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# Technologies and Biological Processes in Phytoremediation

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## ABSTRACT

The use of plants and their associated microbes for environmental cleanup has gained acceptance in the past 10 years as a cost-effective, noninvasive alternative or complementary technology for engineering-based remediation methods. Plants can be used for pollutant stabilization, extraction, degradation, or volatilization. These different phytoremediation technologies and their applicability for various organic and inorganic pollutants and most suitable plant species are reviewed. To enhance the efficiency of phytoremediation, there is a need for better knowledge of the processes that affect pollutant availability, rhizosphere processes, pollutant uptake, translocation, chelation, degradation, and volatilization are essential. Plants and their associated microbes can remediate pollutants via stabilization, degradation in the rhizosphere, degradation in the plant, accumulation in harvestable tissues or volatilization. Although phytoremediation works effectively for a wide range of organic and inorganic pollutants, the underlying biological processes are still largely unknown in many cases. Some important processes that require further study are plant-microbe interactions, plant degradation mechanisms for organics, plant transport and chelation mechanisms for inorganics. Introduction of plants obtained from research is being implemented for phytoremediation in the field. The first field tests with transgenic plants are showing promising results. The effectiveness of phytoremediation reduces cleanup costs and enables the cleanup of more sites. The present review focuses each of these processes for inorganic and organic pollutants and the practical implications for designing phytoremediation strategies.

**Key words:** Pollutant availability, rhizosphere processes, pollutant uptake, translocation, chelation, degradation and volatilization

## INTRODUCTION

Phytoremediation makes use of the naturally occurring processes by which plants and their microbial rhizosphere flora degrade and sequester organic and inorganic pollutants. Phytoremediation is an efficient cleanup technology for a variety of organic and inorganic pollutants. Organic pollutants in the environment are mostly man made and they may be toxic xenobiotic or carcinogenic to organisms. They are Organic pollutants released into the environment via spills [fuel, solvents], military activities [explosives, chemical weapons], agriculture [pesticides, herbicides], industry [chemical, petrochemical], wood treatment, etc. Depending on their properties, organics may be degraded in the root zone of plants or taken up which is followed by degradation, sequestration or volatilization. Inorganics cannot be degraded, but they can be phytoremediated via stabilization or sequestration in harvestable plant tissues. Inorganic pollutants that include plant macronutrients such as nitrate and phosphate [1], plant trace elements such as Cr, Cu, Fe, Mn, Mo, and Zn, nonessential elements such as Cd, Co, F, Hg, Se, Pb, V, and W [2] and radioactive isotopes such as 238U, 137Cs, and 90Sr can be phytoremediated [3].

The *insitu* phytoremediation contributes cost-effectiveness and may reduce exposure of the polluted substrate to humans, wildlife and the environment. Phytoremediation also enjoys popularity with the general public as a “green clean” alternative to chemical plants and bulldozers. The toxic soils may be made more amenable to plant growth by adding amendments. Phytoremediation is also limited by root depth because the plants have to be able to reach the pollutant. Depending on the biological processes involved, phytoremediation may also be slower than the more established remediation methods like excavation, incineration or pump and treat systems. Flow through phytoremediation systems and plant degradation of pollutants work fairly fast [days or months], but the soil cleanup via plant accumulation often takes years by limiting applicability. Phytoremediation may also be limited by the bioavailability of the pollutants. Pollutant bioavailability may be enhanced to some extent by adding soil amendments and by the combination of different technologies.

## PHYTOREMEDIATION TECHNOLOGIES AND THEIR USES

Trees can be used as a hydraulic barrier to create an upward water flow in the root zone which leads to the prevention of contamination to leach down, or to prevent a contaminated groundwater plume from spreading horizontally [4]. The term phytostabilization denotes the use of plants to stabilize pollutants in soil [5], either simply by preventing erosion, leaching or runoff or by converting pollutants to less bioavailable forms [e.g., via precipitation in the rhizosphere]. Plants can also be used to extract pollutants and accumulate them in their tissues followed by harvesting plant material. This technology is called phytoextraction [2]. The plant material can subsequently be used for non edible purposes [e.g., wood, cardboard] or ashed, followed by disposal in a landfill or in the case of valuable metals, recycling of the accumulated element. The latter is termed phytomining [6]. Plants can facilitate biodegradation of organic pollutants by microbes in their rhizosphere. This is called phytostimulation or rhizodegradation [7]. Plants can also degrade organic pollutants directly via their own enzymatic activities by a process called phytodegradation [8]. After uptake in plant tissue, certain pollutants can leave the plant in volatile form; this is called phytovolatilization [9]. In a constructed wetland accumulation, stabilization and volatilization can occur simultaneously [10]. Rhizofiltration is an indoor setup which is relatively expensive to implement and useful for small volumes of wastewater containing hazardous inorganics like radionuclides [11]. Trees can also be used as buffer strips to intercept horizontal migration of polluted ground water plumes and redirect water flow upward [12]. Natural attenuation is suitable for remote areas with little human use with low levels of contamination. Phytoextraction is mainly used for metals and other toxic inorganics [Se, As, radionuclides] [2]. Phytostimulation is used for hydrophobic organics that can be degraded by microbes. Examples are PCBs, PAHs, and other petroleum hydrocarbons [13]. Phytodegradation works well for organics that are mobile in plants such as herbicides, TNT, MTBE, and TCE [14]. Phytovolatilization can be used for VOCs [15] such as TCE and MTBE, and for a few inorganics that can exist in volatile form, i.e., Se and Hg [16].

Favorable plant properties for phytoremediation in general are to be fast growing, high biomass, competitive, hardy and tolerant to pollution. In addition, high levels of plant uptake, translocation, and accumulation in harvestable tissues are important properties for phytoextraction of inorganics. A large root surface area also favors phytostimulation, as it promotes microbial growth; production of specific exudate compounds may further promote rhizodegradation via specific plant-microbe interactions [17]. A variety of emergent, submerged and floating aquatic species are used in constructed wetlands for phytoremediation. Popular genera/species are cattail [*Typha* sp.], parrot feather [*Myriophyllum* sp.], *Elodea* sp., *Azolla* sp., duckweed [*Lemna* sp.], water hyacinth [*Eichhornia crassipes*], *Spartina* sp. Poplar [*Populus* sp.] and willow [*Salix* sp.] can be used on the edges of wetlands. For brackish water, certain species of *Spartina*, pickleweed [*Salicornia* sp.] and saltgrass [*Distichlis spicata*] [3]. For inorganics, the floating species water hyacinth, Azolla, and duckweed are popular because they are good metal accumulators and can be harvested easily; cattail and poplar are also used because they are tolerant, grow fast and attain a high biomass. Aquatic plants that work well for organics remediation include parrot feather and Elodea [12] because they have high levels of organics degrading enzymes. Rhizofiltration involves aeration and therefore is not limited to aquatic species; it often makes use of terrestrial species with large roots and good capacity to accumulate inorganics, such as sun-flower [*Helianthus annuus*] or Indian mustard [*Brassica juncea*] [1]. Fast-transpiring trees such as poplar maintain an upward flow to prevent downward leaching, while grasses prevent wind erosion and lateral runoff with their dense root systems. Grasses tend to not accumulate inorganic pollutants in their shoots as much as dicot species [18] which minimizes the exposure of toxic elements to wildlife. Poplar trees are very efficient at intercepting horizontal groundwater plumes and redirecting water flow upward because they are deep rooted and transpire at very high rates, creating a powerful upward flow [19].

Popular species for phytoextraction are Indian mustard and sunflower because of their fast growth, high biomass, high tolerance and accumulation of metals and other inorganics [2]. A special category of plants are the hyperaccumulators: plant species that accumulate one or more inorganic elements to levels 100-fold higher than other species grown under the same conditions [20]. Hyperaccumulators have been reported for As, Co, Cu, Mn, Ni, Pb, Se, and Zn [21]. These elements are typically hyperaccumulated up to 0.1–1% of dry weight even from low external concentrations. Hyperaccumulators are often slow growing and attain low biomass. So far only one hyperaccumulator species, the Ni hyperaccumulator *Alyssum bertolonii*, has been used for phytoremediation in the field [6]. The recently discovered As hyperaccumulating fern *Pteris vittata* may also show promise for phytoextraction of As [19]. For phytostimulation of microbial degraders in the root zone, grasses such as fescue [*Festuca* sp.], ryegrass [*Lolium* sp.], *Panicum* sp., and prairie grasses [e.g., *Buchloe dactyloides*, *Bouteloua* sp.] are popular because they have very dense and relatively deep root systems and thus a large root surface area [22]. Mulberry trees also have popularity for use in phytostimulation because of their reported ability to produce phenolic compounds that stimulate expression of microbial genes involved in PCB and PAH degradation [16]. Poplar has been the most popular and efficient species for phytodegradation of TCE and atrazine, owing to its high transpiration rate and capacity to degrade and volatilize these pollutants [7]. Poplar is also the most-used species for phytovolatilization of VOCs because of its high transpiration rate, which facilitates the movement of these compounds through the plant into the atmosphere. In general, plant species that take up and volatilize sulfur compounds also accumulate and volatilize Se well because S and Se are chemically similar and their metabolism occurs via the same pathways [23]. Members of the *Brassica* genus are particularly good volatilizers of Se [24]. Among the aquatic species tested, rice, rabbitfoot grass, Azolla, and pickleweed are the best Se volatilizers [10]. Finally, when choosing plant species for a certain site, it is advisable to include species that grow locally on or near the site. These species are competitive under the local conditions and can tolerate the pollutant.

## BIOLOGICAL PROCESSES AFFECTING PHYTOREMEDIATION

Phytoremediation technologies include plant-microbe interactions and other rhizosphere processes, plant uptake, translocation mechanisms, tolerance mechanisms [compartmentation, degradation] and plant chelators involved in storage and transport. Other processes that need more study are movement of pollutants through ecosystems via the soil-water-plant system to higher trophic levels.

### 1. Pollutant bioavailability

Pollutant bioavailability depends on the chemical properties of the pollutant, soil properties, environmental conditions and biological activity. Soils with small particle size [clay] hold more water than sandy soils and have more binding sites for ions, especially cations [CEC] [25]. The concentration of organic matter [humus] in the soil is also positively correlated with CEC, as well as with the capacity to bind hydrophobic organic pollutants. This is because humus mainly consists of dead plant material and plant cell walls have negatively charged groups that bind cations, as well as lignin that binds hydrophobic compounds [14]. Inorganics are usually present as charged cations or anions and thus are hydrophilic. The bioavailability of cations is inversely correlated with soil CEC. At lower soil pH, the bioavailability of cations generally increases due to replacement of cations on soil CEC sites by H+ ions [25]. The bioavailability of ions is also affected by the redox conditions. Most terrestrial soils have oxidizing conditions, and elements that can exist in different oxidation states will be in their most oxidized form [e.g., as selenate, arsenate, Cr [VI], Fe3+]. In aquatic habitats more reducing conditions exist, which favor more reduced elemental forms [e.g., selenite, arsenite, Cr [III], Fe2+]. The oxidation state of an element may affect its bioavailability [e.g., its solubility] its ability to be taken up by plants, as well as its toxicity. Other physical conditions that affect pollutant migration and bioavailability are temperature and moisture. Higher temperatures accelerate physical, chemical and biological processes. Precipitation will stimulate general plant growth and higher soil moisture will increase migration of water soluble pollutants. Bioavailability of pollutant tends to decrease in concentration over time due to physical, chemical and biological processes. Consequently, pollutants in aged polluted soils tend to be less bioavailable and more recalcitrant than pollutants in soil that is newly contaminated, making aged soils more difficult to phytoremediate [16]. Understanding the processes affecting pollutant bioavailability can help optimize phytoremediation efficiency. Amendments may be added to soil that make metal cations more bioavailable for plant uptake. For instance, adding the natural organic acids citrate or malate will lower the pH and chelate metals such as Cd, Pb, and U from soil particles, usually making them more available for plant uptake. The synthetic metal chelator EDTA is also extremely efficient at releasing metals from soil. This principle is used in chelate-assisted phytoextraction where EDTA is added to soil shortly before plant harvesting which greatly increases plant metal uptake [26]. Before chelate-assisted phytoextraction is used, it is important to do a risk assessment study to determine possible effects of the chelator on metal leaching. In other situations it may be desirable to decrease metal bioavailability if metals are present at phytotoxic levels or in phytostabilization. In such cases lime may be mixed in with the soil to increase the pH or organic matter to bind metals. Adding organic matter also decreases the bioavailability of hydrophobic organics, whereas adding surfactants [soap] may increase their bioavailability. Manipulation of soil pH can also affect their solubility and ability to move into plants. Finally, water supply may be optimized to facilitate pollutant migration while preventing leaching or runoff [4, 18].

### 2. Rhizosphere processes and remediation

Rhizosphere remediation occurs completely without plant uptake of the pollutant in the area around the root. The rhizosphere extends approximately 1 mm around the root and is under the influence of the plant. Plants release a variety of photosynthesis-derived organic compounds in the rhizosphere that can serve as carbon sources for heterotrophic fungi and bacteria [25]. As much as 20% of carbon fixed by a plant may be released from its roots [5]. As a result, microbial densities are 1–4 orders of magnitude higher in rhizosphere soil than in bulk soil [27]. In turn, rhizosphere microbes can promote plant health by stimulating root growth [some microorganisms produce plant growth regulators], enhancing water and mineral uptake, and inhibiting growth of other, NO pathogenic soil microbes [28]. Rhizosphere remediation may be a passive process. Pollutants can be phytostabilized simply via erosion prevention and hydraulic control. There is also passive adsorption of organic pollutants and inorganic cations to the plant surface. Adsorption of lipophilic organics to lignin groups in the cell wall is called lignification [23]. Rhizosphere remediation may also be the result of active processes mediated by plants and microbes. These processes may affect pollutant bioavailability, uptake or degradation. Pollutant bioavailability may be affected by various plant and/or microbial activities. Some bacteria are known to release biosurfactants [e.g., rhamnolipids] that make hydrophobic pollutants more water soluble [18]. Plant exudates or lysates may also contain lipophilic compounds that increase pollutant water solubility or promote biosurfactant-producing microbial populations [5].

Bioavailability of metals may be enhanced by metal chelators that are released by plants and bacteria. Chelators such as siderophores, organic acids and phenolics can release metal cations from soil particles. This usually makes the metals more available for plant uptake [29] although in some cases it can prevent uptake [15]. Some plant roots release oxygen, such as aquatic plants that have aerenchyma [air channels in the stem that allow oxygen to diffuse to the root]; this can lead to the oxidation of metals to insoluble forms [e.g., FeO3] that precipitate on the root surface [30]. Conversely, enzymes on the root surface may reduce inorganic pollutants, which may affect their bioavailability and toxicity [e.g., CrVI to CrIII] [21]. Organic pollutants may be degraded in the rhizosphere by root-released plant enzymes or via phytostimulation of microbial degradation. Examples of organics that are degraded in the rhizosphere by microbial activity include PAHs, PCBs, and petroleum hydrocarbons [31]. First, plant carbon compounds released into the rhizosphere facilitate a higher microbial density—the general rhizosphere effect. Second, secondary plant compounds released from roots may specifically induce microbial genes involved in degradation of the organic compound, or act as a co-metabolite to facilitate microbial degradation [16]. Better knowledge of these plant-microbe interactions is needed to more efficiently design phytoremediation strategies. Rhizosphere processes that favor phytoremedation may be optimized by the choice of plant species, e.g., plants with large and dense root systems for phytostimulation or aquatic plants for metal precipitation. In one approach over expression of citrate synthase in plants conferred enhanced aluminum tolerance, probably via enhanced citrate release into the rhizosphere, which prevented Al uptake due to complexation [15]. In another approach to stimulate rhizosphere remediation, certain agronomic treatments may be employed that favor the production of general and specific exudate compounds, such as clipping or fertilization [23]. Inorganic fertilizer is preferred over organic fertilizer [manure] in phytostimulation because the latter provides an easy-to-digest carbon source that microbes may prefer to use instead of the organic pollutant.

An alternative approach to grow these microbial isolates in large amounts and add them to the soil by a process called bioaugmentation. Introducing non native microbes to sites is considered ineffective because they are not competed by the established microbial populations. In another approach to optimize rhizosphere remediation, the watering regime may be regulated to provide optimal soil moisture for plant and microbial growth. If redox reactions are involved in the remediation process, periodic flooding and draining of constructed wetlands may be effective for reducing and oxidizing conditions [23].

## 3. Uptake by Plants

Uptake of pollutants by plant roots is different for organics and inorganics. Organic pollutants are usually man made and xenobiotic to the plant. As a consequence, there are no transporters for these compounds in plant membranes. Organic pollutants therefore tend to move into and within plant tissues driven by simple diffusion, dependent on their chemical properties. An important property of the organic pollutant for plant uptake is its hydrophobicity [24].The tendency of organic pollutants to move into plant roots from an external solution is expressed as the root concentration factor [RCF = equilibrium concentration in roots/equilibrium concentratrion in external solution]. In contrast, inorganics are taken up by biological processes via membrane transporter proteins. These transporters occur naturally because inorganic pollutants are either nutrients [e.g., nitrate, phosphate, copper, manganese, zinc] or chemically similar to nutrients and are taken up inadvertently [e.g., arsenate is taken up by phosphate transporters, selenate by sulfate transporters] [32]. Inorganics usually exist as ions and cannot pass membranes without the aid of membrane transporter proteins. Because uptake of inorganics depends on a discrete number of membrane proteins, their uptake is saturable, following Michaelis Menten kinetics [27]. For most elements multiple transporters exist in plants. The model plant *Arabidopsis thaliana*, for instance, has 150 different cation transporters [30] and 14 transporters for sulfate alone [33]. Individual transporter proteins have unique properties with respect to transport rate, substrate affinity and substrate specificity [27]. These properties may be subject to regulation by metabolite levels or regulatory proteins [e.g., kinases]. Furthermore, the abundance of each transporter varies with tissue type and environmental conditions which may be regulated at the transcription level or via endocytosis. When inorganic pollutants accumulate in tissues they often cause toxicity, both directly by damaging cell structure [e.g., by causing oxidative stress due to their redox activity] and indirectly via replacement of other essential nutrients [29]. Organics tend to be less toxic to plants, partly because they are not accumulated as readily and tend to be less reactive.

Phytoremediation of mixed pollutants [organics and inorganics] is an understudied area, but very relevant because many sites contain mixed pollution. When soils are polluted with a mixture of organics and metals the inorganics are most likely to limit plant growth and phytoremediation. The presence of rhizosphere microbes can affect plant uptake of inorganics. For instance, mycorrhizal fungi can both enhance uptake of essential metals when metal levels are low and decrease plant metal uptake when metals are present at phytotoxic levels [34]. Also, rhizosphere bacteria can enhance plant uptake of mercury and selenium [35]. The mechanisms of these plant-microbe interactions are still largely unclear; microbe-mediated enhanced plant uptake may be due to a stimulatory effect on root growth, microbial production of metabolites that affect plant gene expression of transporter proteins, or microbial effects on bioavailability of the element [36]. Screening studies under uniform conditions are a useful strategy to compare uptake characteristics of different species for different pollutants. Agronomic practices may also be employed to maximize pollutant uptake. Plant species may be selected for suitable rooting depth and root morphology [9]. Furthermore, plant roots can be guided to grow into the polluted zone via deep planting in a casing, forcing the roots to grow downward into the polluted soil and to tap into polluted water rather than rainwater [37]. Supplemental water [via irrigation] and oxygen [via air tube to roots] may also facilitate pollutant uptake, and soil nutrient levels may be optimized by fertilization.

Not only nutrients, uptake of the pollutant may also affect plant uptake of pollutants via ion competition at the soil and plant level. For instance, phosphate supply will release arsenate from soils, making it more bioavailable; on the other hand, phosphate will compete with arsenate for uptake by plants because both are taken up by phosphate transporters [32]. It may also be possible to manipulate plant accumulation by genetic engineering. A transgenic approach that may be used to alter uptake of inorganic pollutants is overexpression or knockdown of membrane transporter proteins. This approach was used successfully to enhance accumulation of Ca, Cd, Mn, Pb, and Zn [28]. The specificity of membrane transporters for different inorganics may also be manipulated via protein engineering [23].

Furthermore, altering plant production of chelator molecules can affect plant metal accumulation [38]. Hyperaccumulator species offer potentially interesting genetic material to be transferred to high-biomass species. Constitutive expression of a Zn transporter in the root cell membrane is one of the underlying mechanisms of the natural Zn hyperaccumulat or *Thlaspi caerulescens* [22].

## 4. Chelation and compartmentation in roots

Plants can release compounds from their roots that affect pollutant solubility and uptake by the plant. Inside plant tissues such chelator compounds also play a role in tolerance, sequestration and transport of inorganics and organics [39]. Phytosiderophores are chelators that facilitate uptake of Fe and perhaps other metals in grasses; they are biosynthesized from nicotianamine which is composed of three methionines coupled via nonpeptide bonds [40]. Nicotianamine also chelates metals and may facilitate their transport [2]. Organic acids [e.g., citrate, malate, histidine] not only can facilitate uptake of metals into roots but also play a role in transport, sequestration and tolerance of metals [31] Chelated metals in roots may be stored in the vacuole or exported to the shoot via the xylem. Chelation in roots can affect phytoremediation efficiency as it may facilitate root sequestration, translocation and tolerance. Root sequestration may be desirable for phytostabilization [less exposure to wildlife] whereas export to xylem is desirable for phytoextraction. If chelation is desirable, it may be enhanced by selection or engineering of plants with higher levels of the chelator. Root sequestration and export to xylem might be manipulated by overexpression or knockdown of the respective membrane transporters involved. [24].

## 5. Chelation and compartmentation in leaves

Organics enter the leaf symplast from the shoot xylem by simple diffusion, the rate of which depends on the chemical properties of the pollutant. Once inside the leaf symplast, the pollutant may be compartmented in certain tissues or cellular locations. In general, toxic pollutants are sequestered in places where they do the least harm to essential cellular processes. At the cellular level, pollutants are generally accumulated in the vacuole or cell wall [41]. At the tissue level they may be accumulated in the epidermis and trichomes [42]. When pollutants are sequestered in tissues, they are often bound by chelators or form conjugates. Organic acids such as malate and citrate are also likely metal [e.g., Zn] chelators in vacuoles, as judged from XAS [28]. Ferritin is an iron chelator in chloroplasts [18]. Additional metal-chelating proteins exist [e.g., MTs] that may play a role in sequestration and tolerance [e.g., of Cu] or in homeostasis of essential metals [43]. There is still much to be discovered about the roles of these different chelators in transport and detoxification of inorganic pollutants.

The glutathione S-conjugates are actively transported to the vacuole or the apoplast by ATP-dependent membrane pumps [44]. An alternative conjugation-sequestration mechanism for organics in plants involves coupling glucose or a malonyl-group to the organic compound, followed by transport of the conjugate to the vacuole or the apoplast [45]. These conjugation steps are mediated by a family of glucosyl transferases and malonyl transferases and the transport steps by ATP dependent pumps [14].To be conjugated, the organic compound may need chemical modification to create suitable side groups for conjugation. These modification reactions can be oxidative or reductive. For example, cytochrome P450 mono oxygenases catalyze an oxidative transformation, incorporating an O atom from oxygen into an organic molecule such as atrazine to create a hydroxyl side group [45]. Nitroreductases are an example of enzymes that mediate a reductive transformation, converting a nitro group of TNT into an amino group [8]. Other enzymes that mediate modifications of organic pollutants include dioxygenases, peroxidases, peroxygenases and carboxylesterases [39]. Thus accumulation of organic pollutants typically comprises three phases: chemical modification, conjugation and sequestration. This sequence of events has been summarized as the “green liver model” because of its similarity to mammalian detoxification mechanisms [29]. Some natural functions of the enzymes and transporters involved are to biosynthesize and transport natural plant compounds such as flavonoids, alkaloids and plant hormones [43].Potentially toxic pollutants are accumulated in plant tissues. The degree of toxicity will depend on leaf concentration and the nature of pollutant which is accumulated. During accumulation the toxicity of the pollutant may change. To test the potential toxicity of the plant material, a laboratory digestibility study may be done using model organisms or in vitro simulations of animal digestion systems. The field exposure to wildlife may be minimized by fencing, netting, noise, and scarecrows.

## 6. Translocation

Translocation from root to shoot requires a membrane transport step from root symplast into xylem apoplast. Organic pollutants pass the membrane between root symplast and xylem apoplast via simple diffusion. Entry of organic pollutants into the xylem depends on similar passive movement over membranes as their uptake into the plant. Inorganics require membrane transporter proteins to be exported from the root endodermis into the root xylem. Better knowledge of the transporters and chelators involved in translocation of inorganics would facilitate the development of transgenics with more efficient phytoextraction capacity. Bulk flow in the xylem from root to shoot is driven by transpiration from the shoot which creates a negative pressure in the xylem that pulls up water and solutes [21]. Plant transpiration depends on plant properties and environmental conditions. Due to metabolic differences [e.g., C3/C4/CAM photosynthetic pathway] and anatomical differences [e.g., surface to volume ratio, stomatal density, rooting depth] plant species differ in transpiration rate [29]. Species such as poplar are phreatophytes or water spenders; they have long roots that tap into the ground water [19]. Mature poplar trees can transpire 200–1000 liters of water per day [39]. Transpiration is generally maximal at high temperature, moderate wind, low relative air humidity and high light [21]. Consequently, phytoremediation mechanisms that rely on translocation and volatilization are most effective in climates with low relative humidity and high evapotranspiration.

## 7. Degradation

Only organic pollutants can be phytoremediated via degradation. Inorganic elements are undegradable and can only be stabilized or moved and stored. In phytodegradation plant enzymes act on organic pollutants and catabolize them, either mineralizing to inorganic compounds [e.g., carbon dioxide, water and Cl2] or degrading them partially to a stable intermediate that is stored in the plant [20]. This enzymatic degradation of organics can happen in both root and shoot tissue. Degradation within plant tissues is generally attributed to the plant, but may in some cases involve endophytic microorganisms [39]. Phytodegradation involves some of the same classes of enzymes responsible for accumulation in tissues. The modifying enzymes that create side groups on organics that increase solubility and enable conjugation also play a role in the initial steps of phytodegradation. Thus, enzyme classes involved in phytodegradation include dehalogenases, mono and dioxygenases, peroxidases, peroxygenases, carboxylesterases, laccases, nitrilases, phosphatases, and nitroreductases [20]. These degradation products of pollutants that accumulate in vacuoles or apoplast of plant tissues are called bound residues [14]. Atrazine and TNT are examples of organic pollutants that are partially degraded followed by storage of the degradation products as bound residues [7, 46]. Phytodegradation of organic pollutants may be optimized by selecting or engineering plant species with higher activities of the enzymes thought to be involved and is rate-limiting. There are some examples of promising transgenic approaches. The expression in plants of bacterial enzymes involved in reductive transformation of TNT [tetra nitrate reductase or nitroreductase] resulted in enhanced plant tolerance and degradation of TNT [26, 47]. Also, the constitutive expression of a mammalian cytochrome P450 in tobacco resulted in 640-fold higher ability to metabolize TCE [13].

## 8. Volatilization

Phytovolatilization is the release of pollutants from the plant to the atmosphere as a gas. Inorganic Se can be volatilized by plants and microorganisms. Volatilization of Se involves assimilation of inorganic Se into the organic selenoaminoacids selenocysteine [SeCys] and selenomethionine [SeMet]. The latter can be methylated to form dimethylselenide [DMSe] which is volatile [48]. Volatilization of the inorganics As and Hg has been demonstrated for microorganisms, but these elements do not appear to be volatilized to significant levels by [nontransgenic] plants [16].Volatilization completely removes the pollutant from the site as a gas, without plant harvesting and disposal. In the case of Se, the volatile form was also reported to be 2–3 orders of magnitude less toxic than the inorganic Se forms [48]. Volatilization may be promoted in several ways. Although volatilization of VOCs is passive, the process may be maximized by using phreatophyte species with high transpiration rates and by promoting transpiration [preventing stomatal closure through sufficient irrigation]. For Se, enzymes of the S assimilation pathway mediate Se volatilization and overexpression of one of the cystathionine-$\gamma$ -synthase promotes Se volatilization [12]. Volatilization of mercury by plants was achieved by introducing a bacterial mercury reductase [MerA]. The resulting plants volatilized elemental mercury and were significantly more Hg tolerant [16]. If a toxic volatile pollutant is emitted by plants during phytoremediation, the fate of the gas in the atmosphere should be determined as part of risk assessment. Such a study was done for volatile Se and Hg, and the pollutant was reportedly dispersed and diluted to such an extent that it did not pose a threat [16].

## CONCLUSION

Phytoremediation is the use of a plant's natural ability to degrade or remove toxic chemicals and pollutants from soil or water. It can be used to clean up metals, pesticides, solvents, explosives, crude oil, and contaminants that may leak from landfill sites [called leachates]. The term phytoremediation is a combination of two words – phyto, which means plant, and remediation, which means to remedy.

Scientists are investigating phytoremediation's potential by using plants such as sunflower, ragweed, cabbage and geranium, as well as other less known species. The plants are often used in combination with other traditional technologies for cleaning up contaminated sites. In order for a technology to be sustainable, it should be economically viable and environmentally compatible.

Phytoremediation uses the existing capabilities of plants and the systems they support to clean up soil and water. It is more cost-effective than traditional remediation methods for contaminated soil, which involve digging up the entire contaminated area and taking it away to another location for chemical treatment, incineration or burial. Phytoremediation takes less labour and does not disturb the natural surroundings of the contamination site. Although phytoremediation takes time, it is a good way to make use of naturally existing resources.

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