Review Article

Indian Journal of Waste Management
Volume 8 Number 2, July - December 2024

Phytoremediation: A Green Approach for the Remediation of Contaminated Soil

Asit Mandal, Jyoti K. Thakur, Asha Sahu, S. Bhattacharjya, K. Bharati, M. H. Devi, Abinash Das, S R Mohanty

How to cite this article:

Asit Mandal, *et al.*, Phytoremediation: A Green Approach for the Remediation of Contaminated Soil. Ind. Jr. Waste Manag. 2024; 8(2): 73–79.

Abstract

Agricultural soil contamination through heavy metal is the most common event due to the indiscriminate use of agrochemicals and associated anthropogenic activities. The soil is losing the carrying capacity to supply essential nutrient elements due to adverse interaction with the toxic elements and soil microorganisms. The environmental contamination, biomagnification of food chain and associated health risk is the major concern in recent decades seriously affecting the soil health and future generations. In this scenario, phytoremediation is a green approach to tackle the soil contamination and reversing soil degradation. Plant response to heavy metal and efficacy of remediation of contaminated soil depends on plant and soil characteristics. In this context, hyperaccumulator plants can be effectively used to extract and remove large concentrations of toxic metals from the contaminated systems. Traditional methods of phyto-remediation approaches are not economical and not suitable for the large area decontamination, however hyperaccumulators are promising that can be integrated with the efficient microbes for better results. In the recent advancement of genetic engineering approach to develop transgenic plants with characters of high biomass production, more metal accumulation, tolerance against metal toxicity and well adapted to a variety of climatic conditions might be more beneficial in this respect. Other more modern methods of phytoremediation include chemically aided phytoextraction andmicrobes assisted phytoremediation using potential endophytic microorganisms to decontaminate polluted soils on large scales.

Keywords: Agriculture, Agrochemicals, Toxic elements, Soil microorganisms.

INTRODUCTION

Soil contamination is considered as one of the major environmental issue due to various anthropogenic activities. With the advancement of agricultural and commercial farming, industrial growth numerous soil contaminants such as heavy metals, organic pollutants *etc.* has entered to soil systems adversely affecting soil health and crop quality. Through, the organic contaminants in the soil degrade by the actions of various microbiota present in the soil but the heavy metals and solid contaminants entering in the soil do not degrade easily and tends to accumulated in the soil. Persistence toxic heavy metals having a great adverse impact on soil ecosystems, economic losses and negatively impact

Author's Affiliation: ICAR-Indian Institute of Soil Science, Nabibagh, Bhopal 462038, Madhya Pradesh, India.

Corresponding Author: Asit Mandal, ICAR-Indian Institute of Soil Science, Nabibagh, Bhopal 462038, Madhya Pradesh, India.

E-mail: asit.iari@rediffmail.com

Received on: 15-10-2024 **Accepted on:** 13-11-2024

the human food chain and human health (Ali *et al.*, 2019; Neeraj *et al* 2023). The widespread pollution by heavy metals is mainly a consequence of rapid urbanization, industrialization and intensive farming, including mining, industrial production, municipal sewage, irrigation and excessive use of fungicides and herbicides. Historically, significant adverse impacts of heavy metals on human health have received great attention as a result of a series of widespread poisonings (Bolan *et al.*, 2014). More recently, case studies of heavy metal pollution have often been reported in several countries across the globe. For example, arsenic contamination in rice is reported in India and Bangladesh, and more than 100 million people are potentially at risk from arsenic poisoning (Bhattacharya *et al.*, 2012). It has been highlighted the Cd accumulation severely affected in the kidneys of grazing animals report in New Zealand (Reiser *et al.*, 2014). Similarly, the presence of toxic heavy metals in soil cause potential economic loss to food yield and toxicity to livestock and human being.

With the widespread public awareness of the adverse impacts of toxic metals on soil-plant-human-animal continuum, there has been growing interest among scientists, researchers and engineers to develop remediation technologies to clean up toxic metals from soil ecosystems. In the past few decades, considerable efforts have been made to remove heavy metals from contaminated environments, including physical, chemical or biological approaches. Each alternative strategies have potential advantages as well as limitations in terms of economy and ecological safety. The traditional methods based on physico-chemical approaches of soil remediation are generally expensive and intrusive and sometimes disturb the soil biological component. The green approaches of remediation using green plants are simple, nonintrusive and sustainable (Mirsal, 2008). Finally, in biological approaches called phytoremediation, which employs green plants to remove, destroy or sequester toxic metals from contaminated environments in an efficient and cost-effective manner has been highly popularized in the last decades.

Sources of heavy metal contamination

In view of chemical perspective, heavy metals are transition metals with an atomic number more than 20 and a specific weight greater than 5 g/ cm^3. Biologically "heavy metal" refers to a series of metallic elements, or metalloids which are toxic for plants and animals even in low concentrations (Rascio and Navari, 2011).

Both geogenic and anthropogenic sources cause soil contamination with various heavy metals and metalloids. There are several cases of soil contamination by anthropogenic activities result in release of most potentially hazardous elements *viz.* Arsenic (As), Cadmium (Cd), Chromium (Cr), Mercury (Hg) and Lead (Pb) (Remon *et al*, 2005). Possible anthropogenic sources of heavy metals contamination to soil are given in the Fig. 1.

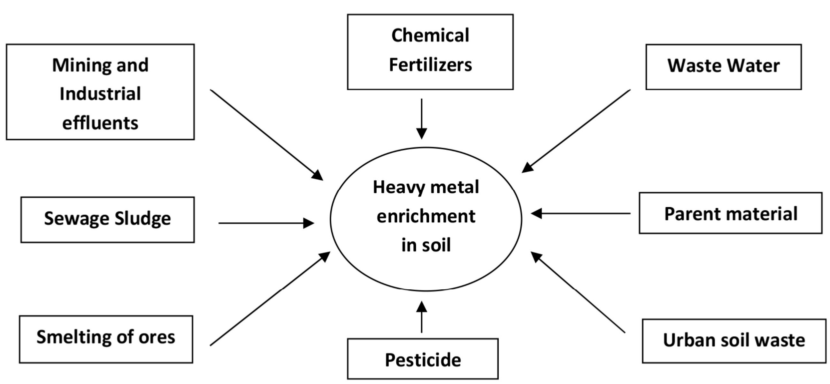

Fig. 1: Major sources of heavy metal in soil

The geogenic or natural way of heavy metal occurrence is due to weathering of parent materials (rocks and minerals). One typical example of geogenic or pedogenic contamination is the extensive arsenic contamination of ground waters in Bangladesh and West Bengal in India (Mahimairaja *et al.*, 2005). As a consequence of the heavy metal contamination, agricultural soils have become one of the serious environmental concerns. Higher concentration of heavy metal accumulation in agricultural soils through wastewater irrigation, may not only cause soil contamination, but also leads to elevated heavy metal uptake by crops, and thus affect food quality. Possible way of heavy metals entering in soil is listed in Table 1.

Table 1: Sources of heavy metal(loid)s in soils

Element	Source
Arsenic (As)	Timber treatment, paints, pesticides, geothermal, Geogenic/natural processes, smelting operations, thermal power plants, fuel burning etc.
Cadmium (Cd)	Electroplating, batteries, fertilizers, Zinc smelting, waste batteries, e-waste, paint sludge, incinerations, fuel combustion
Chromium (Cr)	Timber treatment, leather tanning, pesticides, dyes, Mining, industrial coolants, chromium salts manufacturing
Copper (Cu)	Fungicides, electrical, paints, pigments, Timber treatment, fertilizers, mine tailings, electroplating, smelting operations
Lead (Pb)	Smelting operations, Batteries, chemical preservatives, petroleum additives, paints, E-waste, coal- based thermal power plants, ceramics, bangle industry
Manganese (Mn)	Fertilizer
Mercury (Hg)	Instruments, fumigants, geothermal, Chlor-alkali plants, thermal power plants, fluorescent lamps, hospital waste, (damaged thermometers, barometers, sphygmomanometers), electrical appliances etc.
Molybdenum (Mo)	Fertilizer, Spent catalyst
Nickel (Ni)	Alloys, battery industry, mine tailings Smelting operations, thermal power plants,
Zinc (Zn)	Galvanizing, dyes, paints, timber treatment, fertilizers, mine tailings, Smelting, electroplating

Source: Lone *et al.*, 2008

FATE OF HEAVY METALS AND REMEDIATION APPROACH

Unlike organic pollutants, biodegradation of heavy metals is difficult and hence in long run continuous accumulation may cross the toxicity limits of heavy metals in the soil. The contribution of heavy metals to soil contamination is very significant, so the restoration of these lands is very important for a clean environment. Among the different techniques used for the decontamination of heavy metals based on physico-chemical methods such as ion exchange, solvent extraction, oxidation reduction, reverse osmosis, membrane separation, and precipitation, filtration etc of often found cost intensive and non sustainable, however the biological method of clean up approach such as bioremediation (using microbes) and phytoremediation (using green plants) is the cheapest and involves eco-friendly technology for the removal of heavy metals from contaminated systems.

Phytoremediation utilizes the inherent ability of specific plants to absorb water, available mineral nutrients, and co-contaminants through their roots and transpire through leaves, for transformation of organic compounds, or bioaccumulate toxic trace elements including heavy metals. Recently, the concept of using metal-accumulating plants for environmental clean-up has been vigorously pursued (Garbisu and Alkorta, 2001), promoting the philosophy of "phytoextraction" as an approach under phytoremediation (Kumar *et al*, 1995).

PHYTOREMEDIATION

The term phytoremediation involves the use of green plants and associated microorganisms to minimize the toxic effects of potential contaminant in the environment. The word "phytoremediation" is derived from Greek word *phyto* (mean plant) and Latin word *Remedium* (to correct or remove an evil). The idea of phytoremediation was suggested for the first time by Chaney (1983). The concept seems esthetically pleasant and can have larger acceptability and applicability over a large-scale where other physical remedial measures may not be so efficient and eonomic.

Phytoremediation is a green technology that take advantage of the genetic potential of specific plant species to metabolize, or immobilize a wide range of pollutants. Hyperaccumulation is associated with plant species endemic to metalliferous soils, and it is usually limited to only a very smaller proportion of metallophytes. Some important families and genera such as Brassicaceae (*Alyssum* and *Thlaspi*); Euphorbiaceae (*Phyllanthus*, *Leucocroton*); Asteraceae (*Senecio, Pentacalia*); Lamiaceae, Scrophulariaceae are have been shown to possess heavy metal remediation potential from contaminated soil. There are various phytoremediation approaches that can be employed:

(i) ***Phytoextraction*****:** This process also known as phytoaccumulation is the uptake of contaminants from soil by plant roots and their translocation and accumulation in above ground biomass i.e., shoots. The Chinese brake fern (*Pteris vittata* L) is well known phytoextractor in arsenic (As) contaminated soil. The plants have ability to concentrate multiple heavy metals in their above ground biomass which are then harvested, incinerated, and the ash released into a confined area or the heavy metals are extracted from it (Fig. 2).

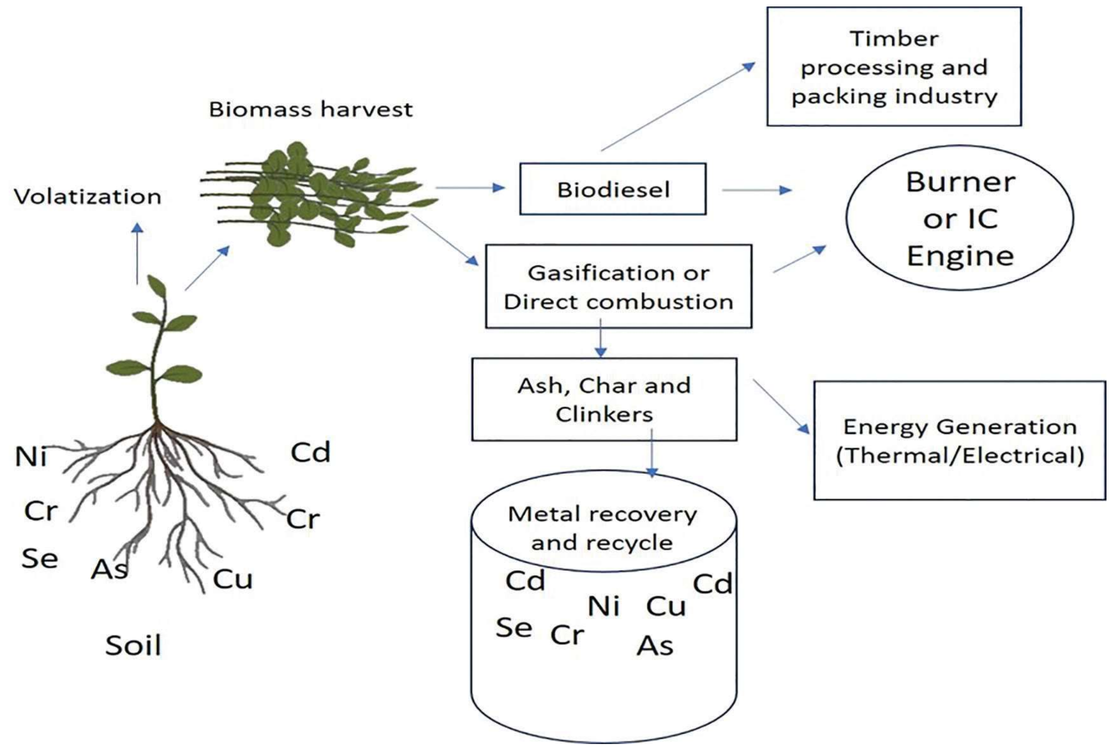

Fig. 2: Phytoextraction of metal from soil and their utilization (***Source:*** Purakayastha and Chhonkar, 2010)

Metal translocation to shoots is a crucial biochemical process desirable for an effective phytoextraction because the harvest of root bio mass is usually not feasible. The discovery of plants–hyperaccumulators capable of absorbing heavy metals in 50–500 times greater content than normal plants has led to the revolutionary advancement of phytoextraction technology.

(ii) ***Phytostabilization:*** Phytostabilization is the process of stabilization of heavy metal near plants roots which limit the bioavailability and mobility and reducing the off-site contamination (Pulford and Watson, 2003). This process is basically plant ability to concentrate specific heavy metal in the root system is also termed as phytodeposition or phytosequestration. Fixation can be enhanced by various plant rhizodeposits, organic acids promoting the precipitation and the sorption/chelation of metals. This method of phytostabilization is used for the cleanup of soil, sediment, and sludges. This process can take place through sorption, precipitation, complexation, or metal valency change. As for eg. Perennial ryegrass (*Lolium perenne* L.) reported as metal-tolerant plant to be used in the reactive amendment aided phytostabilization of Pb-contaminated soil.

(iii) ***Phytovolatilization*:** This process involves the use of plants to take up contaminants from the soil, transforming them into volatile forms into the atmosphere through transpiration. It is basically used for the soil contaminated with toxic metal such as mercury. In this method the growing plants and other plants may take up the contaminants with water and the contaminants may pass through the xylem vessels towards the leaves and converted into volatile non-toxic forms into the atmosphere.

(iv) ***Phytodegradation*:** This approach involves the use of plants and associated microorganisms play important role in degradation of organic pollutants into less toxic forms or to render them immobilized in order to prevent their entry into the food chain or environment. This method is less suitable for the remediation of inorganic contaminants and heavy metals.

(v) ***Rhizofiltration*****:** This is the use of plant roots to absorb and adsorb pollutants, mainly metals, from water bodies and aqueous waste streams. Metal-absorbing or metal-adsorbing plant species are planted in artificial marshes. This method is primarily used to remediate extracted groundwater, surface water, and waste water with low concentrations of contaminant. It is suitable for Pb, Cd, Cu, Ni, Zn, and Cr which are primarily retained within the roots. It is established that sunflower, Indian mustard, tobacco, rye, spinach, and corn can eliminate lead from the water and soil. This method is can be explored in both terrestrial and aquatic plants for *in-situ* or *ex-situ* purposes. The contaminants do not transfer to the shoots when using this strategy.

Phytoremediation includes several strategies such as phytoextraction, phytostabilization and phyto-volatization to combat the pollution of inorganic metals whereas rhizofiltration and phytodegradation is suitable to deals with aquatic ecosystems and organic pollutants respectively (Fig. 3). One of the main drawbacks with phytoremediation is that it is often slow and time consuming for cleanup to acceptable concentration of heavy metals into soil and plants. To some extent, these strategies of phytoremediation can be enhanced with the natural microflora associated with plants, endophytic bacteria, rhizosphere bacteria and mycorrhizae have been shown to be the potential agent to degrade variety of contaminant from the polluted sites.

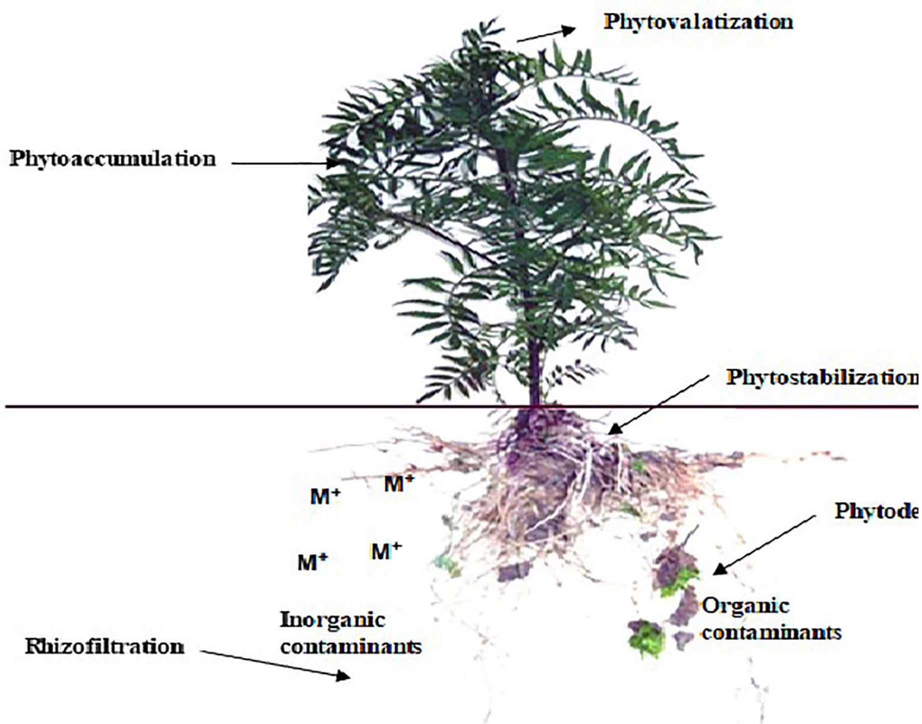

Fig. 3: Different strategies of phytoremediation to counteract soil contaminants

Indicators of phytoremediation efficiency

Based on the levels or contents of heavy metals found in plant roots and shoots and the following indications were used to calculate the soil's trace element concentration:

(i) Translocation factor (TF)

The translocation process capacity of plants to transfer heavy metals from roots to shoots is expressed by the translocation factor (TF), which is calculated as follows:

$TF = C_{shoot}/C_{root}$; where: C_{shoot} = metals concentration in the shoot of plants [mg kg^{-1}], C_{root} = metals concentration in the root of plants [mg kg^{-1}].

Effective process of translocation of heavy metals from the roots of plants shoot occurs at the TF> 1 (Fayiga and Ma 2006).

(ii) Bioaccumulation factor (BAF)

Bioaccumulation process capacity of plants/ organism to accumulate heavy metals from the soil available fraction is expressed by the bioaccumulation factor (BAF), which is calculated as follows:

BAF = C_{shoot}/C_{soil}; where: C_{shoot} = metals concentration in the shoot of plant [mg kg^{-1}], C_{soil} = metals concentration in the soil (rhizosphere zone) [mg kg^{-1}].

Plants can be classified as hyperaccumulators, accumulators (BAF>1), or excluders (BAF <1) based on the level of heavy metal accumulation in the plant tissues and the BAF.

(iii) Metal extraction ratio (MER)

The ability of the plants to absorb heavy metals and the suitability of a specific plant species for the phytoremediation procedure were assessed using the metal extraction ratio.The metal extraction ratio is calculated as follows:

MER = (C_{plant} x M_{plant}/Csoil x $M_{rooted\ zone}$) x100; where: C_{plant} = metals concentration in the aboveground part of the plant [mg kg^{-1}], C_{soil} = metals concentration in the soil (rhizosphere zone) [mg kg^{-1}], M_{plant} = mass [g] of the plant's aboveground portion; Mrooted zone = mass [g] of the soil rhizosphere zone. Plants can be classified as hyperaccumulators, accumulators (BAF>1), or excluders (BAF <1) based on the amount of heavy metal accumulation in the plant tissues and the BAF (Ma *et al.* 2001).

Depending upon the response of heavy metals, plant may be classified as follows and depicted in Fig. 4.

(i) ***Metal excluders*****:** These plants contain high concentration of heavy metals in their roots and shoot/root ratios are less than one. These plants restrict the uptake of metal in their aerial part. These plants have low potential for extraction but suitable for phytostabilization purposes to prevent further contamination.

(ii) ***Metal indicators*****:** The plant uptake and translocation of metals from soil to plants showed a visible toxic these plants accumulate metals in their above-ground tissues, which are reflected as the metal levels in the soil.

(iii) ***Metal accumulators/hyperaccumulator:*** These plants concentrate metals in their above ground tissues, their concentration of metals exceeds the metals concentration present in the soil. Accumulators/hyperaccumulators growing on metal contaminated sites can naturally accumulate higher levels of heavy metals in their shoots than in their roots.

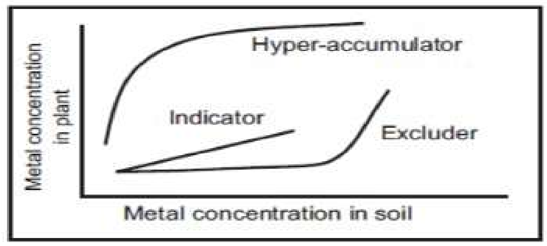

Fig. 4: Different strategies of plants in response to metal concentration in soil

Potentially of phytoremediation approaches

Important factors to consider when choosing a plant for specific phytoremediation approaches (Table 2). Among these approaches, phytoextraction seems to be most attractive due to its versatility in usage. The remediation of heavy metal-contaminated soils is not a good use for phytodegradation because it works best with degradable wastes. While phytovolatilization is restricted to specific unique metals (such as Hg, As, and Se) that have the ability to create volatile chemicals, rhizofiltration is specifically used in the treatment of water. Although the phytostabilization procedure aims to make the metal inactive rather than remove it from the soil system, this means that the issue may recur in the future. These drawbacks with phytostabilization make phytoextraction a more promising technique.

Table 2: Plant parameters to consider when applying different phytoremediation approaches

Strategies	Tolerance	Root uptake	Translocation	Shoot accumulation	Biotrans-formation	Rhizosphere
Phytostabilization or Phytodeposition	X				X	
Phytoextraction or phytoaccumulation	X	X	X	X		X
Phytovolatization	X	X	X		X	X
Rhizofiltration	X	X				

Many of the plants identified, some plant species recognized as hyperaccumulators since they are able to absorb heavy metals and accumulate excess heavy metals. Pteris vittata, Thlaspi caerulescens, Alyssum serpyllifolium, Phytolacca americana, Solanum nigrum, and Sedum plumbizincicola are some of these plants.

CONCLUSIONS AND FUTURE PERSPECTIVES

Heavy metal contamination of agricultural soils is a major environmental concern in recent decades due to potential risk of food chain contamination and other associated health risks. In this situation, phytoremediation serve as key tool to tackle the issues over physical and chemical approaches to clean up the polluted soils. Hyperaccumulator plants can be effectively used to extract and harvest large concentrations of deleterious metals as well as other inorganic and organic pollutants from soil. But traditional phytoremediation approaches are less economical to be applied on large scales as naturally occurring hyperaccumulators are generally slow growing and produce relatively less harvestable aboveground biomass production. Thus, using genetic engineering to create transgenic plants with traits like high biomass production, increased metal accumulation, resistance to metal toxicity, and excellent climate adaptation may be more advantageous in this regard. Some other recent phytoremediation approaches like chemical assisted phytoextraction and microbes assisted phytoremediation using potential endophytes may also be used to decontaminate polluted soils on large scales. Further research is needed in the field of genetic engineering to improve the phytoremediation abilities of transgenic plants, and to understand the mechanisms and effectiveness of phytoremediation techniques in order to make these technologies more effective, time saving and economically feasible.

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