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Review

Phytoremediation Prospects for Restoration of Contamination in the Natural Ecosystems

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Abstract: Toxic substances have a deleterious effect on biological systems if accrued in ecosystems beyond their acceptable limit. A natural ecosystem can become contaminated due to the excessive release of toxic substances by various anthropogenic and natural activities, which necessitates rehabilitation of the environmental contamination. Phytoremediation is an eco-friendly and cost-efficient method of biotechnological mitigation for the remediation of polluted ecosystems and revegetation of contaminated sites. The information provided in this review was collected by utilizing various sources of research information, such as ResearchGate, Google Scholar, the Scopus database and other relevant resources. In this review paper, we discuss (i) various organic and inorganic contaminants; (ii) sources of contamination and their adverse effects on terrestrial and aquatic life; (iii) approaches to the phytoremediation process, including phytoextraction, rhizoremediation, phytostabilization, phytovolatilization, rhizofiltration, phytodegradation, phytodesalination and phytohydraulics, and their underlying mechanisms; (iv) the functions of various microbes and plant enzymes in the biodegradation process and their potential applications; and (v) advantages and limitations of the phytoremediation technique. The reported research aimed to adequately appraise the efficacy of the phytoremediation treatment and facilitate a thorough understanding of specific contaminants and their underlying biodegradation pathways. Detailed procedures and information regarding characteristics of ideal plants, sources of heavy metal contamination, rhizodegradation techniques, suitable species and removal of these contaminants are put forward for further application. Scientists, planners and policymakers should focus on evaluating possible risk-free alternative techniques to restore polluted soil, air and water bodies by involving local inhabitants and concerned stakeholders.

Keywords: ecosystem; degradation; contamination; restoration; concentration

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1. Introduction

Various ecosystems are becoming polluted progressively due to environmental contamination and the release of industrial effluents. The nature of contamination is either organic—for instance, pesticides, polycyclic aromatic hydrocarbons (PAHs), herbicides and polychlorinated biphenyls (PCBs)—or inorganic (toxic metals). Potentially toxic elements are recognized as being deleterious to the health of living beings if present in adequately high concentration levels in the biosphere. The majority of them are heavy metals (Co, Cr, Cd, Fe, Hg, Cu, Mo, Pb, Ni, Mn, V, Sn and Zn), though some are metalloids (Sb, As) and non-metals (Se) [1]. These organic and inorganic toxic substances either originate naturally or result from human influence activities, including from physical weathering of bedrock and minerals [2], application of phosphate fertilizers in agriculture [3], use of insecticides [4], wastewater sludge [5], azo dye manufacture [2], waste incinerators [6], timber treatment [7], metal quarrying and smelting operations [8] and fossil fuel combustion and electroplating operations [9], which indicates an urgent need for treatment of contaminated ecosystems. Physicochemical treatments used to reduce the toxicity of contaminants in polluted areas [10,11], such as adsorption, chemical precipitation, membrane filtration, oxidation with hydrogen peroxide, coagulation–flocculation [10], the photocatalytic degradation process, ion exchange, oxidation with ozone and electrochemical and flotation approaches, are very expensive and cannot be utilized as the sole methods to attain environmental quality standards [12]. Therefore, these conventional physicochemical processes for contaminated ecosystems have led to the emergence of a new bioremediation technology called phytoremediation, a plant-based approach [13].

A meta-analysis of the literature discloses that diverse studies have been carried out in recent years on rehabilitating contaminated ecosystems by employing phytoremediation approaches, but comprehension of and deep insights into the mechanisms of different phyto-techniques have not been properly documented yet. Therefore, this review study assayed the sources and impacts of contamination along with the different methods of phyto-technology and their mechanisms and respective suitable plant species. The review also shows the potential application of the phytoremediation technique, its advantages and its limitations. Overall, this study investigates the possibility of achieving ecosystem remediation objectives by using fast-growing plants that also provide recreational benefits, as well as wildlife habitat.

2. Phytoremediation

The term "phytoremediation" is composed of two roots: (i) the word "phyto" originates from Greek and connotes plant species; and (ii) the word "remedium" is Latin and means ability to treat or re-establish [14]. The technique implies using plant species to extract and eradicate elemental contaminants or reduce their biological availability in soil and water bodies and, hence, improve degraded environments [15]. In other words, it is an approach to lower the amount of contamination in polluted sites to environmentally tolerable levels by using green plants [16]. Phytoremediation consists of two systems: the root system hosting the microbial population and the plant itself, which transforms the toxic compounds to further non-toxic substances. It is an eco-friendly method for the rehabilitation of polluted ecosystems using plants and is relatively less expensive, as it is carried out in situ and exploits solar energy [17]. Plant species selection is a vital factor for successful phytoremediation and plants must possess the characteristics shown [18] (Figure 1). Fast-growing woody plant species, such as *Populus* and *Salix*, are easy to regenerate with extensive roots and have high evapotranspiration rates that stabilize pollutants; hence, they can flourish on soils with contaminated conditions. Such plants also have higher rates of biomass production and can resist a broad range of potentially harmful elements in their root systems [19]. The most important plant species may commonly be situated in colonizing contaminated places [20], such as plants emerging in mining sites. However, the most appropriate selection of plants for phyto-technology predominantly relies on the contaminant characteristics and their concentration levels [21], depth and volatilization rates [22,23], the age of the location [24] and biological degradability [25]. Furthermore, a clear knowledge of the water-use relations for a selected plant is also essential for the success of the phytoremediation approach.

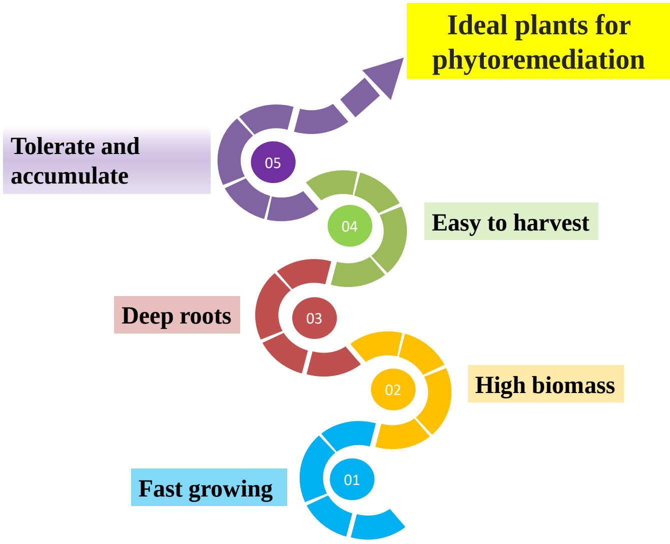


Figure 1. Characteristics of the ideal plants for phytoremediation.

3. Mechanism of the Phytoremediation Technique

On the basis of the type of contaminant, the media in which the treatment take place and the scope of application, the phyto-technique can be categorized into specific mechanisms (Table 1): phytoaccumulation/phytoextraction, rhizodegradation, phytostabilization, rhizofiltration, phytoevaporation/phytovolatilization, phytodesalination, phytodegradation/phytotransformation and phytohydraulics [26]. Once a plant takes up contaminants, it implements different detoxification mechanisms, such as accumulation, translocation, degradation, excretion or volatilization. The process of degradation involves transformation, fragmentation and/or deposition of the pollutant inside plant tissues [27].

Table 1. Various types of phytoremediation methods [28].

Phytoremediation Type	Contaminant Nature	Medium	Mechanism	Scope of Application
Phytoextraction/ phytoaccumulation	Inorganics	Soil, water	Hyperaccumulation	Moderately polluted sites
Rhizodegradation/ phytostimulation	Organics	Soil	Breakdown inside the rhizosphere through microbial activity	Polycyclic aromatic hydrocarbon (PAH) contaminants
Phytostabilization	Inorganics	Soil	Immobilization	Mining contamination
Phytovolatilization/ phytoevaporation	Organics/inorganics	Soil, water	Volatilization	Volatile contaminants
Rhizofiltration	Organics/inorganics	Water	Rhizosphere accumulation	Wastewater
Phytodegradation/ phytotransformation	Complex organics	Water, soil	Breakdown inside the plant through metabolic processes	Soil and wastewater contamination
Phytodesalination	Organics/inorganics	Soil, water	Na hyperaccumulation	Sodic soil and water
Phytohydraulics	Organics/inorganics	Ground water	Uptake, sequestering and degradation of groundwater contaminants	Shallow contaminated sites

3.1. Phytoextraction

Metal contamination impairs biological systems through direct consumption of metal-infected food, drinking contaminated water or the food chain as it can predispose living beings to serious health problems [29]. This type of contaminant does not undergo a process of biological degradation and, hence, necessitates physically eradication or transformation into non-toxic substances [30]. Phytoextraction/phytoaccumulation is the technique through which plants take up pollutants through their roots with subsequent translocation and accretion in their aboveground parts, which is generally followed by harvesting and final disposal of the biomass of the plant (Figure 2). Phytoextraction is also called phytosequestration and phytoabsorption. The process applies to metals (Cd, Ag, Cu, Cr, Co, Mo, Hg, Pb, Mn, Ni and Zn), radionuclides (137Cs, 90Sr, 238U and 234U), metalloids (Sb and As), non-metals (Se) and some organic substances (mainly hydrocarbons) since these do not usually have their structures further transformed or changed inside the plant system [31]. The occurrence of these contaminants in soil and water is the consequence of either natural forces, such as rock disaggregation, volcanoes and soil erosion, or human actions, such as incomplete fossil combustion, refining of metals, mineral mining, solid waste dumping, electronic product manufacturing, agricultural chemicals, pigments, vehicular gas emissions, military functions, etc. Some heavy metals and their respective adverse impacts are outlined in Table 2 [7,28]. It is critical to conduct remediation operations to stop these heavy metals from penetrating terrestrial, aquatic and atmospheric environments, in addition to restoring the polluted ecosystem [32]. Therefore, phytoextraction is the technology through which plants extract heavy elements from water and soil media by creating complexes via chelation with elements/metals and their metabolites [13], thereby reducing their toxicity.

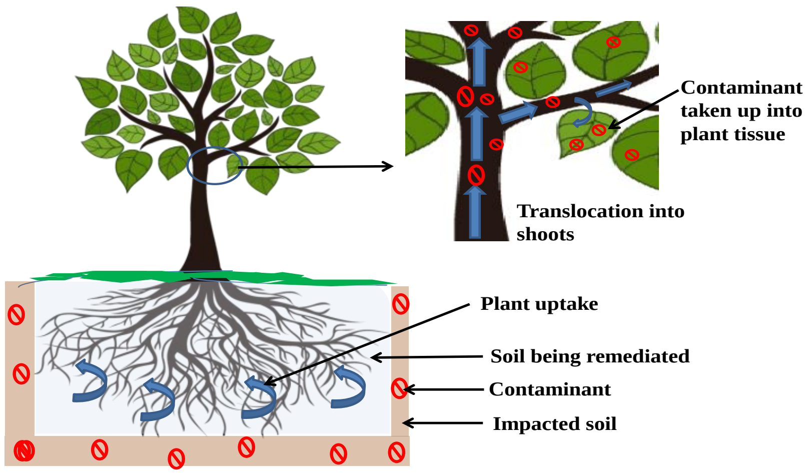


Figure 2. Mechanism of phytoextraction.

There are several factors responsible for the absorption mechanism of heavy metals, as discussed in the sections below.

Table 2. Sources of heavy metal contamination and metals' adverse impacts on terrestrial and aquatic life systems.

Name of the Metal	Source	Impacts				References
		Terrestrial			Aquatic	
		Humans	Plants	Animals		
Arsenic (As)	Fuel burning, pesticides, painting, wood treatment, geothermal processes, natural forces, thermal power plants, smelting	Cancer, skin lesions and increased deaths	Inhibits root extension and proliferation	Abdominal pain, vomiting and diarrhea; subsequently, rapid circulatory collapse	Bioaccumulation, physiological and biochemical disorders	[33–36]
Cadmium (Cd)	Fertilizers, fuel combustion, electroplating, smelting operations, batteries, dead batteries, paint sludge	Lung, prostate, nasopharynx, pancreas, and kidney cancers, as well as itai-itai	Reduces uptake and translocation of nutrients and water and disrupts metabolism	Kidney, lung, bone, liver, blood and nervous system are affected	Increase in mortality rates, deleterious effects on growth and reproduction systems	[37–39]
Chromium (Cr)	Mining operations, pesticide application, industrial coolant liquids, dyes, timber treatment, leather tanning, chromium salt manufacturing	Cancer, asthma, nose sores, skin infections, kidney and liver problems	Influences crop growth rate, productivity and quality of grains	Detrimental effects on wild birds and mammals	Cytotoxicity and detrimental impact	[40–43]
Copper (Cu)	Fertilizers, pigments, fungicides, mining, painting, electrical sources, lumber treatment, electroplating, smelting practices	Inflammation, cancer and anemia	Growth and development are blocked	Disheveled feathers, gizzard erosion, intestinal inflammation, hematochezia and damaged kidneys	Adverse effects on survival, growth and reproduction	[44,45]
Lead (Pb)	Metal products, paints, e-waste products, batteries, petrol additives, preservatives, ceramics, thermal power plants, bangle industry	Weakness, hypertension, brain and kidney damage, impotence and miscarriage	Poor germination, inhibits root growth and biomass production	Salivation, lack of vision, spastic twitching of eyelids, muscle tremors, jaw champing and convulsions	Oxidative stress, neurotoxin, bioaccumulation	[29,43,46]
Manganese (Mn)	Application of fertilizer	Deficits and neurodegenerative diseases, including a disorder called manganism	Triggers oxidative stress and disrupt photosynthesis	Reduced feed intake and growth rate and lethargy	Intestinal inflammatory damages, genotoxicity and oxidative stress	[47,48]

Table 2. *Cont.*

Name of the Metal	Source	Impacts				References
		Terrestrial			Aquatic	
		Humans	Plants	Animals		
Mercury (Hg)	Fumigants, geothermal processes, fluorescent lights, chlor-alkali plants, hospital waste (broken thermometers, sphygmomanometers, barometers), thermal power plants	Loss of memory, kidney and nervous system problems and weakened hearing and vision ability	Growth retardation	Anorexia, stomatitis, vomiting, diarrhea, shock, pain and dehydration	Teratogenic, reproductive and neuro-toxicity	[43,46,49,50]
Molybdenum (Mo)	Fertilizer, spent catalysts	Pain in joints, gout-like signs and high blood levels of uric acid	Reduces seedling growth, yellowish leaves	Induces secondary copper deficiency in animals	Transformations in the forms of aquatic biota systems and instability in fundamental activities	[51,52]
Nickel (Ni)	Alloys, mine tailings, battery manufacturers, smelting processes, thermal power systems	Allergy, kidney disorders, cardiovascular fibrosis, lung and nasal cancer	Lower seed germination, growth, biomass and final yield	Lung disorders in rodents and affects liver, kidney, blood and reproduction processes in rats and mice	Inhibition of respiration, ionoregulatory destruction and enhanced oxidative stress	[53–55]
Zinc (Zn)	Dyes, paints, fertilizers, galvanization processes, lumber treatment, mining, electroplating, smelting practices	Nausea, back pain, vomiting, anemia and lethargy	Slows down photosynthetic and respiratory rates and leads to unbalanced mineral nutrition	Vomiting, diarrhea, depression, damage to red blood cells and lack of appetite	Kills fish by destroying gill tissues	[56,57]

3.1.1. Plant Species

The uptake of heavy metals is influenced by the nature of plant species. The special plants used for phytoextraction, named metallophytes, are divided into three categories, as follows [31]:

Metal excluders: These are the plants that prohibit metals from penetrating aerial shoots or retain low and stable levels of metal concentration across a wide variety of metal concentration levels in the soil. Some examples of excluder species include *Oenothera biennis*, *Commelina communis*, *Salix* spp., *Silene maritime* and *Populus* spp. [58];

Metal indicators: An indicator is defined as a plant species containing the same levels of heavy metals in its tissues as in the surrounding soil environment [59]. They can tolerate the present concentration level of metals by forming chelators (intracellular element-binding substances) or by sequestering metals within the plant biomass [23]. Such plants are of bio-ecological significance because they are indicators of pollution and also resemble accumulators in the way they take up pollutants. Examples are *Pluchea dioscoridis*, *Agave sisalana* and *Cyperus articulates* [60];

Hyperaccumulators: Hyperaccumulators are plants that contain higher levels of metal pollutants concentrated in their root systems, shoots or foliage [61]. The variation in the absorbing potential of different hyperaccumulators relies on the occurrence, regulation and expression of responsible genes and the adjoining environment [62]. Metal-accumulating plants can concentrate most heavy metals, such as Co, Cd, Zn, Ni, Pb and Mn, at levels equal to 100 or 1000 times those in excluder plant species [30]. To date, over 500 plants from above 40 genera have been recognized as natural hyperaccumulating species, comprising $<0.2\%$ of the total angiosperms [63]. Woody plant species, such as poplars and willows, are utilized for phytoextraction because of several advantages, as they have high biomass in comparison to shrubs and herbs, which promotes the absorption of high concentrations of metals in their aboveground shoots. Furthermore, they possess a deep root system, which lessens soil erosion and helps to avoid the movement of polluted soil to adjoining locations [32].

3.1.2. The Properties of the Medium

The remediation treatment for a contaminated ecosystem can be boosted by employing agronomical practices, such as fertilizers, chelator addition and adjustment of pH.

3.1.3. Root Zone

Plant roots can accumulate pollutants and sequester or metabolize them within plant parts. Roots release root exudates, which cause degradation of pollutants in the growing soil media.

3.1.4. Environmental Conditions

Environmental conditions affect the uptake mechanism. For instance, temperatures affect growth materials and, subsequently, the root length of the plant.

3.1.5. Chemical Properties of Contaminants

Phytoextraction relies on contaminant-specific hyperaccumulators and the consequential metabolic products of the contaminants within plants.

3.1.6. Bioavailability of Metals

The biological availability of metals in the soil is defined as the portion of the total metals in the interstitial space of the water and soil particles accessible to the receptor organisms [64]. Metal accumulation by plants is reliant on the bioavailability of metals, which in turn depends on the upholding capacity time of the metals, as well as their interaction with other compounds in the growing media. Plants affect the soil by enhancing the biological availability of metals by adding physicochemical and biodegradable factors.

3.1.7. Chelating Agent Addition

The uptake of heavy metals can be improved by adding biodegradable substances, such as micronutrients and chelating agents. Moreover, in the process of chelate-assisted remediation, chemical chelating agents, such as ethylenediaminetetraacetic acid (EDTA) and nitrilotriacetic acid (NTA), are supplied to improve the phytoextraction of soil-contaminating metals. Table 3 shows the suitable plant species for phytoextraction based on their underlying degradation mechanisms.

Table 3. List of potential plants used for phytoextraction technology.

Plant Species	Heavy Metal	Accumulation(A)/ Translocation (T)	Literature Cited
Althernanthera ficoides	As	A, T	[65]
Brassica juncea	Pb	A	[66]
Cleome rutidosperma DC	Cd and Pb	A	[67]
Helianthus annus	Cu	A	[66]
Hyptis suaveolens	Cr	A	[68]
Berkheya coddii	Ni	A	[69]
Phragmites australis	Ni, Mo, Se and Cu	A/T	[43]
Populus species	Cd	A	[70]
Ricinus communis	Ni	A	[70]
Salix species	Cd and Zn	A, T	[71]
Senna siamea	Pb	A	[70]

3.2. Rhizodegradation

Rhizoremediation is the degradation of different organic contaminants in growing soil through microbial activity, and it can be enhanced by the existing root zone. It is also called phytostimulation, plant-assisted remediation and rhizosphere biodegradation [72] (Figure 3a). Rhizodegradation is recognized as the most efficient method for polycyclic aromatic hydrocarbon (PAH) treatment in soil. The combined action of the microbial population and plant root system in the rhizosphere, such as the discharge of root exudates (amino acids, sugars, organic acids, etc.), hydrogen cyanide (HCN), siderophores and phosphatases and phytohormone production by plant growth-promoting rhizobacteria (PGPR), helps in the breakdown of contaminants [6]. PAHs originate from either natural or anthropogenic activities; among them, the combustion of organic matter is the major source of contamination (Figure 3b). The mechanism of rhizodegradation involves direct phytohormonal activity, enhancing nutrient availability and regulating microbial population, which makes it possible to degrade contaminants by using a growing root system [73]. The pollutants taken up by plants are either accumulated in harvestable parts or volatilized through leaves or stems (Figure 3c). Plant–microbe interactions, soil parameters and the conditions that promote degradation rates are the factors affecting the rate of rhizodegradation (Figure 3d). Soil characteristics limit the bioavailability of contaminants, and root–microbe associations are the key process in PAH phytoremediation. Several microbial enzymes that take part in the PAH breakdown process [6] and their respective biodegradation pathways are given in Table 4.

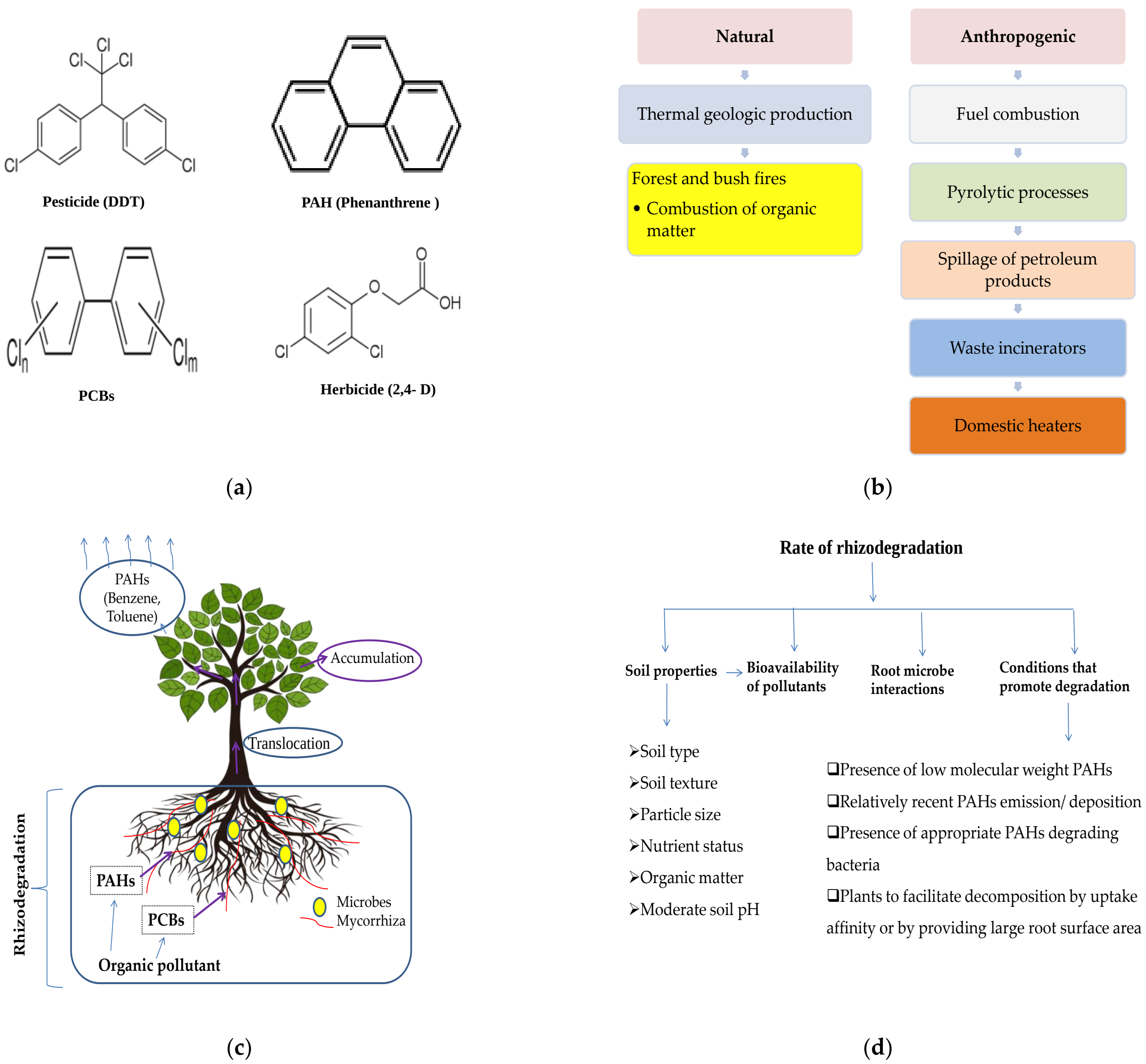


Figure 3. Rhizodegradation techniques: (**a**) chemical structures of different organic contaminants, (**b**) sources of PAH contamination, (**c**) mechanisms of rhizoremediation, and (**d**) factors affecting the rate of rhizodegradation.

3.3. *Phytostabilization*

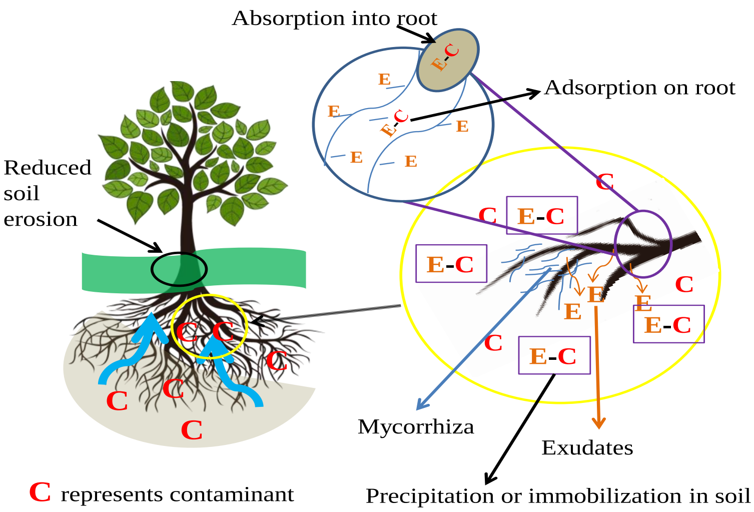
Phytostabilization, also known as phytoimmobilization, is the process of making a contaminant immobile (immovable) in soil media via (a) absorption by the plant roots, (b) adsorption on the roots or (c) precipitation in between the rhizospheres of growing media (Figure 4a). The technique reduces the mobility of contaminants by stabilizing them via the development of a vegetative cover at the root zone of the plant species, helping to avoid migration to the groundwater. Microbial growth correlated with the plant root system may enhance the breakdown of organic contaminants, such as petroleum hydrocarbons and pesticides, to likely non-toxic compounds [64]. Plant, soil, contaminant and environmental factors determine the success of phytostabilization technology in contaminated sites in terms of both revegetation and restoration (Figure 4b). Phytostabilization can be enhanced by increasing biological inoculants, such as plant growth-promoting bacteria (PGPB), organic amendments (biosolids, manures) and inorganic amendments (liming materials, clay materials and phosphate compounds), and through geotextile capping. Some of the suitable plants for phytostabilization and their respective biodegradation mechanisms are listed in Table 5.

Table 4. Important enzymes associated with the process of rhizodegradation.

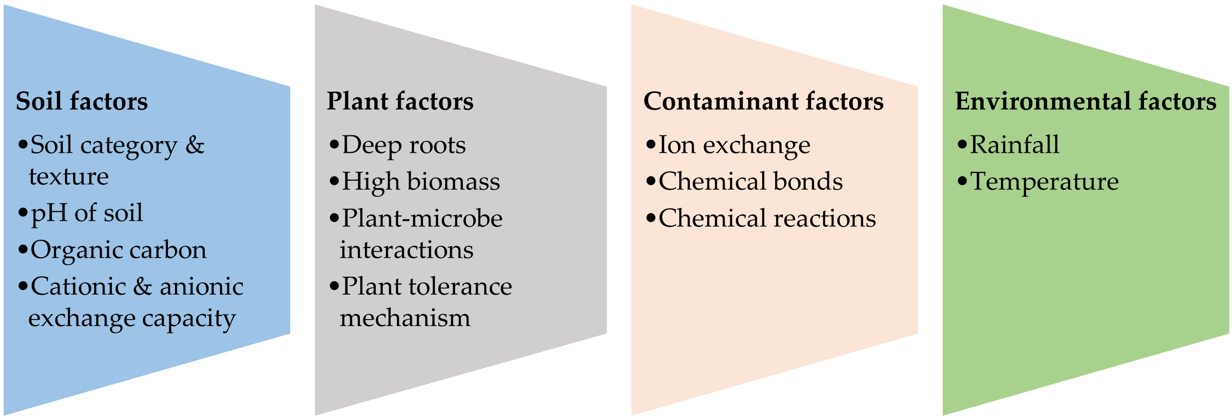
Enzyme	Target Pollutant	Biodegradation Pathway	References
Aromatic dehalogenase	Chlorinated aromatics (DDT, PCBs, etc.)	Hydrolytic dehalogenation	[74]
Carboxylesterases	Xenobiotics	Hydrolysis	[75]
Cytochrome P450	Xenobiotics (PCBs)	Oxidation, reduction, hydrolysis and conjugation	[76]
Dehalogenase	Chlorinated solvents and ethylene	Dehalogenation	[77]
Glutathione s-transferase	Xenobiotics	Dehalogenation	[78]
Peroxygenases	Xenobiotics	Oxygenations and oxidations	[79]
Peroxidases	Xenobiotics	Oxidation and reduction	[80]
Laccase	Xenobiotics, degradation of explosives	Oxidation	[81]
N-glucosyl transferases	Various xenobiotics	Conjugation	[82]
Nitrilase	Herbicides	Degradation of nitrile	[83]
Nitroreductase	Explosives (RDX and TNT)	Reduction	[84]
N-malonyl transferases	Xenobiotics	Conjugation	[82]
O-demethylase	Alachlor, metalachor	*N*-dealkylation	[85]
O-glucosyl transferases	Xenobiotics	Conjugation	[82]
O-malonyl transferases	Xenobiotics	Hydrolysis	[86]
Peroxdase	Phenols	Elimination or reduction	[87]
Phosphatase	Organophosphates	Hydrolase	[88]

Table 5. Suitable plant species for phytostabilization.

Plants	Pollutant	Mechanism	References
Arundo donax	Ni, Pb, Hg	Deposition	[89]
Atriplex portulacoides	Zn	Adsorption	[43]
Cirsium arvense	Pb, Mn, Zn	Absorption/adsorption	[90]
Conyza Canadensis	Cr, Ni, Cu, Pb, Cd	Accumulation	[91]
Euonymus japonicus	Cd	Deposition	[92]
Launaea acanthodes	Ni, Mo	Accumulation	[93]
Populus deltoids	As	Deposition	[89]
Ricinus communis	Cd, Cu, Mn, Zn	Absorption/adsorption	[43]
Salix purpurea	As	Deposition	[89]



(**a**)

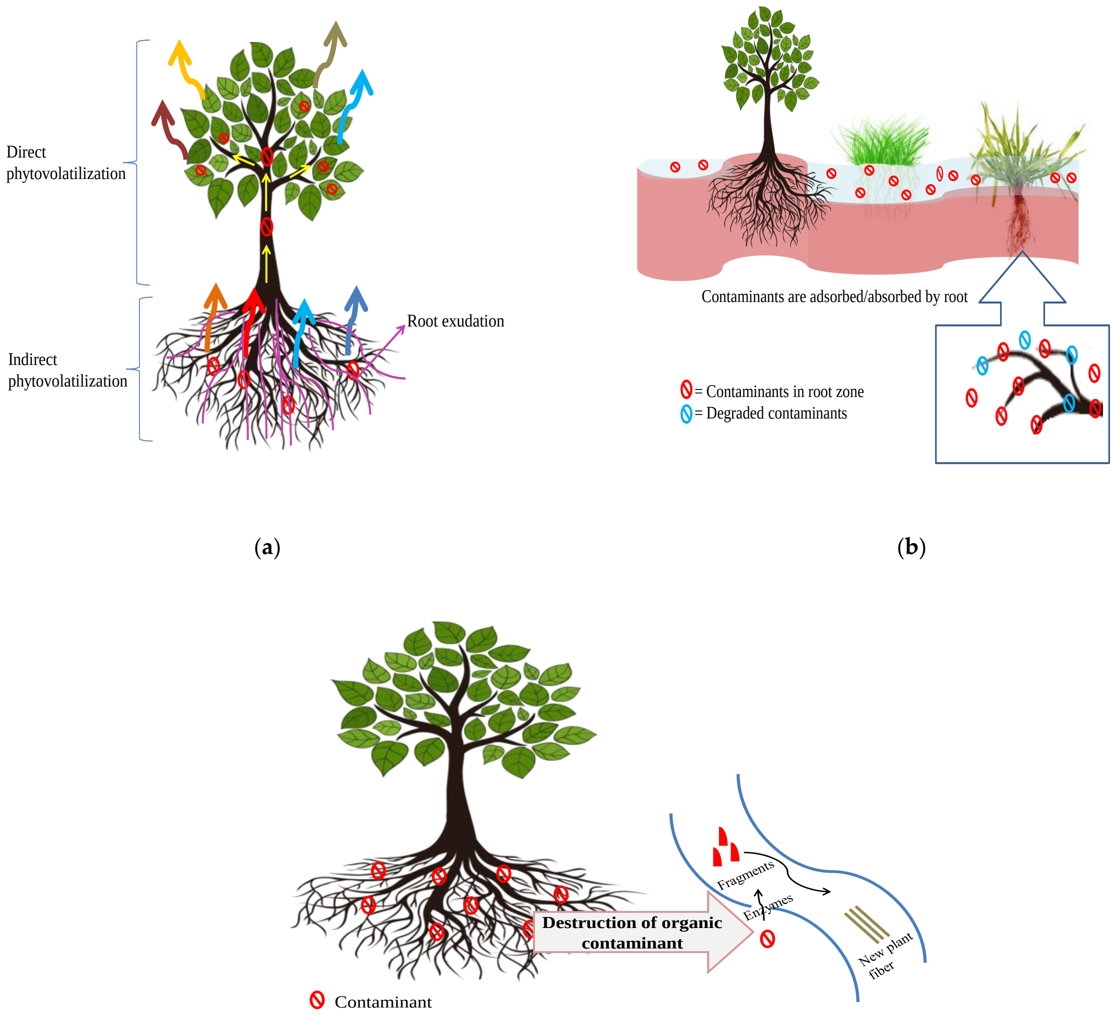


(**b**)

Figure 4. (**a**) Mechanisms of phytostabilization and (**b**) factors affecting the process of phytostabilization.

3.4. Phytovolatilization

Phytovolatilization is the absorption, translocation and evaporation of a pollutant by a plant species, with a modified type of pollutant being discharged into the adjoining atmosphere. Phytoevaporation or phytovolatilization occurs when growing trees and other plant species consume water and pollutants simultaneously, resulting in volatilization through foliage or stems (direct phytovolatilization) or the soil surface because of the root activities of the plant (indirect phytovolatilization process) (Figure 5a). The phytoevaporation process can be employed for detoxification of both hazardous inorganic and organic contaminants [32]. Volatile types of hazardous inorganic substances, such as As, Se and Hg, can be evaporated from plant parts [27]. Examples of some plant species used for phytovolatilization are presented in Table 7.



(**a**) (**b**)

(**c**)

Figure 5. Mechanisms of (**a**) phytovolatilization, (**b**) rhizofiltration, and (**c**) phytodegradation.

3.5. Rhizofiltration

Rhizofiltration is a technique for the assimilation of pollutants present in a solution adjoining the root zone, concentrating and precipitating them on or into plant roots through biotic or abiotic methods (Figure 5b). This approach is mostly employed to rehabilitate polluted groundwater sources. Plant roots release root exudates (secondary metabolites) that undergo various biogeochemical processes, resulting in the precipitation of pollutants onto roots or into water bodies. Later on, adsorption of contaminants onto or into the plant root system and translocation to the aboveground portions occur based on the type of plant species and the pollutant type and concentration [10]. Plant species, the nutrient status and chemical characteristics of contaminants and the conditions of the groundwater are the prime factors that are used to evaluate the effectiveness of the rhizofiltration method in treating inorganic (metals) and organic pollutants present in groundwater resources. Some of the suitable plants for rhizofiltration and their pollutants are listed in Table 7.

3.6. Phytodegradation

The phytodegradation process involves the transformation of contaminants absorbed by plants through metabolic pathways inside the plant system (Figure 5c). It is also known as phytotransformation. The complex organic contaminants are converted into simpler products and integrated into the plant tissues to boost plant growth [94]. Plants release specific enzymes that catalyze and enhance the rate of transformation. The phytodegradation technique can be used for the treatment of chemical pollutants; for instance, chlorinated solvents, herbicides and explosives in groundwater sources, aromatic and petroleum hydrocarbons in growing soils and volatile substances from the atmosphere [95]. In environmental applications, this process relies upon the direct absorption of contaminants from soil water and the resultant metabolites accumulated within the plant tissues, provided that the accumulated metabolites are either non-toxic or less toxic than the original contaminant. Plants reported as suitable for phytodegradation are listed in Table 6.

Table 6. Examples of plant species suitable for the phytodegradation and phytodesalination.

Species	Pollutant	Biodegradation Pathway	References
Phytodegradation			
Elodea Canadensis	DDT	Catalytic degradation	[102]
Ipomoea carnea	Textile azo dyes	Redox reaction	[103]
Populus spp.	Trichloroethylene (TCE)	Catalytic degradation	[94]
Leucaena leucocephala	Ethylene dibromide	Reduction	[104]
Pueraria thunbergiana	DDT	Dehalogenation	[102]
Phytodesalination			
Andropogon gerardii	Na^+	EC reduction and salt accumulation	[105]
Atriplex prostrate	Na^+, Cl^-	Accumulate Na^+ and Cl^-	[106]
Phragmites australis	Na^+	Extraction	[105]
Typha latifolia	Na^+, Cl^-	Accumulate Na^+ and Cl^-	[106]

Table 7. Suitable plants for phytoevaporation and rhizofiltration techniques.

Plant Species	Contaminant	References
Phytoevaporation		
Arundo donax	AS	[96]
Astragalus racemosus	Se	[43]
Brassica napus	Se	[97]
Medicago sativa	Chlorinated solvents	[98]
Nicotiana tabacum	Hg	[99]
Salix spp.	Trichloroethylene (TCE), tetrachloroethylene (PCE)	[27]
Populus spp.	Trichloroethylene (TCE), tetrachloroethylene (PCE)	[27]
Taxodium distichum	Trichloroethylene (TCE)	[27]
Rhizofiltration		
Arundo donax L.	Synthetic dye	[10]
Echinodorus cordifolius	Cd	[100]
Eichhornia crassipes (Mart.) Solms	Ni	[10]
Heliconia psittacorum	Zn	[100]
Iris pseuda-corus	Cr and Zn	[43]
Lepironia articulate	Pb	[43]
Pteris vittata	As	[43]
Raphanus sativus	U	[101]

3.7. Phytodesalination

Phytodesalination is an eco-friendly technology that is employed to remediate water resources and sodic soils by using Na-hyperaccumulating halophytes. It is the process through which plant species are employed as desalination agents [107], which means the use of the halophytes' ability to absorb huge quantities of sodium (Na^+) ions from affected ecosystems and their elimination by means of accumulation and translocation to different harvestable plant parts (Figure 6a) [108]. Saline-sodic soils cover almost 6% (over 800 million ha) of the land surface worldwide and, to overcome this problem, several authors have emphasized the phytodesalination technique by proving the effectiveness of Na^+-hyperaccumulating plants in desalinizing the soil, especially in arid and semi-arid locations [109]. This is because halophytes decrease the ion concentration level of the solution in the plant xylem and cause Na^+ and Cl^- excretion at elevated levels of salt concentration [105]. The potential of phytodesalination is species-specific (Figure 6b) and dependent on soil and climatic conditions (primarily rainfall). Some of the reports utilized for phytodesalination purposes are shown in Table 6.

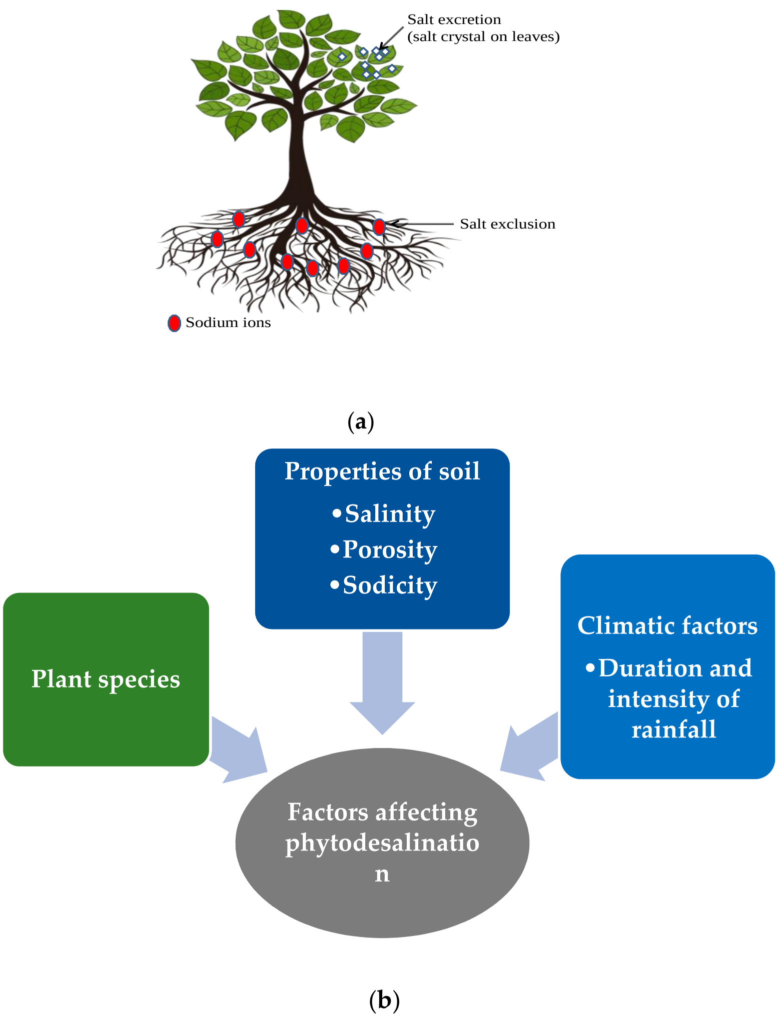


Figure 6. Phytodesalination process: (**a**) mechanism of phytodesalination and (**b**) factors affecting the mechanism of phytodesalination.

3.8. Phytohydraulics

Phytohydraulics is the exploitation of deep-rooted plant species to uptake, sequester and breakdown groundwater pollutants that emerge in contact with their root systems (Figure 7). A special class of plant species called phreatophytes are widely used for this purpose. Phreatophytes are deep-rooted, water-loving plants that have high transpiration rates and penetrate their roots into zones of high moisture, and they can also continue to exist under temporary saturation conditions [110]. *Prosopis, Eucalyptus*, *Populus* and *Salix* are typical phreatophytes.

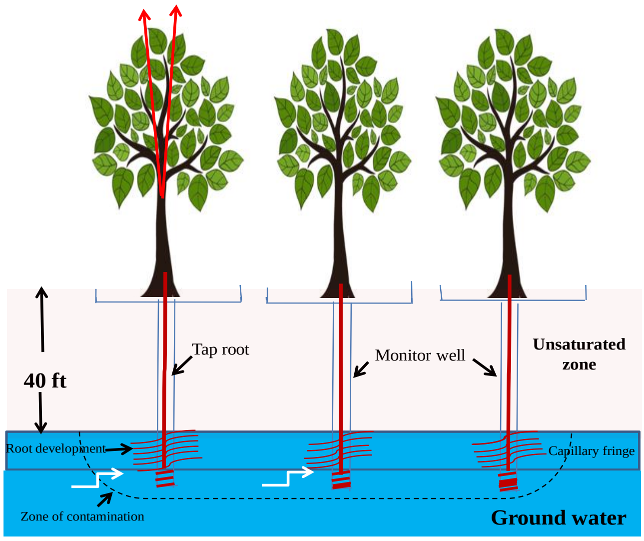


Figure 7. Mechanism of phytohydraulics.

4. Methods Used for Evaluation of Phytoremediation Potential

In attempts to evaluate the phytoremediation competence of different plants, three factors are mainly employed, as described below.

4.1. Biological Concentration Factor (BCF)

The bioconcentration value indicates the accumulation ability of plant roots in relation to the soil. It is estimated as the ratio of the metal/element concentration present in the plant roots to the metal/element concentration levels in soils [111] as determined with the following formula:

$$\text{BCF} = \frac{\text{Metal concentration in plant root}}{\text{Metal concentration in soil}} \quad (1)$$

4.2. Bioaccumulation Coefficient (BAC)

The BAC refers to the concentration levels of metals present in plant shoots divided by the metal concentration in the rhizosphere region of soil [112] and is estimated as follows:

$$\text{BAC} = \frac{\text{Metal concentration level in plant shoot}}{\text{Metal concentration level in soil}} \quad (2)$$

4.3. Translocation Factor (TF)

The TF is defined as the metal ratio of the transfer capacity from a plant's roots to its shoots and is determined by the following formula [111]:

$$\text{TF} = \frac{\text{Metal concentration present in plant shoot}}{\text{Metal concentration in root}} \quad (3)$$

5. Applications of Phytoremediation Technology

Phytoremediation technology can be employed for the purposes shown below (Figure 8).

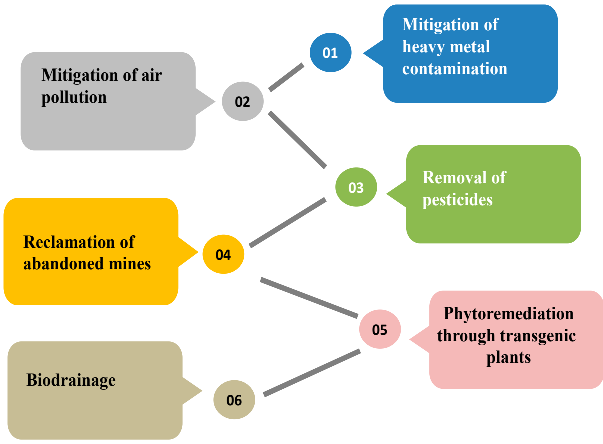


Figure 8. Phytoremediation applications.

5.1. Mitigation of Heavy Metal Contamination

Phytoremediation can assist in the mitigation of heavy metal contamination by using metal excluders [58], metal indicators [60] and hyperaccumulator plants [61].

5.2. Bioremediation of Air Pollutants

Phytofiltration is the use of vegetation to shield from dust. A green vegetation belt 8 m wide may cut down dust fall by two to three times. Various morphological characteristics of plant species, such as leaf orientation on the principal axis, surface nature, size and shape, the existence or lack of trichomes and wax accumulation, are responsible for the entrapment of pollutants from the ambient atmosphere [113]. Inorganic compounds, such as sulfur dioxide (SO_2), nitrogen oxides (NOX), etc., undergo degradation inside plants. SO_2 released due to fossil fuel burning generally enters plants through the stoma and can be exploited in a reductive sulfur cycle by transforming into SO_4^{2-} or SO_3^{2-} in plant cell walls. The final products are cysteine or other organic substances. Likewise, NOX, the predecessor of the photochemical reaction, can enter plant systems through deposition on foliage or roots. The factors affecting NOX penetration into leaves are species, the age of the plant, NOX concentration and other environmental factors.

5.3. Removal of Pesticides

Plant–microbe interactions help in the degradation of xenobiotics in the root zone of plants through the secretion of degrading enzymes [114]. For instance, bacteria segregated from insecticide-polluted soils possess the ability to break down atrazine [115]. Some of the suitable plants with specific pesticide degradation capacities are given in Table 8.

Table 8. Examples of plants involved in the remediation of pesticides.

Name of the Plant	Pesticide
Populus spp.	Atrazine
Corbicula fluminea	Carbaryl, diazinon, carbofuran, glycophosphate, coumphos, parathion
Oryza sativa	Carbaryl, parathion, atrazine, carbofuran, diazinon, coumphos, glycophosphate
Bassia scoparia	Atrazine
Salix spp.	2,4,5-T, 2,4-D, aldrin
Myriophyllum aquaticum	Organo-phosphate pesticides, halogenated pesticides
Elodea Canadensis	Organo-phosphate pesticides, halogenated pesticides
Spirodela oligorrhiza	Organo-phosphate pesticides

5.4. Reclamation of Abandoned Mine Sites

Reclamation of affected mining sites can restore soil fertility and recreational values, thereby increasing areas of rangeland and promoting the formation of wildlife habitats [68]. The major approaches involved in the rehabilitation of abandoned mine locations are metal accretion, translocation, accumulation and phytostabilization processes. Plants suitable for mine spoil treatment [116] are listed in Table 9.

Table 9. Examples of plants involved in the reclamation of mining sites.

Category of Mine Spoils	Plants
Coal mine spoils	*Eucalyptus hybrid*, *Pongamia pinnata*, *Acacia nilotica*
Limestone mine spoils	*Salix tetrasperma*, *Acacia catechu*, *Leucaena leucocephala*
Copper, tungiston, mica, limestone and marble mine spoils	*Prosopis juliflora*, *Acacia Senegal*, *Cynodon dactylon*
Iron ore waste	*Leucaena leucocephala*
Manganese, haematite and magnetite spoil	*Albizia lebeck*

5.5. Biodrainage

Biodrainage is the process of removing excess surface and subsurface water in waterlogged areas using vegetation. Plant species suitable for the biodrainage technique should possess the following characteristics: they should be able to withstand prolonged waterlogging, have a high transpiration rate and water use efficiency and be salt-tolerant and perennial. Examples include *Eucalyptus tereticornis*, *Anthocephalus cadamba*, *Acacia nilotica*, *Pongamia pinnata*, *Bambusa bamboos*, *Prosopis juliflora*, etc.

6. Advantages and Limitations of Phytoremediation

Phytoremediation has the following advantages [20,32,117]: (i) it can be carried out in both in situ and ex situ environments, (ii) the technology is amenable to a diverse variety of inorganic and organic substances, (iii) it is suited for remediation of large areas of terrestrial and aquatic ecosystems and can be simply implemented, (iv) the technique is suitable for places with shallow pollutants, (v) it is cost-effective compared to conventional methods as it does not require procurement of large machines, (vi) it is easy to implement and maintain and accepted by the public, (vii) growing trees on the contaminated sites makes them aesthetic and pleasing to the eyes and (viii) this approach can also recover the fertility of soil by releasing organic matter to the soil surface. The green technology of phytoremediation also has the following limitations: (i) the phytoremediation process takes years to rehabilitate a contaminated site, (ii) it is slower than conventional methods, (iii) the problem of accumulation of contaminants in plant fruit and other edible parts of vegetables and crops arises, (iv) the toxicity and biological availability of the biodegradation compounds are not identified, (v) the technology is controlled by soil and climatic factors and (vi) the process is not as effective for regions with a high concentration of pollutants. In order to overcome the aforementioned disadvantages and to improve the phytoremediation technology, genetically modified plants [118], microbial inoculants [119], microbiologically induced carbonate precipitation (MICP) techniques [120–122] and chelate-assisted approaches [32] have been emphasized.

7. Conclusions

The increasing population is creating the necessity for more developmental activities to address hunger and supplement livelihoods. Industrial development seems to be a viable option to address these two important needs, but increases in the toxicity of contaminants beyond the permissible limits due to these industries can threaten the biological systems of terrestrial and aquatic ecosystems, thus implying the need for environmental remediation/restoration. Hence, phytoremediation can be employed as a sustained, eco-friendly and cost-effective technology to rehabilitate these toxic pollutants by using green plants.

Furthermore, phytoremediation mechanisms vary with the type of pollutant, the media in which remediation occurs and the scope of application. Phytoremediation could emerge as a holistic approach to environmental amelioration and livelihood security. The study also concluded that edible plants should be avoided because of the problem of accumulation of contaminants in plant tissues, from where they can enter into the food chain and cause chronic health issues. For effective treatment of polluted soil, air and water resources, identification of pollutant types and the underlying biodegradation method and selection of a plant species is critical. However, measures should be taken to increase awareness regarding bioremediation technology among native growers while focusing on fast-growing native plant species. Scientists, planners and policymakers, in collaboration with local inhabitants and concerned stakeholders, should focus on determining the opportunities for risk-free alternative techniques to restore polluted ecosystems.

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