# Concept and Types of Phytoremediation

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## Abstract

Phytoremediation is a form of bioremediation which deals with the enormous potential of plants for degrading or immobilizing contaminants in soil and groundwater. Anthropogenic activities release huge amounts of chemicals, wastes, and noxious gases into the environment, which alter the physical, chemical, and biological properties of ecosystem, worldwide. Biological agents utilize these contaminants as part of their metabolism and turn them into less toxic or harmless by-products. It reflects the natural ability of certain plants called hyperaccumulators to clean up a variety of contaminants, viz. polyaromatic hydrocarbons, pesticides, heavy metals, etc., in soil, water, or air. The choice of process; biotransformation, phytodegradation, phytostimulation, phytovolatilization, etc., to be opted for clean-up depends upon the habitats, supply of nutrients, contaminants type, and environmental conditions. Phytoremediation involves life forms, and ensures complete degradation of various toxicants without releasing harmful products, hence is an effective and cheaper solution for waste management.

## Keywords

Phytoremediation · Phytodegradation · Phytostimulation · Phytovolatilization · Phytoextraction

## 1 Introduction

“Phytoremediation” is a combination of two words: the Greek prefix “phyto” meaning plant and the Latin root “remedium” meaning to remove the contaminant. Phytoremediation is an old concept which is used since many decades to clean the toxicity of different contaminants present in soil, groundwater, and other contaminated areas. The theory of phytoremediation depends on the usage of plant species to clean up the environmental pollution, making it an ecologically friendly and cost-effective technology, which can be applied both for in situ and ex situ treatments (Schwitzguébel et al. 2011). The phytoremediation method does not require any expensive instruments or skilled person, but is often based on the selection of appropriate plant which is able to survive in the perilous milieu and can degrade hazardous materials in a wide range of environment. The method can serve as an alternative tool against physical and chemical treatment methods which demand high capital inputs and are labour and energy intensive. Phytoremediation in combination with other remediation processes, viz. microbial remediation can be effectively employed in the treatment of wetlands, establishment of crops in stressed soils, and promoting sustainable agriculture (Garbisu et al. 2002; Gerhardt et al. 2017).

Plants can grow in almost all climatic conditions and can be employed to clean up variety of pollutants, viz. sewage and industrial effluents, pesticides, heavy metals, hydrocarbons, explosives, surfactants, nutrients, mineral oil, etc. (Van Aken 2009; Huang et al. 2011; Sarwar et al. 2017). The different mechanisms of phytoremediation differ on the basis of the type of pollutants which is addressed. The optimization of growth conditions can selectively enhance the process of remediation under suitable climatic conditions which not only improve performance of plant species but also can actively participate in treating varied environmental pollutants of different ecosystems.

Plant-assisted bioremediation involves the interaction of plant roots and the soil microorganisms in the biological treatment of large number of contaminated soils. The possible use of genetically modified plants is also gaining recognition as a potential remediation technique in many parts of the world (Abhilash et al. 2009). Some of the plants are also used as bioindicators to determine water quality, the level and nature of toxicants present in different aquifers, in the evaluation of municipal and industrial waste, etc. Plants called as hyperaccumulators are much studied these days which have the ability to store large amount of metals, without disturbing the normal plant functioning (Dhankher et al. 2002; Chen et al. 2013; Raj et al. 2020). Such metabolically active plant species can be used to inhabit soils contaminated with heavy metals for the enhanced uptake and remediation. It satisfies the concept of green revolution in the field of innovative clean-up technology which can be used for in situ or ex situ applications with minimum distribution of soil and reduced spread of contaminants (Bert et al. 2009).

Phytoremediation technologies are in the early stages of development, involving only laboratory research and limited field trials. Although the beneficial properties of plant species for the treatment of contaminated ecosystems are known and studied, their inherent abilities to remove pollutants from the environment have yet to be explored commercially (Gerhardt et al. 2017). Extensive research including genetic engineering is required to investigate and develop plant species with potential phytoremediation applications, which can be applied for the selective degradation or removal of pollutants at specific sites (Dhankher et al. 2002). Furthermore, the total cost of operation, time required, method of waste disposal, and growth requirements to remediate per acre of land or per gallon water should be worked out and optimized for the industrial and commercial usages of this technology.

## 2 Environmental Contaminants

Extensive human activities are continuously introducing hazardous compounds into the environment at an alarming rate. The soil, air, and water have been contaminated with toxic materials which are altering their physical and chemical properties. The effluents coming out from different industries and also the industrial processes had become a major concern worldwide as the foremost source of environmental contamination. Environmental contaminants are broadly defined as those chemicals that accidentally or deliberately enter the environment, and impair its properties. These contaminants are very stable and they do not break down easily, as a result become persistent and circulate in the environment for indefinite time period (Novak and Trapp 2005). If released to the environment, these contaminants may enter the food chain and disturb all forms of life.

The other naturally occurring chemicals like heavy metals (locked in soils, rocks, and sediments) are introduced into the environment through intensive industrial activity which increase their mobility and availability, allowing them to enter the food chain up to higher levels. Heavy metal accumulation is of primary concern because they cannot be destroyed or degraded. Apart from this, wide variety of environmental contaminants have been detected in food, water, and soil which could be either inorganic or the so-called persistent organic pollutants (POPs). A broad classification of contaminants that can be remediated using plant-assisted bioremediation includes:

1. Heavy metals (As, Hg, Cd, Cr, Pb, Co, Cu, Ni, Se, Zn)
2. Petroleum hydrocarbons
3. Polyaromatic hydrocarbons (PAHs)
4. Dioxins and furans
5. Chlorinated solvents (trichloroethylene)
6. Polychlorinated biphenyls (PCBs)
7. Chlorinated naphthalenes
8. Perfluorinated chemicals in food
9. Chlorinated pesticides
10. Organophosphate insecticides
11. Radionuclides
12. Explosives (TNT, DNT, TNB, RDX)
13. Nutrients (nitrate, ammonium, phosphate)
14. Surfactants

## 3 Principle of Phytoremediation

Phytoremediation relies on the basic principle of using plants such as algae, fungi, grasses, shrubs, trees, etc., for the stabilization, volatilization, degradation, extraction, or precipitation of pollutants present in soil, water, or air. Plants might promote the removal of pollutants from their surroundings by varied mechanisms, in which

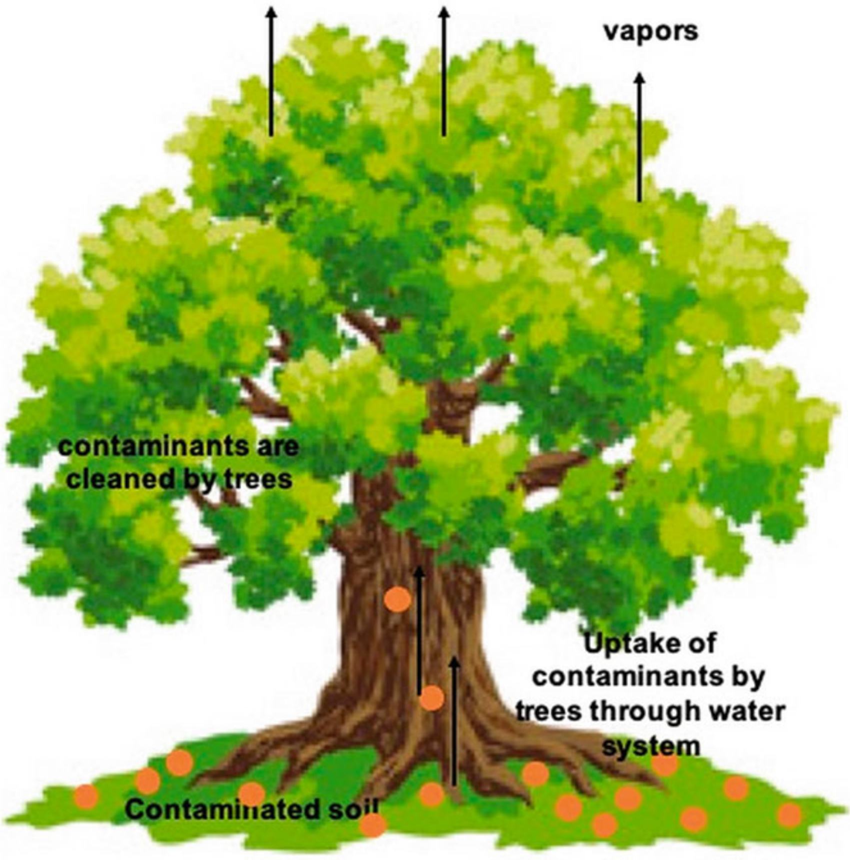

**Fig. 1** Principle of phytoremediation

they not only help in breaking down of the waste products but also promote the growth of bacteria in the root zone that in turn break down pollutants (Garbisu et al. 2002; Schwitzguébel et al. 2011). Plants can also uptake and trap the pollutants from soil by acting as a filter. The uptake of contaminants in plants occurs primarily through the root system, which provides an enormous surface area to absorb and accumulate the non-essential contaminants along with water and nutrients to undertake the process of remediation (Fig. 1).

## 4 How Does Phytoremediation Works?

Phytoremediation is solely dependent upon the metabolic activities of certain plant species and their affinity towards various contaminants. It is a natural process accomplished by plants, which can clean up pollutants as deep as their roots can reach taking the following steps:

1. Plants get adapted and try to establish themselves in the polluted ecosystems (Schwitzguébel et al. 2011). Certain plants are able to remove or break down harmful chemicals from their vicinity by absorbing water and nutrients from the contaminated soil through their extensive root system (Novak and Trapp 2005). The roots of plants play an important role not only in the absorption of contaminants (moderately water soluble) but also locking them to some extent in the soil to limit their uptake and further translocation (Wang et al. 2018). Other plant species tend to remove the pollutants from the soil and accumulate them inside the tissues, without disturbing the vital cell functioning.
2. Uptake of the pollutants is facilitated by specific ion channels and transporter proteins which are present on the cell surface (LeBlanc et al. 2013). These protein channels allow a vast variety of pollutants to enter inside the cell.
3. Entry of the pollutants in the cell is followed by their processing via lignification, volatilization, metabolization, mineralization, transformation, etc.
4. The processes involve the use of enzymes to breakdown complex organic molecules into simpler ones (probably $CO_2$ and water). This step is very significant, as it determines the fate of contaminants in plant tissues (Feng et al. 2017). Further, there are unique enzyme systems present in cells which are specific for a type of chemical/pollutants.
5. The by-products of the remediation processes are either used up by the cells as building blocks, or they are released in the soil. The release of chemicals (exudates) or by-products increases the carbon and oxygen content of soil around roots which promotes microbial activity. The microbes in turn enhance plant growth and establish them in contaminated soils.

## 5 Mechanism of Phytoremediation

Depending on the type of contaminant, its bioavailability and soil properties, distinct plant species have different efficiencies towards noxious waste and show varied mechanisms of phytoremediation. The generously used mechanisms by the plant species to clean up and/or remediate contaminated sites are briefly discussed below:

### 5.1 Phytoextraction

Phytoextraction, also called phytoaccumulation, is the ability of plant roots to absorb, uptake, concentrate, and precipitate metals and other compounds from soil and accumulate it into above-ground portions (shoots and leaves). Once allowed to grow for some time, plants can be harvested and either incinerated or composted to recycle the metals. Plants varieties that can absorb and accumulate heavy metals and metalloids at an extraordinary rate from the contaminated soils have long been studied and identified (Sarwar et al. 2017). These can be grouped into metal accumulating and non-accumulating plants. Studies prove that metals such as As, Pb, Ni, Zn, and Cu can be effectively removed by phytoextraction. Such species have high affinity for the metals, which facilitates permanent removal of contaminants from the surrounding, especially soil (Afonso et al. 2020). They also have mechanism to detoxify and/or tolerate high metal concentration. Phytoextraction of heavy metals represents one of the promising opportunities for phytoremediation because of the significance of environmental problems associated with metals. This approach is highly influenced by rate of metal uptake by roots, soil properties like pH, presence of other components in the soil, cellular tolerance to toxic metals, etc. (do Nascimento et al. 2020).

## 5.2 Phytovolatilization

Phytovolatilization is the uptake, transport, and transpiration of a volatile contaminant by a plant (Doty et al. 2007). The method is generally executed through the plant leaves, from where the modified contaminants or wastes are evaporated and released to the atmosphere. The process of phytovolatilization occurs as growing plants take up the organic contaminants from the soil, convert them into volatile forms and finally release them into the atmosphere through transpiration as detoxified vapour. Many different contaminants such as metals, hydrocarbons, etc., can be treated by this method; however, the released components are recycled through different means which then re-enters into biological system (Feng et al. 2017). Fast growing trees are particularly useful in the process for the rapid uptake of contaminants. Further, experimental success has been achieved for the use of genetically modified variety of plant species having enormous transpiration pull as a useful choice to clean up pollutants.

## 5.3 Phytodegradation

Phytodegradation, also called phyto-transformation, is the breakdown of contaminants through metabolic processes within the plants. Complex organic pollutants are degraded into simpler molecules through the enzyme systems, which are further used as building blocks in the plant tissues to help the plant grow faster (Feng et al. 2017). The process can take place either internally or externally using specific secretory enzymes which catalyze and accelerate chemical reactions. The approach is useful for biodegradation of pollutants like chlorinated hydrocarbons, herbicides, and explosives (Van Aken 2009). In the process, plants modify the surrounding soil by producing root exudates which attracts many rhizosphere-inhabiting microbial species like bacteria and fungi. These microbial species stimulate an array of positive interactions with plants and accelerate the process of biodegradation of xenobiotics.

## 5.4 Rhizofiltration

Rhizofiltration is the methodology which is primarily executed by the intensive root system of plants involving absorption, concentration, and precipitation of contaminants present at lower concentrations for the immediate remediation of the polluted aqueous and land sources. The approach largely involves the locking and retaining of chemicals in the soil by the roots to limit their further transportation. Many different terrestrial plants, viz. Indian mustard, sunflower, rye, spinach, and corn have been investigated for their ability to remove contaminants from the surrounding. The fibrous and extended root system of the plants presents an increased surface area for the pollutants, making them the promising candidates to be used both for in situ or ex situ applications (Salt et al. 1995).

## 5.5 Rhizodegradation

Rhizodegradation, also called as phytostimulation or plant-assisted degradation, is the breakdown of contaminants in the rhizosphere through microbial activity (Abdullah et al. 2020). The plant roots produce certain chemicals, viz. sugars, alcohols, and acids, which attract soil microorganisms like yeast, fungi, or bacteria to inhabit rhizosphere. The microbes then consume and digest organic substances into harmless products for their nutrition and energy. However, the process is much slower than phytodegradation; it is broadly employed in the remediation of contaminated soils.

## 5.6 Phytostabilization

Phytostabilization also known as place-inactivation is the use of certain plant species to immobilize contaminants in the soil and groundwater through absorption and accumulation by roots, or precipitation within the rhizosphere zone of plants. This process reduces movement of contaminants and prevents migration to the groundwater. It also reduces bioavailability of pollutants for entry into the food chain. This technique prevents soil erosion, distribution of toxic metal to other areas, and can be used to re-establish a vegetative cover at sites where natural vegetation is lacking due to high levels of contaminants (Ahsan et al. 2018). Recent studies prove that the use of metal-tolerant plant species can be used to restore vegetation by decreasing the potential migration and leaching of soil contaminants to groundwater. The process can also be effectively used for the treatment of contaminated land areas affected by mining activities and to overcome the problems associated with disposal of hazardous waste.

## 6 Types of Plants Used in Phytoremediation

Many different plant varieties are used since decades for the remediation of varied contaminants and pollutants from distinct ecosystems. Extensive research in this field had added to the knowledge of many existing plant species (both terrestrial and aquatic) that belong to distantly related families and have the ability to grow on stressed soils. These plants can easily prosper on the contaminated and metalliferous soils and accumulate extraordinarily high amounts of pollutants/heavy metals in their roots and aerial organs, without suffering phytotoxic effects (Sarwar et al. 2017). A list of such dynamic plant species used in the phytoremediation technology is presented in Table 1.

Some of the plants are known to uptake and accumulate remarkable amount of contaminants especially heavy metals from their surroundings. Such species are termed as "hyperaccumulators" to describe a number of plants with an enhanced rate of uptake, a faster root-to-shoot translocation, and a greater ability to detoxify the pollutants (Dhankher et al. 2002). Such determinant role is played by the constitutive overexpression of genes encoding transmembrane transporters, which acts as a defence mechanism against many environmental contaminants (Rascio and Navari-Izzo 2011; LeBlanc et al. 2013). Metal accumulating species can be used for phytoremediation to treat the heavy metal contaminated soils which otherwise pose many serious problems to human and animal health. The mechanisms adopted by higher plants in metal clean-up process include: uptake and translocation (Wang et al. 2018); metal removal through volatilization; conversion of metals to less toxic and volatile forms; detoxification and sequestration of metals; accumulation; metal complexation and immobilization, and metal–microbe interaction (Fig. 2). Most of the hyperaccumulating plants have the capability to absorb and accumulate two or more than two heavy metals (Meagher and Heaton 2005). Hyperaccumulators have been studied and identified in different families like Brassicaceae, Poaceae, Hydrangeaceae, Pteridaceae, Asteraceae, Pontederiaceae, and Fabaceae (Raj et al. 2020).

## 7 Factors Affecting Phytoremediation

There are several factors which can affect the phytoremediation process, as described in Fig. 3. Understanding these factors could play a vital role in understanding the fate of pollutants in plants and the mechanisms adopted by different plant species to combat their detrimental effects both in their own cell and in the outer surroundings including humans. Further, the performance of plants can be greatly improved. Some of the important factors are underlined below:

**Table 1** Plant species used in remediation of various contaminants

| S. No. | Contaminants/pollutants | Plant species involved in remediation | References |
|---|---|---|---|
| 1 | Heavy metals: Cd, Cu, Fe, Pb, Sb, uranium, Pb, Zn | *Cynara cardunculus*, poplar plants, *Setaria pumila*, *Pennisetum sinese, Sedum plumbizincicola*, *Elsholtzia splendens*, *Althaea rosea* Cavan, *Pisum sativum* L., *Coronopus didymus* L. | Sidhu et al. (2018), Gupta et al. (2019), Huang et al. (2019a, b), Sidhu et al. (2019), Capozzi et al. (2020), and Cui et al. (2020) |
| 2 | Sewage water | *Typha angustifolia*, *Eichhornia crassipes* | Pandey et al. (2019) |
| 3 | 1-butyl-3-methylimidazolium bromide, Cd | *Lolium perenne* L. | Hu et al. (2019) |
| 4 | Polycyclic aromatic hydrocarbons (PAHs) | *Lolium perenne, Ricinus communis* | Wang et al. (2013) |
| 5 | Mineral oil, industrial waste | *Ricinus communis* | Boda et al. (2017) and Rehn et al. (2019) |
| 6 | Persistent organic pollutants (POPs) | Cucurbits (pumpkin, cucumber, and squash) | Iwabuchi et al. (2019) |
| 7 | Dieldrin | *Sorghum vulgare Moench*, *Helianthus annuus* L., *Glycine max*, *Brassica rapa var. perviridis*, *Lagenaria siceraria var. hispida*, *Cucumis sativus* L., *Cucurbita pepo* L. | Murano et al. (2010) |
| 8 | β-1,2,3,4,5,6-hexachlorocyclohexane (β-HCH), 1,2,3,4,10,10-Hexachloro-6,7-epoxy-1,4,4a,5,6,7,8,8a-octahydro-endo-1,4-exo-5,8-dimethanonaphthalene | *Hordeum vulgare*, *Glycine max*, *Solanum lycopersicum*, *Brassica oleracea*, *Cucurbita pepo* | Namiki et al. (2015) |
| 9 | [$^{14}$C]-1,2,4-triazole | Wheat and tomato | Lamshoeft et al. (2018) |
| 10 | Domestic and textile effluents | *Lemna minor*, *Daphnia magna* | de Alkimin et al. (2019) |
| 11 | Acidic mine waste | *Cymbopogon martini* (*Roxb.*) *Wats* | Jain et al. (2019) |
| 12 | Tetrabromobisphenol A | *A. marina, K. obovata* | Jiang et al. (2019) |
| 13 | Polybrominated diphenyl ethers (PBDEs) | *Avicennia marina* (*Am*), *Aegiceras corniculatum* (*Ac*) | Chen et al. (2017a) |
| 14 | Phenanthrene and pyrene | *Kandelia candel* (L.) *Druce* | Lu et al. (2011) |

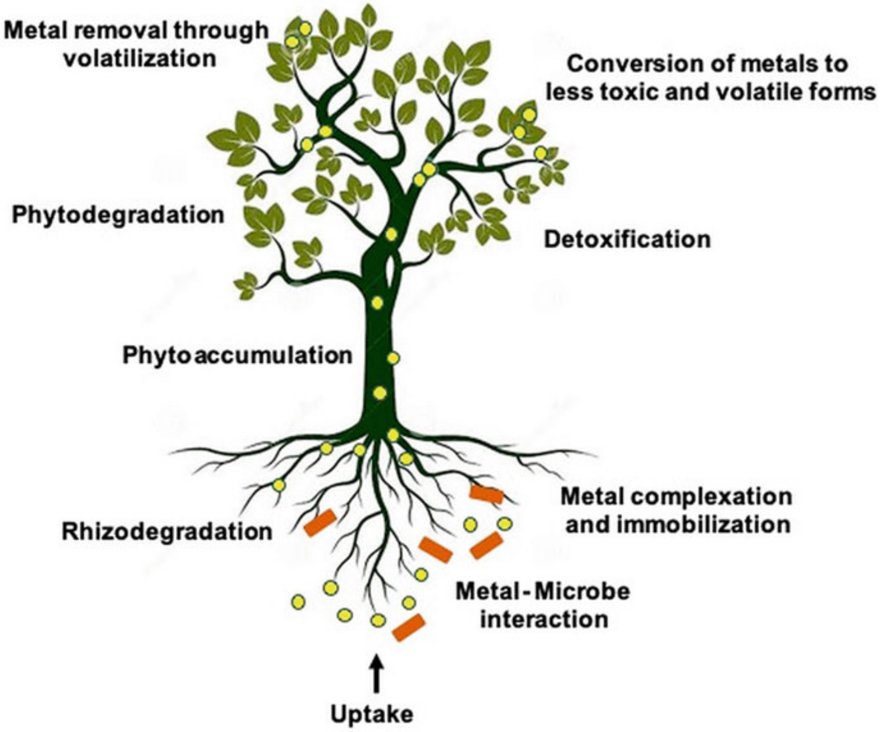

**Fig. 2** Major mechanisms involved in metal remediation by plants

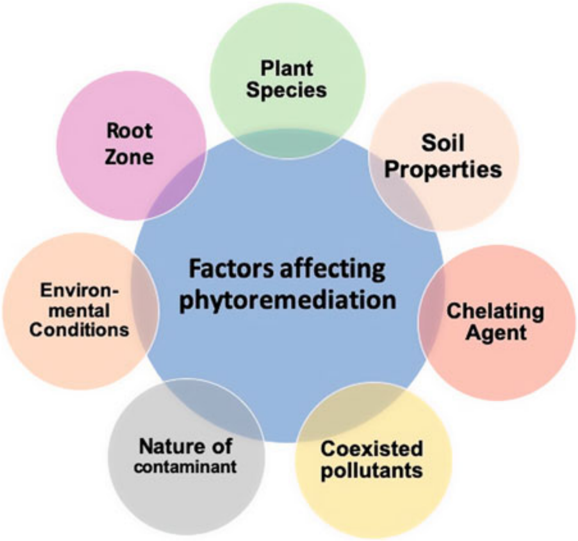

**Fig. 3** Factors affecting the phytoremediation process

## 7.1 Soil Properties

Several soil physical and chemical properties and agronomical practices constitute one of the important factors to enhance remediation. The concentration of pollutants and/or contaminants absorbed by the plants is affected by the organic matter, pH, moisture content, sulphur and phosphorus content of the soil, clay content, cation exchange capacity, and total nitrogen content. Optimization of the soil conditions and evaluation of the effects of relevant soil properties on the distribution of total contaminants can appreciate the levels of phytoremediation and sustainability.

## 7.2 Plant Species

The uptake of any compound is largely affected by the type of plant species, its ability to inhabit polluted soil, and its potential in executing remediation process. Screening of the suitable plant species or varieties with those having superior remediation properties should be selected (Sarwar et al. 2017). The role of plant is to decrease the mobility of contaminants in soil by absorption, complexation, and precipitation in the rhizosphere by successive binding of the chemicals with root exudates. Success of the phytoremediation technique depends upon the increased metabolic rate of plants in the presence of pollutants. Identification of such plant species which can hyperaccumulate varieties of contaminants including heavy metals without generating noxious waste products by establishing itself in the stressed soils is the need of the time.

## 7.3 Environmental Conditions

The phytoremediation process is essentially affected by the environmental conditions which determines the success of the growth of the plants and their establishment in polluted soils. One such factor is temperature which influences plant growth, specifically root length and signifies the binding of contaminants with soil particles. It also affects the level of uptake of the contaminants by the plant roots. Optimal temperature should be maintained between 22 and 40 °C for the smooth accomplishment of phytoremediation. Other environmental factors which contribute towards remediation process are pH (6–8), nutrient concentrations, salinity, microbial population density (ideally should be between $10^4$ and $10^7$ CFU/g of soil), dissolved iron concentration, etc., which are the keys of the applicability of phytoremediation (Zhang et al. 2020).

## 7.4 Root Zone

The Root Zone is the most crucial area which is of special interest in phytoremediation. Root structure determines the applicability of plant species in contributing towards the environmental clean-up. Roots absorb contaminants and affect their mobility by locking the particulates in soil (Dhankher et al. 2002). Extensive root system helps the plants for the increased uptake of contaminants from the root zone which is also facilitated by the microbes inhabiting that area. Complexation and degradation of contaminants in the soil by plant enzymes exuded from the roots is another factor which supports the phytoremediation mechanism. A morphological adaptation in the root system, regardless of the plant used, is marked by an increase in root length and diameter for enhanced uptake and sequestration (Galal et al. 2018).

## 7.5 Nature of Contaminants

Metal uptake by plants depends on the bioavailability of the contaminants, solubility in the water phase, mobility, retention time, and interaction with root, soil particles, and other elements in vicinity. Furthermore, the contaminants remain bounded with the soil which is influenced by the soil characteristics like, pH, redox potential, and organic matter content (Novak and Trapp 2005).

## 7.6 Chelating Agent

The increased uptake of heavy metals by the plant roots is dependent on their availability which is achieved through the addition of biodegradable compounds called as chelating agents. These are chemical compounds that react with metal ions to form a stable and ring-like water-soluble complex known as chelators, or sequestering agents (Dhankher et al. 2002). They stimulate the heavy-metal-uptake capacity of the plant roots and define the microbial community in and around the rhizosphere. Exposing plants to the suitable chelating agent (e.g., EDTA) for a longer time could improve metal translocation in plant tissue as well as the overall plant performance. The process is also influenced with the presence of a ligand that affects the uptake mechanisms through the formation of metal–ligand complexes and changes the potential to leach metals below the root zone. Selection of chelating substances should be solely based on the properties like cost effectiveness and environmental friendly nature, and its ability to promote leaching of the contaminants into the soil.

## 7.7 Co-existed Pollutants

Soils co-contaminated by different levels of pollutants like organic and inorganic compounds, heavy metals, chlorinated mixtures, pesticides, aromatic hydrocarbons, etc., strongly effect the response of the plant species involved in remediation process (Huang et al. 2011; Feng et al. 2017). Extensively polluted ecosystems undeniably reduce the effectiveness of plants to deal with the contaminants. Further, the presence of one chemical could reduce the availability of other which may then be outstripped by the remediation method.

# 8 Applications of Phytoremediation Technique

## 8.1 Ground Water Remediation

Shallow and surface water may be treated well using the techniques of phytoremediation. One such mechanism is rhizofiltration, having vast application to be conducted in situ, with plants being grown directly in the contaminated water body. Rhizofiltration involves the pumping of contaminated water through root systems of appropriate plant species within the rhizosphere. It is facilitated through the efficient absorption of pollutants from the water into root tissues. The intensive root system of plants also assists in precipitation and concentration of the contaminants by releasing low-molecular-weight organic substances in the rhizosphere which accelerate the remediation process (Galal et al. 2018).

Phytotransportation is yet another remediation technique which can be accomplished under large-scale treatment strategy, specifically for ponds or wetlands. In this process, plants take up organic contaminants within the rhizosphere zone by their deep roots and degrade them to less toxic or non-toxic compounds. Roots are harvested, and treated to ensure constant operation results. Oxygen released during plant activity increases the rates of microbial activity and thus the rates of contaminant degradation.

## 8.2 Soil Remediation

This process involves the removal of contaminants and metals from soil, by direct uptake into plant tissue by the method of phytoextraction. The mechanism works in a satisfying way on the application of hyperaccumulators. These species show rapid growth rate, high biomass production, and can tolerate high concentrations of pollutants in harvestable tissue. The process can be boosted by using several plant species at the same time in a site, to remove more than one contaminant. After the remediation process, plant tissues are removed and carefully disposed of. The method of phytoextraction is being used for the treatment of sites contaminated with metals like arsenic and cadmium, radionuclides, hydrocarbons, etc.

Soil remediation also involves the use of certain plant species of high biomass to absorb, precipitate, and immobilize contaminants, reducing their bioavailability and mobility. This technique is called as phytostabilization which signifies the use of metal-tolerant plant species to be established in surface soils. It helps in restoring natural vegetation in the sites, by decreasing the potential migration of contaminants and limiting the transport of soil contamination to groundwater by locking the soil particles around rhizosphere. The contaminants are retained in the roots for a longer time period or are transferred along the upper plant parts as a strategic step towards soil remediation (Ye et al. 2017).

## 9 Technology Performance/Implementation

Use of phytoremediation is an emerging branch of science with unrestricted possibilities; however, it is currently limited to research activities with partial field testing. Different small-scale demonstrations have been tried and reported in lowering contaminant concentrations but full-scale applications are currently limited in number. Further, full-scale research proposals and remediation projects with regulatory approval are necessary to evaluate the applicability of the process (Salt et al. 1995). Optimization and standardization of the methodologies, applicability of the technology for specific pollutant, investigation of the pollutant chemistry, cost estimates, and determination of the regulations for field trials, are necessary to validate the remediation technique for in situ applications (Gerhardt et al. 2017). The general terms followed for the implementation of phytoremediation involve: (1) characterization of soil and water properties, nature of the contaminants, their concentrations and distribution, (2) determination and selection of appropriate plant species and elucidating the fate of contaminants in metabolic machinery of the cell, (3) understanding the environmental conditions and climatic parameters of the area to be treated, (4) illuminating the rates of remediation, treatment time, by-products produced, and density of the plantation after field testing, (5) consideration and monitoring the results obtained for the proper disposition of affected plant material for the future refine design parameters, and (6) estimation of the capital costs of phytoremediation per acre for planting, testing, maintenance, monitoring, verification, waste disposal and loss.

## 10 Genetic Engineering Based Improvements for Phytoremediation

The conventional method of phytoremediation has proved to significantly reduce contamination with limited environmental disturbances. However, the process is largely affected due to diverse reasons; one such is the viability of plants in the presence of extreme toxic compounds. This limits the feasibility of using remediation methods for extended time period and becomes restricted only to plant species which can withstand toxicity. Moreover, the tendency to absorb and withdraw pollutants by the plants from soil and water also possesses high risk of bioaccumulation and its successive transfer to different tropic levels of the food chain. These limitations had contributed towards extended research effort in developing new varieties of plant species using genetic engineering, capable of tolerating high levels of pollutants with its limited transportation to the edible parts (Abhilash et al. 2009; Chen et al. 2017b). Many of the naturally occurring plant species, viz. *Brassica juncea* and *Helianthus annuus* have been genetically engineered to develop transgenic plants for use in phytoremediation process (Raj et al. 2020).

Genetic engineering approach is to enhance and improve the ability of plants to uptake and sequester pollutants from their immediate environment for better phytoremediation results (Van Aken 2008). However, majority of genes have been transferred from other organisms in the progression of the process (James et al. 2008; Ali et al. 2012). Improvement in this approach will have an important role to play in commercial phytoremediation within next few years by adopting several conceivable approaches which have been summarized below:

1. Over expression of metallothionins and phytochelators.
2. Introduction and/or alteration in genes encoding transport proteins for the enhanced metal transport into roots.
3. Engineering of metabolic pathways by introducing genes encoding key biodegradation enzymes.
4. Introduction of genes encoding efficient metal chelators.
5. Genetic manipulation for the enhancement of root growth, branching, depth, biomass, and penetration.
6. Introduction of genes for the stimulation of rhizosphere microflora.

## 10.1 Metallothioneins, Phytochelatins, and Metal Chelators

Metallothioneins (MTs) are a family of cysteine-rich metal-binding proteins which are highly conserved in nature (Cobbett and Goldsbrough 2002). They help the plants to provide protection against oxidative stress and toxic heavy metals. Successful expression of metallothionein genes might support increased metal tolerance and accumulation in plants. Further, the genetic engineering process can be used to transform any suitable plant species to perform remediation. Tobacco and *Brassica* plants have been transformed for the constitutive uptake and Cd tolerance.

Phytochelatins are oligomers of glutathione, produced by the enzyme phytochelatin synthase. They are found in plants, and act as chelators for heavy metal detoxification. Over expression of this gene enhances metal tolerance in plants (Dhankher et al. 2002). Transgenic Indian mustard and cauliflower were developed by overexpression of glutathione synthase for the enhanced Cd tolerance and accumulation. Similarly, overproduction of iron chelator in rice has resulted in enhanced Al tolerance compared to control plants.

## 10.2 Metal Transporters

Many plant genes are involved to encode proteins involved in metal uptake, translocation, and sequestration (Sarwar et al. 2017; Wang et al. 2018). Transfer of these genes into candidate plants or genetic manipulation of metal transporters may result in many fold increase in metal accumulation (LeBlanc et al. 2013). Study of Zn transporter gene from *Thlaspi* to other plant species has been reported to result in two-fold higher Zn accumulation in roots of the transgenic plant. Transgenic *Pteris vittata* has been developed after heterologous expression of arsenite antiporter PvACR3 which reduces arsenic accumulation and transfer in plant shoots (Chen et al. 2017b).

## 10.3 Engineering of Metabolic Pathways

Plants exhibits diverse metabolic pathways for the breakdown of vast variety of compounds. Alteration in the genetic make-up of the genes and enzymes involved at different steps of metabolism can lead to the development of transgenic plants with novel pathways for increased resistance towards diverse types of pollutants (Dhankher et al. 2002; Abhilash et al. 2009). Researchers have reported that the modification in case of specific genes or introduction of new genes into plants resulted in increased uptake and tolerance to heavy metals (Hg, As) (Meagher and Heaton 2005), hydrocarbons, chlorinated compounds, and complex cyclic compounds.

## 10.4 Modification in Roots

Plants have extensive root system which ensures an effective uptake and absorption of the pollutants from their surroundings, especially soil. The large surface area provided by the roots make an efficient platform for the uptake of toxicants. Modifications involving increased branched root system and increase root biomass with large surface area are possible by inducing hairy roots in candidate plants through *Agrobacterium rhizogenes* infection (Ibañez et al. 2016). Transgenic plants developed by this method were shown to have high efficiency for rhizofiltration of radionuclides, pesticides, and heavy metals.

## 10.5 Enhanced Biomass Production

Understanding the biosynthetic pathways for phytohormone synthesis and over production of genes encoding hormones in plant species of interest is becoming an interesting tool which can be effectively employed in biomass production. Such plant species would show extensive growth and could promote higher levels of absorption of contaminants for the remediation of contaminated environment (Van Aken 2008; Wang et al. 2018). Enhanced production of gibberellin in transgenic plants has been shown to promote growth and biomass production for several cycles of decontamination.

## 11 Advantages and Limitations

Phytoremediation has proved to be the efficient mechanism for the management of varieties of contaminants and the technology is largely adopted in the current scenario for in situ and ex situ treatments. Although the process presents phenomenal improvement of the contaminated ecosystems, it does have some drawbacks associated with its use. Some of the merits and demerits of the method are described here:

## 11.1 Advantages

- The method is applicable to a broad range of contaminants and the remediation goals can be achieved without using toxic chemicals.
- The technology offers environmental friendly and cost-effective way of treating pollutants even at large scale.
- The process can be performed with minimal environmental disturbances with the possibility of no or less generation of secondary air, particulates, and water wastes.
- It limits the transfer of pollutants, thereby reduce environmental toxicity.
- Although surface soil and topsoil are moderately disturbed, it is not required to be isolated or disposed and may be reclaimed for agricultural use.
- Reduces volume of contaminated material to be landfilled or incinerated.
- Plant uptake of contaminants prevents off-site migration.
- The clean-up process reduces the risk of exposure by limiting direct contact with contaminated soils.

## 11.2 Limitations and Concern

- Phytoremediation requires a large surface area of land for remediation.
- The time period required for the remediation to get completed is relatively long.
- Treatment is generally limited to shallow soils at less than 3 ft from the surface and water streams within 10 ft of the surface.
- It is a surface phenomenon and does not find application for the treatment of ground water sources.
- The process is completely dependent upon the climatic or hydrologic conditions which may restrict the rate of remediation.
- Appropriate working conditions like optimum pH, temperature, water concentration, metal solubility, presence of chelators, etc., are required for the smooth conduct of the process.
- Plants involved in remediation might transfer the chemicals to the food chain through animals/insects that eat plant material containing contaminants.
- Disposal of harvested plants carrying contaminants can be a problem.
- Degraded by-products may be mobilized in groundwater or bio-accumulated in other living species.
- If contaminant concentrations are too high, plants may die.
- Phytoremediation is not effective for strongly sorbed contaminants such as polychlorinated biphenyls (PCBs).

The use of phytoremediation is limited to shallow soils, streams, and groundwater with lower contaminant concentrations. Additional research is needed to find the ways of using trees rather than smaller plants to treat deeper contamination zone because tree roots penetrate more deeply into the ground. Scientists need to establish the fate of various pollutants in the plant metabolic cycle to ensure that the treatment process does not contribute to the release of toxic or harmful chemicals/products into the food chain.

## 12 Conclusions and Future Prospects

Phytoremediation is a solar energy driven natural phenomenon which harnesses inherent plant processes to clean up the pollutants in the environment. Further, it is a low cost, and eco-friendly technique, which can be applied for the treatment of a wide variety of contaminants and to detoxify various compounds. It is easy to implement and maintain, decreases soil disturbance, reduces the amount of generated waste and the possibility of spreading of contaminants. The technology has been increasingly investigated and employed both for the in situ and ex situ treatments. Sites contaminated with heavy metals, explosives, poly-hydrocarbons, pesticides, solvents, oil, etc., can be effectively remediated. Though the technology has wide applications, it requires a long-term commitment and not all plant species can be used for the process. Intensive research is required to develop new plant varieties to grow and thrive in contaminated ecosystem for the careful remediation of broad spectrum of pollutants.

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