applied sciences

MDPI

Review

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

S. M. Omar Faruque Babu [1], M. Belal Hossain [2,3,*], M. Safiur Rahman [4], Moshiur Rahman [5], A. S. Shafiuddin Ahmed [6], Md. Monjurul Hasan [7], Ahmed Rakib [8,†], Talha Bin Emran [9,*], Jianbo Xiao [10] and Jesus Simal-Gandara [10,*]

[1] EON Group, Technical Service Division, Dhaka 1208, Bangladesh; omar.faruque@eongroup.net.bd
[2] Department of Fisheries and Marine Science, Noakhali Science and Technology University, Sonapur 3814, Bangladesh
[3] School of Engineering and Built Environment, Griffith University, Nathan Campus, Nathan, QLD 4222, Australia
[4] Water Quality Research Laboratory, Chemistry Division, Atomic Energy Centre Dhaka (AECD), Bangladesh Atomic Energy Commission, Shahbag, Dhaka 1000, Bangladesh; safiur.rahman@dal.ca
[5] Department of Fisheries (DoF), Ministry of Fisheries and Livestock, Dhaka 1000, Bangladesh; moshiur01@gmail.com
[6] Technical Service Division, Opsonin Pharma Ltd., Dhaka 1000, Bangladesh; sayeedrrahman@gmail.com
[7] Bangladesh Fisheries Research Institute, Riverine Station, Chandpur 3602, Bangladesh; mhshihab.hasan@gmail.com
[8] Department of Pharmacy, Faculty of Biological Sciences, University of Chittagong, Chittagong 4331, Bangladesh; rakib.pharmacy.cu@gmail.com
[9] Department of Pharmacy, BGC Trust University Bangladesh, Chittagong 4381, Bangladesh
[10] Nutrition and Bromatology Group, Department of Analytical and Food Chemistry, Faculty of Food Science and Technology, University of Vigo, Ourense Campus, E32004 Ourense, Spain; jianboxiao@uvigo.es
* Correspondence: mbhnstu@gmail.com (M.B.H.); talhabmb@bgctub.ac.bd (T.B.E.); jsimal@uvigo.es (J.S.-G.); Tel.: +880-1819-942-214 (T.B.E.); +34-988-387-000 (J.S.-G.)
† Present address: Department of Pharmaceutical Sciences, College of Pharmacy, The University of Tennessee Health Science Center, 881 Madison Ave., Memphis, TN 38163, USA.

check for updates

Citation: Babu, S.M.O.F.; Hossain, M.B.; Rahman, M.S.; Rahman, M.; Ahmed, A.S.S.; Hasan, M.M.; Rakib, A.; Emran, T.B.; Xiao, J.; Simal-Gandara, J. Phytoremediation of Toxic Metals: A Sustainable Green Solution for Clean Environment. *Appl. Sci.* **2021**, *11*, 10348. https://doi.org/10.3390/app112110348

Academic Editor: Massimo Zacchini

Received: 19 September 2021
Accepted: 20 October 2021
Published: 3 November 2021

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 1. Source, effect and limit of different harmful metals.

Toxic Metal	Sources		Harmful Effects on Human	Harmful Effects on Aquatic Lives	Standard Limit for Fresh Water (µg/L)	Standard Limit for Marine Water (µg/L)	Standard Limit for Sediment (µg/g)	References
	Natural Sources	Anthropogenic Sources						
As	Oxyanions of trivalent arsenite	Pesticides, wood additives	essential cellular processes such as oxidative phosphorylation and ATP synthesis disrupted by As (as arsenate)		5 [c]	24 [a]	20 [a]	[43,44]
Cd	Rock phosphate	Plastic stabilizers, dyes and colorants, ement manufacturing, power generating stations, metal recycling industries	Oncogenic, mutagenic, and teratogenic; Disrupt endocrine system; chronic anemia, restricts calcium ruling in biological systems and causes kidney failure	Decrease growth in juvenile, impairs aquatic plant growth	5 [a]	5.5 [a]	1.5 [a]	[43–46]
Cu	Rock phosphate	Zinc mixed fertilizers	brain and kidney mutilation, liver cirrhosis and chronic anemia raised from massive dosage, stomach and intestinal impatience	Inhibit skeletal ossification, decrease vitamin C	50 [b]	1.3 [a]	65 [a]	[47–49]
Cr	Chromite ore ($FeCr_2O_4$) present in mafic and ultramafic rocks	Steel and leather industries, filthy biosolids and composts, fly slag	Elevated dosage Cause hair fall	Cause low growth of both fish and plants; mortality occurs if present in high level	100 [c]	4.4 [a]	80 [a]	[49–51]

Table 1. *Cont.*

Toxic Metal	Sources		Harmful Effects on Human	Harmful Effects on Aquatic Lives	Standard Limit for Fresh Water (μg/L)	Standard Limit for Marine Water (μg/L)	Standard Limit for Sediment (μg/g)	References
	Natural Sources	Anthropogenic Sources						
Hg	Mining from natural sources	coal burning, medical gadgets, medicinal left-over	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 disfunctions.		0.02 [e]	0.02 [e]	0.2 [e]	[52,53]
Ni	Direct leaching from rocks and sediments	Metal rerolling industry, kitchen machines, clinical appliances, batteries and steel amalgams	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	Disrupt plasma and cause trouble in respiration	100 [c]	70 [a]	21 [a]	[52–61]

Table 1. *Cont.*

Toxic Metal	Sources		Harmful Effects on Human	Harmful Effects on Aquatic Lives	Standard Limit for Fresh Water (µg/L)	Standard Limit for Marine Water (µg/L)	Standard Limit for Sediment (µg/g)	References
	Natural Sources	Anthropogenic Sources						
Pb	Atmospheric depositon, occuring ores, and soil errosion	Lead generated fuels use in both urban and aqua traffic, electric based batteries, insecticides and weedicides	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	Cause scoliosis, inhibit photosynthesis and affect the gill of fish	10 [d]	4.4 [a]	50 [a]	[62–65]
Zn	Rock weathering, soil erosion, pedogenetic processes	Pesticides and fertilizers in agricultural soil	dizziness and lethargy caused due to Over dosage		5 [a]	15 [a]	200 [a]	[45,47]

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.

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

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 *Aviciennia 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 inflight 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 phyto-volatilization 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.

Process	Plant Species	Metals	References
Phytoextraction	*Acanthus ilicifolius*	Cu, Pb, Ni, Cr	[101,126]
	Alyssum bertolonii	Ni	[127]
	Aviciennia alba	Pb, Cd, Cr	[101,128]
	Brassica juncea	Pb, Cu, Zn	[114]
	Elsholtzia splendens	Cu, Zn, Pb, Cd	[127,128]
	Helianthus annus	Cd, Ni, Pb, Zn	[129–132]
	Noccaea caerulescens	Zn, Pb	[133]
	Pisum sativum	Cd, Fe	[134]
	Pteris vittata	As, Cu, Cr	[135]
	Ricinus communis	Co, Ni, Mn, Cu, Pb	[135]
	Tagetes sp.	Cd, Pb, Zn	[129]
	Thlaspi caerulescens	Cd, Ni	[135,136]
	Verbena sp.	Pb, Cd	[137–139]

Table 3. *Cont.*

Process	Plant Species	Metals	References
Phytodegradation	*Armoracia rusticana*	As, Cu	[140]
	Canadian waterweed	Zn, Cu, Cd	[141]
	Cyperus alternifolius	Fe, Pd, Cr, Cu	[142]
	Cynodon dactylon	Mn, Cu, Fe, Pb	[143]
	Giant duckweed	Fe, Cr, Cu, Cd	[144]
Phytostabilization	*Agrostis capillaris*	Cu, Pb	[145]
	Arundo donax	Ni, Cd	[146]
	Ascolepis sp.	Co, Cu	[137]
	Brassica Juncea	Pb, Cu, Zn	[147]
	Epilobium dodonaei	Cu, Zn, Pb	[146]
	Eragrostis sp.	Cr, Cd, Pb	[148]
	Gladiolus sp.	Cd, Pb	[137]
	Haumaniastrum sp.	Cu, Co, Ni	[137]
	Iris sibirica	Ni, Co, Pb	[149]
	Nicotiana tabacum	Cd, Cu	[142]
	Nicotiana rustica	Cd, Cu	[150]
	Silene vulgaris	Zn, Cu, Cd	[140]
	Phragmites australis	Cu, Zn, Cr	[150]
	Rose plant	Cr, Zn, Hg	[149]
	Suaeda maritime	Cu, Zn	[112]
	Sedum alfredii	Zn, Cd	[151]
	Sesuvium portulacastrum	Cd, Ni	[112]
	Zannichellia peltata	Cd, Ni	[145]
Phytovolitization	*Arabidopsis thaliana*	Cd, Zn	[130]
	Astragalus bisulcatus	Se, Pb	[112]
	Brassica juncea	Pb, Cu, Zn	[138]
	Brassica napus	Cr, Cu, Pb	[130]
	Cassia tora	Fe, Zn, Cu, Pb	[131]
	Chara Canescens	Cr, Pb	[133]
	Liriodendron tulipifera	Hg, Ni	[126]
	Nicotiana tabacum L.	Pb, Cd, Cu	[128]
	Pteris vittata	As, Cd	[139]
	Stanleya pinnata	Cr, As, Pb, Cu	[33]
Phytofiltration	*Eichhornia crassipes*	Pb, Zn, Hg, Ni, Cd	[93]
	Fontinalis antipyretica	Co, Cr, Cu, As	[151]
	Helianthus annuus	Cd, Ni, Zn	[152]
	Limnocharis flava	Cu, Fe, Mn	[153,154]
	Micranthemum umbrosum	As, Cd	[143]
	Phragmites australis	Cu, Cr, Ni, Fe	[155]
	Pistia stratiotes	Hg, Ag, Pb, Mn	[156]
	Salix matsudana	Cu, Cd	[157–159]
	Spirodela punctata	Cd, Cu, Zn	[153]

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 cassettes (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 H_2O_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 those 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 (S°) 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].

$$S^{o}\ (\text{Sulfur}) + 3O_2\ (\text{Oxyzen}) + 2H_2O \quad \overrightarrow{\text{SOB, Molasses}} \quad 2H_2SO_4\ (\text{Sulfuric Acid})$$

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 (S°) 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 (H_2SO_4). H_2SO_4 reacts with $CaCO_3$ and dissolves it to generate the fertilizer $CaSO_4$ when bioaugmented cow dung is applied, as illustrated in the equation below.

$$H_2SO_4 + CaCO_3 \rightarrow CaCO_4 + H_2O + CO_2$$

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 phytoremediation 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.

Metals	Plants	References
Pb	*Lolium perenne* L., *Eucalyptus*, *Glycine max*	[283–287]
As	*Helianthus annuus*, *Isatis cappadocica*	[280,288]
Cd	*Boehmeria nivea*, *Secale montanum*, *Zea mays*,	[282,289,290]
Trichloroethylene	*Populus deltoides*, *Lolium perenne*	[283]
Cr	*Eucalyptus globulus*, *Jatropha curcas* L., *Eucalyptus*	[102,287,291]
Endosulfan	*Ocimum sanctum*, *Alpinia Calcarata*, *Cymbopogon citratus*	[292]

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 5. Different artificial remediation technique.

Tools/ Techniques	Mechanism	Pre-Requisite	Phytoremediation Potential	Limitations
Induced phytoextractionor use of non-hyperaccumulator plants	Artificial and organic chelating agents; ethylene diamine tetraeacetic acid (EDTA), diethylene triamine pentaeacetic acid (DTPA), and ethylene glycol tetraeacitic 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].	Plants have to be more biomass productive, Enhanced growth rate and comparatively higher above ground surface.	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].	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.
Biochar-assisted phytoremediation	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^+, Ca^{2+}, Mg^{2+}) (Lu et al., 2011).	Low pH, large surface area for extra accumulation of metals, low alkaline nature, law ash, high carbon contents for higher adsorption capacity [295].	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].	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].

Table 5. *Cont.*

Tools/ Techniques	Mechanism	Pre-Requisite	Phytoremediation Potential	Limitations
Microbial-assisted phytoremediation	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 phytoremdiation 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].	Must have availability of Mycorrhizal fungi such as ectomycorrhizas, arbuscular mycorrhizas, orchid mycorrhizas and ericaceous mycorrhizas, with arbuscular mycorrhizal fungi [304]	Enhanced Pb uptake founds in *Kummerowia striata*, *lxeris 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 puteda* inoculams [308].	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].
Use of transgenic/ Genetically modified plants	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-mercuial lyase in transgenic plants upgrade the plant tolerance against Hg.	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.

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 remediated 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.

Author Contributions: Conceptualization, S.M.O.F.B., M.B.H., M.S.R. and M.R.; investigation and resources, S.M.O.F.B., M.B.H., M.S.R., M.R., A.S.S.A., M.M.H., A.R. and T.B.E.; writing—original draft preparation, S.M.O.F.B., M.B.H., M.S.R. and M.R.; writing—review and editing, A.R., J.X., T.B.E. and J.S.-G.; visualization and supervision, M.B.H., T.B.E., J.X. and J.S.-G.; and project administration, M.B.H., T.B.E. and J.S.-G.; funding acquisition, J.X. and J.S.-G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Available data are presented in the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Azhdarpoor, A.; Nikmanesh, R.; Khademi, F. A study of Reactive Red 198 adsorption on iron filings from aqueous solutions. *Environ. Technol.* **2014**, *35*, 2956–2960. [CrossRef] [PubMed]
2. Jadia, C.; Fulekar, M.H. Phytoremediation of heavy metals: Recent techniques. *Afr. J. Biotechnol.* **2009**, *8*, 921–928.
3. Rahman, M.S.; Hossain, M.B.; Babu, S.M.O.F.; Rahman, M.; Ahmed, A.S.S.; Jolly, Y.N.; Choudhury, T.R.; Begum, B.A.; Kabir, J.; Akter, S. Source of metal contamination in sediment, their ecological risk, and phytoremediation ability of the studied mangrove plants in ship breaking area, Bangladesh. *Mar. Pollut. Bull.* **2019**, *141*, 137–146. [CrossRef] [PubMed]
4. Yadav, K.K.; Gupta, N.; Kumar, V.; Singh, J.K. Bioremediation of heavy metals from contaminated sites using potential species: A review. *Indian J. Environ. Prot.* **2017**, *37*, 65.
5. Ahmed, A.S.S.; Hossain, M.B.; Babu, S.M.O.F.; Rahman, M.M.; Sarker, M.S.I. Human health risk assessment of heavy metals in water from the subtropical river, Gomti, Bangladesh. *Environ. Nanotechnol. Monit. Manag.* **2021**, *15*. [CrossRef]
6. Hossain, M.B.; Semme, S.A.; Ahmed, A.S.S.; Hossain, M.K.; Porag, G.S.; Parvin, A.; Shanta, T.B.; Senapathi, V.; Sekar, S. Contamination levels and ecological risk of heavy metals in sediments from the tidal river Halda, Bangladesh. *Arab. J. Geosci.* **2021**, *14*. [CrossRef]
7. FAO. The importance of soil organic matter Key to drought-resistant soil and sustained food production. *FAO Soils Bull. Assess.* **2005**, *78*. Available online: http://www.fao.org/3/a0100e/a0100e00.htm# (accessed on 10 April 2020).
8. Rahman, M.S.; Saha, N.; Molla, A.H.; Al-Reza, S.M. Assessment of Anthropogenic Influence on Heavy Metals Contamination in the Aquatic Ecosystem Components: Water, Sediment, and Fish. *Soil Sediment Contam.* **2014**, *23*, 353–373. [CrossRef]

9. Ahmed, A.S.S.; Hossain, M.B.; Semme, S.A.; Babu, S.M.O.F.; Hossain, K.; Moniruzzaman, M. Accumulation of trace elements in selected fish and shellfish species from the largest natural carp fish breeding basin in Asia: A probabilistic human health risk implication. *Environ. Sci. Pollut. Res.* **2020**, *27*, 37852–37865. [CrossRef]
10. Ahmed, A.S.S.; Sultana, S.; Habib, A.; Ullah, H.; Musa, N.; Hossain, M.B.; Rahman, M.M.; Sarker, M.S.I. Bioaccumulation of heavy metals in some commercially important fishes from a tropical river estuary suggests higher potential health risk in children than adults. *PLoS ONE* **2019**, *14*. [CrossRef]
11. Mani, D.; Kumar, C.; Patel, N.K. Hyperaccumulator Oilcake Manure as an Alternative for Chelate-Induced Phytoremediation of Heavy Metals Contaminated Alluvial Soils. *Int. J. Phytoremediation* **2015**, *17*, 256–263. [CrossRef]
12. Cunningham, S.D.; Shann, J.R.; Crowley, D.E.; Anderson, T.A. Phytoremediation of Contaminated Water and Soil. *ACS Symp. Ser.* **1997**, *664*, 2–17. [CrossRef]
13. Yadav, K.K.; Singh, J.K.; Gupta, N.; Kumar, V. A review of nanobioremediation technologies for environmental cleanup: A novel biological approach. *J. Mater. Environ. Sci.* **2017**, *8*, 740–757.
14. Gupta, A.K.; Sinha, S. Phytoextraction capacity of the plants growing on tannery sludge dumping sites. *Bioresour. Technol.* **2007**, *98*, 1788–1794. [CrossRef]
15. Rahman, M.; Molla, A.; Saha, N. Study on heavy metals levels and its risk assessment in some edible fishes from Bangshi River, Savar, Dhaka, Bangladesh. *Food Chem.* **2012**, *134*, 1847–1854. [CrossRef]
16. Ahmadpour, P.; Ahmadpour, F.; Mahmud, T.M.M.; Abdu, A.; Soleimani, M.; Tayefeh, F.H. Phytoremediation of heavy metals: A green technology. *Afr. J. Biotechnol.* **2012**, *11*, 14036–14043. [CrossRef]
17. Wei, S.H.; Zhou, Q.X. Phytoremediation of cadmium-contaminated soils by Rorippa globosa using two-phase planting. *Environ. Sci. Pollut. Res.* **2006**, *13*, 151–155. [CrossRef]
18. Ebrahimi, A.; Hashemi, H.; Eslami, H.; Fallahzadeh, R.A.; Khosravi, R.; Askari, R.; Ghahramani, E. Kinetics of biogas production and chemical oxygen demand removal from compost leachate in an anaerobic migrating blanket reactor. *J. Environ. Manag.* **2018**, *206*, 707–714. [CrossRef]
19. Bhattacharya, P.T.; Misra, S.R.; Hussain, M. Nutritional Aspects of Essential Trace Elements in Oral Health and Disease: An Extensive Review. *Scientifica* **2016**, *2016*. [CrossRef]
20. Saifullah; Sarwar, N.; Bibi, S.; Ahmad, M.; Ok, Y.S. Effectiveness of zinc application to minimize cadmium toxicity and accumulation in wheat (Triticum aestivum L.). *Environ. Earth Sci.* **2014**, *71*, 1663–1672. [CrossRef]
21. Popova, L.P.; Maslenkova, L.T.; Yordanova, R.Y.; Ivanova, A.P.; Krantev, A.P.; Szalai, G.; Janda, T. Exogenous treatment with salicylic acid attenuates cadmium toxicity in pea seedlings. *Plant Physiol. Biochem.* **2009**, *47*, 224–231. [CrossRef]
22. Cui, Y.; Du, X. Soil heavy-metal speciation and wheat phytotoxicity in the vicinity of an abandoned lead-zinc mine in Shangyu City, eastern China. *Environ. Earth Sci.* **2011**, *62*, 257–264. [CrossRef]
23. Kumar, B.; Smita, K.; Flores, L.C. Plant mediated detoxification of mercury and lead. *Arab. J. Chem.* **2017**, *10*, S2335–S2342. [CrossRef]
24. Rahman, M.S.; Saha, N.; Molla, A.H. Potential ecological risk assessment of heavy metal contamination in sediment and water body around Dhaka export processing zone, Bangladesh. *Environ. Earth Sci.* **2014**, *71*, 2293–2308. [CrossRef]
25. Barceló, J.; Poschenrieder, C. Phytoremediation: Principles and perspectives. *Contrib. Sci.* **2003**, *2*, 333–344. [CrossRef]
26. Tica, D.; Udovic, M.; Lestan, D. Immobilization of potentially toxic metals using different soil amendments. *Chemosphere* **2011**, *85*, 577–583. [CrossRef]
27. Cunningham, S.D.; Ow, D.W. Promises and prospects of phytoremediation. *Plant Physiol.* **1996**, *110*, 715–719. [CrossRef]
28. Danh, L.T.; Truong, P.; Mammucari, R.; Tran, T.; Foster, N. Vetiver grass, Vetiveria zizanioides: A choice plant for phytoremediation of heavy metals and organic wastes. *Int. J. Phytoremediation* **2009**, *11*, 664–691. [CrossRef]
29. Jacob, J.M.; Karthik, C.; Saratale, R.G.; Kumar, S.S.; Prabakar, D.; Kadirvelu, K.; Pugazhendhi, A. Biological approaches to tackle heavy metal pollution: A survey of literature. *J. Environ. Manag.* **2018**, *217*, 56–70. [CrossRef]
30. Placek, A.; Grobelak, A.; Kacprzak, M. Improving the phytoremediation of heavy metals contaminated soil by use of sewage sludge. *Int. J. Phytoremediation* **2016**, *18*, 605–618. [CrossRef]
31. Cluis, C. Junk-greedy greens: Phytoremediation as a new option for soil decontamination. *BioTeach J.* **2004**, *2*, 61–67.
32. Ghosh, M.; Singh, S.P. A review on phytoremediation of heavy metals and utilization of it's by products. *Asian J. Energy Environ.* **2005**, *6*, 214–231.
33. Brooks, R.R. Phytoremediation by volatilisation. In *Plants that Hyper-Accumulate Heavy Metals: Their Role in Phytoremediation, Microbiology, Archaeology, Mineral Exploration and Phytomining*; CAB International: Wallingford, UK, 1998; pp. 289–312.
34. Vaziri, A.; Panahpour, E.; Hossein, M.; Beni, M. Phytoremediation, A Method for Treatment of Petroleum Hydrocarbon Contaminated Soils. Available online: http://ijfas.com/wp-content/uploads/2013/10/909-913.pdf (accessed on 2 September 2021).
35. Ghori, Z.; Iftikhar, H.; Bhatti, M.F.; Nasar-Um-Minullah; Sharma, I.; Kazi, A.G.; Ahmad, P. Phytoextraction: The Use of Plants to Remove Heavy Metals from Soil. In *Plant Metal Interaction: Emerging Remediation Techniques*; Elsevier: Amsterdam, The Netherlands, 2015; pp. 361–384. ISBN 9780128031582.
36. Renu, N.A.; Agarwal, M.; Singh, K. Methodologies for removal of heavy metal ions from wastewater: An overview. *Interdiscip. Environ. Rev.* **2017**, *18*, 124. [CrossRef]

37. Asati, A.; Phichhole, M.; Nikhil, K. Effect of Heavy Metals on Plants: An Overview International Journal of Application or Innovation in Engineering & Management (IJAIEM). *Int. J. Appl. Innov. Eng. Manag.* **2016**, *5*, 2319–4847. [CrossRef]
38. Traina, S.; National, V. Contaminant bioavailability in soils, sediments, and aquatic environments. *Proc. Natl. Acad. Sci. USA* **1999**, *96*, 3365–3371. [CrossRef]
39. Allen, H.E.; McGrath, S.P.; McLaughlin, M.J.; Peijnenburg, W.J.G.M.; Sauvé, S.; Lee, C. *Bioavailability of Metals in Terrestrial Ecosystems: Importance of Partitioning for Bioavailability to Invertebrates, Microbes, and Plants*; Society of Environmental Toxicology and Chemistry: Pensacola, FL, USA, 2002; ISBN 1880611465.
40. van Gestel, C.A.M. Physico-chemical and biological parameters determine metal bioavailability in soils. *Sci. Total Environ.* **2008**, *406*, 385–395. [CrossRef]
41. Luoma, S.; Rainbow, P.S. Why is metal bioaccumulation so variable? Biodynamics as a unifying concept. *Environ. Sci. Technol.* **2005**, *39*, 1921–1931. [CrossRef]
42. Mildvan, A.S. 9 Metals in Enzyme Catalsis. *Enzymes* **1970**, *2*, 445–536. [CrossRef]
43. Hayat, S.; Javed, M. Growth performance of metal stressed major carps viz. Catla catla, Labeo rohita and Cirrhina mrigala reared under semi-intensive culture system. *Pak. Vet. J.* **2007**, *27*, 8–12.
44. Bradl, H.; Kim, C.; Kramar, U.; StÜben, D. Heavy Metals in the Environment: Origin, Interaction and Remediation. *Interface Sci. Technol.* **2005**, *6*, 28–164.
45. Degraeve, N. Carcinogenic, teratogenic and mutagenic effects of cadmium. *Mutat. Res. Genet. Toxicol.* **1981**, *86*, 115–135. [CrossRef]
46. Assessment, O.A. A survey of trace metals in vegetation, soil and lower animal along some selected major roads in metropolitan city of Lagos. *Environ. Monit. Assess.* **2005**, *105*, 431–447. [CrossRef]
47. Wuana, R.A.; Okieimen, F.E. Heavy Metals in Contaminated Soils: A Review of Sources, Chemistry, Risks and Best Available Strategies for Remediation. *ISRN Ecol.* **2011**, *2011*. [CrossRef]
48. Vinodhini, R.; Narayanan, M. The impact of toxic heavy metals on the hematological parameters in common carp (cyprinus carpio l.). *Iran. J. Environ. Heal. Sci. Eng.* **2009**, *6*, 23–28.
49. Ben Salem, Z.; Capelli, N.; Laffray, X.; Elise, G.; Ayadi, H.; Aleya, L. Seasonal variation of heavy metals in water, sediment and roach tissues in a landfill draining system pond (Etueffont, France). *Ecol. Eng.* **2014**, *69*, 25–37. [CrossRef]
50. Tumolo, M.; Ancona, V.; De Paola, D.; Losacco, D.; Campanale, C.; Massarelli, C.; Uricchio, V.F. Chromium pollution in European water, sources, health risk, and remediation strategies: An overview. *Int. J. Environ. Res. Public Health* **2020**, *17*, 5438. [CrossRef]
51. Dabi, S.B. Replacement of clopidogrel with ticagrelor for a patient with polycythemia vera accompanied by repeated myocardial infarction and acute stent thrombosis. *J. Fish Res.* **2020**, *4*. [CrossRef]
52. Padmavathiamma, P.K.; Li, L.Y. Phytoremediation technology: Hyper-accumulation metals in plants. *Water Air. Soil Pollut.* **2007**, *184*, 105–126. [CrossRef]
53. Iqbal, J.; Tirmizi, S.A.; Shah, M.H. Non-carcinogenic health risk assessment and source apportionment of selected metals in source freshwater khanpur lake, Pakistan. *Bull. Environ. Contam. Toxicol.* **2012**, *88*, 177–181. [CrossRef]
54. Ye, R.; Wright, A.L.; Orem, W.H.; McCray, J.M. Sulfur distribution and transformations in everglades agricultural area soil as influenced by sulfur amendment. *Soil Sci.* **2010**, *175*, 263–269. [CrossRef]
55. Genchi, G.; Carocci, A.; Lauria, G.; Sinicropi, M.S.; Catalano, A. Nickel: Human health and environmental toxicology. *Int. J. Environ. Res. Public Health* **2020**, *17*, 679. [CrossRef]
56. Pane, E.F.; Richards, J.G.; Wood, C.M. Acute waterborne nickel toxicity in the rainbow trout (Oncorhynchus mykiss) occurs by a respiratory rather than ionoregulatory mechanism. *Aquat. Toxicol.* **2003**, *63*, 65–82. [CrossRef]
57. Kong, X.; Wang, G.; Li, S. Effects of low temperature acclimation on antioxidant defenses and ATPase activities in the muscle of mud crab (Scylla paramamosain). *Aquaculture* **2012**, *370*, 144–149. [CrossRef]
58. Das, M.; Maiti, S.K. Comparison between availability of heavy metals in dry and wetland tailing of an abandoned copper tailing pond. *Environ. Monit. Assess.* **2007**, *137*, 343–350. [CrossRef]
59. Duda-Chodak, A.; Blaszczyk, U. The impact of nickel on human health. *J. Elem.* **2008**, *13*, 685–693.
60. Mishra, S.; Dwivedi, S.; Singh, R.B. A review on epigenetic effect of heavy metal carcinogens on human health. *Open Nutraceuticals J.* **2010**, *3*, 188–193. [CrossRef]
61. Khan, M.A.; Ahmad, I.; Ur Rahman, I. Effect of environmental pollution on heavy metals content of Withania somnifera. *J. Chin. Chem. Soc.* **2007**, *54*, 339–343. [CrossRef]
62. Smedley, P.L.; Kinniburgh, D.G. Source and behaviour of arsenic in natural waters. In *United Nations Synthesis Report on Arsenic in Drinking Water*; World Health Organization: Geneva, Switzerland, 2001; pp. 1–61.
63. Tripathi, V.; Edrisi, S.A.; Abhilash, P.C. Towards the coupling of phytoremediation with bioenergy production. *Renew. Sustain. Energy Rev.* **2016**, *57*, 1386–1389. [CrossRef]
64. Neustadt, J.; Pieczenik, S. Heavy-metal toxicity—With emphasis on mercury. *Integr. Med.* **2007**, *6*, 26–32.
65. Gulati, K.; Banerjee, B.; Lall, S.; Ray, A. Effects of diesel exhaust, heavy metals and pesticides on various organ systems: Possible mechanisms and strategies for prevention and treatment. *Indian J. Exp. Biol.* **2010**, *48*, 710–721. [PubMed]

66. Authority, S.C. *Australian and New Zealand Guidelines for Fresh and Marine Waters*; Astles, K.L., Winstanley, R.K., Harris, J.H., Gehrke, P.C., Eds.; Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand (ANZECC and ARMCANZ): Melbourne, Australia, 2003; pp. 55–69.
67. WHO. *Expert Consultation for 2nd Addendum to the 3rd Edition of the Guidelines for Drinking-Water Quality*; WHO: Geneva, Switzerland, 2006; pp. 1–136.
68. Holmes, S. *Department of Water Affairs and Forestry Water Quality Guidelines Volume 3*; CSIR Environmental Services, PRETORIA, Republic of South Africa, Department of Water Affairs and Forestry: Durban, South Africa, 1996.
69. Edition, F. Guidelines for Drinking-water Quality. *World Health* **2011**, *1*, 104–108.
70. NSW EPA. Environmental Planning and Assessment Regulation 2010. Available online: https://legislation.nsw.gov.au/view/html/inforce/current/sl-2000-0557#statusinformation (accessed on 2 September 2021).
71. Lasat, M.M. Phytoextraction of Metals from Contaminated Soil: A Review of Plant/Soil/Metal Interaction and Assessment of Pertinent Agronomic Issues. *J. Hazard. Subst. Res.* **1999**, *2*. [CrossRef]
72. Paz-Alberto, A.M.; Sigua, G.C. Phytoremediation: A Green Technology to Remove Environmental Pollutants. *Am. J. Clim. Chang.* **2013**, *2*, 71–86. [CrossRef]
73. Moffat, A.S. Plants proving their worth in toxic metal cleanup. *Science* **1995**, *269*, 302–303. [CrossRef]
74. Li, C.; Zhou, K.; Qin, W.; Tian, C.; Qi, M.; Yan, X.; Han, W. A Review on Heavy Metals Contamination in Soil: Effects, Sources, and Remediation Techniques. *Soil Sediment Contam.* **2019**, *28*, 380–394. [CrossRef]
75. Huang, J.W.; Cunningham, S.D. Lead phytoextraction: Species variation in lead uptake and translocation. *New Phytol.* **1996**, *134*, 75–84. [CrossRef]
76. Xia, W.Y.; Feng, Y.S.; Jin, F.; Zhang, L.M.; Du, Y.J. Stabilization and solidification of a heavy metal contaminated site soil using a hydroxyapatite based binder. *Constr. Build. Mater.* **2017**, *156*, 199–207. [CrossRef]
77. Lim, S.L.; Lee, L.H.; Wu, T.Y. Sustainability of using composting and vermicomposting technologies for organic solid waste biotransformation: Recent overview, greenhouse gases emissions and economic analysis. *J. Clean. Prod.* **2016**, *111*, 262–278. [CrossRef]
78. Fawzy, E.M. Soil remediation using in situ immobilisation techniques. *Chem. Ecol.* **2008**, *24*, 147–156. [CrossRef]
79. Farrell, M.; Perkins, W.T.; Hobbs, P.J.; Griffith, G.W.; Jones, D.L. Migration of heavy metals in soil as influenced by compost amendments. *Environ. Pollut.* **2010**, *158*, 55–64. [CrossRef]
80. Kurniawan, T.; Chan, G.; Lo, W.; Babel, S. Physico–chemical treatment techniques for wastewater laden with heavy metals. *Chem. Eng. J.* **2006**, *118*, 83–98. [CrossRef]
81. Kanamarlapudi, S.L.R.K.; Chintalpudi, V.K.; Muddada, S. Application of Biosorption for Removal of Heavy Metals from Wastewater. In *Biosorption*; IntechOpen Limited: London, UK, 2018. [CrossRef]
82. Mohammadi, T.; Moheb, A.; Sadrzadeh, M.; Razmia, A. Modeling of metal ion removal from wastewater by electrodialysis. *Sep. Purif. Technol.* **2005**, *41*, 73–82. [CrossRef]
83. Bakalár, T.; Búgel, M.; Slovaca, L. Heavy metal removal using reverse osmosis. *Acta Montan. Slovaca* **2009**, *14*, 250–253.
84. Chang, Q.; Wang, G. Study on the macromolecular coagulant PEX which traps heavy metals. *Chem. Eng. Sci.* **2007**, *62*, 4636–4643. [CrossRef]
85. El Samrani, A.G.; Lartiges, B.S.; Villiéras, F. Chemical coagulation of combined sewer overflow: Heavy metal removal and treatment optimization. *Water Res.* **2008**, *42*, 951–960. [CrossRef]
86. Navarro, A.; Cardellach, E.; Cañadas, I.; Rodríguez, J. Solar thermal vitrification of mining contaminated soils. *Int. J. Miner. Process.* **2012**, *119*, 65–74. [CrossRef]
87. RoyChowdhury, A.; Datta, R.; Sarkar, D. Heavy Metal Pollution and Remediation. In *Green Chemistry: An Inclusive Approach*; Elsevier: Amsterdam, The Netherlands, 2018; pp. 359–373. ISBN 9780128095492.
88. Lynch, J.M.; Moffat, A.J. Bioremediation—Prospects for the future application of innovative applied biological research. *Ann. Appl. Biol.* **2005**, *146*, 217–221. [CrossRef]
89. Orłowska, E.; Godzik, B.; Turnau, K. Effect of different arbuscular mycorrhizal fungal isolates on growth and arsenic accumulation in Plantago lanceolata L. *Environ. Pollut.* **2012**, *168*, 121–130. [CrossRef]
90. Sylvia, D.; Fuhrmann, J.; Hartel, P.; Zuberer, D. *Principles and Applications of Soil Microbiology*; Pearson Prentice Hall, Universidade de Michigan, Pearson College Div.: New York, NY, USA, 2005; ISBN 0130941174.
91. Díaz, C.B.; Morales, G.R.; Chávez, A.A. An integrated electrochemical-phytoremediation process for the treatment of industrial wastewater. *Phytoremediation Manag. Environ. Contam.* **2015**, *2*, 335–341. [CrossRef]
92. Nair, A.; Juwarkar, A.A.; Singh, S.K. Production and characterization of siderophores and its application in arsenic removal from contaminated soil. *Water Air Soil Pollut.* **2007**, *180*, 199–212. [CrossRef]
93. Rezania, S.; Taib, S.M.; Md Din, M.F.; Dahalan, F.A.; Kamyab, H. Comprehensive review on phytotechnology: Heavy metals removal by diverse aquatic plants species from wastewater. *J. Hazard. Mater.* **2016**, *318*, 587–599. [CrossRef]
94. Kumari, M.; Tripathi, B.D. Efficiency of Phragmites australis and Typha latifolia for heavy metal removal from wastewater. *Ecotoxicol. Environ. Saf.* **2015**, *112*, 80–86. [CrossRef]
95. Thanh-Nho, N.; Marchand, C.; Strady, E.; Huu-Phat, N.; Nhu-Trang, T.T. Bioaccumulation of some trace elements in tropical mangrove plants and snails (Can Gio, Vietnam). *Environ. Pollut.* **2019**, *248*, 635–645. [CrossRef]

96. Lone, M.; He, Z.; Stoffella, P.J.; Yang, X. Phytoremediation of heavy metal polluted soils and water: Progresses and perspectives. *J. Zhejiang Univ. Sci. B* **2008**, *9*, 210–220. [CrossRef]
97. Ifon, E.B.; Crépin Finagnon Togbé, A.; Arsène Sewedo Tometin, L.; Suanon, F.; Yessoufou, A. Metal-Contaminated Soil Remediation. In *Metals in Soil—Contamination and Remediation*; IntechOpen: London, UK, 2019; pp. 534–554.
98. Prasad, M.N.V. Phytoremediation of Metal-Polluted Ecosystems: Hype for Commercialization. *Russ. J. Plant Physiol.* **2003**, *50*, 686–701. [CrossRef]
99. Kotrba, P.; Najmanova, J.; Macek, T.; Ruml, T.; Mackova, M. Genetically modified plants in phytoremediation of heavy metal and metalloid soil and sediment pollution. *Biotechnol. Adv.* **2009**, *27*, 799–810. [CrossRef]
100. Yadav, K.K.; Gupta, N.; Kumar, V.; Choudhary, P.; Khan, S.A. GIS-based evaluation of groundwater geochemistry and statistical determination of the fate of contaminants in shallow aquifers from different functional areas of Agra city, India: Levels and spatial distributions. *RSC Adv.* **2018**, *8*, 15876–15889. [CrossRef]
101. Dhama, K.; Patel, S.K.; Kumar, R.; Masand, R.; Rana, J.; Yatoo, M.I.; Tiwari, R.; Sharun, K.; Mohapatra, R.K.; Natesan, S.; et al. The role of disinfectants and sanitizers during COVID-19 pandemic: Advantages and deleterious effects on humans and the environment. *Environ. Sci. Pollut. Res.* **2021**, *28*, 34211–34228. [CrossRef]
102. Goutam, S.P.; Saxena, G.; Singh, V.; Yadav, A.K.; Bharagava, R.N.; Thapa, K.B. Green synthesis of TiO2 nanoparticles using leaf extract of Jatropha curcas L. for photocatalytic degradation of tannery wastewater. *Chem. Eng. J.* **2018**, *336*, 386–396. [CrossRef]
103. Mohammadi, H.; Amani-Ghadim, A.R.; Matin, A.A.; Ghorbanpour, M. Fe0 nanoparticles improve physiological and antioxidative attributes of sunflower (*Helianthus annuus*) plants grown in soil spiked with hexavalent chromium. *3 Biotech.* **2020**, *10*, 19. [CrossRef] [PubMed]
104. Jadia, C.D.; Fulekar, M.H. Phytoremediation: The application of vermicompost to remove zinc, cadmium, copper, nickel and lead by sunflower plant. *Environ. Eng. Manag. J.* **2008**, *7*, 547–558. [CrossRef]
105. Kidd, P.S.; Bani, A.; Benizri, E.; Gonnelli, C.; Hazotte, C.; Kisser, J.; Konstantinou, M.; Kuppens, T.; Kyrkas, D.; Laubie, B.; et al. Developing sustainable agromining systems in agricultural ultramafic soils for nickel recovery. *Front. Environ. Sci.* **2018**, *6*, 44. [CrossRef]
106. Van Der Ent, A.; Baker, A.J.M.; Reeves, R.D.; Chaney, R.L.; Anderson, C.W.N.; Meech, J.A.; Erskine, P.D.; Simonnot, M.O.; Vaughan, J.; Morel, J.L.; et al. Agromining: Farming for metals in the future? *Environ. Sci. Technol.* **2015**, *49*, 4773–4780. [CrossRef] [PubMed]
107. Jabeen, R.; Ahmad, A.; Iqbal, M. Phytoremediation of heavy metals: Physiological and molecular mechanisms. *Bot. Rev.* **2009**, *75*, 339–364. [CrossRef]
108. Huang, J.; Chen, J.; Cunningham, S.D. Phytoextraction of lead from contaminated soils. *ACS Symp. Ser.* **1997**, 664. [CrossRef]
109. Surriya, O.; Sarah Saleem, S.; Waqar, K.; Gul Kazi, A. Phytoremediation of Soils: Prospects and Challenges. *Soil Remediat. Plants* **2015**, 1–36. [CrossRef]
110. Jan, A.T.; Arif, A.; Qazi, M.R.H. Phytoremediation: A promising strategy on the crossroads of remediation. In *Soil Remediation and Plants: Prospects and Challenges*; Academic Press: Cambridge, MA, USA, 2014; pp. 63–84.
111. Bolan, N.B.; Aidu, R.N.; Hoppala, G.C.; Ark, J.P.; Ora, M.L.M.; Udianta, D.B.; Anneerselvam, P.P. Solute Interactions in Soils in Relation to the Bioavailability and Environmental Remediation of Heavy Metals and Metalloids. *Pedologist* **2010**, *53*, 1–18.
112. Ali, H.; Khan, E.; Sajad, M.A. Phytoremediation of heavy metals-Concepts and applications. *Chemosphere* **2013**, *91*, 869–881. [CrossRef]
113. Mahar, A.; Wang, P.; Ali, A.; Awasthi, M.K.; Lahori, A.H.; Wang, Q.; Li, R.; Zhang, Z. Challenges and opportunities in the phytoremediation of heavy metals contaminated soils: A review. *Ecotoxicol. Environ. Saf.* **2016**, *126*, 111–121. [CrossRef]
114. Khalid, S.; Shahid, M.; Niazi, N.K.; Murtaza, B.; Bibi, I.; Dumat, C. A comparison of technologies for remediation of heavy metal contaminated soils. *J. Geochem. Explor.* **2017**, *182*, 247–268. [CrossRef]
115. Hossain, M.; Islam, M. *Ship Breaking Activities and its Impact on the Coastal Zone of Chittagong, Bangladesh: Towards Sustainable Management*; Advocacy & Publication Unit, Young Power in Social Action (YPSA): Chittagong, Bangladesh, 2006; ISBN 9843234480.
116. Susarla, S.; Medina, V.; McCutcheon, S.C. Phytoremediation: An ecological solution to organic chemical contamination. *Ecol. Eng.* **2002**, *18*, 647–658. [CrossRef]
117. Razzaq, R. Phytoremediation: An Environmental Friendly Technique—A Review. *J. Environ. Anal. Chem.* **2017**, *4*, 1000195. [CrossRef]
118. Wolfe, N.; Hoehamer, C. *Enzymes Used by Plants and Microorganisms to Detoxify Organic Compounds*; John Wiley and Sons: New York, NY, USA, 2003.
119. Thompson, P.L.; Ramer, L.A.; Schnoor, J.L. Uptake and transformation of TNT by hybrid poplar trees. *Environ. Sci. Technol.* **1998**, *32*, 975–980. [CrossRef]
120. Memon, A.R.; Aktoprakligil, D.; Özdemir, A.; Vertii, A. Heavy metal accumulation and detoxification mechanisms in plants. *Turk. J. Botany* **2001**, *25*, 111–121.
121. Tariq, S.R.; Ashraf, A. Comparative evaluation of phytoremediation of metal contaminated soil of firing range by four different plant species. *Arab. J. Chem.* **2016**, *9*, 806–814. [CrossRef]
122. Sarma, H. Metal hyperaccumulation in plants: A review focusing on phytoremediation technology. *J. Environ. Sci. Technol.* **2011**, *4*, 118–138. [CrossRef]

123. Mesjasz-Przybyłowicz, J.; Nakonieczny, M.; Migula, P.; Augustyniak, M.; Tarnawska, M.; Reimold, W.U.; Koeberl, C.; Przybyłowicz, W.; Bieta Głowacka, E. Uptake of cadmium, lead, nickel and zinc from soil and water solutions by the nickel hyperaccumulator berkheya coddii. *ACTA Biol. Crac. Ser. Bot.* **2004**, *46*, 75–85.
124. Gomes, M. Metal phytoremediation: General strategies, genetically modified plants and applications in metal nanoparticle contamination. *Ecotoxicol. Environ. Saf.* **2016**, *134*, 133–147. [CrossRef]
125. Vymazal, J. Concentration is not enough to evaluate accumulation of heavy metals and nutrients in plants. *Sci. Total Environ.* **2016**, *544*, 495–498. [CrossRef]
126. Ruiz, O.N.; Daniell, H. Genetic engineering to enhance mercury phytoremediation. *Curr. Opin. Biotechnol.* **2009**, *20*, 213–219. [CrossRef]
127. McGrath, S.P.; Zhao, F.J. Phytoextraction of metals and metalloids from contaminated soils. *Curr. Opin. Biotechnol.* **2003**, *14*, 277–282. [CrossRef]
128. Bizily, S.; Rugh, C. Phytoremediation of methylmercury pollution: merB expression in *Arabidopsis thaliana* confers resistance to organomercurials. *Proc. Natl. Acad. Sci. USA* **1999**, *96*, 6808–6813. [CrossRef]
129. Hernández-Allica, J.; Becerril, J.M.; Garbisu, C. Assessment of the phytoextraction potential of high biomass crop plants. *Environ. Pollut.* **2008**, *152*, 32–40. [CrossRef]
130. Pilon-Smits, E.; LeDuc, D.L. Phytoremediation of selenium using transgenic plants. *Curr. Opin. Biotechnol.* **2009**, *20*, 207–212. [CrossRef]
131. Rawat, K.; Pathak, B.; Fulekar, M.H. Enzymatic mechanism during phytoextraction of heavy metals from fly ash amended soil. *Int. J. Sci. Ind. Res.* **2015**, *6*, 1041–1055.
132. Pedron, F.; Petruzzelli, G.; Barbafieri, M.; Tassi, E.; Ambrosini, P.; Patata, L. Mercury mobilization in a contaminated industrial soil for phytoremediation. *Commun. Soil Sci. Plant Anal.* **2011**, *42*, 2767–2777. [CrossRef]
133. Verbruggen, N.; Hermans, C.; Schat, H. Mechanisms to cope with arsenic or cadmium excess in plants. *Curr. Opin. Plant Biol.* **2009**, *12*, 364–372. [CrossRef]
134. Farid, M.; Ali, S.; Shakoor, M.B.; Bharwana, S.A.; Rizvi, H.; Tauqeer, H.M.; Iftikhar, U.; Hannan, F.; Road, A.I. EDTA Assisted Phytoremediation of Cadmium, Lead and Zinc. *Int. J. Agron. Plant Prod.* **2013**, *4*, 2833–2846.
135. Sakakibara, M.; Watanabe, A.; Sano, S.; Inoue, M.; Kaise, T. Phytoextraction and phytovolatili-zation of arsenic from as-contaminated soils by Pteris vittata. In Proceedings of the Association for Environmental Health and Sciences—22nd Annual International Conference on Contaminated Soils, Sediments and Water 2006, Amherst, MA, USA, 16–19 October 2006; Volume 12, pp. 258–263.
136. van der Ent, A.; Baker, A.J.M.; Reeves, R.D.; Pollard, A.J.; Schat, H. Hyperaccumulators of metal and metalloid trace elements: Facts and fiction. *Plant Soil* **2013**, *362*, 319–334. [CrossRef]
137. Favas, P.J.C.; Pratas, J.; Paul, M.S.; Sarkar, S.K.; Prasad, M.N.V. Phytofiltration of metal(loid)-contaminated water: The potential of native aquatic plants. In *Phytoremediation: Management of Environmental Contaminants*; Springer International Publishing: Berlin/Heidelberg, Germay, 2016; Volume 3, pp. 305–343. ISBN 9783319401485.
138. Kathal, R.; Malhotra, P.; Kumar, L.; Uniyal, P.L. Phytoextraction of Pb and Ni from the Polluted Soil by Brassica juncea L. *J. Environ. Anal. Toxicol.* **2016**, *6*. [CrossRef]
139. Yang, J.; Yang, J.; Huang, J. Role of co-planting and chitosan in phytoextraction of As and heavy metals by Pteris vittata and castor bean—A field case. *Ecol. Eng.* **2017**, *109*, 35–40. [CrossRef]
140. Cotter-Howells, J.; Caporn, S. Remediation of contaminated land by formation of heavy metal phosphates. *Appl. Geochem.* **1996**, *11*, 335–342. [CrossRef]
141. Griffioen, W.A.J.; Ietswaart, J.H.; Ernst, W.H.O. Mycorrhizal infection of an Agrostis capillaris population on a copper contaminated soil. *Plant Soil* **1994**, *158*, 83–89. [CrossRef]
142. Mench, M.; Martin, E. Mobilization of cadmium and other metals from two soils by root exudates of Zea mays L., Nicotiana tabacum L. and Nicotiana rustica L. *Plant Soil* **1991**, *132*, 187–196. [CrossRef]
143. Islam, M.; Hossain, M.; Khatun, M.; Hossen, M. Environmental impact assessment on frequency of pesticide use during vegetable production. *Progress. Agric.* **2015**, *26*, 97–102. [CrossRef]
144. Ko, B.G.; Anderson, C.W.N.; Bolan, N.S.; Huh, K.Y.; Vogeler, I. Potential for the phytoremediation of arsenic-contaminated mine tailings in Fiji. *Soil Res.* **2008**, *46*, 493–501. [CrossRef]
145. Galal, T.M.; Gharib, F.A.; Ghazi, S.M.; Mansour, K.H. Phytostabilization of heavy metals by the emergent macrophyte Vossia cuspidata (Roxb.) Griff.: A phytoremediation approach. *Int. J. Phytoremediation* **2017**, *19*, 992–999. [CrossRef]
146. Ranđelović, D.; Gajić, G.; Mutić, J.; Pavlović, P.; Mihailović, N.; Jovanović, S. Ecological potential of Epilobium dodonaei Vill. for restoration of metalliferous mine wastes. *Ecol. Eng.* **2016**, *95*, 800–810. [CrossRef]
147. Ma, N.; Wang, W.; Gao, J.; Chen, J. Removal of cadmium in subsurface vertical flow constructed wetlands planted with Iris sibirica in the low-temperature season. *Ecol. Eng.* **2017**, *109*, 48–56. [CrossRef]
148. Marrugo-Negrete, J. Removal of mercury from gold mine effluents using Limnocharis flava in constructed wetlands. *Chemosphere* **2017**, *167*, 188–192. [CrossRef]
149. Ramana, S.; Biswas, A.; Singh, A. Phytoremediation ability of some floricultural plant species. *Indian J. Plant Physiol.* **2013**, *18*, 187–190. [CrossRef]

150. Raskin, I.; Ensley, B. *Phytoremediation of toxic metals in soils. Hazard. Waste Consult*; John Wiley & Sons, Inc.: New York, NY, USA, 2001; pp. 53–70.
151. Liu, J.N.; Zhou, Q.X.; Sun, T.; Ma, L.Q.; Wang, S. Identification and chemical enhancement of two ornamental plants for phytoremediation. *Bull. Environ. Contam. Toxicol.* **2008**, *80*, 260–265. [CrossRef]
152. Tang, L.; Luo, W.; Chen, W.; He, Z.; Gurajala, H.K.; Hamid, Y.; Deng, M.; Yang, X. Field crops (Ipomoea aquatica Forsk. and Brassica chinensis L.) for phytoremediation of cadmium and nitrate co-contaminated soils via rotation with Sedum alfredii Hance. *Environ. Sci. Pollut. Res.* **2017**, *24*, 19293–19305. [CrossRef]
153. Nie, X.; Dong, F.; Liu, N.; Liu, M.; Zhang, D.; Kang, W.; Sun, S.; Zhang, W.; Yang, J. Subcellular distribution of uranium in the roots of Spirodela punctata and surface interactions. *Appl. Surf. Sci.* **2015**, *347*, 122–130. [CrossRef]
154. Pratas, J.; Favas, P.J.C.; Paulo, C.; Rodrigues, N.; Prasad, M.N.V. Uranium accumulation by aquatic plants from uranium-contaminated water in Central Portugal. *Int. J. Phytoremediation* **2012**, *14*, 221–234. [CrossRef]
155. Nwadinigwe, A.O.; Ugwu, E.C. Overview of nano-phytoremediation applications. In *Phytoremediation: Management of Environmental Contaminants*; Springer: Berlin/Heidelberg, Germany, 2019; Volume 6, pp. 377–382. ISBN 9783319996516.
156. Dolphen, R.; Thiravetyan, P. Phytodegradation of Ethanolamines by Cyperus alternifolius: Effect of Molecular Size. *Int. J. Phytoremediation* **2015**, *17*, 686–692. [CrossRef]
157. Schnoor, J.L.; Licht, L.A.; McCutcheon, S.C.; Wolfe, N.L.; Carreira, L.H. Phytoremediation of Organic and Nutrient Contaminants. *Environ. Sci. Technol.* **1995**, *29*, 318–323. [CrossRef]
158. Chen, F.; Huber, C.; May, R.; Schröder, P. Metabolism of oxybenzone in a hairy root culture: Perspectives for phytoremediation of a widely used sunscreen agent. *J. Hazard. Mater.* **2016**, *306*, 230–236. [CrossRef]
159. Vroblesky, D.A. Phytoremediation: Transformation and Control of Contaminants. *Ground Water* **2005**, *43*, 6–7. [CrossRef]
160. Rylott, E.L.; Bruce, N.C. Plants disarm soil: Engineering plants for the phytoremediation of explosives. *Trends Biotechnol.* **2009**, *27*, 73–81. [CrossRef]
161. Novo, L.A.B.; Covelo, E.F.; González, L. Effect of Salinity on Zinc uptake by Brassica juncea. *Int. J. Phytoremediation* **2014**, *16*, 704–718. [CrossRef]
162. Cherian, S.; Oliveira, M.M. Transgenic plants in phytoremediation: Recent advances and new possibilities. *Environ. Sci. Technol.* **2005**, *39*, 9377–9390. [CrossRef]
163. Chirakkara, R.A.; Cameselle, C.; Reddy, K.R. Assessing the applicability of phytoremediation of soils with mixed organic and heavy metal contaminants. *Rev. Environ. Sci. Biotechnol.* **2016**, *15*, 299–326. [CrossRef]
164. Buescher, J.M.; Moco, S.; Sauer, U.; Zamboni, N. Ultrahigh performance liquid chromatography-tandem mass spectrometry method for fast and robust quantification of anionic and aromatic metabolites. *Anal. Chem.* **2010**, *82*, 4403–4412. [CrossRef]
165. Choppala, G.; Saifullah; Bolan, N.; Bibi, S.; Iqbal, M.; Rengel, Z.; Kunhikrishnan, A.; Ashwath, N.; Ok, Y.S. Cellular Mechanisms in Higher Plants Governing Tolerance to Cadmium Toxicity. *CRC. Crit. Rev. Plant Sci.* **2014**, *33*, 374–391. [CrossRef]
166. Chaudhary, K.; Jan, S.; Khan, S. Heavy Metal ATPase (HMA2, HMA3, and HMA4) Genes in Hyperaccumulation Mechanism of Heavy Metals. In *Plant Metal Interaction: Emerging Remediation Techniques*; Elsevier: Amsterdam, The Netherlands, 2015; pp. 545–556.
167. Li, S.; Zhou, X.; Huang, Y.; Zhu, L.; Zhang, S.; Zhao, Y.; Guo, J.; Chen, J.; Chen, R. Identification and characterization of the zinc-regulated transporters, iron-regulated transporter-like protein (ZIP) gene family in maize. *BMC Plant Biol.* **2013**, *13*. [CrossRef]
168. Chaudhary, K.; Agarwal, S.; Khan, S. Role of Phytochelatins (PCs), Metallothioneins (MTs), and Heavy Metal ATPase (HMA) Genes in Heavy Metal Tolerance. In *Mycoremediation and Environmental Sustainability*; Springer: New York, NY, USA, 2018; pp. 39–60. [CrossRef]
169. Shin, L.J.; Lo, J.C.; Yeh, K.C. Copper chaperone antioxidant Protein1 is essential for Copper homeostasis. *Plant Physiol.* **2012**, *159*, 1099–1110. [CrossRef]
170. Assunção, A.; Herrero, E.; Lin, Y.-F.; Huettel, B.; Talukdar, S.; Smaczniak, C.; Immink, R.G.H.; van Eldik, M.; Fiers, M.; Schat, H.; et al. Arabidopsis thaliana transcription factors bZIP19 and bZIP23 regulate the adaptation to zinc deficiency. *Proc. Natl. Acad. Sci. USA* **2010**. [CrossRef]
171. Rascio, N.; Navari-Izzo, F. Heavy metal hyperaccumulating plants: How and why do they do it? And what makes them so interesting? *Plant Sci.* **2011**, *180*, 169–181. [CrossRef]
172. Yang, X.; Li, T.; Yang, J.; He, Z.; Lu, L.; Meng, F. Zinc compartmentation in root, transport into xylem, and absorption into leaf cells in the hyperaccumulating species of Sedum alfredii Hance. *Planta* **2006**, *224*, 185–195. [CrossRef]
173. Hall, J.L.; Williams, L.E. Transition metal transporters in plants. *J. Exp. Bot.* **2003**, *54*, 2601–2613. [CrossRef] [PubMed]
174. Grotz, N.; Guerinot, M. Lou Molecular aspects of Cu, Fe and Zn homeostasis in plants. *Biochim. Biophys. Acta Mol. Cell Res.* **2006**, *1763*, 595–608. [CrossRef] [PubMed]
175. Clemens, S.; Kim, E.J.; Neumann, D.; Schroeder, J.I. Tolerance to toxic metals by a gene family of phytochelatin synthases from plants and yeast. *EMBO J.* **1999**, *18*, 3325–3333. [CrossRef] [PubMed]
176. Williams, L.E.; Mills, R.F. P1B-ATPaseS—An ancient family of transition metal pumps with diverse functions in plants. *Trends Plant Sci.* **2005**, *10*, 491–502. [CrossRef]

177. Verret, F.; Gravot, A.; Auroy, P.; Leonhardt, N.; David, P.; Nussaume, L.; Vavasseur, A.; Richaud, P. Overexpression of AtHMA4 enhances root-to-shoot translocation of zinc and cadmium and plant metal tolerance. *FEBS Lett.* **2004**, *576*, 306–312. [CrossRef]
178. Küpper, H.; Lombi, E.; Zhao, F.J.; McGrath, S.P. Cellular compartmentation of cadmium and zinc in relation to other elements in the hyperaccumulator Arabidopsis halleri. *Planta* **2000**, *212*, 75–84. [CrossRef]
179. Robinson, B.; Kim, N.; Marchetti, M.; Moni, C.; Schroeter, L.; van den Dijssel, C.; Milne, G.; Clothier, B. Arsenic hyperaccumulation by aquatic macrophytes in the Taupo Volcanic Zone, New Zealand. *Environ. Exp. Bot.* **2006**, *58*, 206–215. [CrossRef]
180. Bidwell, S.D.; Crawford, S.A.; Woodrow, I.E.; Sommer-Knudsen, J.; Marshall, A.T. Sub-cellular localization of Ni in the hyperaccumulator, Hybanthus floribundus (Lindley) F. Muell. *Plant Cell Environ.* **2004**, *27*, 705–716. [CrossRef]
181. Ma, J.F.; Ueno, D.; Zhao, F.J.; McGrath, S.P. Subcellular localisation of Cd and Zn in the leaves of a Cd-hyperaccumulating ecotype of Thlaspi caerulescens. *Planta* **2005**, *220*, 731–736. [CrossRef]
182. Asemaneh, T.; Ghaderian, S.M.; Crawford, S.A.; Marshall, A.T.; Baker, A.J.M. Cellular and subcellular compartmentation of Ni in the Eurasian serpentine plants Alyssum bracteatum, Alyssum murale (Brassicaceae) and Cleome heratensis (Capparaceae). *Planta* **2006**, *225*, 193–202. [CrossRef]
183. Freeman, J.L.; Zhang, L.H.; Marcus, M.A.; Fakra, S.; McGrath, S.P.; Pilon-Smits, E.A.H. Spatial imaging, speciation, and quantification of selenium in the hyperaccumulator plants Astragalus bisulcatus and Stanleya pinnata. *Plant Physiol.* **2006**, *142*, 124–134. [CrossRef]
184. Sarwar, N.; Imran, M.; Shaheen, M.R.; Ishaque, W.; Kamran, M.A.; Matloob, A.; Rehim, A.; Hussain, S. Phytoremediation strategies for soils contaminated with heavy metals: Modifications and future perspectives. *Chemosphere* **2017**, *171*, 710–721. [CrossRef]
185. Ortiz, D.F.; Ruscitti, T.; McCue, K.F.; Ow, D.W. Transport of metal-binding peptides by HMT1, a fission yeast ABC-type vacuolar membrane protein. *J. Biol. Chem.* **1995**, *270*, 4721–4728. [CrossRef]
186. Meister, A. Glutathione metabolism. *Methods Enzymol.* **1995**, *251*, 3–7. [CrossRef]
187. Parisy, V.; Poinssot, B.; Owsianowski, L.; Buchala, A.; Glazebrook, J.; Mauch, F. Identification of PAD2 as a γ-glutamylcysteine synthetase highlights the importance of glutathione in disease resistance of Arabidopsis. *Plant J.* **2007**, *49*, 159–172. [CrossRef]
188. Reichheld, J.P.; Khafif, M.; Riondet, C.; Droux, M.; Bonnard, G.; Meyer, Y. Inactivation of thioredoxin reductases reveals a complex interplay between thioredoxin and glutathione pathways in arabidopsis development. *Plant Cell* **2007**, *19*, 1851–1865. [CrossRef]
189. Rouhier, N.; Lemaire, S.D.; Jacquot, J.P. The role of glutathione in photosynthetic organisms: Emerging functions for glutaredoxins and glutathionylation. *Annu. Rev. Plant Biol.* **2008**, *59*, 143–166. [CrossRef]
190. Li, Z.; Shuman, L.M. Heavy metal movement in metal-contaminated soil profiles. *Soil Sci.* **1996**, *161*, 656–666. [CrossRef]
191. Zhou, J.; Goldsbrough, P.B. Functional homologs of fungal metallothionein genes from Arabidopsis. *Plant Cell* **1994**, *6*, 875–884. [CrossRef]
192. Milner, M.J.; Mitani-Ueno, N.; Yamaji, N.; Yokosho, K.; Craft, E.; Fei, Z.; Ebbs, S.; Zambrano, M.C.; Ma, J.F.; Kochian, L.V. Root and shoot transcriptome analysis of two ecotypes of Noccaea caerulescens uncovers the role of NcNramp1 in Cd hyperaccumulation. *Plant J.* **2014**, *78*, 398–410. [CrossRef]
193. Persans, M.W.; Nieman, K.; Salt, D.E. Functional activity and role of cation-efflux family members in Ni hyperaccumulation in Thlaspi goesingense. *Proc. Natl. Acad. Sci. USA* **2001**, *98*, 9995–10000. [CrossRef] [PubMed]
194. Van De Mortel, J.E.; Schat, H.; Moerland, P.D.; Van Themaat, E.V.L.; Van Der Ent, S.; Blankestijn, H.; Ghandilyan, A.; Tsiatsiani, S.; Aarts, M.G.M. Expression differences for genes involved in lignin, glutathione and sulphate metabolism in response to cadmium in *Arabidopsis thaliana* and the related Zn/Cd-hyperaccumulator Thlaspi caerulescens. *Plant Cell Environ.* **2008**, *31*, 301–324. [CrossRef] [PubMed]
195. Hammond, J.; Bowen, H.; White, P.J.; Mills, V.; Pyke, K.A.; Baker, A.J.M.; Whiting, S.N.; May, S.T.; Broadley, M.R. A comparison of the Thlaspi caerulescens and Thlaspi arvense shoot transcriptomes. *New Phytol.* **2006**, *170*, 239–260. [CrossRef] [PubMed]
196. Schat, H.; Llugany, M.; Vooijs, R.; Hartley-Whitaker, J.; Bleeker, P.M. The role of phytochelatins in constitutive and adaptive heavy metal tolerances in hyperaccumulator and non-hyperaccumulator metallophytes. *J. Exp. Bot.* **2002**, *53*, 2381–2392. [CrossRef]
197. Raskin, I.; Ensley, B.D.; Burt, D. Phytoremediation of Toxic Metals: Using Plants to Clean the Environment. *J. Plant Biotechnol.* **1999**, *1*, 304.
198. Rosa, S. Summary Report. In Proceedings of the Workshop on Phytoremediation Research Needs, Santa Rosa, CA, USA, 24–26 July 1994.
199. Erdei, L.; Mezosi, G.; Mécs, I.; Vass, I.; Foglein, F.; Bulik, L. Phytoremediation as a program for decontamination of heavy-metal polluted environment. *Acta Biol. Szeged.* **2005**, *49*, 75–76.
200. Ge, Y.; Murray, P.; Hendershot, W.H. Trace metal speciation and bioavailability in urban soils. *Environ. Pollut.* **2000**, *107*, 137–144. [CrossRef]
201. Kroukamp, E.M.; Wondimu, T.; Forbes, P.B.C. Metal and metalloid speciation in plants: Overview, instrumentation, approaches and commonly assessed elements. *TrAC Trends Anal. Chem.* **2016**, *77*, 87–99. [CrossRef]
202. Takáč, P.; Szabová, T.; Kozáková, L.; Benková, M.; Takáč, P. Heavy metals and their bioavailability from soils in the long-term polluted Central Spiš region of SR. *Plant Soil Environ.* **2009**, *55*, 167–172. [CrossRef]
203. Moffett, J.W.; Brand, L.E. Production of strong, extracellular Cu chelators by marine cyanobacteria in response to Cu stress. *Limnol. Oceanogr.* **1996**, *41*, 388–395. [CrossRef]

204. Baker, A.J.M.; McGrath, S.P.; Reeves, R.D.; Smith, J.A.C. Metal Hyperaccumulator Plants: A Review of the Ecology and Physiology of a Biological Resource for Phytoremediation of Metal-Polluted Soils. *Phytoremediation Contam. Soil Water* **2020**, 85–107. [CrossRef]
205. Li, R.L.; Liu, B.B.; Zhu, Y.X.; Zhang, Y. Effects of flooding and aging on phytoremediation of typical polycyclic aromatic hydrocarbons in mangrove sediments by Kandelia obovata seedlings. *Ecotoxicol. Environ. Saf.* **2016**, *128*, 118–125. [CrossRef]
206. Lu, H.; Zhang, Y.; Liu, B.; Liu, J.; Ye, J.; Yan, C. Rhizodegradation gradients of phenanthrene and pyrene in sediment of mangrove (Kandelia candel (L.) Druce). *J. Hazard. Mater.* **2011**, *196*, 263–269. [CrossRef]
207. Cristina, C. Eco-Technological Solutions for the Remediation of Polluted Soil and Heavy Metal Recovery. In *Environmental Risk Assessment of Soil Contamination*; IntechOpen Limited: London, UK, 2014. [CrossRef]
208. Mahmood, T. Phytoextraction of heavy metals—The process and scope for remediation of contaminated soils. *Soil Environ.* **2010**, *29*, 91–109.
209. Prasad, M.N.V.; Freitas, D.O.H.M. Metal hyperaccumulation in plants—Biodiversity prospecting forphytoremediation technology. *Electron. J. Biotechnol.* **2003**, *6*, 110–146. [CrossRef]
210. Sherene, T. Mobility and transport of heavy metals in polluted soil environment. *Biol. Forum* **2010**, *2*, 112–121.
211. Evanko, C.R.; Ph, D.; Dzombak, D.A. Remediation of Metals-Contaminated Soils and Groundwater. *Gwrtac Ser.* **1997**, *1*, 1–61.
212. Olaniran, A.; Balgobind, A.; Pillay, B. Bioavailability of heavy metals in soil: Impact on microbial biodegradation of organic compounds and possible improvement strategies. *Int. J. Mol. Sci.* **2013**, *14*, 197. [CrossRef]
213. Hussain, S.; Siddique, T.; Arshad, M.; Saleem, M. Bioremediation and phytoremediation of pesticides: Recent advances. *Crit. Rev. Environ. Sci. Technol.* **2009**, *39*, 843–907. [CrossRef]
214. Gerhardt, K.E.; Huang, X.D.; Glick, B.R.; Greenberg, B.M. Phytoremediation and rhizoremediation of organic soil contaminants: Potential and challenges. *Plant Sci.* **2009**, *176*, 20–30. [CrossRef]
215. Eevers, N.; White, J.C.; Vangronsveld, J.; Weyens, N. Bio-and Phytoremediation of Pesticide-Contaminated Environments: A Review. *Adv. Bot. Res.* **2017**, *83*, 277–318. [CrossRef]
216. Biddlestone, A.J.; Gray, K.R.; Job, G.D. Treatment of dairy farm wastewaters in engineered reed bed systems. *Process Biochem.* **1991**, *26*, 265–268. [CrossRef]
217. Ansola, G.; González, J.; Cortijo, R.; Luis, E. Experimental and full–scale pilot plant constructed wetlands for municipal wastewaters treatment. *Ecol. Eng.* **2003**, *21*, 43–52. [CrossRef]
218. Kyambadde, J.; Kansiime, F.; Gumaelius, L.; Dalhammar, G. A comparative study of Cyperus papyrus and Miscanthidium violaceum-based constructed wetlands for wastewater treatment in a tropical climate. *Water Res.* **2004**, *38*, 475–485. [CrossRef]
219. Bodini, S.F.; Cicalini, A.R.; Santori, F. Rhizosphere dynamics during phytoremediation of olive mill wastewater. *Bioresour. Technol.* **2011**, *102*, 4383–4389. [CrossRef]
220. Chaney, R.L.; Angle, J.S.; Broadhurst, C.L.; Peters, C.A.; Tappero, R.V.; Sparks, D.L. Improved Understanding of Hyperaccumulation Yields Commercial Phytoextraction and Phytomining Technologies. *J. Environ. Qual.* **2007**, *36*, 1429–1443. [CrossRef]
221. Sorek, A.; Atzmon, N.; Dahan, O. "Phytoscreening": The use of trees for discovering subsurface contamination by VOCs. *ACS Publ.* **2008**, *42*, 536–542. [CrossRef]
222. Burken, J.; Vroblesky, D.A. Phytoforensics, dendrochemistry, and phytoscreening: New green tools for delineating contaminants from past and present. *Environ. Sci. Technol.* **2011**, *45*, 7. [CrossRef]
223. Vroblesky, D. *User's Guide to the Collection and Analysis of Tree Cores to Assess the Distribution of Subsurface Volatile Organic Compounds*; U.S. Geological Survey: Reston, VA, USA, 2008.
224. Semple, K.T.; Doick, K.J.; Jones, K.C.; Burauel, P.; Craven, A.; Harms, H. Defining bioavailability and bioaccessibility of contaminated soil and sediment is complicated. *Environ. Sci. Technol.* **2004**, *38*. [CrossRef]
225. Tahmasbian, I.; Sinegani, A.A.S. Improving the efficiency of phytoremediation using electrically charged plant and chelating agents. *Environ. Sci. Pollut. Res.* **2016**, *23*, 2479–2486. [CrossRef]
226. Chen, Z.; Tang, Y.; Zhou, C.; Xie, S.; Xiao, S.; Baker, A.J.M.; Qiu, R.J. Mechanisms of Fe biofortification and mitigation of Cd accumulation in rice (Oryza sativa L.) grown hydroponically with Fe chelate fertilization. *Chemosphere* **2017**. [CrossRef] [PubMed]
227. Chhajro, M.A.; Fu, Q.; Shaaban, M.; Rizwan, M.S.; Jun, Z.; Salam, A.; Kubar, K.A.; Bashir, S.; Hongqing, H.; Jamro, G.M. Identifying the functional groups and the influence of synthetic chelators on cd availability and microbial biomass carbon in cd-contaminated soil. *Int. J. Phytoremediation* **2018**, *20*, 168–174. [CrossRef] [PubMed]
228. Beiyuan, J.; Awad, Y.; Beckers, F.; Tsang, D.; Ok, Y.S.; Rinklebe, J. Mobility and phytoavailability of As and Pb in a contaminated soil using pine sawdust biochar under systematic change of redox conditions. *Chemosphere* **2017**, *178*, 110–118. [CrossRef] [PubMed]
229. Singh, A.; Agrawal, M. Reduction in Metal Toxicity by Applying Different S oil Amendments in Agricultural Field and Its Consequent Effects on Characteristics of Radish Plants (Raphanus). *J. Agr. Sci. Tech* **2018**, *15*, 1553–1564.
230. Murtaza, G.; Javed, W.; Hussain, A.; Wahid, A.; Murtaza, B.; Owens, G. Metal uptake via phosphate fertilizer and city sewage in cereal and legume crops in Pakistan. *Environ. Sci. Pollut. Res.* **2015**, *22*, 9136–9147. [CrossRef] [PubMed]
231. Zhu, H.; Chen, C.; Xu, C.; Zhu, Q.; Huang, D. Effects of soil acidification and liming on the phytoavailability of cadmium in paddy soils of central subtropical China. *Environ. Pollut.* **2016**, *219*, 99–106. [CrossRef]

232. Zhao, L.; Cao, X.; Zheng, W.; Scott, J.W.; Sharma, B.K.; Chen, X. Copyrolysis of Biomass with Phosphate Fertilizers to Improve Biochar Carbon Retention, Slow Nutrient Release, and Stabilize Heavy Metals in Soil. *ACS Sustain. Chem. Eng.* **2016**, *4*, 1630–1636. [CrossRef]
233. Wenzel, W.W.; Unterbrunner, R.; Sommer, P.; Sacco, P. Chelate-assisted phytoextraction using canola (Brassica napus L.) in outdoors pot and lysimeter experiments. *Plant Soil* **2003**, *249*, 83–96. [CrossRef]
234. Ju, W.; Liu, L.; Jin, X.; Duan, C.; Cui, Y.; Wang, J.; Ma, D.; Zhao, W.; Wang, Y.; Fang, L. Co-inoculation effect of plant-growth-promoting rhizobacteria and rhizobium on EDDS assisted phytoremediation of Cu contaminated soils. *Chemosphere* **2020**, *254*. [CrossRef]
235. Yang, L.; Luo, C.; Liu, Y.; Quan, L.; Chen, Y.; Shen, Z. Residual effects of EDDS leachates on plants during EDDS-assisted phytoremediation of copper contaminated soil. *Sci. Total Environ.* **2013**, *444*, 263–270. [CrossRef]
236. Aziz, T.; Maqsood, M.A.; Kanwal, S.; Hussain, S.; Ahmad, H.R.; Sabir, M. Fertilizers and environment: Issues and challenges. *Crop Prod. Glob. Environ. Issues* **2015**, 575–598. [CrossRef]
237. Postigo, C.; Martinez, D.; Grondona, S.; Miglioranza, K. Groundwater pollution: Sources, mechanisms, and prevention. *Water Resour. Prot.* **2018**, *11*, 87–96.
238. Ashraf, S.; Zahir, Z.A.; Asghar, H.N.; Asghar, M. Isolation, screening and identification of lead and cadmium resistant sulfur oxidizing bacteria. *Pakistan J. Agric. Sci.* **2018**, *55*, 349–359. [CrossRef]
239. Smolinska, B. Green waste compost as an amendment during induced phytoextraction of mercury-contaminated soil. *Environ. Sci. Pollut. Res.* **2015**, *22*, 3528–3537. [CrossRef]
240. Patra, D.K.; Pradhan, C.; Patra, H.K. Chelate based phytoremediation study for attenuation of chromium toxicity stress using lemongrass: Cymbopogon flexuosus (nees ex steud.) W. Watson. *Int. J. Phytoremediation* **2018**, *20*, 1324–1329. [CrossRef]
241. Wiszniewska, A.; Hanus-Fajerska, E.; Muszyńska, E.; Ciarkowsk, K. Natural organic amendments for improved phytoremediation of polluted soils: A review of recent progress. *Pedosphere* **2016**, *26*, 1–12. [CrossRef]
242. Evangelou, M.; Ebel, M.; Schaeffer, A. Chelate assisted phytoextraction of heavy metals from soil. Effect, mechanism, toxicity, and fate of chelating agents. *Chemosphere* **2007**, *68*, 989–1003. [CrossRef]
243. Grčman, H.; Velikonja-Bolta, Š.; Vodnik, D.; Kos, B.; Leštan, D. EDTA enhanced heavy metal phytoextraction: Metal accumulation, leaching and toxicity. *Plant Soil* **2001**, *235*, 105–114. [CrossRef]
244. Ali, S.Y.; Chaudhury, S. EDTA-Enhanced Phytoextraction by Tagetes sp. and Effect on Bioconcentration and Translocation of Heavy Metals. *Environ. Process.* **2016**, *3*, 735–746. [CrossRef]
245. Chen, H.; Cutright, T. EDTA and HEDTA effects on Cd, Cr, and Ni uptake by *Helianthus annuus*. *Chemosphere* **2001**, *45*, 21–28. [CrossRef]
246. Vassilev, A.; Schwitzguebel, J.P.; Thewys, T.; Van Der Lelie, D.; Vangronsveld, J. The use of plants for remediation of metal-contaminated soils. *Sci. World J.* **2004**, *4*, 9–34. [CrossRef] [PubMed]
247. Lu, Y.; Luo, D.; Lai, A.; Liu, G.; Liu, L.; Long, J.; Zhang, H.; Chen, Y. Leaching characteristics of EDTA-enhanced phytoextraction of Cd and Pb by Zea mays L. in different particle-size fractions of soil aggregates exposed to artificial rain. *Environ. Sci. Pollut. Res.* **2017**, *24*, 1845–1853. [CrossRef] [PubMed]
248. Sidhu, G.P.S.; Bali, A.S.; Singh, H.P.; Batish, D.R.; Kohli, R.K. Ethylenediamine disuccinic acid enhanced phytoextraction of nickel from contaminated soils using Coronopus didymus (L.) Sm. *Chemosphere* **2018**, *205*, 234–243. [CrossRef] [PubMed]
249. Meers, E.; Ruttens, A.; Hopgood, M.J.; Samson, D.; Tack, F.M.G. Comparison of EDTA and EDDS as potential soil amendments for enhanced phytoextraction of heavy metals. *Chemosphere* **2005**, *58*, 1011–1022. [CrossRef]
250. Song, Y.; Ammami, M.T.; Benamar, A.; Mezazigh, S.; Wang, H. Effect of EDTA, EDDS, NTA and citric acid on electrokinetic remediation of As, Cd, Cr, Cu, Ni, Pb and Zn contaminated dredged marine sediment. *Environ. Sci. Pollut. Res.* **2016**, *23*, 10577–10586. [CrossRef]
251. Luo, C.; Shen, Z.; Li, X. Enhanced phytoextraction of Cu, Pb, Zn and Cd with EDTA and EDDS. *Chemosphere* **2005**, *59*, 1–11. [CrossRef]
252. Wenger, K.; Gupta, S.K.; Furrer, G.; Schulin, R. The Role of Nitrilotriacetate in Copper Uptake by Tobacco. *J. Environ. Qual.* **2003**, *32*, 1669–1676. [CrossRef]
253. Freitas, E.V.d.S.; do Nascimento, C.W.A. The use of NTA for lead phytoextraction from soil from a battery recycling site. *J. Hazard. Mater.* **2009**, *171*, 833–837. [CrossRef]
254. Yulizar, Y.; Sudirman; Apriandanu, D.O.B.; Wibowo, A.P. Plant extract mediated synthesis of Au/TiO2 nanocomposite and its photocatalytic activity under sodium light irradiation. *Compos. Commun.* **2019**, *16*, 50–56. [CrossRef]
255. Bhargava, A.; Srivastava, S. Phytomining: Principles and Applications. In *Biotechnology*; CRC Press: Boca Raton, FL, USA, 2017; pp. 141–159. ISBN 9780203711033.
256. Seidel, H.; Ondruschka, J.; Morgenstern, P.; Stottmeister, U. Bioleaching of heavy metals from contaminated aquatic sediments using indigenous sulfur-oxidizing bacteria: A feasibility study. *Water Sci. Technol.* **1998**, *37*, 387–394. [CrossRef]
257. Kayser, A.; Wenger, K.; Keller, A.; Attinger, W.; Felix, H.R.; Gupta, S.K.; Schulin, R. Enhancement of phytoextraction of Zn, Cd, and Cu from calcareous soil: The use of NTA and sulfur amendments. *Environ. Sci. Technol.* **2000**, *34*, 1778–1783. [CrossRef]
258. Chien, S.H.; Gearhart, M.M.; Villagarcía, S. Comparison of ammonium sulfate with other nitrogen and sulfur fertilizers in increasing crop production and minimizing environmental impact: A review. *Soil Sci.* **2011**, *176*, 327–335. [CrossRef]

259. Li, Y.; Zhao, J.; Guo, J.; Liu, M.; Xu, Q.; Li, H.; Li, Y.F.; Zheng, L.; Zhang, Z.; Gao, Y. Influence of sulfur on the accumulation of mercury in rice plant (Oryza sativa L.) growing in mercury contaminated soils. *Chemosphere* **2017**, *182*, 293–300. [CrossRef]
260. Zhao, C.; Gupta, V.V.S.R.; Degryse, F.; McLaughlin, M.J. Abundance and diversity of sulphur-oxidising bacteria and their role in oxidising elemental sulphur in cropping soils. *Biol. Fertil. Soils* **2017**, *53*, 159–169. [CrossRef]
261. Kaplan, M. Effect of elemental sulphur and sulphur containing waste in a calcareous soil in Turkey. *J. Plant Nutr.* **1998**, *21*, 1655–1665. [CrossRef]
262. Karimizarchi, M.; Aminuddin, H.; Khanif, M.; Radziah, O. Effect of elemental sulphur timing and application rates on soil P release and concentration in maize. *Pertanika J. Trop. Agric. Sci* **2016**, *39*, 235–248.
263. Tsai, L.; Yu, K.; Chen, S.; Kung, P.; Chang, C. Partitioning variation of heavy metals in contaminated river sediment via bioleaching: Effect of sulfur added to total solids ratio. *Water Research* **2003**, *37*, 4623–4630. [CrossRef]
264. Ashraf, S. Phytoextraction of Lead and Cadmium by Grasses from Contaminated Soil Amended with Acidulated Cow Dung Slurry/Extract and Bioaugmented with Sulfur Oxidizing Bacteria. Ph.D. Thesis, University of Agriculture, Faisalabad, Pakistan, 2017.
265. Willig, S.; Varanini, Z.; Nannipieri, P. Function of Siderophores in the Plant Rhizosphere. In *The Rhizosphere*; CRC Press: Boca Raton, FL, USA, 2020; pp. 239–278. ISBN 9780429116698.
266. Crowley, D.; Römheld, V.; Marschner, H.; Szaniszlo, P.J. Root-microbial effects on plant iron uptake from siderophores and phytosiderophores. *Plant Soil* **2015**, *142*, 1–7. [CrossRef]
267. RÖmheld, V. The role of phytosiderophores in acquisition of iron and other micronutrients in graminaceous species: An ecological approach. *Iron Nutr. Interact. Plants* **1991**, 159–166. [CrossRef]
268. Shenker, M.; Fan, T.W.-M.; Crowley, D.E. Phytosiderophores Influence on Cadmium Mobilization and Uptake by Wheat and Barley Plants. *J. Environ. Qual.* **2001**, *30*, 2091–2098. [CrossRef]
269. Higuchi, K.; Suzuki, K.; Nakanishi, H.; Yamaguchi, H.; Nishizawa, N.K.; Mori, S. Cloning of nicotianamine synthase genes, novel genes involved in the biosynthesis of phytosiderophores. *Plant Physiol.* **1999**, *119*, 471–479. [CrossRef]
270. Jankong, P.; Visoottiviseth, P.; Khokiattiwong, S. Enhanced phytoremediation of arsenic contaminated land. *Chemosphere* **2007**, *68*, 1906–1912. [CrossRef]
271. Nie, S.W.; Gao, W.S.; Chen, Y.Q.; Sui, P.; Eneji, A.E. Use of life cycle assessment methodology for determining phytoremediation potentials of maize-based cropping systems in fields with nitrogen fertilizer over-dose. *J. Clean. Prod.* **2010**, *18*, 1530–1534. [CrossRef]
272. Wu, H.; Tang, S.; Zhang, X.; Guo, J.; Song, Z.; Tian, S.; Smith, D.L. Using elevated CO2 to increase the biomass of a Sorghum vulgare × Sorghum vulgare var. sudanense hybrid and Trifolium pratense L. and to trigger hyperaccumulation of cesium. *J. Hazard. Mater.* **2009**, *170*, 861–870. [CrossRef]
273. McGrath, S.P.; Zhao, J.; Lombi, E. Phytoremediation of metals, metalloids, and radionuclides. *Adv. Agron.* **2002**, *75*, 1–56.
274. Bothe, H. *Plants in Heavy Metal Soils*; Springer: Berlin/Heidelberg, Germany, 2011; Volume 30, pp. 35–57.
275. Sheoran, V.; Sheoran, A.S.; Poonia, P. Role of hyperaccumulators in phytoextraction of metals from contaminated mining sites: A review. *Crit. Rev. Environ. Sci. Technol.* **2011**, *41*, 168–214. [CrossRef]
276. Malik, N.; Biswas, A.K. Role of Higher Plants in Remediation of Metal Contaminated Sites. *Sci. Rev. Chem. Commun.* **2012**, *2*, 141–146.
277. Watanabe, M.E. Phytoremediation on the brink of commercialization. *Environ. Sci. Technol.* **1997**, *31*. [CrossRef] [PubMed]
278. Boyd, R.S.; Shaw, J.J.; Martens, S.N. Nickel hyperaccumulation defends Streptanthus polygaloides (Brassicaceae) against pathogens. *Am. J. Bot.* **1994**, *81*, 294–300. [CrossRef]
279. Krämer, U. The Plants that Suck Up Metal. *Ger. Res.* **2018**, *40*, 18–23. [CrossRef]
280. Souri, Z.; Karimi, N.; Sarmadi, M.; Rostami, E. Salicylic acid nanoparticles (SANPs) improve growth and phytoremediation efficiency of Isatis cappadocica Desv., under As stress. *IET Nanobiotechnology* **2017**, *11*, 650–655. [CrossRef]
281. Pradhan, S.; Patra, P.; Das, S.; Chandra, S.; Mitra, S.; Dey, K.K.; Akbar, S.; Palit, P.; Goswami, A. Photochemical modulation of biosafe manganese nanoparticles on vigna radiata: A detailed molecular, biochemical, and biophysical study. *Environ. Sci. Technol.* **2013**, *47*, 13122–13131. [CrossRef]
282. Khan, N.; Bano, A. Modulation of phytoremediation and plant growth by the treatment with PGPR, Ag nanoparticle and untreated municipal wastewater. *Int. J. Phytoremediation* **2016**, *18*, 1258–1269. [CrossRef]
283. Ma, X.; Wang, C. Fullerene Nanoparticles Affect the Fate and Uptake of Trichloroethylene in Phytoremediation Systems. *Environ. Eng. Sci.* **2010**, *27*, 989–992. [CrossRef]
284. Jiamjitrpanich, W.; Parkpian, P. Enhanced Phytoremediation Efficiency of TNT-Contaminated Soil by Nanoscale Zero Valent Iron. In Proceedings of the 2nd International Conference on Environment and Industrial Innovation (ICEII 2012), Hong Kong, China, 2–3 June 2012; Volume 35, pp. 82–86.
285. Singh, J.; Lee, B.K. Influence of nano-TiO2 particles on the bioaccumulation of Cd in soybean plants (Glycine max): A possible mechanism for the removal of Cd from the contaminated soil. *J. Environ. Manag.* **2016**, *170*, 88–96. [CrossRef]
286. Huang, D.; Qin, X.; Peng, Z.; Liu, Y.; Gong, X.; Zeng, G.; Huang, C.; Cheng, M.; Xue, W.; Wang, X.; et al. Nanoscale zero-valent iron assisted phytoremediation of Pb in sediment: Impacts on metal accumulation and antioxidative system of Lolium perenne. *Ecotoxicol. Environ. Saf.* **2018**, *153*, 229–237. [CrossRef]

287. Weng, X.; Jin, X.; Lin, J.; Naidu, R.; Chen, Z. Removal of mixed contaminants Cr (VI) and Cu (II) by green synthesized iron based nanoparticles. *Ecol. Eng.* **2016**, *97*, 32–39. [CrossRef]
288. Vítková, M.; Puschenreiter, M.; Komárek, M. Effect of nano zero-valent iron application on As, Cd, Pb, and Zn availability in the rhizosphere of metal(loid) contaminated soils. *Chemosphere* **2018**, *200*, 217–226. [CrossRef]
289. Gong, X.; Huang, D.; Liu, Y.; Zeng, G.; Wang, R.; Wan, J.; Zhang, C.; Chen, Z.; Qin, X.; Xue, W. Stabilized Nanoscale Zerovalent Iron Mediated Cadmium Accumulation and Oxidative Damage of Boehmeria nivea (L.) Gaudich Cultivated in Cadmium Contaminated Sediments. *Environ. Sci. Technol.* **2017**, *51*, 11308–11316. [CrossRef]
290. Moameri, M.; Khalaki, M.A. Capability of Secale montanum trusted for phytoremediation of lead and cadmium in soils amended with nano-silica and municipal solid waste compost. *Environ. Sci. Pollut. Res.* **2019**, *26*, 24315–24322. [CrossRef]
291. Madhavi, V.; Prasad, T.N.V.K.V.; Reddy, B.R.; Reddy, A.V.B.; Gajulapalle, M. Conjunctive effect of CMC–zero-valent iron nanoparticles and FYM in the remediation of chromium-contaminated soils. *Appl. Nanosci.* **2014**, *4*, 477–484. [CrossRef]
292. Pillai, H.P.S.; Kottekottil, J. Nano-Phytotechnological Remediation of Endosulfan Using Zero Valent Iron Nanoparticles. *J. Environ. Prot.* **2016**, *07*, 734–744. [CrossRef]
293. Saifullah; Meers, E.; Qadir, M.; de Caritat, P.; Tack, F.M.G.; Laing, G.D.; Ziaae, M.H. EDTA-assisted Pb phytoextraction. *Chemosphere* **2009**, *74*, 1279–1291.
294. Shaheen, S.M.; Rinklebe, J. Impact of emerging and low cost alternative amendments on the (im)mobilization and phytoavailability of Cd and Pb in a contaminated floodplain soil. *Ecol. Eng.* **2015**, *74*, 319–326. [CrossRef]
295. Souza, L.A.; Piotto, F.A.; Nogueirol, R.C.; Azevedo, R.A. Use of non-hyperaccumulator plant species for the phytoextraction of heavy metals using chelating agents. *Sci. Agric.* **2013**, *70*, 290–295. [CrossRef]
296. He, J.; Ren, Y.; Pan, X.; Yan, Y.; Zhu, C.; Jiang, D. Salicylic acid alleviates the toxicity effect of cadmium on germination, seedling growth, and amylase activity of rice. *J. Plant Nutr. Soil Sci.* **2010**, *173*, 300–305. [CrossRef]
297. Popova, L.P. Role of jasmonates in plant adaptation to stress. *Ecophysiol. Responses Plants Salt Stress* **2012**, 381–412. [CrossRef]
298. Harel, Y.M.; Elad, Y.; Rav-David, D.; Borenstein, M.; Shulchani, R.; Lew, B.; Graber, E.R. Biochar mediates systemic response of strawberry to foliar fungal pathogens. *Plant Soil* **2012**, *357*, 245–257. [CrossRef]
299. Fellet, G.; Marmiroli, M.; Marchiol, L. Elements uptake by metal accumulator species grown on mine tailings amended with three types of biochar. *Sci. Total Environ.* **2014**, *468–469*, 598–608. [CrossRef]
300. Ahmad, M.; Ok, Y.S.; Kim, B.Y.; Ahn, J.H.; Lee, Y.H.; Zhang, M.; Moon, D.H.; Al-Wabel, M.I.; Lee, S.S. Impact of soybean stover- and pine needle-derived biochars on Pb and As mobility, microbial community, and carbon stability in a contaminated agricultural soil. *J. Environ. Manag.* **2016**, *166*, 131–139. [CrossRef]
301. Wu, L.; Li, Z.; Han, C.; Liu, L.; Teng, Y.; Sun, X.; Pan, C.; Huang, Y.; Luo, Y.; Christie, P. Phytoremediation of soil contaminated with cadmium, copper and polychlorinated biphenyls. *Int. J. Phytoremediation* **2012**, *14*, 570–584. [CrossRef]
302. Cantrell, K.B.; Hunt, P.G.; Uchimiya, M.; Novak, J.M.; Ro, K. Impact of pyrolysis temperature and manure source on physicochemical characteristics of biochar. *Bioresour. Technol.* **2012**, *107*, 419–428. [CrossRef]
303. Zaidi, S.; Usmani, S.; Singh, B.R.; Musarrat, J. Significance of Bacillus subtilis strain SJ-101 as a bioinoculant for concurrent plant growth promotion and nickel accumulation in Brassica juncea. *Chemosphere* **2006**, *64*, 991–997. [CrossRef]
304. Sheng, X.F.; He, L.Y. Solubilization of potassium-bearing minerals by a wild-type strain of Bacillus edaphicus and its mutants and increased potassium uptake by wheat. *Can. J. Microbiol.* **2006**, *52*, 66–72. [CrossRef]
305. Seth, C.S. A review on mechanisms of plant tolerance and role of transgenic plants in environmental clean-up. *Bot. Rev.* **2012**, *78*, 32–62. [CrossRef]
306. Zhaoyong, S.; Yinglong, C.; Runjin, L. Arbuscular mycorrhizal fungi of dipterocarpaceae in Xishuangbanna, southern Yunnan. *Jun Wu Xi Tong Mycosystema* **2003**, *22*, 402–409.
307. Glick, B.R.; Penrose, D.M.; Li, J. A model for the lowering of plant ethylene concentrations by plant growth-promoting bacteria. *J. Theor. Biol.* **1998**, *190*, 63–68. [CrossRef]
308. Farwell, A.J.; Vesely, S.; Nero, V.; Rodriguez, H.; McCormack, K.; Shah, S.; Dixon, D.G.; Glick, B.R. Tolerance of transgenic canola plants (Brassica napus) amended with plant growth-promoting bacteria to flooding stress at a metal-contaminated field site. *Environ. Pollut.* **2007**, *147*, 540–545. [CrossRef]
309. Van Aken, B. Transgenic plants for phytoremediation: Helping nature to clean up environmental pollution. *Trends Biotechnol.* **2008**, *26*, 225–227. [CrossRef]
310. Rugh, C.L.; Senecoff, J.F.; Meagher, R.B.; Merkle, S.A. Development of transgenic yellow poplar for mercury phytoremediation. *Nat. Biotechnol.* **1998**, *16*, 925–928. [CrossRef]
311. Assunção, A.G.L.; Pieper, B.; Vromans, J.; Lindhout, P.; Aarts, M.G.M.; Schat, H. Construction of a genetic linkage map of Thlaspi caerulescens and quantitative trait loci analysis of zinc accumulation. *New Phytol.* **2006**, *170*, 21–32. [CrossRef]
312. Zhuang, P.; Ye, Z.; Lan, C.; Xie, Z.; Shu, W. Chemically Assisted Phytoextraction of Heavy Metal Contaminated Soils using Three Plant Species. *Plant Soil* **2005**, *276*, 153–162. [CrossRef]
313. Ladislas, S.; El-Mufleh, A.; Gérente, C.; Chazarenc, F.; Andrès, Y.; Béchet, B. Potential of aquatic macrophytes as bioindicators of heavy metal pollution in urban stormwater runoff. *Water. Air. Soil Pollut.* **2012**, *223*, 877–888. [CrossRef]
314. Mattina, M.J.I.; Lannucci-Berger, W.; Musante, C.; White, J.C. Concurrent plant uptake of heavy metals and persistent organic pollutants from soil. *Environ. Pollut.* **2003**, *124*, 375–378. [CrossRef]

315. Liu, W.; Zhou, Q.; An, J.; Sun, Y.; Liu, R. Variations in cadmium accumulation among Chinese cabbage cultivars and screening for Cd-safe cultivars. *J. Hazard. Mater.* **2010**, *173*, 737–743. [CrossRef]
316. Wu, Q.; Wang, S.; Thangavel, P.; Li, Q.; Zheng, H.; Bai, J.; Qiu, R. Phytostabilization potential of Jatropha curcas l. in polymetallic acid mine tailings. *Int. J. Phytoremediation* **2011**, *13*, 788–804. [CrossRef]
317. Karami, A.; Shamsuddin, Z.H. Phytoremediation of heavy metals with several efficiency enhancer methods. *Afr. J. Biotechnol.* **2010**, *9*, 3689–3698.
318. Pagiola, S.; von Ritter, K.; Bishop, J. Assessing the economic value of ecosystem conservation. In *Environment Department Paper No. 101*; The World Bank Environment Department: Washington, DC, USA, 2004.
319. Lewandowski, I.; Schmidt, U.; Londo, M.; Faaij, A. The economic value of the phytoremediation function—Assessed by the example of cadmium remediation by willow (Salix ssp). *Agric. Syst.* **2006**, *89*, 68–89. [CrossRef]
320. Wan, X.; Lei, M.; Chen, T. Cost–benefit calculation of phytoremediation technology for heavy-metal-contaminated soil. *Sci. Total Environ.* **2016**, *563–564*, 796–802. [CrossRef] [PubMed]
321. Salido, A.L.; Hasty, K.L.; Lim, J.M.; Butcher, D.J. Phytoremediation of arsenic and lead in contaminated soil using Chinese Brake ferns (Pteris vittata) and Indian mustard (Brassica juncea). *Int. J. Phytoremediation* **2003**, *5*, 89–103. [CrossRef]
322. Van Nevel, L.; Mertens, J.; Oorts, K.; Verheyen, K. Phytoextraction of metals from soils: How far from practice? *Environ. Pollut.* **2007**, *150*, 34–40. [CrossRef] [PubMed]
323. Tian, Y.; Zhang, H. Producing biogas from agricultural residues generated during phytoremediation process: Possibility, threshold, and challenges. *Int. J. Green Energy* **2016**, *13*, 1556–1563. [CrossRef]
324. Dhiman, S.S.; Selvaraj, C.; Li, J.; Singh, R.; Zhao, X.; Kim, D.; Kim, J.Y.; Kang, Y.C.; Lee, J.K. Phytoremediation of metal-contaminated soils by the hyperaccumulator canola (Brassica napus L.) and the use of its biomass for ethanol production. *Fuel* **2016**, *183*, 107–114. [CrossRef]
325. Semple, K.T.; Morriss, A.W.J.; Paton, G.I. Bioavailability of hydrophobic organic contaminants in soils: Fundamental concepts and techniques for analysis. *Eur. J. Soil Sci.* **2003**, *54*, 809–818. [CrossRef]
326. Van Ginneken, L.; Meers, E.; Guisson, R.; Ruttens, A.; Elst, K.; Tack, F.M.G.; Vangronsveld, J.; Diels, L.; Dejonghe, W. Phytoremediation for heavy metal-contaminated soils combined with bioenergy production. *J. Environ. Eng. Landsc. Manag.* **2007**, *15*, 227–236. [CrossRef]
327. Singh, S.; Parihar, P.; Singh, R.; Singh, V.P.; Prasad, S.M. Heavy metal tolerance in plants: Role of transcriptomics, proteomics, metabolomics, and ionomics. *Front. Plant Sci.* **2016**, *6*, 1143. [CrossRef]
328. Rofkar, J.R.; Dwyer, D.F. Effects of light regime, temperature, and plant age on uptake of arsenic by Spartina pectinata and Carex stricta. *Int. J. Phytoremediation* **2011**, *13*, 528–537. [CrossRef]
329. Walsh, É.; Kuehnhold, H.; O'Brien, S.; Coughlan, N.E.; Jansen, M.A. Light intensity alters the phytoremediation potential of Lemna minor. *Environ. Sci. Pollut. Res.* **2021**, *28*, 16394–16407. [CrossRef]
330. Eccles, R.; Zhang, H.; Hamilton, D. A review of the effects of climate change on riverine flooding in subtropical and tropical regions. *J. Water Clim.* **2019**, *10*, 687–707. [CrossRef]
331. Schneider, C.; Laizé, C.L.R.; Acreman, M.C.; Flörke, M. How will climate change modify river flow regimes in Europe? *Hydrol. Earth Syst. Sci.* **2013**, *17*, 325–339. [CrossRef]
332. Padmavathiamma, P.K.; Li, L.Y. Phytoremediation of metal-contaminated soil in temperate humid regions of British Columbia, Canada. *Int. J. Phytoremediation* **2009**, *11*, 575–590. [CrossRef]