to remove lead from water, with sunflower having the greatest ability. In one study, after only one hour of treatment, sunflowers reduced lead concentrations significantly (Raskin and Ensley, 2000).

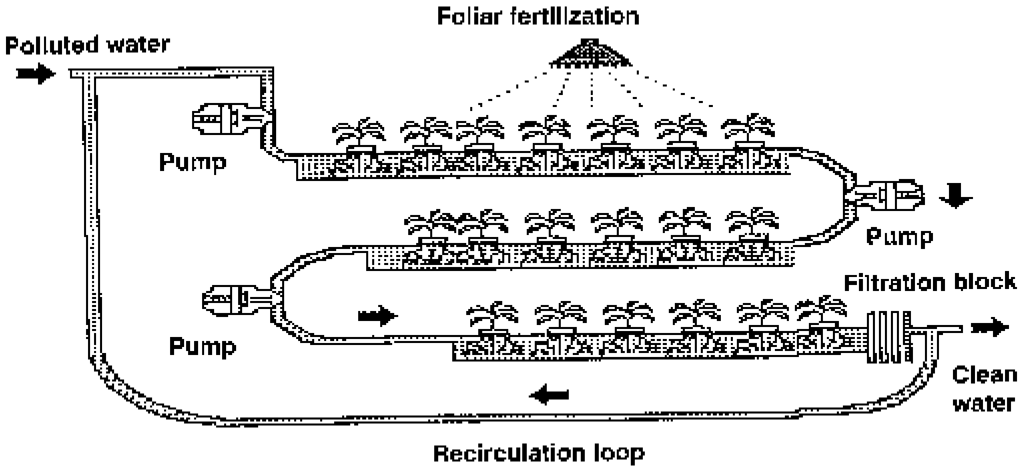

Figure 2. Engineered rhizofiltration system. Source: Phytoremediation: using plant to remove pollutants from the environment. http//www.aspp.org/pubaff/phytorem.htm

The advantages associated with rhizofiltration are the ability to use both terrestrial and aquatic plants for either *in situ* or *ex situ* applications. Another advantage is that contaminants do not have to be translocated to the shoots. Thus, species other than hyperaccumulators may be used. Terrestrial plants are preferred because they have a fibrous and much longer root system, increasing the amount of root area (Raskin and Ensley, 2000).

Disadvantages and limitations include the constant need to adjust pH, plants may first need to be grown in a greenhouse or nursery; there is periodic harvesting and plant disposal; tank design must be well engineered; and a good understanding of the chemical speciation/interactions is needed. The cost of remediation by rhizofiltration has been estimated to be $2-$6 per 1000 gallons of water (USEPA, 2000).

2.3. Phytovolatilization

This involves the use of plants to take up contaminants from the soil, transforming them into volatile forms and transpiring them into the atmosphere (USEPA, 2000). Phytovolatilization also involves contaminants being taken up into the body of the plant, but then the contaminant, a volatile form thereof, or a volatile degradation product is transpired with water vapor from leaves (EPA, 2000). Phytovolatilization may also entail the diffusion of contaminants from the stems or other plant parts that the contaminant travels through before reaching the leaves (Raskin and Ensley 2000).

Phytovolatilization can occur with contaminants present in soil, sediment, or water. Mercury is the primary metal contaminant that this process has been used for. It has also been found to occur with volatile organic compounds, including trichloroethene, as well as inorganic chemicals that have volatile forms, such as selenium, and arsenic (EPA, 2000). The advantage of this method is that the contaminant, mercuric ion, may be transformed into a less toxic substance (i.e., elemental Hg). The disadvantage to this is that the mercury released into the atmosphere is likely to be recycled by precipitation and then redeposited back into lakes and oceans, repeating the production of methyl-mercury by anaerobic bacteria (USEPA, 2000).

2.4. Phytostabilization

This is also referred to as in-place inactivation. It is primarily used for the remediation of soil, sediment, and sludge (USEPA, 2000). It is the use of certain plant species to immobilize contaminants in the soil and ground water through absorption and accumulation by roots, adsorption onto roots, or precipitation within the root zone of plants (rhizosphere). This process reduces the mobility of the contaminant and prevents migration to the ground water and it reduces bio-availability of metal into the food chain. This technique can also be used to reestablish vegetation cover at sites where natural vegetation fails to survive due to high metals concentrations in surface soils or physical disturbances to surface materials. Metal-tolerant species is used to restore vegetation at contaminated sites, thereby decreasing the potential migration of pollutants through wind erosion and transport of exposed surface soils and leaching of soil contamination to ground water. Phytostabilization can occur through the sorption, precipitation, complexation, or metal valence reduction. It is useful for the treatment of lead (Pb) as well as arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu) and zinc (Zn). Phytostabilization takes advantage of the changes that the presence of the plant induces in soil chemistry and environment. These changes in soil chemistry may induce adsorption of contaminants onto the plant roots or soil or cause metals precipitation onto the plant root. Phytostabilization has been successful in addressing metals and other inorganic contaminants in soil and sediments (EPA, 2000).

Some of the advantages associated with this technology are that the disposal of hazardous material/biomass is not required and it is very effective when rapid immobilization is needed to preserve ground and surface waters (Zhang *et al*., 2009). The presence of plants also reduces soil erosion and decreases the amount of water available in the system (USEPA, 2000). However, this clean-up technology has several major disadvantages including: contaminant remaining in soil, application of extensive fertilization or soil amendments, mandatory monitoring is required, and the stabilization of the contaminants may be primarily due to the soil amendments.

2.5. Phytodegradation

This is also referred to as phytotransformation. It involves the degradation of complex organic molecules to simple molecules or the incorporation of these molecules into plant tissues (Trap et al., 2005). When the phytodegradation mechanism is at work, contaminants are broken down after they have been taken up by the plant. As with phytoextraction and phytovolatilization, plant uptake generally occurs only when the contaminants' solubility and hydrophobicity fall into a certain acceptable range. Phytodegradation has been observed to remediate some organic contaminants, such as chlorinated solvents, herbicides, and munitions, and it can address contaminants in soil, sediment, or groundwater (EPA, 2000).

2.6. Hydraulic Control

This is the control of the water table and the soil field capacity by plant canopies. Phytoremediation projects employing hydraulic control generally use phreatophytic trees and plants that have the ability to transpire large volumes of water and thereby affect the existing water balance at the site. The increased transpiration reduces infiltration of precipitation (thereby reducing leaching of contaminants from the vadose zone) or increases transpiration of groundwater, thus reducing contaminant migration from the site in groundwater plumes. Hydraulic control can therefore be used to address a wide range of contaminants in soil, sediment, or groundwater (EPA, 2000). It should be noted that hydraulic control is also a feasible phytoremediation mechanism for control of groundwater contamination in particular, because the characteristics of the contaminants are not as relevant to the success of the technique.

2.7. Rhizodegradation

This is also referred to as phytostimulation. Rhizodegradation refers to the breakdown of contaminants within the plant root zone, or rhizosphere. It is believed to be carried out by bacteria or other microorganisms whose numbers typically flourish in the rhizosphere. Studies have documented up to 100 times as many microorganisms in rhizosphere soil as in soil outside the rhizosphere (USEPA, 2000). Microorganisms may be so prevalent in the rhizosphere because the plant exudes sugars, amino acids, enzymes, and other compounds that can stimulate bacterial growth. The roots also provide additional surface area for microbes to grow on and a pathway for oxygen transfer from the environment. The localized nature of rhizodegradation means that it is primarily useful in contaminated soil, and it has been investigated and found to have at least some successes in treating a wide variety of mostly organic chemicals, including petroleum hydrocarbons, polycyclic aromatic hydrocarbons (PAHs), chlorinated solvents, pesticides, polychlorinated biphenyls (PCBs), benzene, toluene, ethylbenzene, and xylenes (EPA, 2000). It can also be seen as plant-assisted bioremediation, the stimulation of microbial and fungal degradation by release of exudates/enzymes into the root zone (rhizosphere) (Zhang et al., 2005).

3. Conclusion

As highlighted above, there are several ways in which plants are used to clean up or remediate contaminated sites. To remove pollutants from soil, sediment and/or water and air, plants can break down, or degrade organic pollutants or contain and stabilize inorganic contaminants by acting as filters or traps. The success of phytoremediation at a given site cannot always be attributed to just one of these mechanisms because a combination of mechanisms may be at work. Phytoremediation is a low cost, solar energy driven and natural cleanup technique, which are most useful at sites with shallow, low levels of contamination. They are useful for treating a wide variety of environmental contaminants and are effective with or in some cases, in place of mechanical cleanup methods. Phytoremediation harnesses natural processes to assist in the clean-up of pollutants in the environment. The mechanisms by which plants promote the removal of pollutants are varied, including uptake and concentration, transformation of pollutants, stabilization, and rhizosphere degradation, in which plants promote the growth of bacteria underground in the root zone that in turn break down pollutants. Phytoremediation is amenable to a variety of organic and inorganic compounds and may be applied either *in situ* or *ex situ*. *In situ* applications decrease soil disturbance and the possibility of contaminant from spreading via air and water, reduce the amount of waste to be land filled (up to 95%) and are low-cost compared with other treatment methods. In addition to this, it is easy to implement and maintain, does not require the use of expensive equipment or highly specialized personnel and is environmentally friendly and aesthetically pleasing to the public.

References

Brennan, M. A., and Shelley, M. L. (1999). A model of the uptake, translocation, and accumulation of lead (Pb) by maize for the purpose of phytoextraction. *Ecol. Eng.*, **12**: 271-297.

Bundy, J. G., Paton, G. I., and Campbell, C. D. (2002). Microbial communities in different soil types do not converge after diesel contamination. *J. Appl. Microbiol.*, **92**: 276-288.

Cunningham, S. D., Anderson, T. A, Schwab, P. A, and Hsu, F. C. (1996). Phytoremediation of soils contaminated with organic pollutants. *Adv. Agron.*, **56**: 55-114.

Cunningham, S. D., and Ow, D. W. (1996). Promises and prospect of phytoremediation. *Plant Physiol.*, **110**: 715-719.

EPA (2000). *A Citizen's Guide to Phytoremediation*. EPA 542-F-98-011. United States Environmental Protection Agency, p. 6. Available at: http//www.bugsatwork.com/XYCLONYX/EPA_GUIDES /PHYTO.PDF

Raskin, I., and Ensley, B. D. (2000). Recent developments for in situ treatment of metal contaminated soils. In: *Phytoremediation of Toxic Metals: Using Plants to Clean Up the Environment*. John Wiley & Sons Inc., New York. Available at: http//clu-n.org/techfocus

Tanee, F. B. G., and Akonye, L. A. (2009). Effectiveness of *Vigna Unguiculata* as a phytoremediation plant in the remediation of crude oil polluted soil for cassava (*Manihot Esculenta* Crantz) Cultivation. *J. Appl. Sci. Environ. Manage.*, **13**: 43- 47.

Trap, S., Kohler, A., Larsen, L. C., Zambrano, K. C., and Karlson, U. (2005). Phytotoxicity of fresh and weathered diesel and gasoline to willow and poplar trees. *J. Soil Sediments*, **1**: 71-76.

UNEP (Undated). *Phytoremediation: An Environmentally Sound Technology for Pollution Prevention, Control and Remediation. An Introductory Guide to Decision-Makers*. Newsletter and Technical Publications Freshwater Management Series No. 2, United Nations Environment Programme Division of Technology, Industry, and Economics.

United States Environmental Protection Agency (USEPA). (2000). *Introduction to Phytoremediation*. EPA 600/R-99/107, U.S. Environmental Protection Agency, Office of Research and Development, Cincinnati, OH.

Wuana, R. A, Okieimen, F. E., and Imborvungu, J. A. (2010). Removal of heavy metals from contaminated soil using chelating organic acids. *Int. J. Environ. Sci. Tech.*, **7**: 485-496.

Zhang, H., Zheng, L. C., and Yi, X. Y. (2009). Remediation of soil co-contaminated with pyrene and cadmium by growing maize (*Zea mays* L.). *Int. J. Environ. Sci. Tech.*, **6**: 249-258.

Zhang, X., Xia, H., Li, Z., Zhang, P., and Gao, B. (2010). Potential of four forage grasses in remediation of Cd and Zn contaminated soils. *Bioresour. Technol.*, **101**: 2063-2066.

Zhuang, P., Ye, Z. H., Lan, C. Y., Xie, Z. W, and Hsu, W. S. (2005). Chemically assisted phytoextraction of heavy metal contaminated soils using three plant species. *Plant Soil*, **276**: 153-162.