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Phytoremediation: Mechanisms, plant selection and enhancement by natural and synthetic agents

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ABSTRACT

With current intensive agriculture practices and industrialization, pollution of natural resources like land and water with heavy metals, organic pollutants, radionuclides, pesticides, and fertilizers has become a major concern. Phytoremediation is a cost-effective and environmentally friendly technique that utilizes plants to immobilize, uptake, reduce toxicity, stabilize, or degrade the compounds that are released into the environment from different sources. Studies have shown that heavy metals, organic contaminants, radionuclides, antibiotics, and pesticides can be remediated using plants. Though phytoremediation has been practiced since decades, it is still an emerging technology. This review article summarizes existing information and synthesizes the recent findings on plant species suitable for use in phytoremediation through utilizing different mechanisms, aids that can enhance the efficiency of phytoremediation processes, and strengths and limitations that comes with the application of this technique. Diverse plants remediate different pollutants at different rates through one or multiple mechanisms. The limitations of phytoremediation can be overcome by using several aids including natural and chemical amendments, genetic engineering and natural microbial stimulation. Given the low-cost of phytoremediation compared to conventional technology and sustainability associated with plants and use of renewable energy, phytoremediation can be a reliable solution for a sustainable and economical remediation of soil and water from the organic and inorganic pollutants.

1. Introduction

Rapid rise in global population accompanied by ensuing demands for food, water, energy, timber, and other ecosystem services has led to severe stresses on the natural resources and the environment (Kamran et al., 2021; Saleem et al., 2020c; Zaheer et al., 2020). Anthropogenic activities including the agricultural intensification practices (Mózner et al., 2012), speedy urbanization, and rapid industrialization (Cherniwchan, 2012; Wu et al., 2016) are causing serious environmental pollution by heavy metals (HMs) and metalloids (Anyakora et al., 2013; He et al., 2015; Su, 2014), radionuclides (Hu et al., 2010; Prakash et al., 2013), organic compounds (Afzal et al., 2014), agrochemicals (Malik et al., 2017; Sunitha et al., 2012), and oil spills (Ron & Rosenberg, 2014). Mining activities, disposal of effluents from industries and residential areas, heavy use of fertilizers and pesticides, and irrigation of contaminated water have led to contamination of soils (Awad et al., 2014; Tang et al., 2015; Teng et al., 2014). Mining leads to disturbance of many soil properties, including pH, electrical conductivity, and cation exchange capacity (Saleem et al., 2020a). Consequently, HMs such as Copper (Cu), Lead (Pb), Zinc (Zn), Nickel (Ni), Cadmium (Cd),

Abbreviation: HMs, Heavy metals; PCBs, Polychlorinated biphenyls; PAHs, Polycyclic aromatic hydrocarbons; TNT, 2,4,6- Trinitrotoluene; EDTA, Ethylene Diamine Tetraacetic Acid; BCF, Bioconcentration Factor; TF, Translocation Factor; M-PC, Metal-Phytochelatin Complex; SBR, Sugar Beet Residue; EGTA, Ethylene Glycol Tetra Acetic acid; SDS, Sodium Dodecyl Sulfate; PGPR, Plant Growth Promoting Rhizobacteria; PGPE, Plant Growth Promoting Endophytic Bacteria; AMF, Arbuscular Mycorrhizal Fungi; PAHs, Polycyclic Aromatic Hydrocarbons.

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Chromium (Cr), Iron (Fe), Manganese (Mn) and organic pollutants such as hydrocarbons, aromatic compounds, phenols, organo-chlorinated compounds, pesticides have been found at elevated concentrations in the soil and sediments (Gutiérrez-Ginés et al., 2014; Liu et al., 2017b; Song et al., 2017).

HMs accumulation in soil affects soil microbial population, processes and their activity (Huang et al., 2009; Singh & Kalamdhad, 2011). The effects of HMs on microbial population changes and enzymatic activities are dependent upon the type of HMs and their chemical affinity (Karaca et al., 2010). For examples, cadmium (Cd) affects ureases, proteases and basic phosphatases (Lorenz et al., 2006); lead (Pb) affects catalases, ureases, invertase and acid phosphatase (Belyaeva et al., 2005); Arsenic (As) affects sulfatase and phosphatase (Speir et al., 1999); and copper (Cu) restricts b-glucosidase (Geiger et al., 1998). High chromium (VI) concentration in soil exhibits distinct toxicity characteristics causing negative effects in soil microbial cell metabolism (Huang et al., 2009).

The ingestion of food crops contaminated with HMs can lead to bioaccumulation of HMs and subsequent biomagnification along the higher trophic levels in the food chain can threaten both animal and human health (Singh & Kalamdhad, 2011). HMs accumulation in human body can cause serious complications in human health such as Itai-itai disease due to chronic Cd exposure (Pan et al., 2010); kidney dysfunction and anemia due to Zn (Duruibe et al., 2007); mucosa corrosion, hepatic system failure and central nervous system damage due to Cu (Singh & Kalamdhad, 2011); skin irritation and nervous system complications due to Ni (Argun et al., 2007); cardiovascular problems and damage to nervous system due to Pb (Kazemipour et al., 2008; Singh & Kalamdhad, 2011); abortion, nervous breakdown and skin rashes due to Hg (Duruibe et al., 2007); cancer due to Cr (Zohdi et al., 2012); and carcinogenic and immune system dysfunction due to As (Duruibe et al., 2007).

Among different organic contaminants, chlorinated solvents, petroleum hydrocarbons explosives (Alkorta & Garbisu, 2001), polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), pyrene, and trinitrotoluene (TNT) (Chekol & Vough, 2001) are major soil contaminants. Pesticides that often contaminate soils include atrazine, dieldrin, hexachlorobenzene, dichlorodiphenyltrichlorethane (DDT), and 1,2,4- trichlorobenzene (Chiou et al., 2001). These pollutants seriously affect the soil biota, mineral nutrients availability, and soil productivity because of their persistence in soil for long period of time and toxicity.

Like soils, water resources have also been contaminated by different pollutants. Urbanization and industrialization activities release toxic heavy metals through the sewage, runoff and effluents contributing to largest share of factors for water contamination (Masindi & Muedi, 2018; Parveen et al., 2020; Saleem et al., 2020a). Over 80% of world's wastewater reach to environment without treatment causing nearly 58% of health issues like diarrhea, which is a major cause for early child dealth (Connor et al., 2017). Among metals, Cu, Ni, Pb, Cd, Cr, U, and Zn frequently contaminate water resources (Prasad & Freitas, 2005). The HMs degrade the quality of water and can lead to water-borne health hazards through heavy metal accumulation in the food chain (Wongsasuluk et al., 2014). Apart from HMs, organic pollutants contaminate water resources either by erosion, seepage, sludge and effluents from municipal waste and industries, and runoff from agricultural practices (Diez, 2008) and mining (Tanhan et al., 2007). These contaminants can accumulate over time and negatively affect the aquatic as well as terrestrial ecosystems.

Remediation of the soil and water pollutants for sustaining ecosystem processes and functions is one of the major challenges our society faces today. Many physical, chemical, and biological approaches have been employed for remediating the environmental pollution, however, their applications are limited due to the cost and labor requirements, safety hazards, and risks to ecosystems (Ali et al., 2013). An alternative technique, phytoremediation, can be an effective technique and is gaining popularity, acceptance, and implementation.

Phytoremediation technique utilizes plants to remediate the contaminated media including soil and water. Phytoremediation is an economically and environmentally favorable technique as it utilizes green plants to contain, sequester or detoxify contaminants from contaminated soil and water (Ashraf et al., 2019). Phytoremediation utilizes many mechanisms including degradation (rhizo-degradation, phytodegradation), accumulation (phytoextraction, rhizofiltration), dissipation (phytovolatilization), and immobilization (hydraulic control and phytostabilization) to degrade, remove, or immobilize the pollutants (Pivetz, 2001b). Depending upon the contaminants, plants utilize one or more of these mechanisms to reduce their concentrations from soil and water. For examples, plants uptake and accumulate the HMs in their tissues (Mahar et al., 2016) and degrade the organic pollutants (Saleem et al., 2020b) reducing their toxicity from soil and water resources.

Different plant uses different methods or their combinations to remediate soil and water depending upon the contaminant types, forms, and media. Contaminated ground water can be remediated through phytodegradation, phytovolatilization, rhizo-filtration, rhizo-degradation and phytodegradation. Surface and wastewater contaminations can be treated by rhizofiltration, phytodegradation or rhizodegradation. Soil, sediments or sludges contaminations are remediated through phytoextraction, phytodegradations, phytostabilization, rhizodegradation or phytovolatilization.

Ideal plant species for phytoremediation purpose should be hardy in nature, high biomass-producing, tolerant to toxic effects of metals and contaminants, easy to cultivate, have high absorption capacity, and be non-attractive for herbivory (Adesodun et al., 2010; Sakakibara et al., 2011; Shabani & Sayadi, 2012). In many cases, plant species cannot perform well and need aids to enhance phytoremediation. Such aids include soil amendments like biochar (Paz-Ferreiro et al., 2014), Ethylene Diamine Tetraacetic Acid (EDTA) (Shahid et al., 2014), endophytic bacteria (Afzal et al., 2014), Arbuscular mycorrhiza (Gaur & Adholeya, 2004) or even transgenic plants (Abhilash et al., 2009; Kawahigashi, 2009). They promote the phytoremediation process either by reducing the toxicity of pollutants or increasing the availability of pollutants or promoting the growth of plants.

Previous articles have provided information regarding techniques (Jadia & Fulekar, 2009; Sharma & Pathak, 2014; Willey, 2007), plants used (Banuelos et al., 1997; Cheng, 2003; Pilon-Smits & Pilon, 2002), factors affecting the processes (Antoniadis et al., 2017; Sheoran et al., 2016), aids or stimulators (Coninx et al., 2017; Hovsepyan & Greipsson, 2005; Ullah et al., 2015) and are either specific to soil (Belouchrani et al., 2016; Romeh, 2015; Waigi et al., 2017) or water resources (Nazir et al., 2020; Rezania et al., 2015; Ugya & Imam, 2015). Comprehensive information on maximizing the contribution of each phytoremediation mechanism by appropriate selection of plants, and ways to further enhance the performance of phytoremediation technology is still lacking. Recent review article also suggested need for information on the practicability of phytoremediation and the aids that can enhance the phyto-processes (Wei et al., 2021). Moreover, information from latest research on phytoremediation using new plant species, or alternative mangagment practices, or new contaminants need to be comprehended (Kurade et al., 2021). Consequently, this paper attempts to bring together reports and findings on mechanisms that plants utilize and how selection of plants can maximize the benefits of each mechanism, on strengths and limitations of the phytoremediation technology, and on ways to further enhance phytoremediation of pollutants including HMs and organic pollutants in soil and water. We searched published literatures via different online search engines, reviewed, and summarized the findings on the topic of phytoremediation, and how the phytoremediation has been applied to remediate different contaminants. We present the concept of phytoremediation, its strengths and limitations, mechanisms involved, and ways to overcome the limitations by utilizing aids that can enhance the phytoremediation processes.

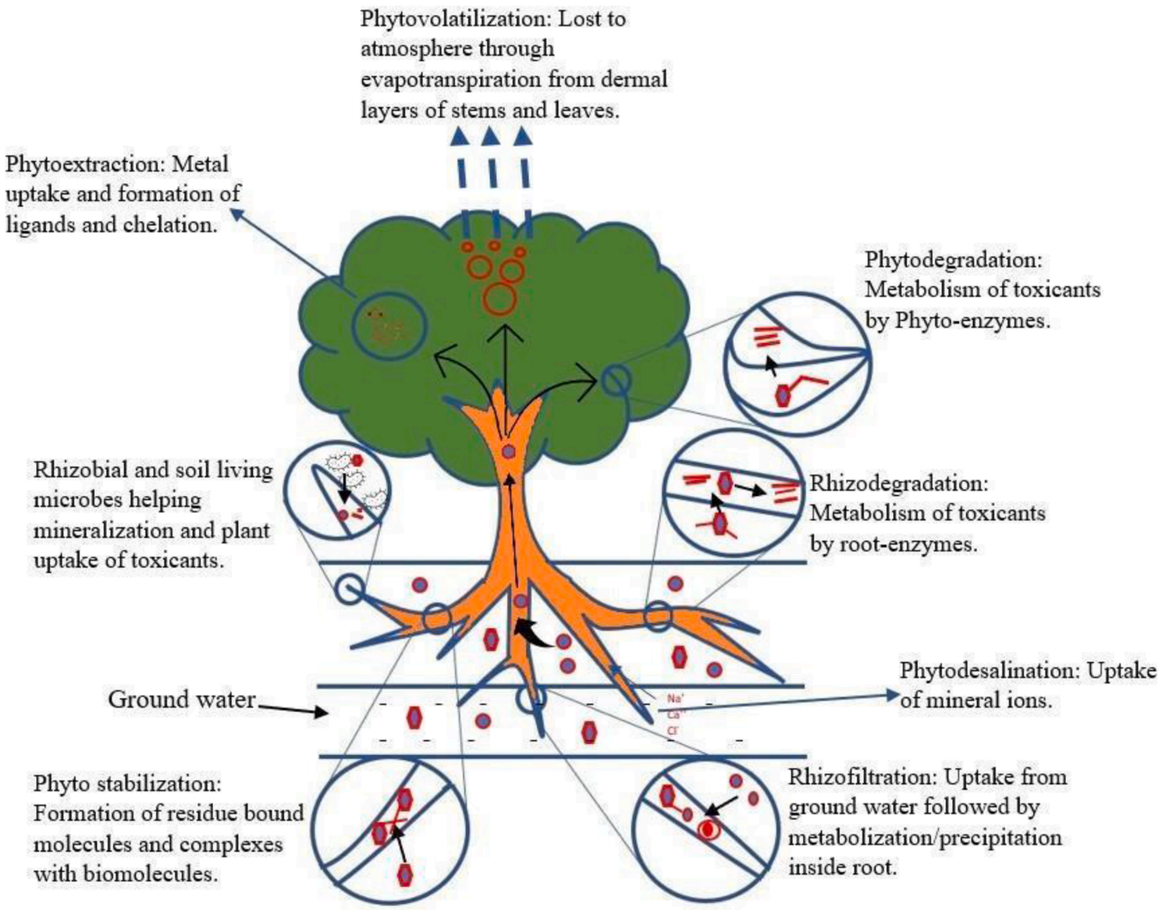

Fig. 1. Phytoremediation processes and their associated functions

2. Phytoremediation Mechanisms and Plants for Optimization of Each Mechanism

Plants can remove organic and inorganic contaminants from soil and water using different mechanisms depending upon plant species and environmental conditions (Anton & Mathe-Gaspar, 2005; Antoniadis et al., 2017). Interaction of plants with the environment (soil, water, and air) and microorganisms play a crucial role in removing the

Table 1.
Plants known to utilize phytoextraction during phytoremediation

Common Name	Scientific Name	Contaminants	Remarks	Reference
Rattlebush	*Sesbania drummondii*	Pb	EDTA enhanced uptake of Pb and accumulation.	Barlow et al. (2000)
Chinese Brake ferns	*Pteris vittate*	Arsenic (As)	126-fold Arsenic in the shoots vs. soil, without the need of chelating agents or other soil amendments.	Salido et al. (2003)
Indian Mustard	*Brassica juncea*	Pb	chelating agents like EDTA (ethylene diamine tetra-acetate) is applied to soil to mobilize Pb and facilitate extraction.	Salido et al. (2003)
Lettuce	*Lactuca sativa*	Ni, Co, and Fe	Higher absorption capacity and lower intrinsic velocity	Hernández et al. (2019)
Perennial rye grass	*Lolium perenne*	Ni, Co, and Fe	Greater survival time	Hernández et al. (2019)
Vygies	*Mesembryanthemum criniforum*	Pb	Bacteria tolerant to Pb used	Manzoor et al. (2019)
Geranium	*Pelargonium hortorum*	Pb	Bacteria tolerant to Pb used	Manzoor et al. (2019)
Tobacco	*Nicotiana tabacum*	Cd	Cd higher in stems and leaves	Yang et al. (2019b)
Corn	*Zea mays*	Pb, Ti	Chelators induced the phytoextraction of Pb and Ti	Huang et al. (2019)
Black Nightshade	*Solanum nigrum*	Cd, Pb	PASP (polyaspartate) or LAAF (liquid amino acid fertilizer) enhance the extraction process	He et al. (2019)
Garden Geranium	*Pelargonium hortorum*	Pb, Cd	EDTA enhanced Pb and Cd phytoextraction	Gul et al. (2019)
Sedum Alfredii Hance	*Sedum alfredii*	Pb	Compounded activation agent enhanced the Pb phytoextraction	Ning et al. (2019)
Common Cocklebur	*Xanthium strumarium*	Cd, Pb, Ni, Zn	Has highest BCF for Ni-1.651, Cd-1.574 and Pb-1.048.	Khalid et al. (2019)
Alpine pennygrass	*Thlaspi caerulescens*	Cd, Zn	Cd transported by Zn and Ca pathway	Cosio et al. (2004)
Mouse ear cress	*Arabdidopsis helleri*	Cd, Zn	Cd transported by other pathways	Cosio et al. (2004)
Commelina	*Commelina communis*	Cu	Hyperacumulator species of Commelina had Cu concentration >1000 μg/g	Wang et al. (2004)

Table 2.
Plants known to utilize phytostabilization or phytoimmobilization mechanism for various pollutants

Common Name	Scientific Name	Contaminants	Remarks	Citations
Holy rope/ hemp-agrimony	*Eupatorium cannabinum*	As	Citric acid (CA) addition 20 mg/ L addition favored phtostabilization	González et al. (2019)
Coastal Mallow/ Seashore Mallow	*Kosteletzkya pentacarpos*	Cd, Zn	Salinity favors plants against metal toxicity. Cytokinin promotes Zn resistance.	Zhou et al. (2019)
Willow	*Salix sps.*	Cd	Non-flooding Salix has higher BCF than flooding species	Yang et al. (2019a)
Black nightshade	*Solanum nigrum*	Cu, Zn, Cd	10% biochar/attapulgite addition recommended	Li et al. (2019)
Sunflower	*Helianthus annuus*	Cu, Zn, Pb, Hg, As, Cd, Ni	Vermicompost as an supplement, usually for low level of metal contaminants	Jadia and Fulekar (2008)
Cowpea	*Vigna unguiculata*	Pb, Zn	Mine waste phytostabilization	Kshirsagar and Aery (2006)

contaminants (Dary et al., 2010). The effectiveness of remediation depends on the contaminant, the plant species, and the soil. Plant biomass and metabolism play a critical role in the efficiency of remediation, which is affected by soil pH, electric conductivity, organic matter contents, microbial processes, and other soil amendments (Anton & Mathe-Gaspar, 2005; Nissim et al., 2018).

Phytoremediation potential of the plants are generally evaluated by determining Bioconcentration Factor (BCF), described as the ratio of pollutant concentration in the plant parts to that in the media, and Translocation Factor (TF), defined as the ratio of elemental accumulation in plant's shoot compared to plant's root (Wu et al., 2011). Based on the processes of phytoremediation involved in the remediation of toxic contaminants from soil and water, the overall mechanisms of phytoremediation depicted in Fig. 1 are explained in detail.

2.1. Phytoextraction

Phytoextraction or phytoaccumulation, involves the absorption of toxic metals by plant roots followed by translocation of absorbed metals to shoots and deposition at vacuole, cell wall, cell membrane, and other metabolically inactive parts in plant tissues. The hyperaccumulator plants, known for remedy of HMs, accumulate a higher concentration of toxic metals in their root and shoot tissues. The general mechanisms durings accumulation of toxic HMs include absorption of metal cations followed by metal-phytochelatin complex (M-PC) or metal-ligand complex formation inside the plant cell (Lajayer et al., 2019). After forming the M-PC, these complex molecules are translocated to the plants' vacuole and stored (Yadav, 2010). The extraction potential of plant species is mainly determined by plant biomass and the concentration of HMs in aboveground plant tissues (Li et al., 2010). Therefore, a best suited phytoremediation species not only need to tolerate and effectively absorb HMs but also be fast-growing with high biomass production and provide economic benefits (Bian et al., 2020). Consequently, certain plant species are more suited to utilize phytoextraction process during phytoremediation of certain metals (Table 1). For examples, *Sesbania drummondii* for Pb (Barlow et al., 2000), *Pteris vittata* for As (Salido et al., 2003), *Sedum alfredii* for Cd (Zhou & Qiu, 2005), *Commoelina communis* for Cu (Wang et al., 2004), etc. have been found to primarily utilize phytoextraction for several metals. Some plant growth-promoting bacteria, i.e., *Stenotrophomonas maltophilia* and *Agrobacterium sp are* found to multiply the Arsenic (As) phytoaccumulation in *Arundo donax* (Guarino et al., 2020).

2.2. Phytostabilization/Phytoimmobilization

The remediation can be achieved through inactivation or immobilization of toxicants or pollutants within the roots or in the rhizosphere. The stabilizing activity of plant roots limits contaminant mobility and bioavailability resulting in the lowered toxic effects. Some plants form bound residue of toxic contaminants which are not further available in the poisonous form or cannot be released from the solid matrix after accumulation. For example, Ryegrass plant can uptake herbicide trifluralin and transform it into bound residue (Li et al., 2002). The contaminants can be immobilized in the rhizosphere with the help of phytochemical exudates, or trapped in the root surface with the help of transport protein, or sequestered inside the vacuole of root cell through cellular processes (ITRC, 2009). HMs and some organic contaminants can be converted into non-toxic compounds through conjugation with derivatives of sugars, proteins, and amino acids or making complexes in the rhizosphere. For instance, plant root epidermis immobilized Arsenic (As) through binding As to ferric sulfate within vacuoles and forming a trivalent complex of As-tris-thiolate in the rhizosphere (Hammond et al., 2018). The hydrophobic organic contaminant can be bound to the surface of the cell wall by hemicellulose and the lipid bilayer of the plasma membrane (Hussain et al., 2009). Glutathione, secreted by plant enzymes glutathione synthetase was found to conjugate organic contaminants and detoxify their effects (Hussain et al., 2009). Besides, some enzymes or organic chemicals released due to soil-root interaction or due to the presence of pollutants help in stabilization of toxic chemicals (Reboreda & Caçador, 2008; Sun et al., 2010). Gujarathi et al. (2005b)

Table 3.
Plants known to utilize rhizofiltration during phytoremediation

Common Name	Scientific Name	Contaminants	Remarks	Citations
Carolina mosquito fern/ Water Velvet	*Azolla caroliniana*	As	BCF: 0.000397	Favas et al. (2012)
Water hyacinth	*Eichhornia crassipes*	Fe, Cr, Cu, Cd, Zn, Ni, As	Translocation factor: Fe: 0.69, Cr:0.56, Cu:0.79, Cd:0.78, Zn:0.67, Ni:0.55, As:0.45	Rai (2019)
Water starwort	*Callitriche lusitanica*	As	BCF: 0.002346	Favas et al. (2012)
Pond-water starwort	*Callitriche stagnalis*	U	BCF: 0.00194841	Pratas et al. (2012)
Water moss	*Fontinalis antipyretica*	U	BCF: 0.00023479	Pratas et al. (2012)
Duckweed	*Lemna minor*	U	BCF: 0.0000529	Pratas et al. (2012)
Water starwort	*Callitriche brutia*	As	BCF: 0.000523	Favas et al. (2012)
Cattail	*Typha angustifolia*	Cu, Pb, Ni, Fe, Mn, and Zn	Industrial waste containing phenol (100–800 mg l^{-1}) and melanoidin (2500–8500 Co–Pt)	Chandra and Yadav (2010)
Threadleaf crowfoot	*Ranunculus trichophyllus*	As	BCF: 0.000354	Favas et al. (2012)

Table 4.
Plants known to ulilize phytovolatilization during phytoremediation

Common Name	Scientific Name	Contaminants	Remarks	Citations
Rabbitfoot grass	*Polypogonmon speliensis*	As	dimethylchloroarsine ($AsCl(CH_3)_2$) and pentamethylarsine($As(CH_3)_5$) is volatilized. More toxic form of As organic form are not volatilized	Ruppert et al. (2013)
Common rush	*Juncus effuses*	Ammonium	Methane is also released.	Wiessner et al. (2013)
Perennial reed grass	*Phragmites australis*	Organochlorines (OCs)	1,4-dichlorobenzene (DCB), 1,2,4-trichlorobenzene (TCB), and γ-hexachlorocyclohexane (γHCH) is volatilized. Solubility and volatility of the OCs affects translocation from roots to shoots	San Miguel et al. (2013)
Broccoli	*Brassica oleracea var. italica*	Se	Methyl selenate are volatilized and is favoured by chelating agents addition.	Raskin et al. (1997)
Mustard	*Brassica juncea*	Se	Brassica spp also has potentiality of phytovolatilization of Se	Banuelos et al. (1997)
Willow	*Salix sps*	tricholoroethylene (TCE) and tretracholoroethylene (PCE)	Willow is an important phytoremediating plant due to it huge biomass as well as it's ability to use various phytoremediation mechanism.	Gordon et al. (1998)
Hybrid poplar tree	*Populus trichocarpa χ Populus deltoïdes,* designated HI 1	TCE, PCE	Hybrid poplar trees HII varieties are popular for TCE phytovolatilization.	Gordon et al. (1998)
Saltmarsh bulrush	*Scirpus robustus*	Se	Wetlands plants	Arthur et al. (2005)
Parrot's feather	*Myriophyllum brasiliense*	Se	Wetlands plants	Pilon-Smits et al. (1999)
Iris-leaved rush	*Juncus xiphioides*	Se	Wetlands plants	Pilon-Smits et al. (1999)
Broad leaf cattail	*Typha latifolia*	Se	Wetlands plants	Pilon-Smits et al. (1999)

reported that the root-secreted compounds of *Helianthus sps* root catalyzed disintegration and removal of tetracycline (TC) and oxytetracycline (OTC). Also, antioxidant enzymes like peroxidase were found to play a vital role in the detoxification of 2,4-D herbicide through polymerization (Agostini et al., 2003). A number of plants known to use phytostabilization mechanisms are listed in the table (Table 2) below. Various bioaccumulation enhancers can improve the efficiency of contaminant stabilization.

2.3. Rhizofiltration

Rhizofiltration involves removing toxic substances using plant roots in a saturated zone to remediate aqueous contaminants from wastewater, ground water or surface water through adsorption, concentration and precipitation onto roots or other submerged organs of metal tolerant aquatic plants (Jadia & Fulekar, 2009). In this technique, plant roots either adsorb or absorb the contaminants and clean the ground or surface water resources. Generally aquatic plants are involved in phytoremediation through rhizofiltration (Table 3). This method is mostly effective for remediation of soil and water highly contaminated with nutrients like nitrogen and phosphorous (Mithembu, 2012). Rhizosphere nitrification by plant roots followed by subsequent denitrification can remove the ammonia in aqueous media (Sikhosana et al., 2020). The rhizofiltration of HMs contaminated water sites can lead to root mediated precipitation and fixation inside the root in an insoluble form. For example, sunflower and mustard can filter Pb contaminated water by precipitation of Pb-phosphate in the root (Dushenkov et al., 1995). Besides, some endophytic bacteria that live inside the root surface help in the rhizofiltration process. Specific strains of *Pseudomonas* and *Ochrobacterium* inside the plant root surface reduced hexavalent Cr (Cr-VI) into trivalent Cr (Cr-III). The reduced Cr-III is then easily precipitated inside the plant root thus cleaning up the water (Dimitroula

Table 5.
Plants known to utilize phytodegradation during phytoremediation

Common Name	Scientific Name	Contaminants	Remarks	Citations
Blumea	*Blumea malcolmii*	Malachite Green (93.41% decolorization within 24 h	Phytodegradation of industrial waste	Kagalkar et al. (2011)
Elodea	*Elodea canadensis*	DDT	Degradation catalyzed by enzyme cofactors or biomolecules.	Garrison et al. (2000)
Kudzu	*Pueraria thunbergiana*	DDT	Reductive dehalogenation of DDT	Garrison et al. (2000)
Unicellular green algae	*Chlorella pyrenoidosa*	Pentachlorophenol (PCP)	Algae activity may have been reduced by the cycling of light exposure	Headley et al. (2008)
Pickly burr	*Datura innoxia*	Petroleum	Petroleum degradation was higher in vegetated contaminated soil than non-vegetated soil	Lucero et al. (1999)
Cockspur coral tree	*Erythrina crista-galli*	Petroleum	Differences in anatomic structure of roots	de Farias et al. (2009)
Coral	*Ipomoea carnea*	Textile azo dyes	Induction of hairy roots in explants of *in vitro* grown seedlings of *Ipomoea carnea* J. with *Agrobacterium rhizogenes*favoured phytodegradation	Jha et al. (2016)
Ipil-ipil	*Leucaena leucocephala*	Ethylene dibromide (EDB; dibromoethane) and trichloroethylene (TCE)	First evidence of tropical tree to remediate EBD and TCE like organic pollutants	Doty et al. (2003)
Perennial reed grass	*Phragmites australis*	Ibuprofen	P. australis could be a good plant in construction on wetland	He et al. (2017)
Water hyacinth	*Pontederia crassipes*	sodium dodecyl sulfate (SDS)	removal efficiency as well as degradation of SDS were enhanced by ascorbate peroxidase (APX) activity in the presence of *Chromolaenaodorata* L. extract.	Gong et al. (2019)
Duck weed	*Spirodela polyrhiza*	ofloxacin (OFX)	(93.73–98.36%) reduction in OFX	Singh et al. (2019)

Table 6.
Plants known to utilize rhizodegradation during phytoremediation

Common Name	Scientific Name	Contaminants	Remarks	Citations
Eastern gamagrass	*Tripsacum dactyloides*	Herbicities (Atrazine)	Atrazine (ATR) degradation enhanced by 84 to 260%	Lin et al. (2011)
Bermuda grass	*Cynodon dactylon*	Total petroleum hydrocarbons (TPHs)	Total petroleum hydrocarbons (TPHs) are degraded by 81%	Nguemté et al. (2018)
Rapeseed	*Brasssica napus*	2,4-Dichlorophenol	Peroxidase enhances the degradation of the 2,4-DCP	Agostini et al. (2003)
Mangrove	*Kandelia candel (L.)* Druce	phenanthrene (Ph) and pyrene (Py)	Dissipation of Ph (47.7%) and Py (37.6%) was observed in rhizosphere.	Lu et al. (2011)
Chinaberry tree	*Melia azedarach*	Benzo(a)pyrene	Cd-resistant plant is required for degradation of benzo(a)pyrene	Kotoky and Pandey (2020)
European blackberry	*Rubus fruticosus*	polycyclic aromatic hydrocarbons (PAHs)	High molecular weight PAHs are degraded with natural grown blueberries	Alagić et al. (2016)
Black willow	*Salix nigra*	Perchlorate	Enhancement of rhizodegradation by organic carbon	Yifru and Nzengung (2008)
Cucurbits	*Cucurbita sps.*	Polycyclic aromatic hydrocarbons (PAHs)	PAHs degradation are enhanced by plant-bacterial interaction	Ely and Smets (2017)
Sesbania	*Sesbania cannabina*	Pb	Natural plant-microbe interaction in the rhizosphere of *S. cannabina* was efficient enough to degrade petroleum hydrocarbon	Maqbool et al. (2012)
Maize	*Zea mays*	Petroleum	Inoculation *Piriformospora indica* could enhance the degradation of petroleum hydrocarbons	Zamani et al. (2018)

et al., 2015). Bioconcentration factor for several metals by aquatic plants, which are suitable for rhizofiltration applications, was as high as 0.001948 of dry weight of plant (Table 3).

2.4. Phytovolatilization

Phytovolatilization involves a series of steps. First, plants take up contaminants from the soil and transform the less volatile chemicals into more volatile forms, and lose the contaminants to the atmosphere through volatilization process. This technique works well when the volatilized contaminants have less toxic effects when partitioned from soil to the atmosphere. The volatilization method works well mostly for organic pollutants (Limmer & Burken, 2016). While some compounds can directly volatilize from stem and leaves, some compounds can volatilize because of the root-soil interaction. The hydrophobic organic compounds exitstem and leaves from the hydrophobic barriers of the plant, such as cuts, epidermis, suberin, and other dermal layers. Also, some compounds move upward in the plant system through the transpiration stream and can be lost into the atmosphere during the process of transpiration. The trifluralin compounds are reported to be residue bound and transpired from the leaves by ryegrass (Li et al., 2002). Several plants are capable of volatilizing the toxic organic contaminants through volatilization mechanism and releasing it to the atmosphere in benign form (Table 4).

2.5. Phytodegradation and rhizodegradation

Plants can metabolize and destroy contaminants within plant tissues through the process known as phytodegradation. Organic pollutants such as pesticides can be remediated through degradation or transformation by various plant parts. In phytodegradation, plant parts can play a crucial role directly or indirectly. In the direct process, plant absorbs the contaminants and metabolizes or breaks into small less harmful compounds and distributes it within plant tissue. As plants do not contain active transporters, these organic contaminants are absorbed through passive uptake. When degradation of contaminants occurs in rhizosphere the process is called rhizodegradation. Tables 5 and 6 enlist the plants known to utilize phytodegradation and rhizodegradation, respectively for specific contaminants. The chlorinated hydrocarbons can be dechlorinated and transformed into non-toxic chemicals by plants such as *Tegetes patula, Ipomea balsamina*, and *Mirabilis jalapa*. The reductive dehalogenation of DDT was also observed in aquatic plant Elodea and terrestrial plant Kudzu (Garrison et al., 2000). *I balsamina*, and *P nil* were found to absorb and degrade petroleum hydrocarbons (Liu et al., 2017a). A study on phytodegradation also revealed some intermediate product formation and detoxification of Ibuprofen through metabolism in australia (He et al., 2017). The saturated hydrocarbons go through the degradation process because they act as source of carbon for rhizosphere bacteria (Liu et al., 2017a). Therefore, some microbes living synergistically on plant root surface metabolize and degrade the organic contaminants (Van Eerd et al., 2003). The rhizospheric microbes can mineralize the organics like polyaromatic hydrocarbons and polychlorinated biphenyls. Moreover, the enzymatic degradation by some enzymes, such as dehalogenase, nitro-reductase, laccase peroxidase etc., secreted by specific plants and associated microbe species act on hazardous xenobiotics (Cherian & Oliveira, 2005). *Brassica napus* root culture was found to degrade 2,4-DCP (2, 4-Dichlorophenol) through oxidation (Agostini et al., 2003), however,

Table 7.
Plants known to utilize phytodesalination mechanism during phytoremediation

Common Name	Scientific Name	Contaminants	Remarks	Citations
Alkali grass	*Puccinellia nuttaliana*	Sodium ion (Na^+), chloride ion (Cl^-)	Irrigation could increase the contaminats bioaccumulation	Xu et al. (2019)
Cattail	*Typha latifolia*	Na^+, Cl^-	Irrigation could increase the contaminats bioaccumulation	Xu et al. (2019)
Sea purslane	*Sesuvium portulacastrum*	Na^+	*S. portulacastrum* Na^+accumulation is more suitable in arid regions.	Rabhi et al. (2010)
Water spinach	*Ipomoea aquatica*	Na^+	*I. aquatic* have phytodesalination capacity of 130 kg Na^+ ha^{-1}).	Islam et al. (2019)
Alligator weed	*Alternanthera philoxeroides*	Na^+	Alligator weed have phytodesalination capacity of 105 kg Na^+ ha^{-1}.	Islam et al. (2019)
Water primerse	*Ludwigia adscendens*	Na^+	*L. adscendens* have phytodesalination capacity of 80 kg Na^+ ha^{-1}.	Islam et al. (2019)
Honeysuckle	*Lonicera japonica Thunb*	Na^+	Leaching of $Na^+$is favoured by honeysuckle	Yan et al. (2016)

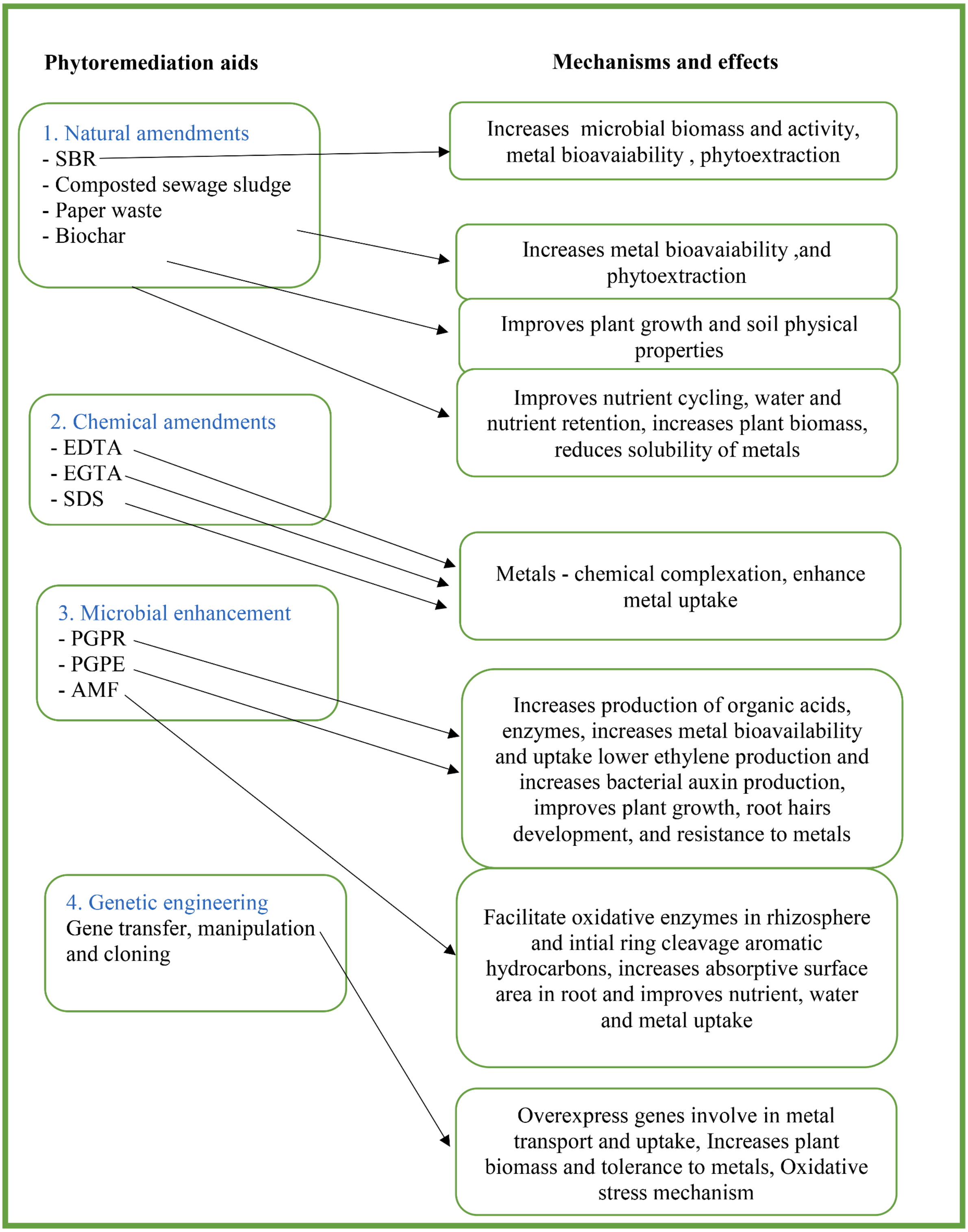

Fig. 2. Phytoremidiation aids, mechanisms involved and their effect on phytoremediation (SBR = Sugar beet residue, EDTA = Ethylenediaminetetraacetic acid, EGTA = Ethylene glycol tetra acetic acid, SDS = sodium dodecyl sulfate, PGPR = Plant growth promoting rhizobacteria, PGPE = Plant growth promoting endophytic bacteria, AMF = Arbuscular mycorrhizal fungi)

the main mechanism of polymerization was enhanced by peroxidase (Table 5).

2.6. *Phytodesalination*

Some salt-tolerant plants can extract significant amounts of salts from the soil and recover the saline soil to increase productivity, by a process called phytodesalination. Saline soil decreases the reduction potential that leads to dehydration and alters plant physiology (Arif et al., 2020). Excessive saline exposure is also harmful to soil organisms and plants which are susceptible to saline stress. As a biological and clean approach, halophytic plants are used for desalination purposes

(Table 7). The halophytic plants tolerate a higher halogen level in their growing environment i.e., soil or groundwater, because of their phylogenetic adaptation. These plants uptake Na^+ and Cl^- and accumulate these salt ions in plant root and shoot. Alternatively, plants remediate soil through enhanced leaching of salts from the soil by expansive roots improving the soil porosity. *Lonicera japonica* (Yan et al., 2016) and some of the halophytic plants enlisted in Table 7 contributes to phytodesalination through its plant growth and physiology. The halophytic legumes and rhizospheric bacteria can play an important role in enhancing the leaching of Na^+ ions. Microbes involved and catalytic activity of root exudates dissolve the $CaCO_3$ releasing Ca^{++} ion. The Ca^{++} ion released replaces the Na^+ ion from salts, and the rate of leaching or desalination increases (Rabhi et al., 2015).

3. Aids for enhanced phytoremediation

While phytoremediation can accomplish contaminant removal, there is a scope for further performance enhancement by utilizing different aids such as synthetic and natural amendments, microbes, and genetically modified plants. These aids improve the formation of metals - chelators complexes, increase plant resistance and tolerance level to metals, and enhance translocation and accumulation of metals within the plants, thereby increasing overall phytoremediation efficiency (Fig. 2). More detailed explanations for different phytoremediation aids and mechanisms behind it are discussed below.

3.1. Amendments

Amendments, either natural or synthetic, are applied in soil as an aid to improve phytoremediation efficiency mainly by increasing phytoextraction, plant growth, and water and nutrient retention (Fig. 2). Natural amendments are produced by processing natural materials such as sugar beet, paper, rice staw etc. In contrast, chemical amendments consist of synthetic chemicals.

3.1.1. Natural organic amendments

Natural organic amendments are naturally produced materials used to improve phytoremediation. Sugar beet residue (SBR), produced after sugar extraction and fermentation process, when used by treating with *Aspergillus niger*, enhanced plant growth and phytoextraction process due to the presence of a high number of polysaccharides and phosphatase (Azcón et al., 2009; Medina et al., 2006). A few studies observed an enhancement of phytoextraction of various HMs such as Ni, Zn, Fe, B, Cr, Cd by the addition of SBR using different plants such as *Trifolium repens* L. (Azcón et al., 2009; Medina et al., 2006), *Tetraclinisarticulata sps* (Vahl) Mast, and *Crithmummaritimum sps* L. (Fernández et al., 2012). Increased phytoextraction efficiency by applying SBR is believed to be the result of increased microbial biomass in the rhizosphere zone. Also, the reduction of metals by microbes led to an increased metal bioavailability (Azcón et al., 2009; Medina et al., 2006).

A composted sewage sludge is an industrial waste that can be used as a soil amendment. Liphadzi and Kirkham (2006) applied sewage sludge in a study on Cd and Ni phytoextraction by sunflower and concluded that natural chelating agents present in sewage sludge contributed to an increased metal bioavailability. The beneficial effect of paper wastes on the phytoremediation process was reported by Doichinova and Velizarova (2013). The application of paper waste reduced the uptake of Pb and Cd by seedlings of red oak (*Quercus rubra* L.) and Austrian pine tree (*Pinus nigra* Arn). This effect was due to improved plant growth and soil physical properties such as density and water holding capacity.

Another soil amendment is biochar, which can be made by the pyrolysis of crop and animal residues. It has unique properties such as high surface area and porosity, carbon content, pH, and cation exchange properties (Jiang et al., 2012; Lehmann et al., 2011). Several studies reported the beneficial effects of biochar for reducing metal bioavailability and their phytotoxicity. The beneficial effects of biochar in the soil can be accompanied by increasing adsorption sites on the soil surface, water and nutrient retention, water holding capacity, biological activity, and nutrient cycling. Application of wood biochar in soil decreased As, Cd, and Cu contents in shoots of *Zea mays* and Pb content in the soil (Namgay et al., 2010). In another study, bamboo and rice straw biochar increased the plant biomass of *Sedum plubizincicola*, and Cu and Pb concentration were reduced by 46 and 71 %, respectively, in plant shoots by the addition of rice straw biochar (Lu et al., 2014). In a recent study, biochar and hydrochar addition in mining soils improved phytoremediation by *Sinapis alba* (Cárdenas-Aguiar et al., 2020). In another study conducted by Chuaphasuk and Prapagdee (2019), biochar-immobilized bacteria showed improvement in cadmium phytoextraction by *Chlorophytumlaxum* sps R.Br. Despite various benefits, the use of biochar holds some limitations. Biochar making process, i.e., pyrolysis, can be harmful to the environment and may cause air pollution (dos Santos Barbosa et al., 2006). It has also been reported that biochar may influence pre-emergence herbicide in the agriculture field (Jones et al., 2011) or contribute to release HMs or polycarbonate hydrocarbon in the soil (Méndez et al., 2012).

Artificial root exudates can lower the pH in rhizosphere facilitating the dissolution of metal ions thereby improving phytoextraction of HMs from the soil (Thangavel & Subbhuraam, 2004). Lu et al. (2017) applied artificial root exudates including glucose, organic acid and serine in soil contaminated with an organic pollutant pyrene. The results indicated enhanced degradation of pyrene by glucose compared to organic acids and serine. The enhancement was likely due to the effects of root exudates on dehydrogenase activity and microbial community. As an alternative to chemical chelators, humic acid was used as an phytoremediation aid in metal contaminated soil (Evangelou et al., 2004; Figueroa et al., 2008; Halim et al., 2003). The organic matter with humic substances can immobilize metal ions by forming stable complexes with ions (Hattab et al., 2014). Since Cu and Pb ions have a strong affinity to the organic matter, these metal ions' low bioavailability suggests that metal binding to humic acids may occur (Wiszniewska et al., 2016). In the study conducted by Bandiera et al. (2009), humic substances effectively transported metals to the shoots of fodder radish due to natural chelating properties.

3.1.2. Chemical amendments (synthetic chelators)

Chemical enhanced technology is an effective method to facilitate HMs uptake and their translocation in the plants (Jiang et al., 2019; Yan & Lo, 2012). There are several chemical amendments (chelating agents) that are used to enhance the phytoextraction process. Among them, three chemical amendments- ethylenediaminetetraacetic acid (EDTA), ethylene glycol tetra acetic acid (EGTA), and sodium dodecyl sulfate (SDS) are popular chelating agents in the soil remediation process. Among them, EDTA is largely studied and considered to be the most effective chemical in the phytoextraction process.

EDTA is often used in agriculture due to its' role in mobilizing heavy metals. Several studies have been reported for HMs uptake enhancement by EDTA in the plants. Mostly, hyperaccumulator plant species can take up metal-EDTA complexes (Awokunmi et al., 2012). The factors affecting EDTA effectiveness to remediate contaminated soil are EDTA concentration, plant species, HMs concentration, metal chemical properties, and soil type (Evangelou et al., 2007). In the study by Zhao et al. (2010), EDTA enhanced Pb uptake in *Zea mays* grown in hydroponic condtions; Pb uptake was 6-7 folds higher as compared to the control. The use of EDTA resulted in an increased Pb accumulation in *Sedum alfredii* roots (Sun et al., 2009), *Vicia faba* seedlings (Shahid et al., 2014), *Vetiveria zizanioides* roots (Andra et al., 2009), and in the shoots of *Canavalia ensiformis* L. (Gabos et al., 2009).

EGTA, another widely used chelating agents like EDTA, has been found to increase metal uptake and accumulation. Higher Cd concentration was found in *A. rosea* (Liu et al., 2008), *Mirabilis jalapa* (Wang & Liu, 2014), and *Calendula officinalis* (Liu et al., 2010). Also, increased Pb accumulation was found in above-ground parts of *Cicer arietinum* plants after the application of EGTA (Sakouhi et al., 2016).

SDS is a commonly used surfactant that has been used in contaminant remediation in the soil (Pierattini et al., 2018). The solubility of HMs such as Cu, Zn, Pb, and Cd can be enhanced by applying the SDS buttressing phytoremediation process involving herbaceous species (Messina et al., 2014) and soil flushing (Ramamurthy & Schalchian, 2013). Cd accumulation was promoted in roots and shoots of *Althaea rosea* (Liu et al., 2009) and the shoot of *Calendula officinalis* (Liu et al., 2010) after SDS application. In the study conducted by Pierattini et al. (2018), an enhanced Zn translocation was observed in *Populus alba*.

Adopting the chemical-based phytoremediation process may introduce an environmental concern that chelating agents can be toxic to soil microbes (Mühlbachová, 2011), enzyme activities, and plant species (Neugschwandtner et al., 2012). Also, because of the poor biodegradability of chelating agents, they can persist in the soil for a long time leading to metal leaching and adverse effects on the environment (Lee & Sung, 2014; Smolińska & Król, 2012). Thus, chemical amendments should be applied at optimum concentrations limiting adverse environmental effects.

3.2. Microbial enhanced/stimulated phytoremediation: the role of microbes

Microbes can influence phytoremediation process through various mechanisms. The microbial degradation of organic pollutants and microbial mediated HMs uptake can be achieved through biostimulation and bioaugmentation. Biostimulation is the process of stimulating existing microorganisms in polluted soil, through addition of nutrients such as nitrogen, phosphorus, and electron donors, to degrade toxic pollutants (Goswami et al., 2018). Bioaugmentation is the process where natural or genetically modified microorganisms are added to polluted soil to remove toxic pollutants (Goswami et al., 2018). The addition of organic matter followed by bioaugmentation with actinobacteria consortium combined with *Brassica napus* was found to be most effective to transform hexavalent chromium to trivalent chromium and lindane to less toxic form (Lacalle et al., 2020). Bioaugmentation with *Pseudomonas fluorescens* was able to degrade 2,4 dinitritolene thus reducing toxicity to growth of *Arabidopsis thaliana* (Monti et al., 2005). In another study, biostimulation with nitrogen and phosphrus had a great influence on isoproturon degradation (Perrin-Ganier et al., 2001).

The use of PGPR (Plant Growth Promoting Rhizobacteria) and PGPE (Plant Growth Promoting Endophytic bacteria) was found to enhance metal solubility by secreting organic anions and protons (Becerra-Castro et al., 2011; Gill et al., 2021). PGPR has the potential to increase phytoremediation efficiency by increasing plant growth and biomass, improving plant resistance to pathogens, increasing plant tolerance to metals, improving nutrient uptake and translocation of HMs through the production of organic acids, enzymes, antibiotics, phytohormones, and siderophores (Ma et al., 2011). Maize plant inoculated with siderophores producing bacteria enhanced Cr and Pb bioavailability and uptake (Braud et al., 2009). The ability of PGPR to produce 1-aminocyclopropane-1-carboxylic acid (ACC) deaminase can result in lower ethylene production promoting plant growth (Chang et al., 2014). Increased plant biomass and improved phytoremediation were reported due to *Bacillus* (Babu et al., 2013), *Pseudomonas* (Agnello et al., 2016), and *Serratia* (Dong et al., 2014) through the release of ACC deaminase. Also, PGPR can promote the emergence of lateral roots and the development of root hairs by producing bacterial auxin, which improves plant growth, thus enhancing phytoremediation (DalCorso et al., 2019; Glick, 2014). Plant-microbe interaction at rhizosphere can synergistically improve phytoremediation of organic and inorganic pollutants (Rane et al., 2022).

Use of fungi also benefits phytoremediation through its direct or indirect interactions with the contaminants. As fungus can grow in air-water interface, the mycoremediation has advantage over bacteria which requires water phase for its action (Kumar et al., 2019). Mycorrhizal fungi affect metal bioavailability through influencing soil properties and composition of root exudates secreted by plants (Bhantana et al., 2021; Sarwar et al., 2017). Specifically, Arbuscular Mycorrhizal Fungi (AMF) increase the absorptive surface area in plant roots, which improves nutrient and water uptake and metal bioavailability (Göhre & Paszkowski, 2006). Also, the phytohormones production by AMF can promote plant growth and facilitate phytoremediation (Vamerali et al., 2010). Chen et al. (2003) found a higher yield of red clover (*Trifolium pratense* L.) when inoculated with AMF in Zn contaminated soil. They also reported a higher accumulation of Zn in plant roots as AMF absorbed Zn from the soil and transported it to the roots. Besides HMs remediation, mycorrhizal fungi also have a role in organic pollutant degradation in soil. It was reported that organic pollutants such as 2,4-dichlorophenol (Meharg et al., 1997), 2,4,6-trinitrotoluene (Scheibner et al., 1997), atrazine (Donnelly et al., 1993), polychlorinated biphenyls (Donnelly & Fletcher, 1995) and polycyclic aromatic hydrocarbons (Braun-Lüllemann et al., 1999) could be degraded by ECM (ectomycorrhizal fungi). The observed effects may be related to the effects of mycorrhizal fungi on oxidative enzyme activity in the roots and rhizophere (Joner & Leyval, 2003). Oxidative enzymes have a role in initial ring cleavage of polycyclic aromatic hydrocarbons as reported by Criquet et al. (2000) and Salzer et al. (1999).

3.3. Genetic engineering

The genetic engineering tools to produce transgenic plants is a cutting-edge technology to improve the phytoremediation process. Unlike traditional breeding methods, genetic engineering practice can transfer desirable genes to plant species for the phytoremediation process. One of the main objectives of producing transgenic plants is to increase heavy metal tolerance and accumulation. The main characteristics of transgenic plants are high biomass producing, fast-growing, metal tolerant, etc. Specifically, genetic engineering is used to overexpress the genes functioning in uptake, translocation, and sequestration of heavy metals and antioxidant activity. Overexpressing genes will increase HMs accumulation (Das et al., 2016; Mani & Kumar, 2014) and tolerance (Koźmińska et al., 2018). Genetic engineering can be done in various ways such as metallothionein, phytochelatins, metal chelators genes manipulation, metal transporters genes cloning, and alteration of oxidative stress mechanisms, alteration in roots, and alteration in biomass (Eapen & D'souza, 2005). Enhanced Cd tolerance was observed after transferring the Metallothionein – II gene to tobacco or oilseed rape (Misra & Gedamu, 1989). In another study, enhanced Cu accumulation was reported when the pea MT gene was transferred to *Arabidopsis thaliana* (Evans et al., 1992). Transfer of Yeast protein (YCF 1) to *A. thaliana* resulted in enhanced Pb and Cd tolerance (Song et al., 2003). Bizily et al. (2000) reported an improved tolerance to Hg and improved volatilization of elemental mercury when introducing MerA and MerB genes into plants. Ezaki et al. (2000) expressed glutathione-*S*-transferase and peroxidase enzymes and observed enhanced Al tolerance. A list of genetically engineered plants used in phytoremediation studies is provided in table (Table 8). Though genetic engineering was found to be effective for better phytoremediation performance in several applications, most research are limited to the in-situ and hydroponic environments. More studies analyzing the phytoremediation of transgenic plants in real environmental conditions need to be explored to fully understand the potential of the transgenic plants in enhancing phytoremediation.

4. Strengths

4.1. Sustainable and environmental friendly

Plants provide an environmental friendly remedy option to clean up the pollutants at lower energy and cost than that are required for conventional methods (decontamination technologies) for environmental cleanup as it utilizes solar energy and plant's physiological mechanisms (Susarla et al., 2002). Plants possess capacity in lowering the pollutants from diverse media including soil, air and water. As an indirect advantage, carbon sequestration will be enhanced due to phytoremediation applications because more plants planted for removal of toxic pollutants from the environment will lower the amount of atmospheric carbondioxide.

Phytoremediation when combined with sustainable site management, called as phytomanagement, generates wider scope of benefits including economical, environmental and social welfare (Burges et al., 2018). Some authors purposed the concept of linking phytoremediation with ecosystem services that involves nutrient re-cycling, fertility, carbon sequestration, water movement, and water purification (Burges et al; 2016; Burges et al., 2017; Rutgers et al., 2012). While phytoremediation only includes the mitigation of risk, phytomanagement adds benefits along with risk mitigation and site management (Burges et al., 2018). The goal of phytoemediation should not only focus in removing the polluations from soil or water but also to restore the quality and functionality of the resources (Epelde et al., 2009). The indicators that reflects the quality and functionality of restored soil can be monitoted by measuring parameters including pH, texture, Cation Exchange Capacity, and abundance and diversity of microbial population (Burges et al., 2018). Ecological Risk Assessment (ERA) is used to assess the soil health in the phytoremediated area that promoted soil conservation practices (Gutiérrez et al., 2015; Garbisu et al., 2011). Epelde et al (2014) proposed the concept of long term monitoring programs for the prediction of success of phytomanagement.

4.2. Suitable for remediation of diverse pollutants in diverse media

4.2.1. Soil

Phytoremediation methods can be widely used in treating HMs, organic pollutants and radionuclides concentrations in soil. More than 400 species of hyperaccumulators that can absorb 50-500 times more heavy metals from the rhizosphere than the normal plants have been known. Species belonging to family Asteraceae, Brassicaceae, Caryophyllaceae, Fabaceae, Flacourtaceae, Lamilaceae, Poaceae, Violaceae, Euphorbiaceae, and 0.2 percent of angiosperms, (Baker, 2000; Vara Prasad & de Oliveira Freitas, 2003) can amass >1 mg Au and Ag; >100 mg Cd, Se and Ta; >1000 mg Cu, Co, Cr, Ni, Pb, U, and As; and >10000 mg Mn and Zn per 1 kg dry mass of shoots (Baker & Brooks, 1989; Padmavathiamma & Li, 2007). *Thlaspi caerulescens* can be used to extract Zn and Cd (Epelde et al., 2008). These plants can be harvested and burned so that the ashes can be used as a fertilizer in micronutrients deficient fields (Koptsik, 2014).

Moreover, *Medicago sativa* and *Tagetes patula* can be useful in removing organic pollutants like pthalic esters and polycyclic aromatic hydrocarbons (PAHs) (Fu et al., 2012; Hamdi et al., 2012; Sun et al., 2011) through continuous phytoextraction (Sophia & Shetty Kodialbail, 2020). *Lewia* sp. in association with *Festuca arundinacea* can be used to treat polycyclic hydrocarbon and pyrene present in the soil (Cruz-Hernández et al., 2013). Similarly, 2,4,6-trinitrotoluene (TNT) can be remediated by associating TNT-cometabolizing *Pseudomonas* sp. with *Bromus rectus* Huds (Newman et al., 1998).

Similarly, radionuclides like Uranium can be remediated by terrestrial plants like *Phaseolus vulgaris* (Lee & Yang, 2010), *Zea mays* (Stojanović et al., 2010), *Vetiveria zizanoides* (Pentyala & Eapen, 2020), and *Helianthus annuus* (Lee & Yang, 2010; Roongtanakiat et al., 2010). Cs in the soil can be removed by *Brassica campestris* (Chou et al., 2005), *Amaranthus retroflexus* (Fuhrmann et al., 2002), *Calotropis gigantea* (Eapen et al., 2006), *H. annuus* (Soudek et al., 2006) and *Vetiveria zizanoides* (Singh et al., 2008). Hu et al. (2014) found that Ra could be effectively remediated from the soil by using plants like *Pteris multifida, Pteridium aquilinum,* and *Drypteris scottii. H. annuus* (Soudek et al., 2006), *Calotropis gigantea* (Eapen et al., 2006), *Vetiveria zizanoides* (Singh et al., 2008), and *Amaranthus retroflexus* (Fuhrmann et al., 2002) were also found to be effective for extraction of Strontium (Sr).

Additionally, antibiotics remediation has been demonstrated by applying phytoremediation. Study by Hoang et al. (2013) on phytoremediation remedy of antibiotic (ciprofloxacin and norfloxacin) contaminated sediment revealed that the use of *Acrostichum aureum* and *Rhizophora apiculata* can lower the level of antibiotics in the sediment. Furthermore, plant species like *Mirabilis jalapa* and *Tagetes patula* can also be used to treat the alkaline soil co-contaminated with Cd and tetracycline (antibiotics) (Li et al., 2020).

Phytoremediation provides ample opportunity to integrate with other component to remediate the contaminants from the environment. One of the examples is the use of nanomaterial with phytoremediation which adds nano-scale materials with higher absorptivity and potential to degrade pollutants and uptake the degraded pollutant (Srivastav et al., 2018). Integration of nano-phytoremediation components has potential to increase remediation efficiency (Srivastav et al., 2018).

4.2.2. Water (wastewater and groundwater)

4.2.2.1. Wastewater. Phytoremediation techniques can also be used for the treatment of wastewater. In past, several free-floating plants such as *Pistia stratiotes, Salvinia molesta, Lemna* spp., *Azolla pinnata, Landoltia punctata, Spirodela polyrhiza, Marsilea mutica, Eichhornia crassipes*, and *Riccia fluitans,* submerged plants like *Hygrophilla corymbosa, Najas marina, Ruppia maritima, Hydrilla verticillata, Egeria densa, Vallisneria americana* and *Myriophyllum aquaticum,* and emergent plants like *Distichlis spicata, Cyperus spp*., *Imperata cylindrical, Iris virginica, Nuphar lutea, Justicia americana, Diodia virginiana, Nymphaea spp*., *Typha spp*., *Phragmites autralis* and *Hydrochloa caroliniensis* were used to treat the wastewater (Ekperusi et al., 2019; USDA, 2019). Due to high absorbing capacity, these plants can treat wide range of HMs and organic pollutants from the wastewater produced from the agricultural, industrial and domestic sectors (Mustafa & Hayder, 2021). *Azolla pinnata* was used for treating the dairy wastewater and the results obtained indicated maximum efficiency of removal when the dairy wastewater was diluted at 75% (Goala et al., 2021).

Water hyacinth can be used to treat the polluted water due to its rapid growing, easy availability, high yielding, easy harvesting, and high absorption properties (Rezania et al., 2015). Wang et al. (2002) found that Cd polluted water could be treated by water hyacinth and duckweeds, Hg by water dropwort, and Pb by calamus. Chandanshive et al. (2017) remediated As, Cd, Cr and Pb from the textile wastewater, while Guittonny-Philippe et al. (2015) remediated HMs like, Cd, Cu, Cr, Fe, Mn, Ni, Pb, Zn and organic pollutants from the industrial wastewater by *Alisma lanceolatum, Carex cuprina, Epilobium hirsutum* and *Juncus inflexus*. Not only aquatic plants, some terrestrial plants like *Brassica juncea* and *Helianthus annuus* can also remediate Cu, Cd, Cr, Ni, Pb and Zn from water (Dushenkov et al., 1995). *Halimione portulacoides*, a halophyte, was found to be effective in converting highly toxic hexavalent Cr into less toxic trivalent Cr in salt marshes through the process of phytotransformation (Caçador & Duarte, 2015).

Moreover, some algal species are used to remediate organic pollutants like benzene, toluene, pyrene (Gavrilescu, 2010), bisphenol (Gattullo et al., 2012), herbicides (Zhang et al., 2011) from the water sources. *Salvania cucullata, Trapa natans* (Alam & Hoque, 2017) helped in treatment of nitrate and ammonium nitrate (NH_3-N). Hybrid poplar remediated the Tetrachloroethylene (TCE) contamination by degrading into simpler metabolic products from water (Newman et al., 1997).

In case of radionuclides, sunflower (*Helianthus annuus* L.) and bean (*Phaseolus vulgaris* L. var. *vulgaris*) were utilized in U polluted water and removal efficiencies were > 80% and 60-80% respectively (Lee & Yang, 2010). *Helianthus sp.* were found to extract radioactive strontium and cesium from the contaminated ponds of Chernobyl area (Miller, 1996). Similarly, aquatic plants like *Apium nodiflorum, Lemma minor, Callitriche stagnalis* (Favas & Pratas, 2013), *C. hamulata, C. lusitanica, Fontinalis* *antipyretica and Typha latifolia* (Favas et al., 2014) can as well be used as remediation for U from water resources. Besides, Cs can be removed by *Eichhornia crassipes* (Saleh, 2012) from the water.

Antibiotics in wastewater can be effectively removed using *Lupinus albus* L., *Hordeum vulgare* L., *Phragmites australis* (Cav.) Trin. ex Steud., *Myriophyllum aquaticum* (Vell.) Verdc., and *Pistia stratiotes* L. (Gujarathi et al., 2005a; Kotyza et al., 2010). Sikha and Gauba (2016) demonstrated that *Cicer arietinum* could significantly lower the antibiotic called ciprofloxacin, and steroid hormones like progesterone and estrogen in aqueous media. Pharmaceutical contaminats like doxylamine was reduced to 48-80.5% by *T. angustifolia* and *I. aquatica* through enhancement of some bacteria in the wastewater phytobed (Xiong et al., 2021). Singh et al. (2021) also emphasizes on biological management through plant-based using water lettuce for removing the contaminants from the effluent. Plants like Vetiveria zizanioides, which is a perennial bunchbrush showed 93% removal of textile dye Remazol Red from the waste water (Chandanshive et al., 2020). Some garden ornamental plants like *Tagetes patula, Gaillardia grandiflora, Portulaca grandiflora* and *Aster amellus* planted in the ridges of constructed wetland showed 59, 73, 46 and 50% reduction of American Dye Manufacturers Institute color value along with some heavy metals like Pb, Cd, Cr (Chandanshive et al., 2018).

4.2.2.2. Groundwater. Phytoremediation has been utilized to remediate ground water as well. Deep roots of poplar trees possessing phreatophytic root development with high evaporation rate and fast-growing ability (Barac et al., 2009; Marmiroli & McCutcheon, 2003; Weyens et al., 2009) can effectively remidiate the ground water as a hydraulic barrier at a low cost (Al-Yousfi et al., 2000; Ferro et al., 2001; Hong et al., 2001; McCutcheon & Schnoor, 2003).

4.2.3. Air

Phytoremediation can also play an important role in removal of air pollutants, mostly by phytovolatilization. For instance, tricholoroethylene (TCE) and perchloroethylene (PCE) were found to be phytovolatilized by willow tree and hybrid poplar (Gordon et al., 1998). Similarly, *Nephrolepsis obliterate* and *Chamaedorea elegans* was found to be 90% to 100% and 65% to 100% efficient, respectively, in removing the formaldehyde within 2 days (Teiri et al., 2018). *Azalea indica* removed toluene with 95% efficiency within 7 to 76 hours (De Kempeneer et al., 2004).

4.3. Economically viable

Another broad and most important area that a phytoremediation has shown its strength is on the cost effectiveness. Many research have shown that the cost required for using phytoremediation is significantly less than that for other conventional methods of treatment. Estimated cost of treatment by using phytoremediation was found to be 5-13 times lesser than the chemical treatment, that is, the cost of using phytoremediation was $20 to $40 per ton of waste removed, whereas, the cost of chemical treatment was $100 to $500 per ton of waste removed (Raskin & Ensley, 2000). Mulbry et al. (2008) found that phytoremediation for dairy wastewater treatment proved to be more economical than the conventional methods. Similarly, Cunningham et al. (1996) compared cost of phytoremediation with other bioremediation techniques such as microbial treatment for removal of petroleum hydrocarbons and found that cost of using phytoremediation was $2,500 to $15,000 per hectare and cost of using microbial treatment was $20, 000 to $60,000 with in-situ microbial treatment ranging from $7,500 to $20,000 per hectare. Moreover, excavation method for removal of Pb from the contaminated sites proved to be highly expensive ($141,500 to $182,100) compared to the phytoremediation method ($40,500 to $48, 600). Gatliff (1994) also reported higher economic efficiency of phytoremediation compared to a conventional method as the total 5-year cost of $660,000 for a pump and treat system (conventional method) was much higher than the cost of $250,000 for phytoremediation. Hence, the phytoremediation technique provides efficient yet highly economical option compared to other concventional techniques for environmental cleanup.

5. Limitations

Even though phytoremediation provides an effective alternative method for cleaning up contaminants from the environment, it has several limitations and drawbacks. For starter, most of the research are carried out in the controlled environment within a small-time frame. This might not yield true representative results as if carried out under field conditions for a long time. Hence, there is need for conducting numerous field research based on longer time frame for figuring out the true potential of phytoremediation.

Another limitation is that phytoremediation success depends on the successful and fast growth of plant species used. As the soil and climate vary in each site, the specific phytoremediation technique applied for one species of plant in one site may not work in another site. As such, it is site-specific. Besides soil and climate, plants physiology might be affected by different living organisms and microbes (insects, pests and pathogens) within the site. Combination of insects, pests, and pathogens along with presence of pollutants like HMs, organic pollutants, radionuclides, or antibiotics could make the plants more vulnerable to diseases and phytoremediation attempt might be jeopardized. Moreover, plants can thrive only within certain level of contaminant concentration. The sensitivity of plants to the higher level of contaminants could lead to slower growth of the plants affecting the phytoremediation capacity (Huang et al., 2000). For instance, while remediating highly concentrated metallic pollutants like Pb, As and U, growth of metal hyperaccumulators was found to be very slow along with low biomass (Salt et al., 1998). Also, microbial diversity and biomass facilitating the phytoremediating plants in phytodegradation can be lowered due to the toxicity of contaminants, which can further lower the efficiency of the phytoremediation. Using mixed and local species or genetically engineered species and adding amendments can lower the problem of plant being the site specific and also minimize the risks of diseases and pests.

Additionally, the contaminants must be within the reach of the plants roots in the rhizosphere for plants to be able to translocate the pollutants through its root system. Hence, screening for plants with long and deep roots and higher root biomass will lead to better efficiency of the remediation systems. Design of the phytoremediation systems, for example, in a staggered pattern, will be important for providing the required coverage.

Furthermore, phytoremediation is a slow process than the conventional methods and may take three to five years to show the full results. Another concern with the technology is handling and proper disposal of the plants that may have uptaken toxic contaminants. Consumption of such plants with high concentration of translocated contaminants can be toxic to animals and other living organisms. Hence, appropriate handling of such plants, their treatment, disposal or monitoring is required to minimize the deleterious effect of phytoremediation. However, this can increase the cost. As a remedy, potential recovery of useful chemicals from plants or use of such plants for applications where there is low risk of exposure and movement can offset the additional cost of handling.

Additionally, it may not work for all kinds of pollutants. For instance, phytoremediation was found to be limited to lower molecular weight chlorinated PCBs (Aken et al., 2010) because the hydrophobicity of higher molecular weight chlorinated PCBs are higher and cannot be translocated by the plants (Jing et al., 2018).

6. Status and future prospects of phytoremediation

Phytoremediation is considered to be economically viable and

Table 8.
Genetically engineered plants used in phytoremediation studies

Common Name	Scientific Name	Contaminants	Remarks	Citations
Rabbitfoot grass	*Polypogon monspeliensis*	As	dimethylchloroarsine ($AsCl(CH_3)_2$) and pentamethylarsine ($As(CH_3)_5$) form of As are volatilized	Ruppert et al. (2013)
Common rush	*Juncus efuses*	Artificial sewage	Ammonium and methane are released.	Wiessner et al. (2013)
Perennial reed grass	*Phragmites australis*	Organochlorines (OCs)	1,4-dichlorobenzene (DCB), 1,2,4-trichlorobenzene (TCB), and γ-hexachlorocyclohexane (γHCH) are volatized.	San Miguel et al. (2013)
Membranous mild-vetch	*Astragalus sp.*		Chelating agents favors phytoremediation	Raskin et al. (1997)
Mustard	*Brassica juncea*	Se	Brassica spp also has potentiality of phytovolatilization of Se	Banuelos et al. (1997)
Saltmarsh bulrush	*Scirpus robustus*	Se	Wetlands plants	Arthur et al. (2005)
Thale cress	*Arabidopsis thaliana*	Cu	Enhanced Cu accumulation	Evans et al. (1992)
Thale cress	*Arabidopsis thaliana*	Pb, Cu	Pb and Cd tolerance	Song et al. (2003)

environmentally sound technique for remediating the pollutants originating from different sources in the environment (Ashraf et al., 2019). The basic idea of using plants in remediating the pollution from environment is old, however, the field is still emerging. The limitations described in the limitations section poses challenges for its implementation and acceptance. Some of the limitations including site-specificity, climate-specificifity, and contaminant-specificifity will continue to hinder its development. However, research findings have advanced the field significantly and continue to make inroads into overcoming the limitations. A couple of such examples, amendments and genetic engineering, have been discussed in prior sections. The acceptance and recognition has been steadily increasing as environmental scientists and engineers look for nature-based solutions. The enormous number of results testing its feasibility and ability, which has attracted attention of many people in this technology, are positive developments (Alkorta and Garbisu, 2001). The public perception including the policymaker's perception has been improving steadily due to mostly positive experience with phytoremediation results.

While research advances and findings have generated a new, emerging, promoising and cost-effective technology (Salt et al., 1998), there are even more areas where more research is needed. For instance, further research is needed if the released or accumulated byproducts/contaminants have negative effects in the the ecosystem. Ways to enhance the growth of hyperaccumulating species in highly contaminated sites including mining fields unsuitable for plant growth is needed as well (Pivetz, 2001a). A new opportunity also exists in finding the commercial opportunities through market niches of green roof construction, phytotoming and some plant-based bio-engineering projects (Pandey & Souza-Alonso, 2019).

7. Conclusions

Phytoremediation is a sustainable technology due to its cost-effectiveness and utilization of environment-friendly method for remediating the pollution in soil, water and air. This technology utilizes plants for remediating environmental pollutants through different mechanisms like phytoextraction, phytostabilization, rhizofiltration, phytovolatilization, phytodegradation and phytodesalination. It has wide range of applications for remediating diverse pollutants such as HMs, organic pollutants, radionuclides, pesticides, petroleum wastes, and antibiotics. However, plants differ in their remediation capacity depending on the target contaminants. Hence, selection of plants per the contaminants and site conditions is crucial. This paper has listed plants that are suitable for remediation of diverse pollutants by utilizing certain mechanism of phytoremediation.

While there are limitations such as long development time, dependence on climate and plant growth, many of these limitations can be overcome by proper designing, and proper selection of the species. Another concern is with the lower efficiency of phytoremediation, which can be enhanced by utilizing several aids as described in detail in this paper. The addition of amendments can enhance the mechanism involved, increase water and nutrient uptake, and improve plant growth. Besides, microbial population can increase the absorptive surfaces of roots, thereby improving metal uptake and degradation of organic pollutants. Genetically engineered plants have high potential for phytoremediation through higher plant growth rate and over expression of genes that regulate metal uptake and translocation.

Compared to other contaminant remediation technique, phytoremediation is 5-13 times more economical. Given the strengths and potential for remediating many of the weeknesses, more studies should be conducted to demonstrate the effectiveness of phytoremediation technology and increase its application even further. Additionally, researchers can look into secondary benefits of phytoremediation applications, for example, link phytoremediation to biomass production which can be utilized in production of biomass-based energy, feedstock for pyrolysis and biofortified products, and carbon sequestrations, which can contribute to phytomanagement. We also believe that phytoremediation can be studied at molecular genetic as well as nano scale level. Such type of combination approaches open ideas for the researcher to study in detail (Table 8).

Declaration of Competing Interest

None.

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Authors contribution statement

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