

Phytoremediation:

A plant-based remediation technology to clean up the contaminants

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Environmental pollution has become a serious public health concern because it is a major source of health risk that causes several serious diseases worldwide. Heavy metal contamination is one of the most important hazardous pollutants which can even lead to death after long time exposure. Due to urbanization and industrial developments, the environmental pollution by heavy metals has increased. Trace metals, called potentially toxic trace elements, cause degradation of the active surface of the earth and constitute a major threat to the food chain of plants, animals and humans. Phytoremediation is a good remediation technology to clean up contaminants from the environment by using green plants.

Key words: Hazardous pollutants, Metal contamination, Phytoremediation, Plant

HEAVY metal contamination has increased rapidly since the early twentieth century. A huge area of the world has been contaminated by organic and inorganic pollutants. Trace metals, called potentially toxic trace elements, cause degradation of the active surface of the earth and constitute a major threat to the food chain of plants, animals and humans. The traced elements present in the salt solutions, which are by-products or wastes of various branches of industry and agriculture, are highly toxic. Heavy metals are initially accumulated on the soil surface without causing visible changes or they are too slow to be noticed. Changes in the soil become apparent when there is a destruction of the vegetation and transforming the entire surface of the soil in the wasteland. The most common heavy metals in soils and plants are lead (Pb), cadmium (Cd), chromium (Cr), mercury (Hg), zinc (Zn) and copper (Cu). All these cause health problems especially mercury which is highly toxic if breathed or ingested. Mercury is residual in the environment, showing biological accumulation in

all aquatic organisms, especially in fish and shellfish. Chronic exposure to airborne mercury can have serious effects on the central nervous system (CNS).

Phytoremediation involves the use of plants to remove, transfer, stabilize and/or degrade contaminants in soil, sediment, and water. This plant-based technology has gained acceptance in the past few years as a cheap, efficient and environmentally friendly technology especially for removing toxic metals. Currently, USD 6-8 billion is spent annually for environmental clean-up in the United States, and worldwide it is USD 25-50 billion/year. Phytoremediation has become popular both scientifically and commercially, and considerable attention is given to phytoextraction in which certain plant species are selected to grow on contaminated soils. The pollutants are removed from contaminated soils and accumulated in plant biomass. Metal contaminated soil can be remediated by chemical, physical and biological techniques.

These can be grouped into two categories.

Ex-situ method

It requires removal of contaminated soil for treatment on or off-site, and returning the treated soil to the resorted site. The conventional *ex-situ* methods applied for remediating the polluted soils rely on excavation, detoxification and/or destruction of contaminant physically or chemically, as a result the contaminant undergo stabilization, solidification, immobilization, incineration or destruction.

In-situ method

It is remediation without excavation of contaminated site. It is a destruction or transformation of the contaminant, immobilization to reduce bioavailability and separation of the contaminant from the bulk soil. *In-situ* techniques are favoured over the *ex-situ* techniques due to their low cost and reduced impact on the ecosystem. Conventionally, the *ex-situ* technique is to excavate soil contaminated with heavy metal and their burial in landfill site. But the off-site burial is not an appropriate option because it merely shifts the contamination problem elsewhere

Table 1. Recalcitrant pollutants for phytoremediation technology

Contaminant	Contaminant	Contaminant
Benzene	Chlorinated Pesticides wastes	Nitrotoluene ammunition
Toluene	Organophosphates	Petroleum Hydrocarbons
Ethylbenzene	Insecticides	Nutrients like nitrate, phosphate and ammonium
Xylene	Polyaromatic Hydrocarbons CPAHs)	Radionuclides (Cesium, Strontium, Uranium, etc.)
Chlorinated Solvents (TCE & PCE)	Polychlorinated Biphenyls (PCBs)	Hazardous Air Pollutants e.g. Oxides of Sulfur and Nitrogen
Toxic heavy metals (Cadmium, Lead, Nickel, Chromium, Mercury, Arsenic, etc.)		

and also because of hazards associated with the transport of contaminated soil.

Contaminants suitable for removal by phytoremediation

Recalcitrant organic and inorganic pollutants, radioactive contaminants best suited for phytoremediation technology are given in Table 1.

Plants have three basic strategies for growth on metal contaminated soil and its responses to heavy metals are:

Metal excluders

The plant prevent metal from entering their aerial parts or maintain low and constant metal concentration over a broad range of metal concentration in the soil, it mainly restrict metal in their roots. The plant may alter its membrane permeability, change metal binding capacity of cell walls or exude more chelating substances.

Metal indicators

The species which actively accumulate metal in their aerial tissues and generally reflect metal level in the soil. It tolerate the existing concentration level of metals by producing intracellular metal binding compounds (chelators), or alter metal compartmentalization pattern by storing metals in non-sensitive parts.

Metal accumulator plant species

The species can concentrate metal in their aerial parts, to levels far exceeding than soil.

Hyper-accumulators are plants that can absorb high levels of contaminants concentrated either in their roots, shoots and/or leaves.

Metal hyper-accumulator as plants that contain more than or up to 0.1% i.e. more than (1000 mg/g) of copper, cadmium, chromium, lead, nickel cobalt or 1% (>10,000 mg/g) of zinc or manganese in the dry matter. Approximately 400 hyper-accumulator species from 22 families have been identified. The *Brassicaceae* family contains a large number of hyper-accumulating species with the widest range of metals; these include 87 species from 11 genera.

Mechanism of phytoremediation of contaminated soils

Phytoremediation of organic and inorganic contaminants involves either physical removal of compounds (phytoextraction) or their bioconversion (phytodegradation or phytotransformation) into biologically inert forms. The conversion of metals into inert forms can be enhanced by raising the pH (e.g. through liming), or by addition of organic matter (e.g. sewage sludge, compost etc.), inorganic anions (e.g. phosphates) and metallic

oxides and hydroxides (e.g. iron oxides). The plants themselves can play a role here by altering soil redox conditions and releasing anions and / or lignins.

Phytoextraction (Phytoaccumulation of contaminants)

Plant roots uptake (extract) metal or radioactive contaminants from the soil, polluted water and wastewater, translocate and accumulate them in their roots. Plant roots absorb both organic and inorganic. A considerable amount of the contaminants may be translocated above through the xylem and accumulated in the shoots and leaves. The radionuclide uptake by plant roots need not necessarily result in translocation to shoots. Major limiting factor for phytoextraction are lower availability of metals in soil and poor translocation from roots to shoots. This technique has been effectively used for the removal of lead (Pb) and cadmium (Cd) from contaminated soil. Excessive selenium (Se) in farm soils is also successfully remediated by this technology. The plants identified with potential for phytoextraction of metals like Indian mustard (*Brassica juncea*), sunflower (*Helianthus annuus*), rapeseed, amaranthus (*Amaranthus retroflexus*), chenopodium (*Chenopodium album*), etc.

Phytostabilization (Immobilization of contaminants)

It is a stabilizing process for contaminated soils and sediments in place using plants, thus preventing the lateral or vertical migration of

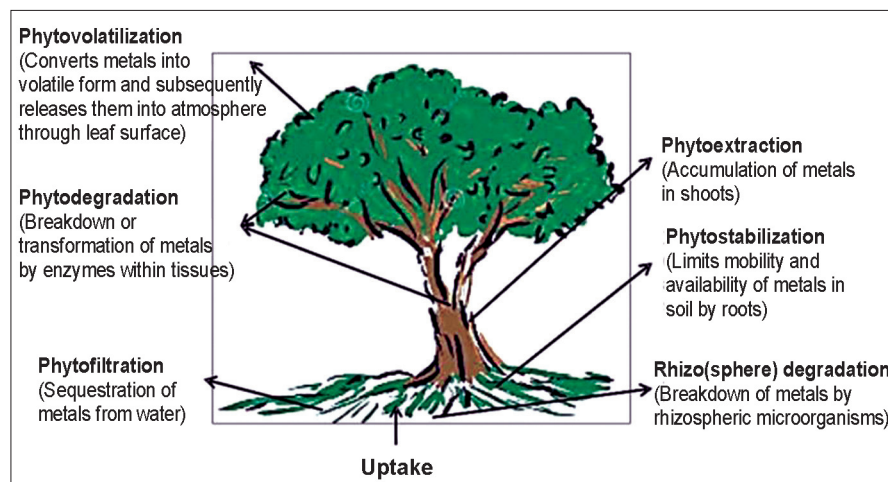


Fig. 1. Various mechanisms involved in the phytoremediation of heavy metals

toxic metals by leaching. Certain plant species immobilize contaminants in the soil and groundwater through absorption by and adsorption on to roots or precipitation within the root zone (rhizosphere). Plants capable of tolerating high level of metal contaminants and having efficient growth rate with dense root systems (to bind/sorb contaminants) and canopies are preferred. Trees which transpire large amounts of water for hydraulic control (e.g. poplar) and grasses with fibrous roots (e.g. vetiver grass) to bind and hold soil are best suited for phytostabilization. Generally, plants suitable for soil conservation are good for phytostabilization. This technique is best applicable in phytostabilizing metal contaminants of waste landfill sites (e.g. Pb, Cd, Zn, As, Cu, Cr, Se, and U) where the best option is to immobilize them *in-situ*.

Phytovolatilization (Evapo-transpiration of detoxified contaminants)

Phytovolatilization exploits a plant's ability to transpire a large amount of water from their leaf pores (stomata). Plants absorb and transpire the impurities from soil through their aerial organs (leaves). This system is a combination of hydraulic control and enhanced evapotranspiration. It is a mechanism by which plants convert a contaminant into volatile form and transpire the detoxified vapour through their aerial organs. Rate of transpiration is a key factor for this technology. For a 5 year old poplar tree (*Populus* spp.) it was estimated to be 26 gpd (gallon per day). A single willow tree (*Salix* Spp.) has been found to transpire 5,000 gpd and an individual cottonwood tree transpire 50 to 35 gpd.

Rhizofiltration

Rhizofiltration is the use of plant roots to absorb, concentrate or precipitate metal contaminants from aqueous medium. Although the technology is more suitable for decontamination of polluted water or removal of organic and inorganic impurities from wastewater by the use of aquatic plants, terrestrial

species can also be used by growing hydroponically or on floating platforms in treatment ponds. An ideal plant for rhizofiltration should quickly produce a significant amount of root biomass with large surface

area when grown hydroponically. The plants which have been identified to promote rhizosphere degradation of petroleum compounds are:

- Big bluestem (*Andropogon gerardii*)
- Indian grass (*Sorghastrum nutans*)

Table 2. Important plant species identified for phytoremediation

Plants	Heavy metals	Contaminated areas
<i>Brassica juncea</i> L. (Indian mustard)	Cd, Cu, Zn, Pb	Soil and water
<i>Brassica napus</i> L. (canola)	Cd, Cu, Zn, Pb	Soil
<i>Cajanus cajan</i> L. (pigeon pea)	As, Cd	Soil
<i>Cicer arietinum</i> L. (chickpea)	Cd, Pb, Cr, Cu	Soil
<i>Cucumis sativus</i> L. (cucumber)	Pb	Water
<i>Eichhornia crassipes</i> L. (water hyacinth)	As, Cr, Zn, Cs, Co	Water
<i>Jatropha curcas</i> L. (Jatropha)	Fe, Al, Cu, Mn, Cr, As, Zn, Hg	Soil
<i>Lantana camara</i> L. (lantana)	Pb	Soil
<i>Lens culinaris</i> Medic. (lentil)	Pb	Soil
<i>Lepidium sativum</i> L. (cress)	As, Cd, Fe, Pb, Hg	Soil
<i>Lactuca sativa</i> L. (lettuce)	Cu, Fe, Mn, Zn, Ni, Cd, Pb, Co, As	Soil
<i>Medicago sativa</i> L. (alfalfa)	Cd	Soil
<i>Oryza sativa</i> L. (rice)	Cu, Cd	Soil
<i>Pistia stratiotes</i> L. (water lettuce)	Cr, Cd, As	Water
<i>Pisum sativum</i> L. (pea)	Pb, Cu, Zn, Fe, Cd, Ni, As, Cr	Soil
<i>Raparus sativus</i> L. (radish)	As, Cd, Fe, Pb, Cu	Soil
<i>Spinacia oleracea</i> L. (spinach)	Cd, Cu, Fe, Ni, Pb, Zn, Cr	Soil
<i>Solanum nigrum</i> L. (black nightshade)	Cd	Soil
<i>Sorghum bicolor</i> L. (sorghum)	Cd, Cu, Zn, Fe	Soil
<i>Zea mays</i> L. (corn)	Cd, Pb, Zn, Cu	Soil

Table 3. Some wonder plants for phytoremediation of contaminated lands (Potential for commercialization)

Vetiver Grass (<i>Vetiveria zizanioides</i>)	Alpine pennycress (<i>Thlaspi caerulescens</i>)
Brake Fern (<i>Pteris vittata</i>)	Bermuda grass (<i>Cyanodon dactylon</i>)
Hybrid Poplar (<i>Populus canadensis</i>)	Nightshade (<i>Solanum nigrum</i>)
Sunflower (<i>Helianthus annuus</i>)	Drum-Stick tree (<i>Moringa oleifera</i>)
Indian Mustard (<i>Brassica juncea</i>)	Strychnos tree (<i>Strychnos potatorum</i>)

Table 4. Some known hyperaccumulator species of different metals

Metal	Plant species	Concentration of metal accumulated (mg/kg)
Nickel	<i>Thlaspi</i> spp. (Brassicaceae)	2000–31,000
	<i>Alyssium</i> spp. (Do)	1280–29,400
	<i>Berkheyacodii</i> (Asteraceae)	11,600
	<i>Pentacalia</i> spp. (Do)	16,600
	<i>Psychotria corinota</i> (Rubiaceae)	25,540
Zinc	<i>Thlaspi caerulescens</i> (Brassicaceae)	43,710
	<i>Thlaspi rotundifolium</i> (Do)	18,500
	<i>Dichopetalum gelonioides</i>	30,000
Cadmium	<i>Thlaspi caerulescens</i> (Brassicaceae)	2,130
Lead	<i>Minuartia verna</i> (Caryophyllaceae)	20,000
	<i>Agrostis tenius</i> (Poaceae)	13,490
	<i>Vetiveria zizanioides</i>	> 1500
Cobalt	<i>Crotolaria cobalticola</i> (Fabaceae)	30,100
	<i>Haumaniastrum robertii</i> (Lamiaceae)	10,232
Copper	<i>Ipomea alpina</i> (Convolvulaceae)	12,300
Manganese	<i>Maystenus sebertiana</i> (Celastraceae)	22,500
	<i>Maystenus bureaviana</i> (Celastraceae)	19,230
	<i>Macadania neurophylla</i> (Proteaceae)	55,200
Selenium	<i>Astragalus racemosus</i> (Leguminosae)	1,49,200
	<i>Lecythis ollaria</i> (Lecithidiaceae)	18,200
Arsenic	<i>Pteris vittata</i> (Fern)	-

Table 5. Advantages and disadvantages of phytoremediation

Advantages	Disadvantages
Amendable to a variety of organic and inorganic compounds.	Restricted to sites with shallow contamination within rooting zone of remediative plants.
<i>In situ</i> / <i>Ex situ</i> application possible with effluent/soil substrate respectively.	May take up to several years to remediate a contaminated site.
<i>In situ</i> applications decrease the amount of soil disturbance compared to conventional methods.	Restricted to sites with low contaminant concentrations.
Reduces the amount of waste to be landfilled (up to 95%), can be further utilized as bio-ore of heavy metals.	Harvested plant biomass from phyto-extraction may be classified as a hazardous waste hence disposal should be proper.
<i>In situ</i> applications decrease spread of contaminant via air and water.	Climatic conditions are a limiting factor.
Does not require expensive equipment or highly specialized personnel.	Introduction of non-native species may affect biodiversity.
In large scale applications the potential energy stored can be utilized to generate thermal energy.	Consumption or utilization of contaminated plant biomass is a cause of concern.

- Switch grass (*Panicum virgatum*)
- Canada wild rye (*Elymus canadensis*)
- Western wheat grass (*Agropyron smithii*) and some more.

Wheat grass (*Agropyron cristatum*) has been found to enhance microbial degradation of pentachlorophenol (PCP) and *Phragmites australis*, the microbial degradation of phenols in soil.

Phytostimulation (Microbe stimulated phytoremediation)

Soil microbes have been found suitable to enhance the bioavailability of metals for phytoremediation and increase the phytoremediation potential of plants by complimenting the process in many ways. Soil microbes may degrade organic pollutants into simpler organic compounds and supply them as nutrient to plants for enhanced phytoremediation of the polluted site.

Mycorrhiza assisted phytoremediation

It is generally considered that the majority of plants growing under natural conditions have a symbiotic relationship with mycorrhizal fungi roots, which results in increase in root surface area and enhanced absorption of nutrients. The fungi have been reported in plants growing on heavy metal contaminated soils/sites indicating its heavy metal tolerance and a potential role in heavy metal phytoremediation. Mycorrhizal species *Glomus*, *Gigaspora* and *Entrophospora*, have been reported to be associated with most of the plants growing in the heavy metal polluted soils indicating its obvious role in assisting the plants in tolerating and removal of metals by phytoremediation.

Plant species involved in phytoremediation

Several plants have been identified

and trialed to be used in phytoremediation task (Table 2). A number of them are still wild, while others have been domesticated for their food value. They are highly salt and toxicity tolerant, have extensive root binding system and were tried in the rehabilitation works. Ideal species for the job are members of the grass family *Graminae* and *Cyperaceae* and the members of families *Brassicaceae* (in particular the genera *Brassica*, *Alyssum* and *Thlaspi*), and *Salicaceae* (in particular willow and poplar trees). Grasses such as the vetiver, clover and rye grass, bermuda grass, tall fescue, etc. have been particularly effective in the remediation of soils contaminated by heavy metals and crude oil (Table 2 and 4).

Hybrid poplar, willows, sunflower, alpine pennycress, clover, Indian mustard, redroot pigweed and ferns have been plants of choice for many commercial phytoremediation applications (Table 3).

CONCLUSION

Phytoremediation is a good remediation technology to clean up contaminants from the environment by using green plants. It can be an alternative solution as a green technology to treat heavy metal contaminated areas. Several plants have a high potential as heavy metals bioaccumulator and can be used for phytoremediation process.

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