Phytoremediation of Toxic Metals: A Sustainable Green Solution for Clean Environment

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Abstract: Contamination of aquatic ecosystems by various sources has become a major worry all over the world. Pollutants can enter the human body through the food chain from aquatic and soil habitats. These pollutants can cause various chronic diseases in humans and mortality if they collect in the body over an extended period. Although the phytoremediation technique cannot completely remove harmful materials, it is an environmentally benign, cost-effective, and natural process that has no negative effects on the environment. The main types of phytoremediation, their mechanisms, and strategies to raise the remediation rate and the use of genetically altered plants, phytoremediation plant prospects, economics, and usable plants are reviewed in this review. Several factors influence the phytoremediation process, including types of contaminants, pollutant characteristics, and plant species selection, climate considerations, flooding and aging, the effect of salt, soil parameters, and redox potential. Phytoremediation’s environmental and economic efficiency, use, and relevance are depicted in our work. Multiple recent breakthroughs in phytoremediation technologies are also mentioned in this review.

Keywords: phytoremediation; toxic metals; pollution; aquatic plant; environment

1. Introduction

With the help of much technical improvement, our world is progressing at an astounding rate. Nonetheless, these developments are causing several difficulties in our environment by disrupting the ecosystem’s unique condition [1,2]. Metal contamination in a particular environment such as water, soil, and in organisms is a global issue [3,4]. Water and sediment quality is critical for supporting aquatic life and maintaining a healthy
environment [5,6]. Furthermore, the soil is an essential component for the success of crops as a source of nutrients [7]. However, natural and artificial activities contaminate these potential areas of our environment for a lengthy period [3,8–12]. These contaminants reach our bodies through the food chain directly or indirectly [4,10,13–15].

Toxic metals that are non-biodegradable create a chronic hazard to the environment [16]. The presence of toxic chemicals is now a prevalent scenario and has a remarkably dangerous effect on the environment [17,18]. Some of these metals, such as Fe, Zn, Mn, Cu, Zn, Ni, and Co, are essential for certain species in their various physiological functions, but excessive amounts harm the organisms [19]. Some metals have such a high toxicity level that they can reduce the rate of water transpiration in plants. Toxic metals can harm plant chloroplasts, reducing photosynthetic activity [20]. For example, when the concentration of Cd surpasses the threshold value, it inhibits plant development and cell death in the long run [21]. Cd toxicity induces reactive oxygen species, known as ROS, which causes damage to biomolecules in the cellular area [22].

Furthermore, while toxic metals are not biodegradable and cannot be removed biologically, they can be transformed from one form to another; hence, their negative effects can occasionally be mitigated by changing their chemical state [23,24]. However, decontaminating a facility from toxic metal pollution is a time-consuming and expensive process. Furthermore, toxic metals pose a serious threat to human and animal health because of their long-term persistence in the environment [10,25,26]. The removal of significant amounts of metal content using current processes is costly and results in massive secondary waste [16,27,28]. On the contrary, biological factors such as microbes, plants, and so on provide environmentally friendly and cost-effective methods of removing metal contents and decontaminating the environment from pollution at a safe and acceptable level [2,29]. Phytoremediation is a practical, dependable, environmentally friendly, long-term practicable, and cost-effective method of decontaminating an area from toxic metal pollution [30–32]. Andrea Cesalpino discovered phytoremediation in the 16th century [33]. Phytoremediation is a natural method of removing harmful metals using plants. Because it is a biological technique, no mechanical equipment is required. In comparison to alternative manual procedures (acid leaching and electrokinetic soil remediation) or natural ways (membrane filtration, ion exchange, and adsorption), the operation cost for phytoremediation is minimal, and there are no environmental side effects [34–36]. However, several small investigations on phytoremediation have recently been undertaken. As a result, this study is intended to cover a variety of topics of phytoremediation. For example, (i) key aspects influencing phytoremediation, (ii) types and advancements of phytoremediation, and (iii) advantages, scopes, and limitations of phytoremediation.

In addition, prior works on phytoremediation have been reviewed and summarized in this publication. However, it is believed that this review effort will assist policymakers and prominent academicians throughout the world in quenching their insatiable desire for the phytoremediation of various toxic metals. Furthermore, this study may pave the path for developing a sophisticated model to rescue the environment from metal pollution.

2. Methodology

Search engines such as Google Scholar, Scopus, Web of Science, and Science Direct were utilized to locate the standard literature on phytoremediation to cover all relevant and advanced material. Furthermore, the information in the review study will allude to the role of plants in mitigating metal pollution, resulting in a phytoremediation outlook of 40 years. The review study followed and analyzed probable references from various scientific journals about metal buildup in plants, phytoremediation approaches, and prospects. As a result, the keywords (i) phytoremediation, (ii) contaminated soil, (iii) toxic metal contamination, and (iv) mangrove plants in phytoremediation were employed to complete our work.
3. Source, Effect and Limit of Different Harmful Metals

Massive industrialization and urbanization contribute to the attribution of metal contents in the biosphere, resulting in an increase in their status in the soil and aquatic habitats [37]. On the other hand, metal bioavailability is affected by a variety of parameters, including soil qualities, exposure pathways, and animal physiological traits, and might differ from one organism to the next [38–41]. Toxic metals, for example, can inhibit plant growth, altering the water and nutrient absorption balance, impact on the transportation of these to aboveground plant parts, and cause negative effects concerning shoot growth [21]. Metals such as Cu and Zn, on the other hand, operate as cofactors and activators of an enzyme’s proper action [42]. Toxic metals such as As, Pb, Hg, and Cd, on the other hand, are hazardous to plants and all living organisms [37]. The source, effect, and limit of many hazardous metals are depicted in this diagram (Table 1).
<table>
<thead>
<tr>
<th>Toxic Metal</th>
<th>Sources</th>
<th>Harmful Effects on Human</th>
<th>Harmful Effects on Aquatic Lives</th>
<th>Standard Limit for Fresh Water (µg/L)</th>
<th>Standard Limit for Marine Water (µg/L)</th>
<th>Standard Limit for Sediment (µg/g)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>As</td>
<td>Natural Sources: Oxyanions of trivalent arsenite</td>
<td>Essential cellular processes such as oxidative phosphorylation and ATP synthesis disrupted by As (as arsenate)</td>
<td>Does not affect aquatic life</td>
<td>5&lt;sup&gt;c&lt;/sup&gt;</td>
<td>24&lt;sup&gt;a&lt;/sup&gt;</td>
<td>20&lt;sup&gt;a&lt;/sup&gt;</td>
<td>[43,44]</td>
</tr>
<tr>
<td></td>
<td>Anthropogenic Sources: Pesticides, wood additives</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Cd</td>
<td>Rock phosphate</td>
<td>Oncogenic, mutagenic, and teratogenic; Disrupt endocrine system; chronic anemia, restricts calcium ruling in biological systems and causes kidney failure</td>
<td>Decrease growth in juvenile, impairs aquatic plant growth</td>
<td>5&lt;sup&gt;a&lt;/sup&gt;</td>
<td>5.5&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.5&lt;sup&gt;a&lt;/sup&gt;</td>
<td>[43–46]</td>
</tr>
<tr>
<td>Cu</td>
<td>Rock phosphate</td>
<td>Brain and kidney mutilation, liver cirrhosis and chronic anemia raised from massive dosage, stomach and intestinal impatience</td>
<td>Inhibit skeletal ossification, decrease vitamin C</td>
<td>50&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1.3&lt;sup&gt;a&lt;/sup&gt;</td>
<td>65&lt;sup&gt;a&lt;/sup&gt;</td>
<td>[47–49]</td>
</tr>
<tr>
<td>Cr</td>
<td>Chromite ore (FeCr₂O₄) present in mafic and ultramafic rocks</td>
<td>Elevated dosage Cause hair fall</td>
<td>Cause low growth of both fish and plants; mortality occurs if present in high level</td>
<td>100&lt;sup&gt;c&lt;/sup&gt;</td>
<td>4.4&lt;sup&gt;a&lt;/sup&gt;</td>
<td>80&lt;sup&gt;a&lt;/sup&gt;</td>
<td>[49–51]</td>
</tr>
<tr>
<td></td>
<td>Steel and leather industries, filthy biosolids and composts, fly slag</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Toxic Metal</td>
<td>Natural Sources</td>
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<td>Harmful Effects on Human</td>
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<td>Standard Limit for Sediment (µg/g)</td>
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</tr>
<tr>
<td>Hg</td>
<td>Mining from natural sources</td>
<td>coal burning, medical gadgets, medicinal left-over</td>
<td>Apprehension, autoimmune illnesses, depression, disrupt balancing, lethargy, fatigue, hair fall, sleeplessness, irritability, disrupt memory, periodic infections, vision disruptions, tremors, anger eruptions, abscesses and brain dysfunctions, renal and respiratory dysfunctions.</td>
<td></td>
<td>0.02&lt;sup&gt;e&lt;/sup&gt;</td>
<td>0.02&lt;sup&gt;e&lt;/sup&gt;</td>
<td>0.2&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
<tr>
<td>Ni</td>
<td>Direct leaching from rocks and sediments</td>
<td>Metal rerolling industry, kitchen machines, clinical appliances, batteries and steel amalgams</td>
<td>nickel itch: Allergic dermatitis; lungs, nose, sinuses, throat and stomach cancer have been recognized to its inhalation; hematotoxic, immunotoxic, neurotoxic, genotoxic, propagative toxic, respiratory toxic, nephrotoxic, and hepatotoxic; causes hair fall in massive dosage</td>
<td>Disrupt plasma and cause trouble in respiration</td>
<td>100&lt;sup&gt;c&lt;/sup&gt;</td>
<td>70&lt;sup&gt;a&lt;/sup&gt;</td>
<td>21&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>
Table 1. Cont.

<table>
<thead>
<tr>
<th>Toxic Metal</th>
<th>Sources</th>
<th>Harmful Effects on Human</th>
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<th>Standard Limit for Fresh Water (µg/L)</th>
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<th>Standard Limit for Sediment (µg/g)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb</td>
<td>Natural Sources: Atmospheric deposition, occurring ores, and soil erosion</td>
<td>Lead generated fuels use in both urban and aqua traffic, electric based batteries, insecticides and weedicides</td>
<td>children are the possible victim from Pb effects such as lessened mental development, compact brainpower, short-term memory loss, learning frailties and synchronization complications; kidney failure; cardiac disease development</td>
<td>Cause scoliosis, inhibit photosynthesis and affect the gill of fish</td>
<td>10 (^d)</td>
<td>4.4 (^a)</td>
<td>50 (^a)</td>
</tr>
<tr>
<td>Zn</td>
<td>Natural Sources: Rock weathering, soil erosion, pedogenetic processes</td>
<td>Pesticides and fertilizers in agricultural soil</td>
<td>dizziness and lethargy caused due to Over dosage</td>
<td></td>
<td>5 (^a)</td>
<td>15 (^a)</td>
<td>200 (^a)</td>
</tr>
</tbody>
</table>

Here, \(^a\) Australian sediment quality low trigger value [66]. \(^b\) World Health Organization (WHO) guidelines for drinking water quality [67]. \(^c\) South African Water Quality Guidelines [68]. \(^d\) World Health Organization (WHO) guidelines for drinking water quality [69]. \(^e\) Environmental Planning and Assessment Regulation 2000 [70].
4. Natural Remediation Technique

More than 300 years ago, the natural phytoremediation process was reported [71]. Following that, humans began using these plants to remove pollutants from contaminated soil [72]. Researchers uncovered the genetic basis for the accumulation of metal contents in plants thanks to advanced genetic technology [73]. Furthermore, various natural strategies for removing harmful contaminants are available, including physicochemical techniques, microorganisms (Table 2), and phytoremediation. Phytoremediation has proven to be a viable alternative to traditional treatments since it is cost-effective, environmentally beneficial, and aesthetically pleasing [74]. It was discovered that the cost ranged from $600,000 to $3,000,000 per square hectometer, depending on the severity of the poisonous metal compounds [75].
Table 2. Physico-chemical and microbial remediation techniques for toxic metal contaminated soil.

<table>
<thead>
<tr>
<th>Name</th>
<th>Technique</th>
<th>Disadvantages</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solidification</td>
<td>Binding agents (zeolite, manure) are used to encase the contaminants and make them immobile</td>
<td>Long duration, volatile compounds may come out</td>
<td>[76–79]</td>
</tr>
<tr>
<td>Ion exchange</td>
<td>Ion is exchanged between solid and liquid phase.</td>
<td>High energy consumption</td>
<td>[80,81]</td>
</tr>
<tr>
<td>Reverse osmosis</td>
<td>A semi permeable membrane (polyamide thin-film) is used, through which the metals are allowed to pass and are removed from the solution</td>
<td>High cost due to membrane fouling</td>
<td>[82,83]</td>
</tr>
<tr>
<td>Coagulation</td>
<td>Coagulants (aluminium and sulfate) are used to remove metals from water</td>
<td>Can not remove contaminants completely</td>
<td>[84,85]</td>
</tr>
<tr>
<td>Vitirfication</td>
<td>High temperature is provided to contaminated soil in order to make the metals immobile and turn them into a glass-like product</td>
<td>Costly and unsafe because it deals with flammable liquids</td>
<td>[86,87]</td>
</tr>
<tr>
<td>Phytobial remediation</td>
<td>Microbes in the sediments helps in the reduction of metal contents.</td>
<td>Remediation rate is very slow and not enough satisfactory</td>
<td>[88]</td>
</tr>
<tr>
<td>Endophyte remediation</td>
<td>Bacteria and fungi in plant’s body increase accumulation and uptake of metals in plants</td>
<td>Further depends on plants remediation</td>
<td>[89,90]</td>
</tr>
<tr>
<td>Rhizomicrobe remedation</td>
<td>Certain microbes in a plant’s root secrete siderophores to increase solubilisation of metals</td>
<td>Need vast amount of Rhizomicrobe growth with suitable environment</td>
<td>[91,92]</td>
</tr>
</tbody>
</table>
5. Phytoremediation and Basic Types

Phytoremediation is the most straightforward and cost-effective method of reducing harmful metals by utilizing plants with metal-accumulating abilities. The potential of plants to remove toxic metals, particularly mangrove plants, has been demonstrated in several studies worldwide [3,93,94]. The researchers discovered that the production of iron plaques on the roots of mangrove plants plays a critical function in preventing Fe and As transfer to the aerial portions [95]. We expressed interest in this venture since some countries, particularly poor countries such as Bangladesh, cannot change the situation overnight because many people rely on the lines of work that pollute our environment regularly. Furthermore, due to their low national wealth, many countries’ governments cannot invest excessive amounts of money to keep the environment clean. Furthermore, scientists are developing a low-cost method of removing toxic metals from the ecosystem [27]. In this case, phytoremediation is the best option. Metals can be extracted without causing harm to the environment [96]. Phytoremediation, on the other hand, has a limited impact on depth intervention [97]. Phytoremediation can be accomplished in a variety of ways, as detailed below. The following are some of the most prevalent types of decontamination appliances.

5.1. Phyto-Extraction

Phytoaccumulation is another name for the process. This procedure described the toxic metals that accumulate in plants and are removed when harvested [98,99]. Because they require long-term treatment, highly contaminated regions such as shipbreaking yards can be considered for the phytoextraction procedure [100,101]. The phytoextraction technique can remove trace metals such as Cr, Cd, Cu, Co, Ag, Zn, Ni, Mo, Pb, and Hg [102]. Plants such as Avicennia alba and Acanthus ilicifolius [101] that can store metals in their aerial biomass (Table 3) are strong contenders for the phytoextraction process [98,99]. Mobile metals in roots enter the xylem tissue, where they are then translocated from roots to shoot and leaf tissues [71]. Continuous or natural phytoextraction and chemically induced phytoextraction are two ways to phytoextraction [103]. First, a network of roots extracts continuous phytonutrients, which are subsequently directed to upper plant tissues, which infil the soil to remove toxic metals [104] (Jadia and Fulekar, 2008). The harvested plant biomass, which is the result of continuous phyto-extraction, can produce biogas and be burned. Metal can also be recovered by combusting plant biomass and encasing it in bricks or dumping it in abandoned regions [105]. Agromining is also a good method for planting, harvesting the biomass, drying, ashing, and refining hyperaccumulator plants to recover target metals such as Ni [105,106]. By removing the aerial portions of the plants after the maximal accumulation in the body, any area can be successfully decontaminated using the phyto-extraction technique [104,107]. Metal content extraction is restricted to a maximum depth of 24 inches and shallow soil [108]. Deep-rooted popular trees are utilized for deeper depths, such as 6 to 10 feet, to avoid leaf litter and hazardous residuals [108].

5.2. Phytovolatilization

Plants (Table 3) receive volatile substances in this process and release them into the environment through their leaves at relatively low amounts [77]. Direct and indirect phytovolatilization are also possible. It has been proven that phytovolatilization eliminates toxic metals such as Se and Hg [109]. This method consists of three steps: first, plants absorb contaminants from the soil, then convert the contaminants into volatile molecules, and finally, release the volatile chemicals into the atmosphere. Metals such as mercury can be removed very effectively using phyto-volatilization [110]. It can convert Hg$^{2+}$ to HgO, a less harmful form of mercury. Furthermore, unlike phyto-extraction, the contaminated plant organs do not need to be disposed of [110]. In the phyto-volatilization process, porous soil decreases water levels, and chemical redistribution can aid [77].
5.3. Phyto-Stabilization

Phytostabilization involves plants absorbing metals from the soil and sequestering them in their roots, where they are converted into a non-toxic form and the soil is protected from contamination [111–114]. Several plants can endure various types and doses of harmful metals for extended periods, which is beneficial to this process [100,101] (Table 3). Of course, the level of toxicity and formation of metals differs from one metal to the next. However, in highly contaminated areas such as shipbreaking yards and tannery zones, the phyto-stabilization method can remove various harmful toxic metals such as Pb, Cr, Cu, and As [100,101,112]. These metal contents are kept in shipbreaking wastes such as lead-acid storage alloys, batteries, bearings, connections, couplings, anodes, bolts, nuts, and paints in the ship’s body structure [115]. Phytostabilization minimizes pollutant leaching by boosting the system’s evapotranspiration [111]. Furthermore, mechanical stabilization prevents soil erosion caused by wind or water [111].

5.4. Phyto-Reduction

Plants digest hazardous organic pollutants (Table 3), employing enzymes near the root-soil interface in this technique [116]. Metal concentration reduction can also occur outside of plants, as some plants secrete enzymes [117]. The following enzymes are involved in the phytodegradation process: (i) nitroreductase (reduction of aromatic nitro groups), (ii) oxidases (useful in TNT detoxification), (iii) phosphatases (most abundant in the environment and can transform organophosphate compounds), and (iv) nitrilases (change nitrile groups to carboxylic acid) [107,116,118]. It has been demonstrated that contaminants such as the herbicide atrazine, explosives trinitrotoluene [119], and the chlorinated solvent trichloroethane are metabolized [109].

5.5. Rhizo/Phyto-Filtration

Phyto-filtration is a method that reduces metal mobility in sediment by eliminating pollutants from the aqueous environment [120,121]. Plants (Table 3) remove toxins from polluted water by absorbing them in their roots throughout this process [77,122]. According to the plant parts employed, phyto-filtration can be classed as rhizofiltration (using plant roots), blastofiltration (using seedlings), or caulofiltration (using plant shoots) [123,124]. Toxic metals such as Pb, Cd, Cu, Ni, Zn, and Cr can be easily removed from the environment using the rhizofiltration process [109]. Phyto-filtration works best in coastal areas with high root biomass aquatic plants [93,125]. For rhizofiltration, terrestrial plants with fibrous root systems and rapid growth are preferred [109].

Table 3. Lists of plants which can be used in different phytoremediation techniques.

<table>
<thead>
<tr>
<th>Process</th>
<th>Plant Species</th>
<th>Metals</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phytoextraction</td>
<td>Acanthus ilicifolius</td>
<td>Cu, Pb, Ni, Cr</td>
<td>[101,126]</td>
</tr>
<tr>
<td></td>
<td>Alyssum bertoloni</td>
<td>Ni</td>
<td>[127]</td>
</tr>
<tr>
<td></td>
<td>Avicennia alba</td>
<td>Pb, Cd, Cr</td>
<td>[101,128]</td>
</tr>
<tr>
<td></td>
<td>Brassica juncea</td>
<td>Pb, Cu, Zn</td>
<td>[114]</td>
</tr>
<tr>
<td></td>
<td>Elsholtzia splendens</td>
<td>Cu, Zn, Pb, Cd</td>
<td>[127,128]</td>
</tr>
<tr>
<td></td>
<td>Helianthus annus</td>
<td>Cd, Ni, Pb, Zn</td>
<td>[129–132]</td>
</tr>
<tr>
<td></td>
<td>Noccaea caerulescens</td>
<td>Zn, Pb</td>
<td>[133]</td>
</tr>
<tr>
<td></td>
<td>Pisum sativum</td>
<td>Cd, Fe</td>
<td>[134]</td>
</tr>
<tr>
<td></td>
<td>Pteris vittata</td>
<td>As, Cu, Cr</td>
<td>[135]</td>
</tr>
<tr>
<td></td>
<td>Ricitus communis</td>
<td>Co, Ni, Mn, Cu, Pb</td>
<td>[135]</td>
</tr>
<tr>
<td></td>
<td>Tagetes sp.</td>
<td>Cd, Pb, Zn</td>
<td>[129]</td>
</tr>
<tr>
<td></td>
<td>Thlaspi caerulescens</td>
<td>Cd, Ni</td>
<td>[135,136]</td>
</tr>
<tr>
<td></td>
<td>Verbena sp.</td>
<td>Pb, Cd</td>
<td>[137–139]</td>
</tr>
</tbody>
</table>
Table 3. Cont.

<table>
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<th>Process</th>
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<th>Metals</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Phytodegradation</td>
<td>Armoracia rusticana</td>
<td>As, Cu</td>
<td>[140]</td>
</tr>
<tr>
<td></td>
<td>Canadian waterweed</td>
<td>Zn, Cu, Cd</td>
<td>[141]</td>
</tr>
<tr>
<td></td>
<td>Cyperus alternifolius</td>
<td>Fe, Pd, Cr, Cu</td>
<td>[142]</td>
</tr>
<tr>
<td></td>
<td>Cydonia dactylon</td>
<td>Mn, Cu, Fe, Pb</td>
<td>[143]</td>
</tr>
<tr>
<td></td>
<td>Giant duckweed</td>
<td>Fe, Cr, Cu, Cd</td>
<td>[144]</td>
</tr>
<tr>
<td>Phytostabilization</td>
<td>Agrostis capillaris</td>
<td>Cu, Pb</td>
<td>[145]</td>
</tr>
<tr>
<td></td>
<td>Arundo donax</td>
<td>Ni, Cd</td>
<td>[146]</td>
</tr>
<tr>
<td></td>
<td>Ascolepis sp.</td>
<td>Co, Cu</td>
<td>[137]</td>
</tr>
<tr>
<td></td>
<td>Brassica juncea</td>
<td>Pb, Cu, Zn</td>
<td>[147]</td>
</tr>
<tr>
<td></td>
<td>Epilobium dodonaci</td>
<td>Cu, Zn, Pb</td>
<td>[146]</td>
</tr>
<tr>
<td></td>
<td>Eradostis sp.</td>
<td>Cr, Cd, Pb</td>
<td>[148]</td>
</tr>
<tr>
<td></td>
<td>Gladiolus sp.</td>
<td>Cd, Pb</td>
<td>[137]</td>
</tr>
<tr>
<td></td>
<td>Haumaenestrum sp.</td>
<td>Cu, Co, Ni</td>
<td>[137]</td>
</tr>
<tr>
<td></td>
<td>Iris sibirica</td>
<td>Ni, Co, Pb</td>
<td>[149]</td>
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<td>Nicotiana tabacum</td>
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<tr>
<td></td>
<td>Nicotiana rustica</td>
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<td>[150]</td>
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<tr>
<td></td>
<td>Silene vulgaris</td>
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<tr>
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<td>Cu, Zn, Cr</td>
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<td>Rose plant</td>
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<td>Astragalus bisulcatus</td>
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<td>Brassica juncea</td>
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<td>Cassia tora</td>
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<td></td>
<td>Chara canescens</td>
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<td>[133]</td>
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<td>Liriodendron tulipifera</td>
<td>Hg, Ni</td>
<td>[126]</td>
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<tr>
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<td>Nicotiana tabacum L.</td>
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<td>[128]</td>
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<td>Pteris vittata</td>
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<td>Fontinallis antipyretica</td>
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<td>[151]</td>
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<td></td>
<td>Helianthus annuus</td>
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<td>[152]</td>
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<tr>
<td></td>
<td>Limnocharis flava</td>
<td>Cu, Fe, Mn</td>
<td>[153,154]</td>
</tr>
<tr>
<td></td>
<td>Micranthum umbrosum</td>
<td>As, Cd</td>
<td>[143]</td>
</tr>
<tr>
<td></td>
<td>Phragmites australis</td>
<td>Cu, Cr, Ni, Fe</td>
<td>[155]</td>
</tr>
<tr>
<td></td>
<td>Pistia stratotes</td>
<td>Hg, Ag, Pb, Mn</td>
<td>[156]</td>
</tr>
<tr>
<td></td>
<td>Salix matsudana</td>
<td>Cu, Cd</td>
<td>[157–159]</td>
</tr>
<tr>
<td></td>
<td>Spirodela punctata</td>
<td>Cd, Cu, Zn</td>
<td>[153]</td>
</tr>
</tbody>
</table>

6. Molecular Adaptation Mechanisms of Toxic Metals in Higher Plants

Toxic metals such as Cd, Cu, and Fe harm plant cells because of their transitional nature, undermining oxidative potential and decreasing different biomolecules (e.g., GSH) [159–163]. The reaction of such biomolecules and other transition metals with harmful metals could improve the plant cell’s redox state. Furthermore, some hazardous metals can directly divide genetic materials (e.g., RNAs and DNAs) and plant protein linkages. The poisonous natures of toxic metals that cause physical damage to plants are avoided by maintaining a minimal concentration of free metal ions in the plant cell [164]. Metal accumulations and translocation into the cell, followed by protein interactions with the metals and the formation of organic ligands, are some of the steps that regulate this ionic state optimization [161,162]. Some transporter protein maintains the first two processes, metal accumulations, their translocation into the cell, and protein connections with...
the metals [165]. Zn and Fe regulated transport proteins (ZIP), toxic metal ATPase genes such as HMA2, HMA3, and HMA4, metal-binding proteins such as Cu-chaperone ATX1 proteins, metallothioneins (MTs), and phytochelatins (PCs) are the most important transporter proteins [165,166]. ZIPs have a critical role in the uptake and transport of divalent metal ions, which helps maintain homeostasis and equilibrium [167]. In the phytoremediation process, toxic metal ATPase genes are involved in metal uptake, translocation, and sequestration [168]. When combined with protein molecules, Cu binding domains are thought to aid in Cu intracellular homeostasis due to their Cu-chelating capabilities [169]. Furthermore, antioxidant proteins such as ATX1 and ATX2 have a high degree of sequence homology [169]. Forming organic ligands that interact with plant genes and are regulated by transcription and post-translational activities is the third phase. Molecular techniques in Arabidopsis thaliana hypersensitive mutants are utilized to identify the genes that produce organic ligands in plant tissue [164].

6.1. Accumulation and Translocation of Toxic Metals

Compared to typical plants, hyperaccumulator plants have several special properties, such as large amounts of metal uptake and a rapid and effective translocation rate of toxic metals from roots to shoots. Furthermore, they have remarkable effectiveness in binding or generating toxic metals into various chemical compositions, resulting in a decreased concentration of those toxic metals in the free ionic form. These characteristics resulted in hyper-accumulator species with enhanced ion transport tissue. For example, [170] found that A. halleri and T. caerulescens have genes linked to the ZIP family that encode the plasma membrane located transporters such as ZIP6 and ZIP9 in A. halleri and ZTN1 and ZTN2 in T. caerulescens and make additional uptake of Zn compared to non-hyperaccumulators. Though hyper-accumulators efficiently transport toxic metals from roots to shoots via xylem tissue, sensitive plant species must first detoxify metals in the cytoplasm of root cells, or vacuoles, before translocating and accumulating in shoots [171]. Compared to metals-sensitive plants, a representative hyper-accumulator plant such as T. caerulescens had a nearly two-fold faster translocation rate for Zn from roots to shoots and a near 50–70 percent lower concentration of Zn in roots [71,172]. If hyper-accumulators want to control the accumulation of metals and metalloids, they must maintain a balanced state in their plant tissues. Hyper-accumulators use a variety of transporters to maintain this equilibrium, including ATPases, ATP-binding cassette (ABC), cation diffusion facilitators (CDF), cation exchangers (CAXs), copper transporters (COPTs), and ZIPs, among others [173,174]. Hyper-accumulators, on the other hand, use non-selective channels or membranes to transport non-essential toxic metals such as Cd. Process transporters primarily aid in the movement of important plant nutrients such as Zn [175]. The P1B-ATPase subgroup of the HMA transporter family detoxifies metals and is involved in ATP-dependent transmembrane transport of essential and toxic metals [176]. The HMA4 and HMA5 transporters are members of the HMA family and are thought to be involved in long-distance root to shoot metal translocation [177].

6.2. Toxic Metals Detoxification

Hyper-accumulators can detoxify a large number of toxic metals without harming their leaves and stems. Cuticle, epidermis, and trichomes [178–183] are the principal sites of metal detoxification in plants [178]. Metal detoxification is an enzyme-controlled process that begins with the removal of organic ligands from the metabolic region and ends with ROS detoxification [184]. Biomolecules with thiol-producing capabilities, such as PCs, MTs, and GSH, can effectively detoxify toxic metals in plants [165]. These complexes are crucial in the plant’s metal tolerance mechanism. Phytochelatins, as well as heavy metals (PC-HM) Complexes, abound in plant tissue vacuoles. The HMT1 transporter, a member of the ABC family, first discovered in yeast, transports PC-HM complexes across vacuolar membranes [185] (Ortiz et al., 1995). The plant has a mechanism that is comparable to that of yeast. GSH, as with HMT1, aggressively detoxifies toxic metals and
works as a potent reducing agent, particularly for reactive oxygen species (ROS). When plants have a contact with a high concentration of toxic metals, ROS are produced in the plant’s sensitive organelles [165]. GSHs have also been linked to the reduction of $\text{H}_2\text{O}_2$ toxicity, the reduction of xenobiotics, a causative agent of a toxicant to flower growth, and the formation of salicylic acid [186–189]. Another GSH-regulated hazardous metal detoxification pathway is GSH-HM complexation and impoundment in vacuoles, with these complexes possibly being released to the apoplast [190]. Furthermore, metallothiones create MT-HM complexes (low molecular weight chelating protein molecule groups mainly found in cysteine). MTs are classified into four categories based on cysteine deposits’ formation [99], with differences in tissue structural specificity and metal element selectivity. MT1 and MT2b are two of the four types of chelators involved in Cd detoxification [191]. The fourth type of MTs, on the other hand, primarily detoxify Zn and, in comparison to the other three types, store larger Zn amounts at a given period [192].

6.3. Organic Acids and Toxic Metal Tolerance

Toxic metal annexation is a genetically overexpressed feature in plants carried out by CDF (cation diffusion facilitator family) genes [193]. MTPs (metal transporter proteins) are CDF twisted molecules involved in metal translocation across the plasma membrane and tonoplast [194]. MTP1, a CDF found in the tonoplast of leaves, is a key driver of Zn/Ni hyper-accumulation in hyperaccumulative plants’ leaves. The vacuole of *T. goesingense*, for example, is Zn/Ni hyperaccumulative due to overexpression of the CDF gene [193,195]. Furthermore, higher molecular mass organic ligands, such as phytochelatins, are unable to control the process of toxic metal decontamination since their synthesis requires a significant amount of metabolic cost and the presence of excessive sulfur [196]. Toxic metal detoxification, on the other hand, is the controlling mechanism of an antioxidant enzyme. As a result, antioxidant enzymes can easily deal with ROS-mediated stress caused by toxic metal toxicity in plants [194]. In hyper-accumulators, both antioxidant defense systems and increased production of GSH, which is overexpressed by genes, detoxify toxic metals.

7. Factors Influencing Phytoremediation

7.1. Types of Metal Elements in Plants

The effectiveness with which plants remove metals from a contaminated site is determined by the types of contaminants present, whether organic or inorganic. For example, metals existing in the environment as a single metal, such as Cr, Cu, Ni, Cd, Zn, and Pb, may be easily eliminated with greater efficiency [197]. On the other hand, micronutrients for plants, such as B, Zn, Fe, Cu, Mo, and Mn, are obtained from the soil in small amounts by a more efficient mechanism [102]. Such contents created chelating agents, plant-induced pH changes, and redox reactions that can solubilize in the soil are taken with the help of plants [198]. Metal-accumulative plant species can also concentrate and assimilate metal elements such as Pb, Co, Cd, and Ni linked with bacteria and fungus [102]. These bacteria can help with metal ion mobilization and the bioavailability of metals [199].

7.2. Pollutant Characteristics

Knowing the properties of contaminants is critical for selecting the best plants for removing them from the environment. Varying inorganic toxicants offer different threats to humans and the environment, depending on their speciation and overall concentration in the environment [200]. Furthermore, metal speciation in different plant species is well understood to determine metal bioaccumulation, metal remediation, and future metal fortification investigations [201]. As a result, scientists have determined that metal speciation in the soil is an important element in plant metal uptake [202]. The fraction of free metal contents present in the soil and the total metal concentration in the solid phase, on the other hand, can impact the bioavailability of metal elements and potential uptake [202,203]. Therefore, it is critical to understand the inorganic pollutants’ ion exchange capacity and water solubility for a successful phytoremediation process.
7.3. Selection of Plant Species

The choice of plant species is critical for achieving the greatest phytoremediation results. Plants typically have two types of roots: fibrous and tap root [109]. Taproots may be more efficient in absorption, whereas fibrous roots make more significant contact with the soil and eliminate a greater amount of contaminant [75]. According to the literature, in about 40 years more than 400 phytoextraction-capable plant species have been identified globally [204].

7.4. Climate Considerations

Temperature, weather, and water availability from rainfall, sunlight, and precipitation levels significantly impact seed germination and plant growth [109,204]. Further, climate considerations are to be described as follows:

7.4.1. Flooding, Aging, Light and Temperature

Enzyme activity rises when the environment is flooded. As a result, in flooded or aged mangrove sediment, the percentage of PAHs removed from the contaminated site is higher [205]. Microorganisms degrade the majority of the contaminant in this situation [206]. A mixture of warm and cold seasons can influence on the maximum uptake of arsenic, particularly in a temperate climate [207]. Light is essential for plant growth and also for phytoremediation. However, the impact of light intensity in phytoremediation is still poorly understood [208]. River flooding can extremely affect the process, especially the tropical and subtropical regions. Flow regime greatly dependents on hydrological droughts to floods which further include maintenance of biotic composition, integrity, and evolutionary potential of a river ecosystem associated with the floodplains and wetlands [209]. Sometimes, plants near the temperate maritime climate zone show suitable phytostabilisation of Cu, Pb, Mn, and Zn [210].

7.4.2. Effect of Salt and Other Soil Properties

The level of salinity in coastal regions is increasing due to saline water intrusion, directly impacting plant development patterns. In the end, it lowers the level of plant remediation. Furthermore, high salinity causes mangrove trees to have a small leaf area [161]. Because pH impacts the solubility and transport of metals in the soil, it directly impacts phytoremediation efficacy [207]. Metalloids (most anions) are immobilized, and the bioavailability of metals (metallic cations) rises in an acidic environment, but toxic metals, particularly Pb and Cr, become immobile in a neutral state [208]. Agronomical methods such as pH correction, the addition of chelators, and fertilizers can help promote phytoremediation [209]. The size of soil particles is important because fine particles hold more contaminants than coarse-textured soil [210,211]. Metal phytotoxicity is prevented by the presence of organic matter in the soil [14].

7.5. Waste Disposal Consideration

For better function of the phytoremediation, wastages should be managed in some ways. The wastage should be disposed of off-site regularly, which should be considered during the phytoremediation process because metal accumulated plant biomass removal is largely dependent on waste disposal [68].

7.6. Redox Potential

By utilizing oxidation-reduction reactions, redox potential alters metal speciation and turns contaminants into a less harmful, more stable, and inert form [111]. This type of reaction, however, is slow in sediment [212].
8. Other Uses of Phytoremediation

8.1. Remediation of Pesticides

The high concentration of pesticides in the sediment could impact soil productivity [213]. Degradation happens as a result of an enzyme-driven biological reaction [213]. Plant roots can release enzymes that degrade pesticides while also providing important nutrition for rhizospheric bacteria [214,215].

8.2. Treatment of Wastewater

Phytoremediation can also be used to treat wastewater. For example, dairy waste can be removed from water using plants such as Phragmites australis [216]. This method is very useful in the treatment of wetlands. Typha latifolia, Salix atrocinerea [217], Cyperus papyrus, Miscanthidium violaceum [218], and Quercus ilex [219] have all been shown to be capable of removing undesirable and dangerous contaminants from water.

8.3. Phyto-Mining

Phytomining is most likely the best solution for phytoremediation plants’ future. Plants employed in phytoremediation can be burned for energy much safer than coal-fired power plants [112]. Following the burning of plants, the residue is known as ‘bio-ore’, from which metals can be extracted quickly. For the extraction of Ni from phytoremediation plants, phytomining is a viable approach [220].

8.4. Phyto-Screening

Plants can accumulate metals in their body parts, which can be utilized as biosensors to detect toxins below the surface [221,222]. Phytoscreening will make the phytoremediation procedure easier to implement in the field and save money by allowing for a more efficient site evaluation [223].

9. Enhancement Technique of Phyto-Extraction Efficiency

Phyto-extraction efficiency can be enhanced by using the following approaches:

9.1. Common Approaches to Increase Toxic Metal Bioavailability

The accessibility of a soil-bound chemical for absorption and possible toxicity that can be chemically absorbed to reach an organism’s systemic circulation is referred to as bioavailability [224]. Phyto-availability of toxic metals can be improved with two conventional techniques: the use of synthetic chelates and a lowering of soil pH [205,225–229]. To lower the pH of the soil, A unique technique is employed; the soil is treated with acids or acid-producing fertilizers [229–232]. Synthetic chelates, such as EDTA and EDDS, on the other hand, are particularly effective options for enhancing the approachability of toxic metals entering plant roots and forming decipherable complexes with metals [204,233–235]. Nonetheless, there is a major issue with soil quality; in general, these technologies have negative effects on the soil’s physical and biochemical characteristics and polluting groundwater [152,229,236,237]. However, using acidified guano to lower soil pH has proven to be a sustainable method of increasing toxic metal bioavailability [238].

9.1.1. Chelate-Assisted or Induced Phyto-Extraction

Chemically induced phyto-extraction has been offered as an alternative to plants’ slow growth rate and low biomass, in which large biomass and fast-growing crops are employed to extract vast quantities of toxic metals whose mobility in soil is increased by chelating agents [11,239,240]. Plants have been identified as chelating agents for removing and detoxifying harmful metals [20,241]. Chemically induced phyto-extraction with chelating agents can be accomplished in several ways. For example, increasing the concentration of toxic metals in the soil solution promotes the migration of metal-EDTA complexes towards roots. Second, many subsequent complexes and less negative complexes destroy negatively charged cell components of the plant cell wall or physiological barriers in roots.
Third, greater mobility of complexes has more metal translocation capability from roots to shoots than free ions [242]. EDTA (ethylene diamine tetra acetic acid) has been utilized as a chelating agent to improve the phyto-extraction process since the 1990s. Even though EDTA can increase toxic metal accumulation by a factor of a hundred in comparison to EDTA-trace element complexes [243,244], both are extremely hazardous to plants and the soil microbial population [245,246]. Although EDTA has poor biodegradability, it also promotes toxic metal leaching, resulting in groundwater pollution [247]. In this way, microorganism-produced ethylene diamine disuccinate (EDDS) is a naturally occurring boosting material that is particularly successful at increasing toxic metal intake while reducing the risk of water pollution [248]. In contrast to EDTA, which is less bioavailable to Pb and Cd, EDDS improves the solubilizing and mobilization of Cu, Ni, and Zn [249,250].

Trace element-EDDS complexes penetrate the roots and are subsequently delivered directly to the shoots [251]. EDDS, on the other hand, is harmful to some plants but not to soil microbes. Furthermore, nitrilotriacetic acid (NTA) is a biodegradable chelating agent with no phytotoxic effects that have been employed to improve phyto-extraction proficiency [127,252–255].

9.1.2. Biological Sulfur Oxidation to Reduce pH and Enhance Metal Bioavailability in Soil

Elemental sulfur, which has a slow-release acidifying property and is easily available, has a beneficial influence on soil pH and helps to improve metal solubility [54,256–259]. Moreover, sulfur is one of the most common and cost-effective natural acidifying components, among most other factors. The most active bacterium is Thiobacillus [260]. Thiobacillus acidifies the soil by oxidizing one mole of elemental sulfur and returning two moles of hydrogen ions [261]. For example, [262] found that soil fed with elemental sulfur at rates of 0.5, 1, and 2 g/kg soil resulted in pH decreases from 7.51 to 6.66, 5.45, and 4.8, respectively, after a 40-day experiment. Although soil temperature and humidity are two important parameters that influence the amount of microbial sulfur oxidation acid produced by Thiobacillus bacteria in soil, the ratio of sulfur to total soil solids is also important [263].

9.1.3. Through the Application of Microbial Augmented Acidified Cow Dung

According to Ashraf et al., 2018, the application of the acidified product in Pb- and Cd-polluted soil improved the bioavailability of those metals. The concentrations of Pb and Cd in ryegrass shoots were found to be 114 percent and 126 percent, respectively. To begin, isolated toxic metal resistant sulfur-oxidizing bacteria (SOB) were used to bio-augment cow dung, and acidity was achieved by adding elemental sulfur (S⁰) and molasses solution. The bioavailability of Pb and Cd from soil to grasses employed for phyto-extraction was then increased in tub trials by introducing bio-augmented acidified cow dung. The mechanism of acidity in cow dung is based on the equation below [238].

\[
{S}^{0} \text{(Sulfur)} + 3{O}_2 \text{(Oxyzen)} + 2{H}_2{O} \xrightarrow{\text{SOB, Molasses}} 2{H}_2{SO}_4 \text{(Sulfuric Acid)}
\]

According to Ashraf et al., 2018, the MIC of added SOB for Pb and Cd was 1000 mg/L and 180 mg/L, respectively, and SOB oxidize elemental sulfur (S⁰) and create sulfuric acid (H2SO4). As a result, by lowering the pH of the soil, acidified cow dung increased the bioavailability of Pb and Cd. According to Ashraf 2017, diluted acidified cow dung reduced the soil pH by 0.92 points, which increased the content of Pb and Cd in the ryegrass sprout. Pb increments ranged from 44 to 94.32 mg/kg, while Cd increments ranged from 34 to 77 mg/kg. The key ingredients in phyto-extraction are high plant biomass and acidified cow dung, rich in nutrients and microorganisms with a low pH. As a result, plant growth is aided by both nutrients and microbes. For a short time, acidified cow dung lowered soil pH and increased Cd and Pb bioavailability. Sulfate ions in acidified cow manure react with water to generate sulfuric acid (H2SO4). H2SO4 reacts with CaCO3 and dissolves it to...
generate the fertilizer $\text{CaSO}_4$ when bioaugmented cow dung is applied, as illustrated in the equation below.

$$\text{H}_2\text{SO}_4 + \text{CaCO}_3 \rightarrow \text{CaCO}_4 + \text{H}_2\text{O} + \text{CO}_2$$

9.1.4. Phyto-Siderophores

In reaction to Fe scarcity, microbes and graminaceous plants secrete siderophores, which are Fe chelating compounds. As a result, the necessity of plant disease suppression through the mediation of healthy competition, such as Fe, is being investigated [264,265]. In general, it is investigated to verify that microorganisms do not affect a plant’s Fe uptake in a non-sterile condition [266]. Plants absorb Fe via this process [107]. Phyto-siderophores also help with Cu, Mn, and Zn absorption [267,268]. Three methionines are connected with non-peptide bonds to generate phyto-siderophores, a type of nicotinamide [269].

9.2. Increasing Plant Biomass and Decreasing Phyto-Extraction Cycle

Phyto-extraction, which removes toxic metals from plants, relies heavily on plant biomass. As a result, fertilizers and adequate watering systems can help boost phytoremediation capacity [270,271]. However, shortening the long cycle of phytoextraction pathways is another strategy to improve phytoremediation efficiency. The phytoremediation cycle can be shortened by meeting specific plant species requirements, such as moving seedlings of specific plant species directly to the desired field to confirm the extra time for phytoremediation. This method will shorten the time it takes for a plant to adapt to a certain field. Because [272] discovered that the largest accumulation of toxic metals in plant shoots occurs during the blossoming phase, this method is critical.

10. Use of Metallophytes for Phyto-Extraction

Metallophytes are plants that belong to the Brassicaceae plant family that can survive in toxic metal-polluted soil. They are divided into three categories: excluders, indicators, and hyper-accumulators [273–275]. Metal excluders are plants that take in toxic metals from the environment and store them in their roots but are unable to transport them to above-ground plant tissues [276]. On the other hand, metal indicators absorb toxins from polluted soil and store them in their top sections [275]. The accumulative capability of a metal hyperaccumulator should be at least 100 mg/kg for As and Cd, 1000 mg/kg for Cu, Cr, Co, Ni, and Pb, and 1000 mg/kg for Mn and Ni [277]. In response to plant pathogenic agents, the hyper-accumulator of toxic metals act as a resistance mechanism [278]. More than 400 hyper-accumulator plant varieties have been identified, all of which grow slowly and produce minimal biomass [127,279].

11. Nanoparticles in Phytoremediation

The ability of plants to absorb metals is critical to phytoremediation’s success. Plants’ stress tolerance is increased by nanoparticles, which cause them to produce more phytohormones [280]. The plant does not accept metals in complex forms. Nanoparticles such as nano-chlorapatite, nZVI, and carbon nanotubes can break down contaminants and shorten their lifetimes, allowing plants to absorb metals in their natural state (Table 4). [281]. Furthermore, the nanoparticle can swiftly infiltrate the polluted area and is more reactive than bulk metals [282,283]. The authors of [147] discovered that adding fullerene nanoparticles to phytoremediation increased the absorption rate of trichloroethylene by 82 percent. After using nZVI particles to remove trinitrotoluene from the site using Panicum maximum, it was discovered that the process took half the time it usually did to disinfect the site [284].
Table 4. List of plants used with nanoparticles to remove pollutants.

<table>
<thead>
<tr>
<th>Metals</th>
<th>Plants</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb</td>
<td><em>Lolium perenne</em> L., <em>Eucalyptus</em>, <em>Glycine max</em></td>
<td>[283–287]</td>
</tr>
<tr>
<td>As</td>
<td><em>Helianthus annuus</em>, <em>Isatis cappadocica</em></td>
<td>[280,288]</td>
</tr>
<tr>
<td>Cd</td>
<td><em>Boehmeria nivea</em>, <em>Secale montanum</em>, <em>Zea mays</em>,</td>
<td>[282,289,290]</td>
</tr>
<tr>
<td></td>
<td><em>Trichloroethylene</em></td>
<td></td>
</tr>
<tr>
<td>Cr</td>
<td><em>Eucalyptus globulus</em>, <em>Jatropha curcas L.</em>, <em>Eucalyptus</em></td>
<td>[102,287,291]</td>
</tr>
<tr>
<td></td>
<td><em>Endosulfan</em></td>
<td>[292]</td>
</tr>
</tbody>
</table>

12. Modified Remediation Techniques

The degree of pollution, as well as the level of toxicity, is rising with time. As a result, various artificial procedures, such as induced phytoextraction, biochar-assisted phytoremediation, microbial-assisted phytoremediation, and the use of transgenic plants, are utilized around the world to remove contaminants from the environment in a short period (Table 5).
<table>
<thead>
<tr>
<th>Tools/Techniques</th>
<th>Mechanism</th>
<th>Pre-Requisite</th>
<th>Phytoremediation Potential</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Induced phytoextraction or use of non-hyperaccumulator plants</td>
<td>Artificial and organic chelating agents: ethylene diamine tetraacetic acid (EDTA), diethylene triamine pentaacetic acid (DTPA), and ethylene glycol tetraacetic acid (AGTA) are used to enhance the metal bioavailability of Non-hyperaccumulator plants [293]. Phenolic compound such as salicylic acid (SA) acts as signaling molecule in hyperaccumulate plants under biotic and abiotic stress conditions [294] and protect the plants from HM stress. Acetic acid, citric acid, malic acid and oxalic acid form biodegradable metal complexes with HM [295].</td>
<td>Plants have to be more biomass productive, Enhanced growth rate and comparatively higher above ground surface.</td>
<td>Pretreatment of combined SA and different chemical molecule alleviate toxic effects of toxic metals. Therefore, metal extractor plants resulting increased biomass production. SA treatment in Cd containing growth medium influenced the Seed germination parameters and seedling growth in rice [296], as well as chlorophyll substances, proline levels, leaf, and relatively improved water content in maize [297].</td>
<td>High uptake rate of toxic metal causes toxicity [295] and creates low biomass production of toxic tolerant plants. High economic costs of synthetic chelating agents and phytoextraction at large scale [297] are the critical limitations.</td>
</tr>
<tr>
<td>Biochar-assisted phytoremediation</td>
<td>toxic metals-biochar complexes (functional groups existing in biochar) can formed either by direct adsorption in surface area or by interchanging of toxic metal cations with other metal cations (i.e., Na⁺, K⁺, Ca²⁺, Mg²⁺) (Lu et al., 2011).</td>
<td>Low pH, large surface area for extra accumulation of metals, low alkaline nature, law ash, high carbon contents for higher adsorption capacity [295].</td>
<td>By proving necessary environment for useful microbes, Biochar Influences the soil microbial community. Containing some suppressing chemical compounds it also destroys pathogens for plants in soil as well [298]. High nutrient and water holding capacity, cation exchange capacity (CEC), and High pH of biochar effects nutrient cycling and improves nutrient turnover, indirectly enhance plants growth and biomass production up to 10% [299,300].</td>
<td>High pH and alkalinity properties of biochar may lead to depression of the bioavailability of metals, sometime creates reverse effect of metal uptake from soil rather to increase their precipitation in soil [301,302].</td>
</tr>
<tr>
<td>Tools/Techniques</td>
<td>Mechanism</td>
<td>Pre-Requisite</td>
<td>Phytoremediation Potential</td>
<td>Limitations</td>
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<td>Microbial-assisted phytoremediation</td>
<td>Microorganisms live in association with plant roots and free living can influence toxic metal phytoremediation by up taking in plants at the rhizosphere. Mycorrhizal modifies the chemical composition of the plant root exudates and associate soil pH, enhances toxic metal bioavailability from the soil to plant through. Moreover, These fungi in plant roots indirectly provide service to phytoremediation through assisting the plant by supplying available metals (Zn, Co, Ni and Cu) as nutrients through wide hyphal network [303,304]. Plant growth promoting bacteria (PGPR) remediate toxic metal contamination by symbiosis and free rhizobacterial activity [305].</td>
<td>Must have availability of Mycorrhizal fungi such as ectomycorrhizas, arbuscular mycorrhizas, orchid mycorrhizas and ericaceous mycorrhizas, with arbuscular mycorrhizal fungi [304]</td>
<td>Enhanced Pb uptake founds in Kummerowia striata, Ixeris denticulate and Echinochloa crusgalli when they together work with arbuscular mycorrhizal fungi (AMF) inoculums [306]. PGPR bacteria reduces ethylene production under stress as well as nitrogen fixation and specific enzyme activity results in increased plant growth [307]. Cu toxicity alleviates by Brassica napus in association with Pseudomonas putida inoculums [308].</td>
<td>The use of suitable microbial inoculum for assisting plant species to remediate toxic metals from soil effectively is very troublesome work. Consideration or selection of hyperacculaters or non-hyperaccumulators friendly combined fungus community is a research specific work [308].</td>
</tr>
<tr>
<td>Use of transgenic/Genetically modified plants</td>
<td>The removal or detoxification of hazardous organic pollutants based on the over expression of specific genes involved in uptake, translocation, appropriation and plant acceptance of xenobiotic complexes through genetic engineering in transgenic plants [309]. Specific genes to develop transgenic plants achieved from microbes, plants and animals can be introduced using two ways either direct DNA methods of gene transfer or Agrobacterium tumefaciens-mediated transformation [305]. Transgenic plants such as Arabidopsis thaliana and Nicotiana tabaccum having overexpression of gene responsible for expressing mercuric ion reductase to increase Hg tolerance and a yeast metallothionein expressing gene for tolerance against Cd respectively were developed for remediation of metals from soil [310]. Bacterial gene ArsC achieved from E. Coli applied into transgenic species Thlaspi caerulescens reeducates arsenate from soils [311]. Seth 2012 proposed bacterial genes merA encodes mercuric ion reductase and merB organo-mercurial lyase in transgenic plants upgrade the plant tolerance against Hg.</td>
<td></td>
<td>Single metal accumulation is not sufficient to fulfill the target of phytoremediation because phytoremediation must be cost effective and the transgenic plants must be more metals accumulative.</td>
<td></td>
</tr>
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</table>
13. Quantification of Phyto-Extraction Efficiency

A bio-concentration factor, a translocation factor, and the period of phytoremediation are used to determine the quantitative potentiality of phyto-extraction [312]. The bio-concentration factor assesses a plant’s ability to concentrate metals from the environment into its tissues [313]. The translocation factor measures a plant’s ability to move concentrated metals from its roots to its shoots [52]. As a result, the translocation factor is defined as the ratio of toxic metal concentration in the plant’s tissues to its roots [314,315]. When choosing natural hyper-accumulators for metal phyto-extraction, bio-concentration and translocation characteristics are critical [316]. To be excellent natural hyper-accumulators, the plant must show a translocation factor greater than one, indicating that metal concentrations are higher in above-ground tissues than in below-ground tissues. As a result, phyto-extraction is linked to the translocation factor, which entails extracting plant components while flying [17,317].

14. Duration of Phytoremediation

Before beginning the phytoremediation process, it is necessary to examine the length, which is determined by numerous elements such as the type of pollutants and their level of toxicity, the age and power of the plants chosen, the duration of pollution, and the surrounding environment [52,284].

15. Economics of Phytoremediation

Phytoremediation is a cost-effective, environmentally benign method that may be easily implemented in impoverished countries. It is superior to and more successful than other traditional soil and aquatic cleanup techniques [98,109]. The majority of phytoremediation research focuses on biological, biochemical, and agronomic factors [112]. The Total Economic Value (TEV) strategy is a well-known tool for assessing the benefits of land re-establishment among various approaches [318]. The TEV technique is based on the direct appraisal of productivity changes before and after soil degradation. Phytoremediation with native wetland plants is much less expensive than other approaches [187]. Phytoremediation costs are broken down into three categories: operation, design, and installation, each of which impacts the bottom line [109]. The amount of money required for phytoremediation varies depending on the methodology. Despite this, the cost of physically or chemically removing lead from the soil is expected to be double that of phytoremediation [109,319]. Lewandowski et al., 2006 and Wan et al., 2016 both reported comparable findings. Phytoremediation was 50–80 percent less expensive than earlier approaches for soil reclamation [109].

16. Advantages of Phytoremediation

As opposed to conventional physical and chemical processes, phytoremediation procedures can be more publicly acceptable, less disruptive, and overall environmentally beneficial [320,321]. Furthermore, after phyto-extraction, the harvested plant biomass can be a plentiful supply for biosorbent, bio-oil, and bioenergy generation [63,322–324]. Phytoremediation is a promising clean-up approach for removing trace metals from contaminated soil, despite some limitations, such as the sluggish development rate of metal-accumulating plant species. Another drawback is that soils with higher ion exchange rates have higher adsorption rates but lower bioavailability [325–328]. Furthermore, when the frequency of contact between the pollutants and the soil rises, the bioavailability decreases [325,329]. On the other hand, phytoremediation is best suited to big sites and is a low-cost choice and strategy for cleaning up environmental media [326,330–332].
17. Scope for Future Research

The phytoremediation technique has a wide range of research opportunities. For an effective phytoremediation process, plants with a high tolerance and high root biomass should be discovered. Methods for preventing aquatic organisms from feeding on remedi- ated plants should be developed. Future research should also examine the development of transgenic plants and the usage of microbes. To acquire the optimum results from phytoremediation, its duration should be reduced, and more beneficial uses of phytoremediated plants should be made.

18. Conclusions

Phytoremediation is a time-consuming process, and if plant development is slow, remediation efficiency will be low. Types of pollutants, pollutant characteristics, plant species selection, climatic considerations, waste disposal concerns, floods and aging, salt, soil properties, and redox potential are some notable aspects that influence the phytoremediation process. Phytoremediation methods are also being investigated to lessen their problems, despite their remarkable effectiveness and advantages with progress. On the other hand, phytoremediation may not be the best option in a substantially polluted area for a long time. Contamination of the food chain can occur due to a lack of sufficient care and management. Phytoremediation is a new method that may minimize contamination in both the soil and the water. It is a low-cost, ecologically friendly method that has been proven to be superior to traditional procedures. The scope of phytoremediation, on the other hand, is immense and has to be researched.


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