An overview of Phytoremediation: An environmental friendly approach for pollution control

Amanjot Kaur, Assistant Professor, Department of Botany, D.A.V.College,Amritsar, India.

amanjotdav@gmail.com

Abstract: Phytoremediation is a type of bioremediation which is applicable to chemical or physical processes involving plants for immobilizing contaminants in soil sludges, sediments, surface water and groundwater. Phytoremediation is an environment friendly alternative to current remediation technologies. Although this technology is not new but current trends suggest that its popularity is growing. This article reviews some techniques of phytoremediation namely phytostabilization, phytoextraction, rhizodegradation, phytofiltration, phytodegradation, phytovolatilization and hydraulic control along with discussion about its advantages and disadvantages and some factors for testing of phytoextractors.

Keywords: Phytoremediation, Bioremediation, Contaminants, Remediation technologies, phytoextractors.

I. INTRODUCTION

In present world, areas of land, surface waters and groundwater are increasingly affected by contamination from industrial and agricultural activities. This may be due to ignorance, lack of vision or carelessness. The build-up of toxic pollutants affects our natural resources and causes a major strain on ecosystems. One of the major reasons for environmental pollution all over the world is due to heavy metals. Heavy metals are non-biodegradable elements. The accumulation of heavy metals in the soil and water has threatening effects on the human health. In soil ecosystem, heavy metals exhibit toxicological effects on soil microbes which may lead to the decrease of their number and activities [1]. Heavy metals can be classified into two types depending upon their role in the biological system: biological essential heavy metals and non-biological essential heavy metals. Biological essential heavy metals include copper (Cu), nickel (Ni), iron (Fe) and zinc (Zn). Iron for instance forms an essential part of hemoglobin, a protein in our blood which transports oxygen from the lungs to other tissues. Although they are necessary, they become toxic at high concentrations. Non-biological essential heavy metals include lead (Pb), mercury (Hg), cadmium(Cd) and tin (Sn). These metals can be tolerated at low levels but become toxic at higher concentrations [2]. Heavy metals have the tendency to interfere with the normal functioning of human body and they are very harmful for living systems above certain limits. There are conventional practices for remediation of contaminated soil i.e. mechanical cleanup methods like 'pump-and-treat' and 'dig-and-dump' techniques but these techniques are quite expensive and are usually applicable to small areas. Further, these conventional techniques of remediation can make the soil infertile and can also destroy the microenvironment. So there is the need to apply some alternative environment friendly and cost effective techniques for remediation. Phytoremediation is an environment friendly and cost-effective approach of remediation process involving plants for immobilizing contaminants in soil sludges, sediments, surface water and groundwater. This technique uses the ability of plants to concentrate elements and compounds from the environment and to metabolize various molecules in their tissues. There is a natural ability of certain plants called hyperaccumulators to bioaccumulate, degrade or render the contaminants in soils, water or air harmless. The word Phytoremediation has originated from the Greek word *phyto* meaning "plant" and the Latin word *remedium* meaning "restoring balance." The use of plants to clean up polluted environment is centuries old. More than 300 years ago, for treatment of wastewater, the use of plants was proposed[3]. Towards the end of nineteenth century, *Thlaspi caerulescens* and *Viola calaminaria* were the first plant species which are documented to accumulate high levels of metals in their leaves[4]. Byers in 1935 suggested that plants of the genus *Astragalus* were capable of accumulating up to 0.6 % selenium in dry shoot biomass. Later on, Minguzzi and Vergnano identified plants able to accumulate up to 1% Ni in shoots[5]. In 1977, Rascio suggested high Zn accumulation in shoots of *Thlaspi caerulescens* [6]. The idea of plants to absorb metals from contaminated soil was again thoroughly introduced and developed first by Utsunamyia in 1980 and later on in 1983 by Chaney[7]. In 1991, the very first field trial on phytoextraction of Zn and Cd was successfully conducted[8]. In the recent times, much extensive research is being conducted to investigate phytoremediation. Although there is significant success in this area yet the understanding of the plant mechanisms to allow metal extraction is still emerging. In addition, relevant applied aspects, such as the effect of agronomic

 DOI : 10.18231/2454-9150.2018.0490

practices on metal removal by plants are largely unknown. The occurrence of plant species in nature that is capable of accumulating extraordinarily high metal levels makes the further research of this process significantly interesting. Plants are unique organisms equipped with remarkable metabolic and absorption capabilities as well as transport systems that can take up nutrients or contaminants selectively from the soil or water. These plants can be subsequently harvested, processed and disposed. Phytoremediation can also be used for river basin management through the hydraulic control of contaminants. Phytoremediation takes advantage of the natural processes of plants. These processes include water and chemical uptake, metabolism within the plant, exudates release into the soil that leads to contaminant loss and the physical and biochemical impacts of plant roots[9].There are many ways in which plants can be used to clean up contaminated sites. Plants have ability to break down organic pollutants and stabilize metal contaminants by acting as filters. The uptake of pollutants in plants occurs mainly through the roots. The root system provides an enormous surface area that absorbs and accumulates the water and nutrients essential for growth as well as other non-essential contaminants. Root exudates by themselves can increase or decrease directly the availability of the contaminants in the root zone of the plant through changes in soil characteristics, changes in chemical composition of soil or increase in plant-assisted microbial activity. The use of native plants for phytoremediation is advantageous as these plants would be better in terms of survival, growth and reproduction under environmental stress than plants introduced from other environment. Heavy metals can cause severe phytotoxicity and may act as powerful force for the evolution of tolerant plant populations. Therefore, it is possible to identify metal-tolerant plant species from natural vegetation in field sites that are contaminated with various heavy metals.

II. Types of Phytoremediation

Phytoremediation technique can be used for the removal of heavy metals from the soil and besides that it can also be used for the removal of other environmental pollutants like organic pollutants that includes polychlorinated biphenyls (PCBs), polyaromatic hydrocarbons (PAHs) and pesticides. There are a number of different forms of phytoremediation. The following are the different types of phytoremediation with explanations describing how they work. The discussion of the different types of phytoremediation is important to understand the different processes that can occur due to vegetation, what happens to a contaminant, where the contaminant remediation occurs and what should be done for effective phytoremediation. The different forms of phytoremediation may apply to specific types of contaminants or contaminated media and may require different types of plants.

2.1 Phytostabilization

Phytostabilization uses vegetation to modify chemical, biological, and physical conditions in the soil. This process involves absorption by roots, adsorption to the surface of roots or the production of bio chemicals by the plant that are released into the soil or groundwater in the immediate vicinity of the roots and can sequester, precipitate, or otherwise immobilize nearby contaminants. It reduces the risks posed by a contaminated soil by decreasing contaminant' bioavailability using plants, eventually in combination with soil amendments[10]. These soil amendments strongly reduces the availability of the pollutants to plant uptake and thus limits eventual toxicity to plants, allowing revegetation of contaminated sites. Phytostabilization reduces the risk presented by a contaminated soil by decreasing the metal bioavailability using a combination of plants and/or soil amendments. This is in fact not a technology for real clean-up of contaminated soil but for stabilizing or inactivating trace elements which are potentially toxic. In phytostabilization, contamination is inactivated in place preventing further spreading. In Phytostabilization technique, plants protect the contaminated soil from wind and water erosion. It reduce water percolation through the soil to prevent leaching of the contaminants. It alter the chemical form of the contaminants by changing the soil environments (e.g. pH, redox potential) around plant roots.Plants which are used for phytostabilization should be able to decrease the amount of water percolating through the soil matrix which may result in the formation of a hazardous leachate. Also these prevent soil erosion and the distribution of the toxic metal to other areas. [11] Phytostabilization technique is useful for the cleanup of Pb, Cd, As, Cr, Cu, and Zn [12].

2.2 Phytoextraction

Phytoextraction is the use of plants to remove heavy metals from the soil and accumulate them in the harvestable parts. This is less expensive and less damaging to the environment than conventional remediation systems that consist mainly in the excavation and incineration of soil. [13] The idea of using plants to remove metals from soils came from the discovery of different wild plants, often endemic to naturally mineralized soils, that accumulate high concentrations of metals in their foliage[14]. In phytoextraction, roots uptake contaminant with subsequent accumulation in the aboveground portion of a plant, generally to be followed by harvest and ultimate disposal of the plant biomass.It is a contaminant removal process. Some of the metals like Ag, Cd, Co, Cr, Cu, Hg, Mn, Mo, Ni, Pb, Zn, metalloids like As, Se, radionuclides like 90Sr, 137Cs, 234U, 238U, and non-metals like B [15,16] are generally not further degraded or changed in form within the plant. So phytoextraction is successful on all these metals, metalloids, radionuclides and non-metals. In phytoextraction, generally soil is the target medium. But

 DOI : 10.18231/2454-9150.2018.0490

contaminants present in sediments and sludges can also undergo phytoextraction. One can think of using phytoextraction, in conjunction with rhizofiltration for soluble metals in surface water or extracted ground water. The production of biomass during phytoextraction is another advantage of this technology which can be used in producing energy and other commodities. The efficiency of phytoextraction depends largely on the metal bioavailability present in the contaminated matrix as well as on several characteristics of the plant such as the capability to hyperaccumulate essential and nonessential metals, fast growth, a deep and extended root system and the ability to translocate metals to the aerial parts. The phytoextraction of heavy metals is one of the biggest economic opportunities for phytoremediation because of the scope of environmental problems associated with metal-contaminated soils and the cost-effective advantage offered by a plant-based remediation technology [17].

2.3 Rhizodegradation

Rhizosphere is the area of soil surrounding the roots of the plants. Rhizodegradation is the degradation of contaminants in the rhizosphere using microbial activity which is enhanced by the presence of plant roots. This takes place in the soil or groundwater immediately surrounding the plant roots. Some of the microorganisms like yeast, fungi or bacteria use these contaminants as their source of energy and nutrition. During this biodegradation, some microorganisms break down hazardous pollutants such as fuels or solvent into nontoxic and harmless product. Biodegradation is aided by plants. Plants release natural carbon containing substances such as sugar, alcohols and acid and thereby, providing the microorganisms with additional nutrients which stimulate their activity. The increased microbial populations are due to stimulation by plant exudates, compounds produced by plants and released from plant roots. The increased microbial populations and activity in the rhizosphere can result in increased contaminant biodegradation in the soil and degradation of the exudates can stimulate metabolism of contaminants in the rhizosphere. Rhizodegradation occurs primarily in soil, although stimulation of microbial activity in the root zone of aquatic plants could potentially occur. One of the major features of rhizodegradation is the destruction of the contaminant in situ, the potential complete mineralization of organic contaminants and the translocation of the compound to the plant or atmosphere is less likely than with other phytoremediation technologies since degradation occurs at the source of the contamination. Further the harvesting of the vegetation is not necessary since there is contaminant degradation within the soil, rather than contaminant accumulation within the plant. Paul E. Olson [18] examined the root structure of a mature 12-year-old mulberry tree growing in a former waste disposal basin. He examined the relationship between root system of the tree to the distribution of polycyclic aromatic hydrocarbons (PAHs) in soil/sludge beneath the tree. The results suggested that the mulberry root system develops gradually over time in a vertical direction with fine roots serving as the leading edge of a moving front. The degradative properties of this biological front (root-microbe combination) toward toxic chemicals hold great importance for successful development of phytoremediation technology designed to degrade deep contaminants in former sludge basins [18]. The depth of the root zone is the most serious impediment to successful rhizodegradation. Some plants have relatively shallow root zones and the depth of root penetration can also be limited by soil moisture conditions or by soil structures such as hard pans or clay pans that are impenetrable by roots. Another limitation is substantial time that may be required to develop an extensive root zone.

2.4 Phytofiltration

Phytofiltration is also known as Rhizofiltration. Phytofiltration prevent the organic pollutants in waste water and surface water from mixing into the water streams or groundwater using plants for filtration purpose as they can adsorb or precipitate onto the roots or absorption into the roots the pollutants. Rhizofiltration is similar to phytoextraction in a way that both result in accumulation of the contaminant in or on the plant. But the fundamental difference between both is that in rhizofiltration the accumulation occur either in the roots or in the portion of the plant above water whereas in phytoextraction, the accumulation occurs above ground, not in the roots. Another difference is that in rhizofiltration, contaminants are initially in water and in phytoextraction contaminants are in soil. Rhizofiltration is used to treat surface water and groundwater, industrial and residential effluents, downwashes from power lines, storm waters, agricultural runoffs, diluted sludges, and radionuclide-contaminated solutions. Plants suitable for rhizofiltration applications can efficiently remove toxic metals from a solution using rapid-growth root systems. Various terrestrial plant species have been found to effectively remove toxic metals such as Cu^{2+}, Cd^{2+}, Cr^{6+}, Ni^{2+}, Pb^{2+}, and Zn^{2+} from aqueous solutions[19]. The common plants that have ability to remove toxins from water via rhizofiltration are Sunflower, Indian Mustard, Tobacco, Rye, ,Corn, Parrot's Feather, Iris-leaved Rush, Cattail.[20] One major limitation of rhizofiltration is that any contaminant below the rooting depth will not be extracted. The plants used may not be able to grow in highly contaminated areas. Further it can take years to reach regulatory levels which results in long-term maintenance.

2.5 Phytodegradation

Phytodegradation is also called phytotransformation. In this technique, enzymes are used for the breakdown of harmful organic pollutants like chlorinated solvents, herbicides, insecticides and inorganic nutrients. Phytodegradation is the

 DOI : 10.18231/2454-9150.2018.0490

uptake, metabolizing, and degradation of contaminants within the plant or the degradation of contaminants in the soil, sediments, sludges, ground water, or surface water by enzymes produced and released by the plant. Phytodegradation is also used to remove contaminants from petrochemical sites and storage areas, fuel spills, landfill leachates and agricultural chemicals. Sometimes phytodegradation may be used along with other remediation technologies or as a polishing treatment. This technology usually requires more than one growing season to be efficient. Soil must be less than 3 ft in depth and groundwater within 10 ft of the surface. Further Soil amendments may be required, including chelating agents to facilitate plant uptake by breaking bonds binding contaminants to soil particles [21].

2.6 Phytovolatilization

Plants can interact with a number of organic compounds and thus affect the fate and transport of many environmental contaminants. Volatile organic compounds may be volatilized from stems or leaves which is called direct phytovolatilization or from soil due to plant root activities which is called indirect phytovolatilization. Fluxes of contaminants volatilizing from plants are important across scales ranging from local contaminant spills to global fluxes of methane emanating from ecosystems biochemically reducing organic carbon [22]. Phytovolatilization is primarily a contaminant removal process in which plants take up volatile compounds through their roots, and transpire the same compounds or their metabolites through the leaves, thereby releasing them into the atmosphere. Phytovolatilization is the uptake of a contaminant by a plant, and the subsequent release of a volatile contaminant, a volatile degradation product of a contaminant, or a volatile form of an initially non-volatile contaminant. For effective phytoremediation, the degradation product or modified volatile form should be less toxic than the initial contaminant. This process occurs during absorption of water and organic contaminants in growing plants. When water moves from the roots to the leaves along the vascular system of the plant, it is changed and modified along the way. During this process, some of the contaminants move through the plants to the leaves and evaporate or volatilize into the atmosphere. Phytovolatilization has been primarily used to remove mercury; the mercuric ion is converted into less toxic elemental mercury. Masayuki Sakakibara et. al. [23] examined the As-contaminated soil collected from a deposit site of neutralized acid mine drainage in Japan. It accumulated up to 6,540±380 mg As/kg-dry weight (DW). It was determined that vapour released from the frond of *Pteris vittata* included arsenic compounds, arsenite and arsenate. The results suggest that *Pteris vittata* effectively volatilizes As; it removed a maximum ratio of 90% of the total uptake of As from As-contaminated soils in greenhouse where the environment was similar to the subtropics. However, if a large amount of arsenic had been released from the contaminated site into the atmosphere by the fern, the process may have caused a secondary As-contamination to the surrounding environment [23].

2.7 Hydraulic control

Some plants play the role of hydraulic pumps as their roots reach down in the water table and form a dense root mass to take up large volumes of water. Hydraulic control is the use of plants to affect the movement of ground water through consumption of large volumes of water by plants. For hydraulic control and remediation of ground water, water uptake and transpiration rates are important factors. Water uptake and the transpiration rate depend on the species, age, mass, size, leaf surface area and growth stage of the plant as well as climatic factors such as temperature, precipitation, humidity, wind velocity etc and may vary seasonally. For example a cottonwood can absorb up to 350 gallons per day and a poplar tree can transpire between 50 and 300 gallons of water per day out of the ground. The water consumption by the plants decreases the tendency of surface contaminants to move towards groundwater and into drinking water. There are several applications that use plants for this purpose such as riparian corridors/buffer strips and vegetative caps. Hydraulic control of polluted ground water is very important as it prevents moving of contaminants into streams, natural wetland or aquifers.

2.7.1 Vegetated Caps

The cap is a barrier located over contaminated media that mitigates exposure to potential receptors. Vegetative cover or vegetative cap is a long-term, self-sustaining cap composed of soil and plants growing in and/or over waste in a landfill. This type of cover is an alter-native to composite clay or plastic layer caps. Plants control erosion and minimize seepage of water that could otherwise percolate through the landfill and form contaminated leachates. In addition, a vegetative cap can be designed not only to control erosion and seepage of water but also to enhance the degradation of underlying materials in the landfill. As with any selected remedial action, the capping remedy must be protective of human health and the environment. Typically such protection is provided by interrupting an exposure pathway or by exerting control of contaminant movement. Vegetative caps are generally 2 feet thick but can vary based on site specific conditions. Vegetative caps will also tend to have a more stringent inspection and maintenance program than low-permeability caps.

2.7.2 Riparian corridors

The term 'riparian' means 'located on the bank of a river'. Plant habitats and communities along the river margins and banks are called riparian vegetation, characterized by hydrophilic plants. Riparian zones are important in ecology, environmental management and civil

 DOI : 10.18231/2454-9150.2018.0490

engineering because of their role in soil conservation, their habitat biodiversity and the influence they have on fauna and aquatic ecosystems, including grasslands, woodlands, wetlands or even non-vegetative areas. Riparian corridors or buffer strips are applications of phytoremediation that may also incorporate aspects of phytodegradation, phytovolatilisation and rhizodegradation to control, intercept, or remediate contamination entering a river or groundwater plume. In a riparian corridor, plants may be applied along a stream or river bank while buffer strips may be applied around the perimeter of landfills. Applications of these systems prevent contamination from spreading into surface water and/or groundwater. Riparian zones are very useful in water quality improvement for both surface runoff as well as water flowing into streams through subsurface or groundwater flow.

III. ADVANTAGES AND DISADVANTAGES OF PHYTOREMEDIATION

It is very difficult to remediate metal-contaminated soils. Current technologies that are available for remediation, use the technique of soil excavation and either land filling or soil washing followed by physical or chemical separation of the contaminants. The cost occurring in this process is highly variable and depends on the factors like contaminants that are concerned, soil properties and site conditions. Further the Cleaning of metal-contaminated soils using conventional engineering methods is much expensive[24]. So there is an urgent need for some less-expensive cleanup technologies. Phytoremediation is emerging as a cost-effective alternative and its cost is only a fraction of that associated with conventional engineering technologies. Phytoremediation remediates the soil in situ so it avoids landscape disruption and preserves the ecosystem. In spite of these advantages, some there are some limitations of phytoremediation. Some of its limitations that are related to biology of plants are like low plant tolerance, lack of contaminant translocation from root to shoot and small size of remediating plants. The other limitations are regulatory limitations like non-availability of cost and performance data, regulators unfamiliarity with the technology and disposal of contaminated plant waste and risk of food chain contamination. Some other limitations are like Contaminant beneath root zone, lengthy process, contaminant in biologically unavailable form and lack of remediating plant species.

IV. TESTING OF PHYTOEXTRACTORS

The prime objective of the remediation is to reduce the content of toxic heavy metals in soil. The following are the important factors related to phytoremediation for testing of phytoextractors:

1. Bio concentration factor (BCF)

   Bio concentration factor indicates the heavy metal uptake efficiency of a plant species into its tissues from the surrounding environment. It is calculated as follows [25]:

$$\text{BCF} = \frac{\text{Concentration of the target heavy metal in the plant harvested tissue}}{\text{concentration of the same heavy metal in the soil or other substrate}}$$

2. Transfer factor (TF)

   Transfer factor indicates the efficiency of the plant in translocating the accumulated heavy metal from its roots to shoots. It is calculated as follows [26]:

$$\text{TF} = \frac{\text{concentration of the heavy in plant aboveground part}}{\text{concentration of the heavy metal in plant roots}}$$

3. Adaptability Factor

   Adaptability factor indicates the dominance of the phytoextractor plant at sites of different pollution levels.

4. Accumulating capability (AC)

   Accumulating capability is the natural ability of plants to accumulate metals in their above-ground parts with concentration more than 100 mg kg^{-1} for Cd [27], 1000 mg kg^{-1} for Cu, Cr, Pb, and Co, 10 mg kg^{-1} for Hg [28] and 10000 mg kg^{-1} dry weight of shoots for Ni and Zn [29].

5. Tolerance capability

   Tolerance capability is the ability of plants to grow in heavy metal contaminated soil and to have considerably high tolerance to heavy metals without showing any adverse effects like chlorosis, necrosis, whitish brown color or reduction in the above-ground biomass[30].

6. Removal efficiency (RE)

   RE is calculated as follows[31]:

$$\text{RE} = \frac{(\text{total concentrations of metals})\ \text{x}\ (\text{root biomass of plant})}{\textit{total added metal}}$$

V. CONCLUSION

The major impact of environmental contamination on the society today can be viewed as an ecological malaise. Heavy metals are, in general, persistent in the environment leading to pollution by entering into groundwater and food chain. Phytoremediation can be used as an alternative way which can be used along with or in some cases in place of mechanical conventional clean-up technologies. Several plant species have shown promising potential for phytoremediation of many highly toxic and recalcitrant organic compounds such as PCBs, PAHs, nitroaromatic explosives, etc. The major advantage of phytoremediation is its low cost. Further phytoremediation offers permanent in situ remediation rather than shifting the contaminants to a different site. The development of phytoremediation requires integrated multidisciplinary research efforts that combine plant biology, genetic engineering, soil chemistry, and soil microbiology, agricultural and environmental engineering. It is the fast, innovative, emerging, eco friendly and cost effective alternative to the conventional

 DOI : 10.18231/2454-9150.2018.0490

remedial method for pollution control. In the recent time, much extensive research is being conducted to investigate phytoremediation. Although there is significant success in this area yet the understanding of the plant mechanisms to allow metal extraction is still emerging. In addition, relevant applied aspects, such as the effect of agronomic practices on metal removal by plants are largely unknown. The occurrence of plant species in nature that is capable of accumulating extraordinarily high metal levels makes the further research of this process significantly interesting.

VI. REFERENCES

[1] Khan S, Hesham AEL, Qiao M, Rehman S, He JZ (2010) Effects of Cd and Pb on soil microbial community structure and activities. Environmental Science and Pollution Research February 2010, Volume 17, Issue 2, pp 288–296

[2] Kennish M.J. 1998 Pollution impacts on marine biotic environments; CRC Press 310 pp

[3] Hartman, W. J., An evaluation of land treatment of municipal wastewater and physical siting of facility installations, Washington DC, US Department of Army, 432-467. 1975.

[4] Baumann A., Das Verhalten von Zinksatzen gegen Pflanzen and in Boden., Landwirtsch. Vers,-Statn, 31, 1-53, (1885).

[5] Minguzzi C, Vergnano O., "II content di nichel nelli ceneri di Alyssum bertlonii Desv. Atti della societa Toseana di Science Naturali", MemSer A, 55, 49-77, (1948).

[6] Rascio W., "Metal accumulation by some plants growing on Zn mine deposits".,Oikos, 29, 250-253, (1977).

[7] Chaney RL. 1983. Plant uptake of inorganic waste. In Land Treatment of Hazardous Waste, eds JE Parr, PB Marsh, JM Kla, pp 50-76, Noyes Data Corp, Park Ridge II.

[8] Baker AJM, Reeves RD, McGrath SP, "In situ decontamination of heavy metal polluted soils using crops of metal-accumulating plants a feasibility study., In situ Bioreclamation", eds RE Hinchee, RF Olfenbuttel, 539-544, (1991).

[9] Bruce E. Pivetz, Phytoremediation of Contaminated Soil and Ground Water at Hazardous Waste Sites Ground Water Issue United States Environmental Protection Agency EPA/540/S-01/500 February 2001.

[10] Vangronsveld J, Colpaert J, Van Tichelen K (1996) Reclamation of a bare industrial area contaminated by non-ferrous metals: physicochemical and biological evaluation of the durability of soil treatment and revegetation. Environ Pollut 94:131–140

[11] I. Raskin and B. D. Ensley, Phytoremediation of Toxic Metals: Using Plants to Clean Up the Environment, John Wiley & Sons, New York, NY, USA, 2000.

[12] C. D. Jadia and M. H. Fulekar, "Phytoremediation of heavy metals: recent techniques," African Journal of Biotechnology, vol. 8, no. 6, pp. 921–928, 2009.

[13] Cunningham, S. D., & Ow, D. W. (1996). Promises and prospects of phytoremediation. Plant Physiology, 110, 715–719.

[14] Brooks, R.R., Morrison, R.S., Reeves, R.D., Dudley, T.R., Akman, Y., 1979. Hyperaccumulation of nickel by Alyssum linneaeus (Cruciferae). Proc. R. Soc. London B 203, 387-403

[15] Salt, D.E., M. Blaylock, P.B.A. Nanda Kumar, V. Dushenkov, B.D. Ensley, I. Chet, and I. Raskin. 1995. Phytoremediation: A novel strategy for the removal of toxic metals from the environment using plants. Biotechnol. 13:468-474.

[16] Kumar, P.B.A. Nanda, V. Dushenkov, H. Motto, and I. Raskin. 1995. Phytoextraction: The use of plants to remove heavy metals from soils. Environ. Sci. Technol. 29(5):1232-1238.

[17] Raskin, I., Smith, R.D., Salt, D.E., 1997. Phytoremediation of metals: using plants to remove pollutants from the environment. Curr. Opin. Biotechnol. 8, 221-226.

[18] Olson, P.E., and J.S. Fletcher. 1999. Field evaluation of mulberry root structure with regard to phytoremediation, Bioremediation J. 3(1):27-33.

[19] Dushenkov, Viatcheslav, Harry Motto, Ilya Raskin, and P Nanda Kumar. "Rhizofiltration: the use of Plants to Remove Heavy Metals From Aqueous Streams." Environmental Science & Technology 30 (1995): 1239-1245.

[20] Ellen L. Arthur , Pamela J. Rice , Patricia J. Rice , Todd A. Anderson , Sadika M. Baladi Keri L. D. Henderson & Joel R. Coats (2005) Phytoremediation—An Overview, Critical Reviews in Plant Sciences, 24:2, 109-122, DOI: 10.1080/07352680590952496

[21] https://bohatala.com/application-and-techniques-for-phytoremediation/

[22] Limmer M, Burken, J Environ Sci Technol. 2016 Jul 5;50(13):6632-43. doi: 10.1021/acs.est.5b04113. Epub 2016 Jun 16,Phytovolatilization of Organic Contaminants.

[23] Masayuki Sakakibara, Proceedings of the Annual International Conference on Soils, Sediments, Water and Energy Volume 12 Article 26 January 2010, Phytoextraction And Phytovolatilization of Arsenic from As-Contaminated Soils by Pteris vittata

[24] Salt DE, Blaylock M, Kumar PBAN, Dushenkov V, Ensley BD, Chet I, Raskin I. 1995. Phytoremediation: A novel strategy for the removal of toxic metals from the environment using plants. Biotechnology 13: 468-475

[25] Zhuang, P.; Yang, Q.; Wang, H.; Shu, W. Phytoextraction of heavy metals by eight plant species in the field. Water Air Soil Pollut. 2007, 184, 235–242.

[26] Padmavathiamma, P.K.; Li, L.Y. Phytoremediation technology: Hyper-accumulation metals in plants. Water Air Soil Pollut. 2007, 184, 105–126.

[27] Zhou QX, Song YF (2004). Principles and methods of contaminated soil remediation, Science Press, Beijing p.568.

[28] Baker AJM, McGrath SP, Reeves RD, Smith JAC (2000). Metal hyperaccumulator plants: A review of the ecology and physiology of a biological resource for phytoremediation of metal-polluted soils. In N. Terry and G. Banuelos (Ed.): Lewis Publishers, Boca Raton, FL pp. 5-107.

[29] Lasat MM (2002). Phytoextraction of toxic metals: A review of biological mechanisms. J. Environ. Qual. 31:109-120

[30] Sun Y, Zhou Q, Wang L, Liu W (2009). Cadmium tolerance and accumulation characteristics of Bidens pilosa L. as a potential Cdhyperaccumulator. J. Hazard. Mater. 161(2-3): 808-814.

[31] Soleimani M, Hajabbasi MA, Afyuni M, Mirlohi A, Borggaard OK, Holm PE (2010). Effect of endophytic fungi on cadmium tolerance and bioaccumulation by Festuca arundinaceaand Festuca pratensis. Int. J. Phytoremediation 12(6):535-549.

 DOI : 10.18231/2454-9150.2018.0490