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Research Note

Phytoremediation: A Potential Alternative Technique for Environmental Cleanup

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Abstract

Heavy metals and other inorganic and organic pollutants contaminate soil and water. This causes ecological imbalances leading to major environmental problems and pose a threat to human health. The conventional methods to cleanup such polluted sites are very costly and sometimes impractical as they are environmentally disturbing and limited to smaller polluted sites. Studies indicate that phytoremediation, an emerging technology that uses plants to clean up pollution, could be a better alternative to conventional methods as it is cost effective, environmentally nonintrusive, and can be used to remediate larger polluted sites. The basis of phytoremediation, an innovative and a promising technology, is pollutant uptake by plants. This paper focuses on understanding and applications of phytoremediation based on the existing information in this emerging field of science.

Keywords: Phytoremediation, heavy metals, metal pollution.

1.0 Introduction

The term phytoremediation is derived from the words “phyto”, meaning plant, and “remediation”, meaning to amend vice. Phytoremediation is a natural process that uses plants to remove heavy metals (metals with an atomic number > 20, such as cadmium, copper, lead, zinc, etc.) and various inorganic and organic pollutants from soil and water. These pollutants are present in the soil as natural components, and also as a result of human activities such as mining, fossil fuel burning, energy and fuel production, fertilizer and pesticide usage in agriculture, industrial waste disposal, etc. Such activities introduce hazardous pollutants into the environment (Salt *et al.*, 1995; Zaman, 2003; Park *et al.*, 2012; Lee, 2013). Pollutants accumulated in the soil eventually contaminate ground water and become hazardous to human health.

Plants growing in contaminated soils may absorb pollutants into their tissues. Once translocated into the plant tissues, organic contaminants are mostly broken down into non-hazardous substances and the inorganic contaminants are concentrated within the plant body. Consumption of such polluted plants by herbivorous animals introduces contaminants into the food chain. Soil contaminants such as copper (Cu), zinc (Zn), nickel (Ni), aluminum (Al), cadmium (Cd), lead (Pb), cobalt (Co), chromium (Cr), mercury (Hg), and other heavy metals have been proven to cause hazardous effects in animals and humans (Adriano, 1992; Klimisch, 1993; Jarup *et al.*, 1998; Salt *et al.*, 1998; ATSDR, 1999; Aykin-Burns, 2003; Endo, 2003, Addae *et al.*, 2010; Shumaker *et al.*, 2011). Environmental policies mandate that such metal contaminated sites must be remediated before any public use. The most common soil remediation methods are soil venting, washing, chemical treatment, and excavation and burial. Such methods are not practical for large areas, as they are extremely expensive, costing $0.6 – 3.0 million to clean-up one hectare to a depth of one meter depending on the type and intensity of the pollution (Moffat, 1995). It is needless to point out that these processes not only dramatically disturb the landscape (Lasat, 2002), but also pose a grave threat to the ecosystem. Plummer (1997) had estimated that it would cost about $12 million to clean-up a 10-acre Pb contaminated land using conventional remediation, versus only $500,000 using phytoremediation. Brown (1995) projected that between 1995 and 2000, the United States would be spending an estimated $42-billion in cleaning up sites contaminated with metals, organic, and inorganic contaminants using conventional methods. Therefore, remediation methods that are cost-effective, environmentally friendly, and aesthetically pleasing have the potential for becoming a good substitute to environmental remediation methods currently in use.

Some plant species, such as members of brassica family, have the unique ability to tolerate, take up, and hyperaccumulate heavy metals from the soil through their roots and concentrate them in their stems, roots, and leaves (Moffat, 1995; Dudka *et al.*, 1996; Brown *et al.*, 1996; Pitchell *et al.*, 1999; Zaman *et al.*, 2003, Marques *et al.*, 2009; Park *et al.*, 2012; Wang *et al.*, 2012). These are the ideal plants for phytoremediation of contaminated soils. Even though, the concept of phytoremediation was formally introduced by Rufus Chaney of the United States Department of Agriculture in 1983, the use of phytoremediation has been recognized for over 300 years (Lasat, 2000). Plants capable of accumulating high levels of zinc, selenium, and nickel (Byers, 1935; Minguzzi and Vergnano, 1948) have been reported earlier. Following Chaney's introduction in 1983, it took almost a decade for the broader scientific community to understand the potential of phytoremediation, and at present, this subject matter has created a wide interest within the scientific, business, and the regulatory communities (Zaman, 2003).

Phytoremediation uses vegetation to remove, accumulate, degrade, contain, or immobilize harmful environmental pollutants from soil or water, and plants that can accumulate such contaminants in high concentrations, are the hyperaccumulators. Hyperaccumulation has been defined as a plant's ability to accumulate metals at levels 100-fold greater in the shoot tissue as compared to the common nonaccumulator plants (Lasat, 2002). According to Baker *et al.* (2000), a typical hyperaccumulator should bioaccumulate at least 10 ppm Hg; 100 ppm Cd; 1000 ppm Co, Cr, Cu, and Pb; 10000 ppm Zn, and Ni.

Hyperaccumulator plant species are able to tolerate soil metal toxicity while carrying out their normal physiological processes. According to Rufus Chaney (1983), ideal hyperaccumulator plants should be fast growing, easy to harvest, deep rooted, with larger biomass, and able to retain their leaves so that the leaves can be harvested along with the plant stem (Becker, 2000). And according to Clemens *et al.* (2002), an ideal phytoremediator is a plant that grows fast, creates large biomass, and is equipped with an extensive root system. Since such an ideal hyperaccumulators are yet to be found in the nature, development of transgenic plant species using genetic engineering technology, could make this wish a reality.

Following completing the natural growth processes in contaminated soils, plant parts can be harvested, compacted, and incinerated. This will minimize the volume of the waste which can be disposed of properly at hazardous waste sites, or incinerated products containing high concentrations of metals may be used as bio-ore. Such incinerated products may yield 30 to 40 percent metals and can be considered as high-grade ore (Becker, 2000).

The acceptance of phytoremediation is evolving as scientists are gradually discovering its versatility. It is a novel approach with a great potential to serve as a cost effective, sustained, nonintrusive, and ecologically responsible green technology to remediate contaminated soils and water. It promises to be a safe alternative to conventional cleanup techniques.

2.0 Areas of Phytoremediation

Phytoremediation occurs through composite interactions between plants, soil, and the soil microbes. Based on applications, it can be divided into the following areas (as shown in Figure 1):

- **Phytoextraction or Phytoaccumulation:** Plants absorb contaminants from the soil through the roots, and bioconcentrate them in the plant tissues. Plants suitable for phytoextraction are able to tolerate high level of contaminants in the soil. Such plants with a higher biomass (such as poplar) should be able to accumulate larger quantities of the pollutants (Targeted media: Soil).
- **Rhizofiltration:** This is the process of uptaking inorganic contaminants dissolved in water through the plant roots. Plants that are suitable for rhizofiltration, typically have rapidly growing and prominent root systems

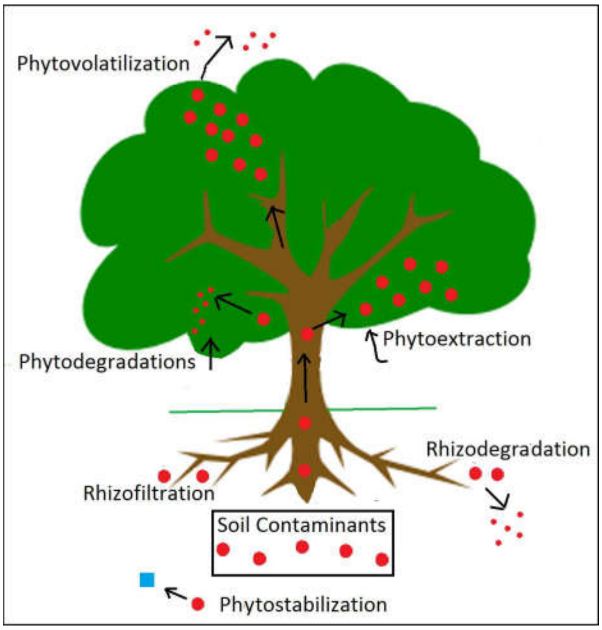

Figure 1: Areas of Phytoremediation

(Targeted media: Surface water and water pumped through troughs).

- **Phytodegradation or Phytotrans-formation:** Plants uptake organic pollutants such as pesticides, herbicides, hydrocarbons, etc. which are then degraded or metabolized within the plant tissue (Targeted media: Surface water, groundwater).
- **Rhizodegradation or Phytostimulation:** Soil microorganisms play an important role in this process. This is performed by the release of compounds (exudates) by plant roots that enhance biodegradation of organic contaminants with the help of soil microorganisms (Targeted media: Soils, groundwater within the rhizosphere).
- **Phytovolatilization:** Plants transport organic contaminants to their leaves that transpire, evaporate, or volatize the contaminants into the atmosphere (Targeted media: Soils, groundwater).
- **Phytostabilization:** This is the use of plants to limit the contaminant movement in the environment. Barren lands are more susceptible to erosion and leaching and this spreads contaminants in the environment. Planting pollutant tolerant plant species in such soils will help stabilize the soil and limit pollution movement. Trees are ideal for phytostabilization as they are perennial and their extensive root systems can reach greater areas as compared to smaller plants (Targeted media: Soils, groundwater, mine tailings).
- **Phytohydraulics:** This process contains contaminant migration within the soils by creating a hydraulic barrier. These plants establish a dense root mass that reaches down toward the water table and takes up large quantities of water (e.g. 50 – 300 gallons for poplar trees). This upward water movement decreases the tendency of surface contaminants to move toward the groundwater and into drinking water (Targeted medium: Soils).

3.0 Contaminant Mobility

Most phytoremediation studies focus on remediation of soils contaminated with the most common metal contaminants such as Cd, Pb, Zn, Cr, etc. and hazardous organic or inorganic pollutants (Marques *et al.*, 2009; Ye *et al.*, 2011, Park *et al.,* 2012). Remediation of soils containing radioactive compounds is also gaining significant interests (Becker, 2000; Eapen *et al.*, 2006; Rylott, 2009; Cerne *et al.*, 2011; Saleh, 2012). The pollutant uptake efficacy of plants depends on several factors, such as the bioavailability of the pollutants to the plants, plant's tolerance to pollutant toxicity, transport mechanism, transpiration rate, concentrations of the contaminants in the media (soil or water), and the physicochemical properties of the contaminants and the media. In general, only a fraction of soil metal is readily bioavailable for plant uptake. The greater portion of metal exists as insoluble compounds unavailable for root absorption. Metals like Zn and Cd occur primarily as soluble or exchangeable forms (Pitchel *et al.*, 1999). Since such metals are more mobile within the soils and plant tissues, root absorption and tissue accumulation of these metals is relatively efficient. On the other hand, Pb exists as insoluble precipitates, tends to bind to soil particles, and therefore, it is largely unavailable for plant uptake (Pitchel *et al.*, 1999). Alkaline soils and soils containing high amounts of clay tend to hold the metal particles, making metals less bioavailable for plant uptake. Sandy or acidic soils are favorable for phytoabsorption of heavy metals.

Several external factors may also influence bioavailability of pollutants for plant uptake. Plants can stimulate bioavailability of soil pollutants by secreting exudes in the rhizosphere (Fushiya *et al.*, 1982; Takagi *et al.*, 1984; Bienfait *et al.*, 1982; Chekol *et al.*, 2004; Hernandez-Ortega *et al.*, 2012). Application of organic citrate to soils greatly increases the bioavailability and absorption of uranium (U) by plants. Citrate application was shown to enhance plant tissue U concentration to over 2,000 ppm - 100 times higher than the control plants (Becker, 2000). Cesium (Cs)-137 is not readily bioavailable, but ammonium was found to be effective in dissolving Cs-137 in soils. Electrical charges in cell membranes prevent free movement of metals through plant roots. Thus, metal ion transport through roots is mediated by membrane proteins (Lasat, 2002).

Roots either accumulate the metal ions or translocate them to the shoot. Probably, such translocation occurs through the xylem and then the redistribution of ions within the shoot occurs through the phloem. The use of metal chelating agents may enhance the movement of such metal ions through the xylem cell walls (Salt *et al.*, 1995). The use of chelating agents in phytoremediation has been reported by many investigators (Zaman *et al.*, 2003; Ehsan *et al.*, 2007).

When an organic pollutant is taken up, plants can mineralize the chemical to carbon dioxide and water, volatilize the chemical, or store the chemical in plant structures (Schnoor *et al.*, 1995). Plant release of exudates (acids, alcohols, and sugars) to the root-soil environment also helps degrade the organic chemicals. Roots harbor mycorrhizae fungi. These fungi have enzymatic pathways to degrade organic pollutants. Plant exudates stimulate bacterial transformation and build up organic carbon in the rhizosphere. The decay of fine roots is also another source of carbon. Organic carbon in the soil enhances microbial mineralization and retards transport of contaminants in the groundwater (Anderson *et al.*, 1993). Increased microbial habitat surrounding the roots also increases the soil oxygen available to the roots. Typical rhizosphere communities contain 5 x 106 bacteria, 9 x 105 actinomycetes, and 2 x 103 fungi per gram of air-dried soil (Schnoor *et al.*, 1995).

Studies suggest that certain genes may regulate the uptake and accumulation of pollutants in plants (Rugh *et al.*, 1998; Suh *et al.*, 1998, French *et al.*, 1999; Becker, 2000; Song *et al.,* 2003; Rugh, 2004; Afzal *et al.*, 2011). These genes may control processes that enhance the solubility of metals in the root-soil environment. Transport proteins help move metals into root cells and then the plant vascular systems help movement of metals within the plants. A study involving cloning of a zinc transport gene suggested that metal transport may be regulated differently in normal and hyperaccumulator plants (Becker, 2000).

4.0 Advantages of Phytoremediation

- It is a highly cost effective method as compared to the conventional remediation techniques. According to Lee (2013), it is 50 – 80%, or even less of the cost of the current conventional methods.
- It is aesthetically pleasing, nonintrusive to the environment, and thus friendly to the ecosystem.
- Plant roots stabilize the soil, reduce soil erosion, and thus prevent contaminant migration.
- As roots absorb water and nutrient from the soil, downward movement of chemicals by percolation is reduced and that reduces groundwater contamination.
- Plants help to increase the amount of organic carbon in the soil. This helps stabilize soil contaminants and thus limits contaminant movement.
- There is a potential of the recovery and reuse of valuable metals from harvested plants.

4.1 Limitations of Phytoremediation

- This is a time consuming method as compared to conventional soil remediation processes.
- It appears to be most effective at sites with shallow contaminated soils.
- Phytoremediation is a challenging process for hydrophobic pollutants that are tightly bound to the soil particles.
- Plant enzymes and exudates in the root-soil environment enhance degradation of organic pollutants. Some of these degraded compounds may migrate off site due to their

high mobility even before they are absorbed through the plant root system.

- Toxic pollutants absorbed in plant tissues may enter food chain and pose potential health risks.
- Seasonal conditions and climate can interfere with plant growth.
- Toxicity of contaminants may interfere with plant growth.

5.0 Conclusion

Phytoremediation of contaminated soil and water is an evolving, fascinating, promising, but challenging area of science. Despite its potential, the progression of phytoremediation to become a commercially available technology is taking an unpredictably longer time. This is mainly because of our limited understanding of the plant mechanisms that allow the hyperaccumulators to absorb and bioaccumulate contaminants, and the complex interactions between the plant root system, contaminants, soil microbes, and physical and chemical properties of the soil matrix. The other reason for such delay is the limited availability of hyperaccumulators with larger biomass. Hopefully, development of transgenic plants (Rugh, 2004; Epen and D'Souza, 2005; Dowling and Doty, 2009; Rylott and Bruce, 2009) will help us to develop hyperaccumulators with elaborate root system and significant biomass.

Each cleanup condition distinctive by specific ecological condition will require different hyperaccumulator plant species, adapted to that particular environmental condition. According to Clemens *et al.* (2002), an ideal phytoremediator is a plant that grows fast, creates large biomass, and is equipped with an extensive root system. Since the natural phytoremediators often lack these qualities, scientists are focusing on developing bioengineered plants to fit the requirements of different cleanup conditions (Rugh, *et al.*, 1998; Abhilash *et al.,* 2009; French *et al.,* 1999; Bizily *et al.*, 2000; Grichko *et al.*, 2000). With the further advancement of transgenic biotechnology, it is expected that in the near future, genetically modified hyperaccumulator plant species with tolerance to high levels of pollutants and adaptations to varied environmental conditions, will be commercially available. In addition to transgenic modification of plants, researchers are also concentrating on the processes that can enhance the pollutant bioavailability in the soil and water to enhance plant uptake of the pollutants (Kirkham, 2000; Wu *et al.*, 2000; Ehsan *et al.*, 2007).

Phytoremediation is an emerging and promising green technology. In the beginning, most researchers focused on remediation of sites polluted with heavy metals. Gradually their focus included other inorganic and organic pollutants, and recently, remediation of sites with radioactive wastes have gained a lot of interest. Most of the findings indicate that this is a novel and feasible technology that holds greater promise for the future. However, at present, because of its current limitations as described earlier, it is not a remedy for all hazardous waste problems. This technology has to be further developed before it can be commercially available, and with the gradual involvement of scientists from varied branches of science and encouragements from entrepreneurs, commercialization of phytoremediation should not be far from reality.

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References

Abhilash, P.C., Jamil, S. and Singh, N. 2009, "Transgenic plants for enhanced bioremediation and phytoremediation of organic xenobiotics. Biotechnol. Adv. **27,** 474-488.

Addae, C.L., Piva, M., Bednar, A.J., and Zaman, M.S. 2010, "Cadmium and Lead Bioaccumulation in Cabbage Plants Grown in Metal Contaminated Soils", Adv. Sci. Tech. **4 (1),** 79-82.

Adriano, D.C. 1992, Biogeochemistry of trace metals (Boca Raton: Lewis Publicación).

Afzal, M., Yousaf, S., Reichenauer, T.G., Kuffner, M. and Sesitsch, A. 2011, "Soil type affects plant colonization, activity and catabolic gene expression of inoculated bacterial strains during phytoremediation is diesel", J. Hazard. Mater. **186,** 1568-1575.

Anderson, T.A., Guthrie, E.A. and Walton, B.T. 1993, "Bioremediation", Environ Sci Technol. **27(13),** 2630-2636.

ATSDR. 1999, "Agency for Toxic Substances and Disease Registry. Toxicological profile for cadmium", US Department of Health and Human Services.

Aykin-Burns, N., Laegeler, A., Kellogg, G. and Ercal, N. 2003, "Oxidative effects of lead in young and adult Fisher 344 rats", Environ. Contam. Toxicol. **44,** 417-420.

Baker, A.J.M., Reeves, R.D. and Smith, J.A.C. 2000, "Metal Accumulator plants: A Review of the Ecology and Physiology of a Biological Resource for Phytoremediation of Metal-polluted soils", Phytoremediation of Contaminated Soil and Water, Boka Raton: Lewis Publication.

Becker, H. 2000, "Phytoremediation: Using Plants To Clean Up Soils", Agri. Res. June, 4-9.

Bienfait, H.F., Duivenvoorden, J. and Verkerke, W. 1982, "Ferric reduction by roots of chlorotic bean plants: Indication for an Enzymatic process", J. Plant Nutr. **5,** 451-456.

Bizily, S.P., Rugh, C.L. and Meagher, R.B. 2000, "Phytodetoxification of hazardous organomercurials by genetically engineered plants", Nature Biotech. **18,** 213-217.

Brown, K.S. 1995, "The Green Clean", Bioscience **45 (9),** 579-582.

Brown, S.L., Chaney, R.L., Lloyd, C.A., Angle, J.S. and Ryan, J.A. 1996, "Relative uptake of cadmium by garden vegetables and fruits grown on long-term biosold-amended soils", Environ. Sci. Technol. **30,** 3508-3511.

Byers, H.G. 1935, "Selenium occurrence in certain soils in the United States, with a discussion of the related topics", U.S. Dept. Agri. Technol. Bull. **482,** 1-47.

Chaney, R.L. 1983, "Plant uptake of inorganic waste constituents. In F.J. Parr, P.B. Marsh and J.M. Kla. [eds], "Land Treatment of Hazardous Wastes," Noyes Data Corp., Park Ridge, New Jersey, USA. 50-76.

Cerne, M., Smodis, B. and Strok, M. 2011, "Uptake of radionuclides bya common weed (*Phragmites Australia*) grown in the vicinity of the former uranium nine at Zirovski vrh", Nucl. Eng. Des. **241,** 1282-1286.

Chekol, T., Vough, L.R. and Chaney, R.L. 2004, "Phytoremediation of polychlorinated biphenyl-contaminated soil: The rhizosphere effect", Environ. Int. **30,** 799-804.

Clemens, S., Palmgren, M.G. and Kramer, U. 2002, "A long way ahead: Understanding and Engineering Plant Metal Accumulation", Trends in Plant Sci. **7(7),** 309-314.

Dowling, D.N. and Doty, S.L. 2009, "Improving phytoremediation through biotechnology", Curr. Opin. Biotechnol. **20,** 204-206.

Dudka, S., Piotrowska, M. and Terelak, H. 1996, "Transfer of cadmium, lead, and zinc from industrially contaminated soil to crop plants: a field study", Environ. Pollut. **94,** 181-188.

Eapen, S. and D'Souza, S.F. 2005, "Prospects of genetic engineering of plants for phytoremediation of toxic metals", Biotech. Adv. **23,** 97-114.

Eapen, S., Singh, S. Thorat, V., Kaushik, C.P., Raj, K. and D'Souza, S.F. 2006, "Phytoremediation of radiostrontium (Sr-90) and radiocesium (Cs-137) using giant milky weed (Calotropis gigantean) plants", Chemosphere **65,** 2071-2073.

Ehsan, S., Prasher, S.O. and Marshall, W.D. 2007, "Simultaneous mobilization of heavy metals and polychlorinated biphenyl (PBC) compounds form soil with cyclodextrin and EDTA in admixture", Chemosphere **68,** 150-158.

Endo, T., Haraguchi, K. and Sakata, M. 2003, "Renal toxicity in rats after oral administration of mercury-contaminated boiled whale livers marketed for human consumption", Environ. Contam. Toxicol. **44,** 412-416.

French, C.E., Rosser, S.J., Davies, C.J.., Nicklin, S. and Bruce, N.C. 1999, "Biodegradation of explosives by transgenic plants expressing pentaeryerythritol reductase", Nat. Biotech. **17,** 491-494.

Fushiya, S., Takahashi, K.,Nakatsuyama, S., Sato, T., Nozoe, S. and Takagi, S. 1982, "Co-occurrence of nicotianamine and avenic acids in Avena sativa and Oryza sativa", Phytochemistry **21,** 1907-1908.

Grichko, V.P., Filby, B. and Glick, B.R. 2000, "Increased ability of Transgenic plants expressing the bacterial enzyme ACC deaminase to accumulate Cd, Co, Cu, Ni, Pb and Zn", J. Biotech. **81,** 45-53.

Hernandez-Ortega, H.A., Alarcon, A., Rerrera-Cerrato, R., Zaveleta-Mancera, H.A., Lopez-Delgado, H.A. and Mendoza-Lopez, M.R. 2012, "Arbuscular mycorrhizal fungi on growth, nutrient ststus, and total antioxidant activity of *Melilotus albus* during phytoremediation of a diesel-contaminated substrate. J. Environ. Manage. **95,** 319-324.

Jarup, L., Berglund, M. Elinder, C.G., Nordberg, G. and Vahter, M. 1998, "Health effects of cadmium exposure - a review of the literature and risk estimate:, Scand. J. Work Environ. Health. 24 (Suppl), 1-52.

Kirkham, M.B. 2000, "EDTA facilitated phytoremediation of soil with heavy metals from Sewage Sludge", Int. J. Phytol. **2,** 159-172.

Klimisch, H.J. 1993, "Lung deposition, lung clearance and renal accumulation of inhaled cadmium chloride and cadmium sulphide in rats", Toxicology **84,** 103-124.

Lasat, M.M. 2000, "Phytoextraction of Metals from contaminated soil: A review of plant/soil/metal interaction and assessment of pertinent agronomic issues", J. Hazard. Sub. Res. **2,** 1-25.

Lasat, M.M. 2002, "Phytoextraction of Toxic Metals: A review of biological mechanisms", J. Environ. Quality. **31,** 109-120.

Lee, J.H. 2013, "An overview of phytoremediation as a potentially promising technology for environmental pollution control", Biotech. Biopro. Eng. **18,** 431-439.

Marques, A.P.G.C., Rangel, A.O.S.S. and Castro, P.M.L. 2009, "Remediation of heavy metal contaminated soils: Phytoremediation as a potentially promising clean-up technology. Crit. Rev. Environ. Sci. Tech. **39,** 622-654.

Minguzzi, C. and Vergnano, O. 1948, "Il contento di nichel nelli ceneri di alyssum bertlonii desv atti della Societa Toscana di Science", Naturali. Mem. Ser. A **55,** 49-77.

Moffat, A.S. 1995, "Plants Proving Their worth in Toxic Metal Cleanup", Science **269,** 302-303.

Park, J., Kim, Y.J. and Kim, K.W. 2012, "phytoremediation of soil contaminated with heavy metals using *Brassica napa*", Geosyst. Eng. **15,** 10-18.

Pitchell J., Kuroiwa, K. and Sawyer, H.T. 1999, "Distribution of Pb, Cd and Ba in soils and plants of two contaminated soils", Environ. Pollut. **110,** 171-178.

Plummer, C. 1997, "Interest Increases in Using Plants for Environmental Remediation. In: Industrial Uses of Agricultural Materials-Situation and Outlook Report", Economic Research Service, U.S. Department of Agriculture.

Rugh, C. 2004, "Genetically engineered phytoremediation: One man's trash is another man's transgene. Trends Biotech. **22,** 496-498.

Rugh, C.L., Senecoff, J.F., Meagher, R.B. and Merkle, S.A. 1998, "development of transgenic yellow poplar for mercury phytoremediation", Nat. Biotech. **16,** 925-928.

Rylott, E.L. and Bruce, N.C. 2009, "Plants disarm soil: Engineering plants for phytoremediation of explosives", Trends Biotech. **29,** 73-81.

Saleh, H.M. 2012, "Water hyacinth for phytoremediation of radioactive waste stimulate contaminated with cesium and cobalt radionuclides", Nucl. Eng. Des. **242,** 425-432.

Salt, D.E., Prince, R.C. Pickering, I.J. and Raskin, I. 1995, "Mechanisms of cadmium mobility and accumulation in Indian mustard", Plant Physiol. **109,** 427-433.

Salt, D.E., Smith, R.D. and Raskin, I. 1998, "Phytoremediation", Annu. Rev. Plant Physiol. Plant Mol. Biol. **49,** 643-668.

Schnoor, J.L., Light, L.A., McCutcheon, S.C., Wolfe, N.L. and Carreira, L.H. 1995, "Phytoremediation of Organic and Nutrient Contaminants", Environ. Sci. Tech. **29 (7),** 313-323.

Shumaker, K.L., Ghosh, S. and Zaman, M.S. 2011, "Phytoextraction of Cadmium and Responses of Indian Mustrad Plants to Cadmium Contaminated Soil", Adv. Sci. Tech. **5 (1),** 70-75.

Song, W.Y., Sohn, E.J., Martinola, E., Lee, Y.J., Yang, Y.Y., Jasinski, C., Forestier, C., Hwang, I. and Lee, Y. 2003, "Engineering tolerance and accumulation of lead and cadmium in transgenic plants", Nat. Biotech. **21,** 914-919.

Suh, M.C., Choi, D. and Liu, J.R. 1998, "Cadmium resistance in transgenic tobacco plants expressing the *Nicotiana glutinosa* L. methallothionein-like gene", Mol. Cells **8,** 678-684.

Takagi, S., Nomato, K. and Takemoto, T. 1984, "Physiological Aspects of Mugineic acid, a possible phytosiderophore of graminaceous plants", J. Plant. Nutr. **7,** 469-477.

Wang, M.C., Chen, Y.T., Chen S.H., Chang, S.W. and Sunkara, V. 2012, "Phytoremediation of pyrene contaminated soils amended with compost and planted with ryegrass and alfalfa", Chemosphere **87,** 217-225.

Wu, J., Hsu, D.F.C. and Cunningham, S.D. 1999, "Chelate-assisted Pb phytoextraction: Pb availability, uptake, and translocation constraints", Environ. Sci. Technol. **33,** 1898-1904.

Ye, W.L., Khan, M.A., McGirth, S.P. and Zhao, F.J. 2011, "Phytoremediation of arsenic contaminated paddy soils with *Pteris vittata* markedly reduces arsenic uptake by rice", Environ. Pollut. **159,** 3739-3743.

Zaman, M.S. 2003, "Phytoremediation - A Novel Strategy for Environmental Cleanup Using Plants", The Botanica **53,** 121-126.

Zaman, M.S., Jennings, C.P. and Shumaker, K.L. 2003, "Chelate-induced phytoaccumulation of cadmium in Brassica juncea grown in cadmium contaminated soil", J. Miss. Acad. Sci. **48,** 13-14.