



RESEARCH ARTICLE

Weeds as sustainable green remediation technocrats

Arti Manhas¹, Noopur Sharma¹ and Shveta Saroop^{2*}

Abstract

Rapid globalization, industrialization, urbanization and land use changes have led to the Heavy Metal crisis. Heavy metals (HMs) by virtue of strong resistance to chemical or microbial degradation persist in the ecosystem for longer periods which deteriorates the overall function of any soil/aquatic ecosystem. HMs possess mutagenic, carcinogenic, genotoxic, and teratogenic potential even at low concentration. Invading the biotic and abiotic extremities and their interactions the accumulation of heavy metals is surpassing the maximum threshold level thereby altering the pedo-microbiological equilibrium, soil fertility, food chain and trophic structure and functioning. The removal of HMs from contaminated environments is thus crucial to rehabilitate nature and its balance. To cope with the same, phytoremediation being green in its approach has emerged as an eco-sustainable, economical way out. Further phytoremediation via weed species can serve as a most preferred alternative as compared to other groups of plant species. By virtue of stronger growth traits like annual life cycle, rapid growth rate, enviro-ecological traits of interest like mixed mating system, high reproductive efficiency in terms of seed banks and survival strategies, stress tolerant nature, invasiveness and many more, weeds serve as preferred candidate for phytoremediation. In light of this, present communication/review provides insight into the potential of weed species in HMs mitigation process.

Keywords: Phytoremediation, Heavy metals, Weeds, Detoxification, Sustainability.

Introduction

Climate change, land degradation, habitat destruction are the alarming issues nature is facing today. Apart from this, rapid rate of globalization, industrialization, economic growth, urbanization, and land use changes has resulted in the addition of deleterious heavy metals (HMs) in environmental complexes (Saroop and Tamchos, 2021). Elements with atomic number >20 and displaying metallic properties are termed as heavy metals. As a natural ingredient, metals lie in dynamic balance within the environment. However, levels above threshold result in toxicity for plants, animals and microbes. Some of the most common HMs are Arsenic (As), Chromium (Cr), Copper (Cu), Cadmium (Cd), Cesium (Cs), Mercury (Hg), Strontium (Sr), Lead (Pb), Uranium (U) and Zinc (Zn) (Saroop and Tamchos, 2021).

Invading the biotic and abiotic extremities and their complexes and interactions thereof, the concentration/level of heavy metals (HMs) is surpassing the maximum threshold. Shifting the pedo-biological stability and soil productiveness, toxic HMs bioaccumulation in the soil ecosystem interferes with the food chain function and its components. Heavy metals are thus altering the existing biodiversity and posing a serious concern to the ecosystem, balance, services and survival. Serving as an active sink for heavy metals and their metalloids, the aquatic ecosystem is also deteriorating at a faster speed (Yaashikaa *et al.*, 2022). Greater HMs penetration and accumulation hampers the population size, life span strategies and survivorship curves prevailing within aquatic ecosystems. Heavy metals by virtue of strong resistance to chemical or microbial degradation persist in the ecosystem for longer periods which deteriorates the overall function of the ecosystem and its constituents (Yaashikaa *et al.*, 2022). Naturally, HMs are directed in regulated manner in the ecosystem, and from natural processes like volcanic eruptions, weathering of rock, leaching and erosion. Anthropogenic activities involve fossil fuels combustion, industrial emissions and wastes, petroleum combustion, wastewater irrigation, sewage sludge, petrochemicals spillage, microelectronics, paper textile processing, and wood preservation techniques and mine tailings add HMs to the environment. Extensive

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use of agrochemicals (fertilizers and pesticides) also leads to HMs influx into the environment and ecosystem therein (Kumar *et al.*, 2021).

The ecosystems and biodiversity prevailing therein are the possessions that nature owes. Thus, protection of all these assets is a global accountability. Environmentalists, ecologists, conservationists, technocrats, policy makers and national agencies are raising issues and addressing the heavy metals (HMs) concern and their implications. Environmental assessment, monitoring and mitigation take care of this. It assesses the reasons and effects of HMs toxicity in biotic and abiotic interactions, ecological complexes and trade-offs active in any ecological network and their mitigation (Yaashikaa *et al.*, 2022).

The remediation and mitigation technologies involve physico-chemical mechanisms (like soil flushing, vitrification, landfilling, surface capping), electro-kinetic extraction and phytoremediation. While the former two conventional techniques which are expensive and associated with secondary pollution (Futughe *et al.*, 2020). The latter one is emerging as a low-priced, green and ecologically sustainable key with no secondary waste. Phytoremediation as the name specifies refers to the use of plants and associated soil microbes to monitor and mitigate the heavy metal accumulation, toxicity in the environment (Futughe *et al.*, 2020).

A wide range of biota have been employed which makes phytoremediation economically, ecological and environmentally friendly to combat the global surge in heavy metal toxicity. Further, in the light of Environment protection, ecosystem restoration and sustainable development goals the phytoremediation via weed species can serve as a most preferred detoxifying organisms as compared to other (Futughe *et al.*, 2020). Exhibiting stronger growth traits like annual life cycle, rapid growth rate, environmental traits of interest like mixed mating system, high reproductive efficiency in terms of seed banks and survival strategies, stress tolerant nature, invasiveness, weeds serves as a potent candidate for phytoremediation. The easy growth and cultivation thereof in barren/degraded or uncongenial land areas of the contaminated sites proves the relevance of weeds in heavy metal mitigation. Weed plant species possess intrinsic potential to accumulate different Heavy metals into their parts like roots, shoots and leaves. They do so by forming phyto-chelates and other stable compounds with ion species. This phytochelation and stable compound formation property is harnessed as a tool for phytoremediation activity. Therefore, in context to ecologically heavy metal toxicity, sustainable monitoring and mitigation strategies it is foremost requisite to explore the status of weed species, heavy metal accumulation potential, and ability in offering ecologically viable services (Yaashikaa *et al.*, 2022). The present review provides the consolidated account on phytoremediation potential of weedy plant species.

Weeds as sustainable green remediation technocrats

Past couple of year's research have reported the phytoremediation potential of various weed species. The list include *Abutilon indicum* (Link.), *Acalypha indica* L., *Achyranthes aspera* L., *Amaranthus hybridus* L. (Slim amaranth), *Amaranthus viridis* L., *Datura stramonium* L., *Calotropis procera* (Aiton) W.T., *Croton bonplandianum* L., *Cyperus rotundus* L. (s), *Euphorbia hirta* L., *Parthenium hysterophorus* L., *Phyllanthus niruri* L., *Phyllanthus amarus* Schum. & Thonn., *Solanum nigrum* L., *Sida cordifolia* L., *Solanum xanthocarpum* Schrad., *Spinacia oleracea* L., *Tridax procumbens* L., *Xanthium strumarium* L. and many more (Table 1 and 2) Panda *et al.*, 2020).

These "Sustainable green phytoremediation technocrats" do the job through processes involving extraction, stabilization, degradation, filtration, and volatilization (Saroop and Tamchos, 2021). These processes/strategies through which weeds detoxify heavy metal polluted environments (Figure 1) are as follows:

Phytoextraction

It involves uptake of metal from contaminated soil/water phases via root absorption followed by their translocation to and sequestration in harvestable aboveground parts or shoots (Figure 1) (Shah and Daverey, 2020). A potent hyperaccumulator plant should have some associated necessary characters. These characters are enumerated in Figure 2. Plants characterised by high biomass like *Cannabis sativa*, *Helianthus annuus* and *Nicotiana tabacum* are potent

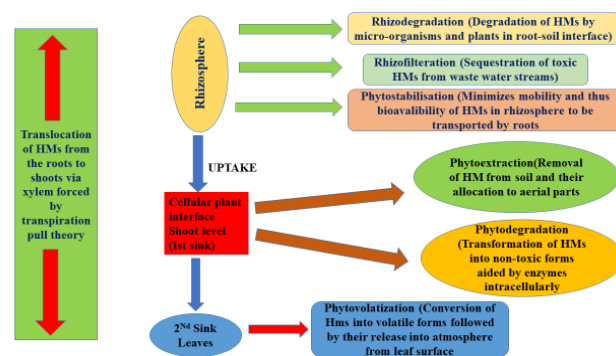


Figure 1: Scheme involved in phytoremediation of Heavy metals

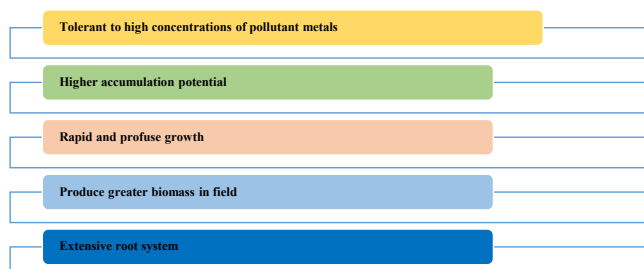


Figure 2: Traits possessed by Hyperaccumulator plant

Table 1: Phytoremediation of heavy metal of some selected plant species.

<i>Mechanism of phytoremediation</i>	<i>Heavy metal remediated</i>	<i>Species involved</i>	<i>Reference</i>
Phytoextraction	Zn	<i>Thlaspi caerulescens</i>	Wei et al., 2018
	Zn, Cr, Cu, Cd and Ni	<i>Arabidopsis thaliana</i> <i>Bidens pilosa</i> <i>Calandula officinalis</i> , <i>Brassica juncea</i> <i>Cynodon dactylon</i>	
	Pb	<i>Kyllinga erecta</i> <i>Dissotis rotundifolia</i> <i>Chromolaena odorata</i> <i>Sida acuta</i> <i>Nicotiana tabacum</i>	Lum et al., 2014 Oseni et al., 2018 Kramer and Muthukrishnan, 1997
	Fe	<i>Paspalum orbiculare</i>	
	Cd	<i>Solanum nigrum</i> <i>Arabidopsis halleri</i> <i>Taraxacum officinale</i> <i>Portulaca oleracea</i> <i>Cardamine hirsute</i> <i>Abutilon indicum</i>	Wei et al., 2006 Dahmani-Muller et al., 2000 Azab et al., 2020 Zhong et al., 2019 Ramadan and Balah, 2021 Varun et al., 2015.
	Pb, Cd, Cr, Co, Ni	<i>Acalypha indica</i> <i>Amaranthus viridis</i>	Ramanlal et al., 2020.
	Ni	<i>Alyssum murale</i> <i>Phyllanthus nummularioides</i> <i>Alyssum bertolonii</i>	Reeves, 2003 Ramanlal et al., 2020.
	As	<i>Tagetes minuta</i> <i>Lemna gibba</i>	Salazar and Pignata, 2014 Kramer, 2005
	Hg	<i>Erato polymnioides</i>	Chamba et al., 2017
	Cu and Pb	<i>Eleusine indica</i>	Lum et al., 2014
	Pb, Cd, Zn	<i>Deschampsia cespitosa</i>	Kucharski et al., (2005)
	Cr, As	<i>Pteris vittata</i>	Ramanlal et al., 2020.
	Pb, Cd, Mn, Cu, Zn	<i>Typha latifolia</i>	Kramer, 2005
Rhizofiltration	Fe, Mn, Cr, Pb, Cu, Zn, Ni, Co, Cd.	<i>Berkheya coddii</i> <i>Pistia stratoites</i>	Mesjasz-Przybylowicz, et al. 2016 Galal et al., 2014
	Pb	<i>Noccaea caerulescens</i>	Dinh et al., 2018
	Mn	<i>Phytolacca americana</i>	Min et al., 2007
	Se	<i>Lactuca sativa</i>	Banuelos et al., 2005
Phytostabilization	Cu, Pb and Cd	<i>Amaranthus spinosus</i> L. <i>Jatropha curcas</i>	Abdullahi and Abdulrahman, 2021 Chinmayee et al., 2012
	Ar, Zn	<i>Epilobium dodonaei</i>	Randelovic et al., 2016.
	Cu	<i>Vassia cuspidata</i>	Galal et al., 2014
	Re	<i>Trifolium repens</i> <i>Salvinia natans</i> L.	Tzvetkova and Bozhkov 2009
	Ni	<i>Alyssum bertolonii</i>	Bini et al., 2017
Phytofiltration	Ar	<i>Warnstorfia fluitans</i>	Sandhi et al., 2018
	Cd	<i>Micranthemum umbrosum</i>	
	Cr	<i>Phalari arundinacea</i>	Vymazal, 2016
Phytovolatilisation	Se	<i>Brassica</i> sp.(Wild type)	Banuelos et al., 2005
Bioaccumultion	Cd, Pb, Co	<i>Polypogon monspeliensis</i>	Ramadan and Balah, 2021

Zn (Zinc), Cr (Chromium), Cu (Copper), Cd (Cadmium), Ni (Nickel), Lead (Pb), Cobalt (Co), As (Arsenic), Mn (Manganese) Cr (Chromium), Hg (Mercury), Re (Rhenium), Fe (Iron), Se (Selenium)

Table 2: Heavy metal accumulation potential of some weeds by different workers

Study	Representative Species	Target Metal(s)	Accumulation/Tolerance	Phytoremediation Potential
Cadmium accumulation in weeds (Abe <i>et al.</i> , 2008)	<i>Matricaria chamomilla</i> , <i>Cichorium intybus</i>	Cd	Greater Cd accumulation in shoots than roots	Suitable for phytoextraction due to efficient translocation
	<i>Calystegia sepium</i> , <i>Oenothera biennis</i> , <i>Cassia obtusifolia</i>		Greater Cd accumulation in roots than shoots	Suitable for phytostabilization
	<i>Amaranthus viridis</i> , <i>Bidens frondosa</i> , <i>Bidens pilosa</i>		High Cd accumulation capacity	Promising Cd phytoremediators
Heavy metal uptake by Nigerian weeds (Eddy & Ekop, 2007)	<i>Phyllanthus amarus</i>	Zn, Cr, Ni, Cu	Highest Zn, Cr, Ni and Cu accumulation among tested weeds	Strong multi-metal accumulator
	<i>Stachytarpheta indica</i>	Pb, Mn	Highest Pb and Mn concentrations	Potential Pb remediation species
	<i>Murraya koenigii</i>	Cd	Highest Cd accumulation among tested weeds	Potential Cd phytoremediator
	<i>Chromolaena odorata</i>	Pb, Zn, Cr, Mn, Ni, Cu, Cd	Consistent uptake of multiple metals	Broad-spectrum accumulator
	<i>Thlaspi caerulescens</i>	Cd, Zn	Extremely high Cd and Zn accumulation	Model species for Cd/Zn phytoextraction
	<i>Alyssum bertolonii</i>	Ni	Hyperaccumulates Ni	Nickel remediation
	<i>Pteris vittata</i>	As	Exceptional As accumulation	Arsenic phytoremediation
	<i>Brassica juncea</i>	Cd, Se	High Cd, Se accumulation	Cadmium and Selenium remediation
	<i>Parthenium hysterophorus</i>	Cu	Highest reported Cu accumulation	Copper phytoremediation
	<i>Amaranthus viridis</i>	Pb	Very high Pb accumulation	Lead phytoextraction
Root-shoot metal partitioning (Girdhar <i>et al.</i> , 2014)	<i>Cannabis sativa</i>	Pb, Cu, Zn, Ni, Co, Cr	Greater translocation from roots to shoots	Efficient phytoextraction species
	<i>Solanum nigrum</i>	Pb, Cu, Zn, Ni, Co, Cr	Higher retention in roots	Better suited for phytostabilization
Weeds around Enyigba lead mines (Wilberforce, 2015)	<i>Chromolaena odorata</i>	Pb, Cd, Cu, Cr, Mn, Ni	Highest concentrations for most metals	Best overall accumulator among field weeds
	<i>Sida acuta</i>	Pb, Cd, Cu, Cr, Mn	High accumulation across several metals	Multi-metal remediation potential
	<i>Helianthus annuus</i>	Pb, Cu, Cr, Mn	Moderate-to-high accumulation	Useful remediation species
	<i>Eleusine indica</i>	Multiple metals	Moderate accumulation and tolerance	Suitable for revegetation of polluted sites
Boron toxicity tolerance (Aydin & Cakir, 2009)	<i>Sorghum halepense</i>	B	Highest boron tolerance	Most suitable for boron-contaminated soils
	<i>Cyperus rotundus</i> , <i>Cynodon dactylon</i>	B	High tolerance	Adapted to boron stress
	<i>Chenopodium album</i>	B	Lowest tolerance	Least suitable for boron-contaminated sites

phytoextraction agents. Similarly *Trifolium alexandrinum* owing to characteristics like high growth potential, shorter life cycle, greater biomass and greater stress tolerance levels can serve as a suitable phytoextraction agent for Cu, Cd, Zn and Pb (Anarado *et al.*, 2018).

Many weed species are reportedly implicated in the phytoextraction of Cu, Cd, Cr, Ni and Zn (Wei *et al.*, 2018).

These include *Arabidopsis thaliana*, *Alyssum bertolonii*, *Bidens pilosa*, *Brassica juncea*, *Calendula officinalis*, *Cynodon dactylon*, *Pteris vittata* etc. *Alyssum bertolonii* as Ni hyperaccumulator, *Pteris vittata* and *Brassica juncea*, accumulate both Ar and Pb, *Thlaspi caerulescens* accumulate two HMs namely Zn and Ni in shoots. *Thlaspi caerulescens*, is possibly the best known Zn hyperaccumulator plant is reported to accumulate Zn

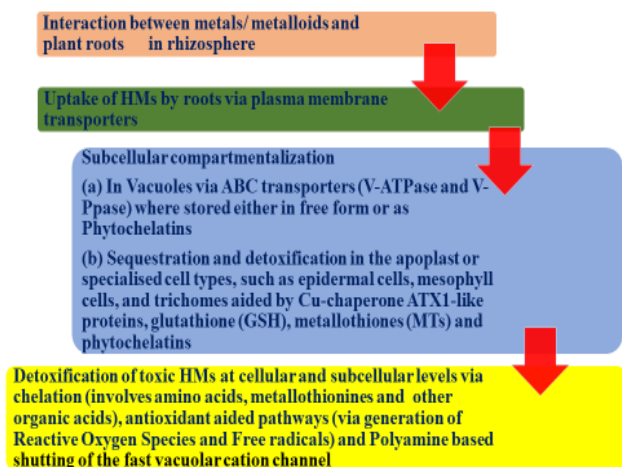


Figure 3: Schematic pathway of Metal acquisition and channelization by plants

to a level of 26 000 mg/Kg with no expression of any injury. *B. juncea* is a hyper-accumulator of Cd, *T. caerulea* of Zn and Cd, and *B. coddii*, *A. bertonii* and *Thlaspi goesingense* of Ni respectively (Lasat *et al.*, 2000).

These hyper-accumulator plants reallocate the absorbed toxic metals towards the leaves (Psaras and Manetas, 2001). Leaves being active sinks reallocate toxic metals to the epidermal cells and trichomes (Psaras and Manetas, 2001). The accumulation of heavy metal to leaves and their trichomes serve as a detoxification and defensive strategy against herbivores. Table 1 enlists few hyperaccumulator species of different heavy metals.

Several workers have worked out the heavy metal accumulation potential of various weeds in different areas. Their results are given in Table 2. Abe and coworkers (2008) evaluated the Cd accumulation potential of various weed species (shown in Table 2). It was found that two species, *Matricaria chamomilla* and *Cichorium intybus* accumulate greater Cd level in their shoots. Contrary to it *Calystegia sepium*, *Oenothera biennis*, and *Cassia obtusifolia* accumulate higher Cd concentrations in root and species belonging to Compositae are superior Cd translocator from roots to shoots as compared to Gramineae species. Of all the studied weeds *Amaranthus viridis*, *Bidens frondosa* and *Bidens pilosa* possess the ability to accumulate more Cd which proves helpful for Cd phytoremediation.

The natural process of phytoextraction makes use of natural hyperaccumulator plants for the elimination of HMs.

In this process of HM accumulation, the heavy metals are absorbed on the root surface and then translocated via cell membrane into the root cells. Thereafter these metal ions are immobilised in the vacuoles.

The intracellular mobile metal ions cross the cell membrane barrier and enter into the root xylem and subsequently translocated to above ground parts of the plant. Contrary, the induced phytoextraction involves

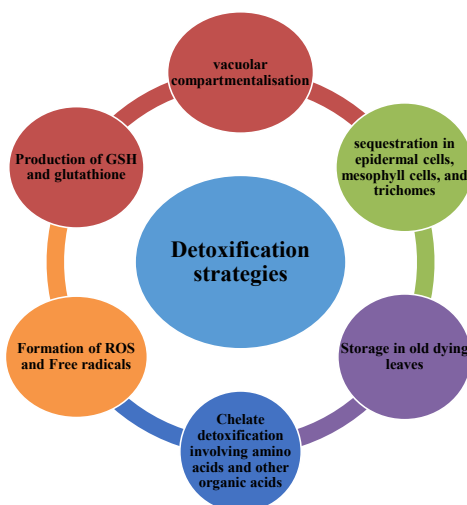


Figure 4: Detoxification strategies in plants

addition of chemical agents like citric acid, EDTA, Ammonium sulphate etc. to the contaminated soil to enhance the metal uptake capability of the plants. Weeds are not only involved in the phytoremediation of heavy metals but of certain other compounds also. For instance, in the treatment of household, industrial, and agricultural wastewater, aquatic species *Pistia stratiotes* and *Salvinia molesta* have been utilized extensively. These plants are widely used in phytoremediation activities due to their accessibility, resistance to toxicity, bioaccumulation potential, invasiveness, and biomass (Cristaldi *et al.*, 2020).

The potential of several weedy plants in phytoremediation has been investigated by a variety of other researchers. For instance, the roots of *Thlaspi caerulea* have the capacity to accumulate 2900 mg Kg⁻¹ and 8400 mg Kg⁻¹ dry weight of Zn and Ni respectively. In-depth studies on the accumulation potential of various weeds has been done by several workers. Their results are enumerated in Figure 4.

Furthermore, Ye and colleagues (2011) observed that *Pteris vittata* removed 3.5 to nearly 11.4 percent of the arsenic in the soil. Additionally, Kumar and colleagues (1995) found that the roots of *Brassica juncea* accumulated 108 mg of Pb/g dry weight. Genetically altered *Arabidopsis thaliana* was found to convert harmful Hg²⁺ to less toxic Hg⁰. Additionally, it has been reported that the plant *Pteris vittata* has ability to accumulate As and Cr upto 35,303 and 20,707 mg kg⁻¹ dry weight respectively, *Alyssum murale* accumulate 4730-20100 mg kg⁻¹ dry weight of Ni. *Tagetes minuta* accumulates 380.5 mg per kg dry weight of As while *Eleocharis acicularis* accumulate 11,200 mg kg⁻¹ dry weight of Zn (Salazar and Pignata, 2014).

In addition to normal terrestrial and aquatic plants, there are certain halophytes which can be used in the process of phytoremediation. For instance, *Tamarix smyrnensis* removes 9.4, 19.7 and 38.3 µg of Cd in concentrated solution ranging in strength from 0, 0.5 and 3% NaCl respectively.

Reeves 2003 studied the Ni hyperaccumulation potential of different species growing in four different areas viz Queensland, the Caribbean especially Puerto Rico the Dominican Republic; (iii) Southeast Asia, particularly Sulawesi (Celebs Indonesia). *Stackhousia tryonii*, a serpentine endemic, growing in Queensland accumulated Ni in the highest concentration range of 3640–7900–41260 mg kg⁻¹; thus making it a strong hyperaccumulator. Similarly *Phyllanthus nummularioides*, a member of the Euphorbiaceae family growing in Puerto Rico and the Dominican Republic showed highest accumulation Ni in a range of 19 030–26 560 mg Kg⁻¹. Comparable to this *Phyllanthus insulae-japen* growing in Japen area of Indonesia accumulated highest concentration of Ni in range of 34 330–38 720 mg Kg⁻¹. As far as accumulation of Polycyclic aromatic hydrocarbons (PAHs) is concerned, the *Avicennia germinans* exhibit the highest accumulation of 107,680 µg/kg in the leaves.

Rhizofiltration

It is the technique by which plant roots absorb, concentrate and precipitate toxic HMs from polluted groundwater or polluted effluents (Figure 1). A potent technique of removing a wide range of organic and inorganic contaminants; its efficiency is highly dependent on how efficiently roots produce chemicals which leads to heavy metals increase in plant parts. Several root exudates like simple phenolics and other organic acids cause the precipitation of metals onto root surfaces (Mustafa and Hayder, 2021). They alter the speciation (or form) of metals, as well as their uptake and simultaneous release of protons, which causes the medium to become acidic, promoting metal transport and bioavailability. Rhizofiltration is used for metals like Cr, Cu, Cd, Ni, and Pb that are retained only within the roots (Mustafa and Hayder, 2021). This process works only when the metals are volatile in nature (Hg and Se) (USPA 2000).

Young plants of *Berkheya coddii* growing in pots on soil supplemented with Cd, Ni, Zn or Pb substantially accumulated a considerable amount of these metals. Contrary to this, excised shoots in solutions having the same heavy metals accumulated a higher amount of these metals in their leaves (Mesjasz-Przybylowicz *et al.*, 2016). Indian mustard has a potential to eliminate lead in a concentration ranging from 4 to 500 mg/l. *Boehmeria nivea* have the potential to reduce the Pb and Cd bioavailability via immobilization of HMs and their absorption in the rhizosphere (Lan *et al.*, 2020).

Many plant species are involved in the process of rhizofiltration of more than one heavy metal. For instance *Brassica juncea* can remediate Cd, Pb; *Pistia stratiotes* Cd, Al, Fe, Mn; *Salvinia auriculata* Cd, Pb; *Typha domingensis* Al, Fe, Zn, Pb and *Eichhornia crassipes* Zn, Ni, Cu. Galal and coworkers, 2018 in their work on *Pistia stratiotes* found the rhizofiltration potential of water lettuce in an increasing trend of Fe < Mn < Cr < Pb < Cu < Zn < Ni < Co < Cd (Lan *et al.*, 2020).

Annual and perennial weedy species like *Carex stricta*, *Lolium perenne*, *Panicum virgatum*, *Populus* spp., *Sagittaria latifolia*, *Salix exigua* and *Tripsacum dactyloides* and have been shown to remove more total petroleum hydrocarbons (TPHs) from soil through rhizodegradation process. In terrestrial plants, *Brassica juncea* L. removed more than 95% of Hg in 5 days from an initial concentration of 0-10 mg/L. *Pteris vittata* removes 80% while *Micranthemum umbrosum* 73-60% of As. On contrary to *Pteris vittata*, *P. multifida* removed 90% Pb, 36% Cd and 50% of As from their initial concentrations of 9.5 ± 1.2 mg/L, 4.2 ± 0.1 mg/L and 6.6 ± 2.0 mg/L respectively (Rahman *et al.*, 2018).

Contrary to this, aquatic plant *Pistia stratiotes* remediated 68.75% of Cu (Niazy, 2019). Other aquatic species *Azolla japonica* and *Azolla pinnata* removed Cu >80% and Zn > 60% respectively (Rahman *et al.*, 2018).

Phytostabilisation

By this process phytoremediation potent plants prevent pollutants from moving through the soil rhizosphere (Figure 1). Deactivation is another word for phytostabilization. In this metal-tolerant plant species are used to immobilise heavy metals belowground, limiting metal mobility and the threat of metals entering the food chain (Ramadan and Balah, 2021).

Processes like absorption, complexation, precipitation and metal valence reduction are involved in phytostabilization by plants. This process effectively is used to treat Arsenic, Lead, Cadmium, Copper, Chromium and Zinc. It has a potential to effectively remediate soil, sludge, and sediment. It does not obstruct natural processes. It is a much safer alternative option for detoxifying the environment. It prevents the direct contact of man with harmful heavy metal pollutants by providing a suitable surface for their absorption and precipitation (Ramadan and Balah, 2021). Numerous weedy plants are involved in this phytostabilization process. Few of them are *Solanum nigrum* in Rhenium (Re) phytostabilization; Cu, Pb and Cd stabilization by *Amaranthus spinosus* (Tzvetkova and Bozhkov, 2009); *Clerodendrum indicum* involved in Fe stabilisation (Chinmayee *et al.*, 2012) and many more. They do so by secreting special redox enzymes which transform hazardous heavy metals to comparatively less toxic state thereby reducing potential metal stress and toxicity. *Eleusine indica* possesses the phytostabilization potential for Cu and Pb contaminated soils (Ramadan and Balah, 2021).

Phytodegradation

Known by synonyms like “phytotransformation” it involves the breakdown of complex organic compounds taken up by the plant into simpler molecules that are absorbed into the plant tissues (Figure 1). Various enzymes by plant act on the organic compounds; thus mineralising them entirely into simple inorganic compounds like carbon dioxide and water

or into stable molecules like lignin which are accumulated in plant tissues (Ramadan and Balah, 2021). A variety of enzymes involved in the photodegradation process include Cytochrome P450s, dehalogenases, laccases, peroxygenases, phosphatases, peroxidases, and nitroreductases. Moreover the plant transformation processes vary on the basis of pollutant, plant species, and tissue type. Oxidation, reduction, conjugation, and sequestration are the four major types of processes involved. Munitions, chlorinated solvents, herbicides, insecticides, toluene, ethyl benzene, benzene, xylene, and inorganic fertilisers are all contaminants that are degraded by the plants. However, the efficiency of uptake, transpiration efficiency, and pollutants load in soil and water; all influence the uptake of these chemicals into plant tissue (Meagher, 2020).

Phytovolatilization

It involves the uptake of toxic heavy metals from the soil by the plant roots; their conversion into less harmful volatile compounds and ultimate release into the atmosphere through the stomatal openings (Figure 1). Plants species *Liriodendron tulipifera* can volatise Hg (Rascio and Navarizlo, 2011). *Brassica napus* volatises Se (Meagher *et al.*, 2020); *Pteris vittata* found to volatise nearabout 90% of As of the total uptake in a greenhouse experiment. Adding to this, genetically modified *Arabidopsis thaliana* and *Nicotiana tabacum* are created by introducing bacterial Hg ion reductase genes. These can reduce Hg with the help of introduced genes that convert Hg (II) to Hg (0), which is comparatively very less toxic metallic mercury and can be volatilized to the atmosphere easily (Meagher, 2020).

Phytotransformation

It is the process of transformation of highly toxic metal (oids) to a less toxic state. This is followed by subsequent breakdown and mineralization of the metal ions either externally in the soil-root interfaces via release of degrading enzymes or internally via metabolic pathways within the plant cell. *Halimione portulacoides* (L.) Aellen minimizes toxicity of Chromium by transforming Cr (VI) to Cr (III) (Sikdar and Kundu, 2018).

Phytodesalination

It refers to the process wherein halophytes are used to remove excessive salts from salt-contaminated soils. Halophytic plants with phytodesalination potential detoxify the environment from heavy metals.

Mechanism involved in Phytoremediation mechanism

Heavy Metal acquisition and channelization

Plant and heavy metal interact at root level as these are present in the root surroundings. Heavy metal uptake is mediated by the same transporters that allow macro- and

micronutrients to enter the plant root system. Toxic metals are absorbed by plants through their roots and stored in the roots or translocated to the shoots via xylem vessels, where they are sequestered inside the vacuoles (Figure 3). Perfus-Barboeche *et al.*, (2002) have revealed Cd uptake via Ca channels in *Arabidopsis thaliana*. The same possibly reveal the fact that Cd mimicking Ca and thus is carried via the transporters of the latter ion (Jan *et al.*, 2016).

Plants have designed a number of strategies to boost the uptake of HMs from the soil. Production of carboxylates, phytosiderophores and rhizosphere acidify soil which aid in the chelation followed by solubilization of soil bound metals. Moreover, the soil microorganisms in the rhizosphere, as well as the enzymes they secrete, play an important role in regulating the metal ions availability for root absorption (Burns and Dick, R. P. Eds. 2002).

After subsequent absorption by roots, metal ions initially arrive in contact with the cell wall, which is an ion exchanger exhibiting affinity and low selectivity. Heavy metals are absorbed by roots either via passive diffusion involving cell membrane or via active transport against concentration gradient and/or electrochemical potential facilitated by carriers, which is the more typical method. Complexing agents such as proteins and organic acids that bind to the metal species can also be used as carriers (Ghosh and Singh, 2005).

Metal ions enter into roots by two ways either apoplastically or symplastically. Thereafter, these are immobilised in apoplastic and symplastic compartments after generating precipitates of carbonate, phosphate or sulphate because as such they are insoluble and immobile (Garbisu and Alkorta 2001). Heavy metal ions come in the xylem stream symplastically within roots. Metal ions must cross the plasma membrane in order to travel symplastically. Due to the electrochemical gradient, the plasma membrane's strong negative resting potential favours the inward flow of metal ions (Tester and Leigh 2001). Metal ions stored within vacuoles may also reach the xylem through the stele. Thus, metal ion sequestration in root cells, their symplastic transport via stele, and subsequent influx into the xylem are the three mechanisms that influence metal entry from the root into the xylem (Saxena and Misra 2010).

Detoxification strategies evolved in response to HMs

Heavy metal detoxification/sequestration occurs preferentially in places like the epidermis, trichomes and even the cuticle, where they cause the slightest harm to the photosynthetic apparatus. HMs are frequently expelled from stomata's subsidiary and guard cells. This could help to protect functioning stomatal cells from metal phytotoxicity (Broadhurst *et al.*, 2004).

Plants cells have developed an array of detoxification strategies in order to maintain the low heavy metal concentration in various plasmatic components including

stroma, cytosol, nucleoplasm and matrix (Figure 3 and 4). Vacuolar compartmentalisation is one of them. Vacuoles are the final destination for the storage of the heavy metals either freely in the ion form or bound with certain phytochemicals called phytochelatins (PC) (Figure 3). The phytochelatin formation occurs during exposure to certain heavy metals particularly Cd and Ar using GSH as precursor. ATP binding cassette (ABC) transporters are involved in the sequestration of the HMs-phytochelatin complex inside the vacuole. In addition, vacuolar compartmentalization of toxic HMs is primarily dependent on tonoplast energization and proton motive force developed which is facilitated by the H⁺ translocating activities of V-PPase and V-ATPase as well as a variety of other tonoplast localised transporters. On the tonoplast membrane, V-PPase and V-ATPase produce the pmf (proton motive force), allowing proton-coupled antiport, membrane potential-driven transport, and acidic trapping (Verbruggen *et al.*, 2009).

In addition to membranous transporters, vesicle transport is expected to have a role in HM vacuolar compartmentalization. There is little research on the subject. Leitenmaier & Kupper (2011) identified Cd-rich vesicle-like structures in leaf cell protoplasts of the Cd/Zn hyperaccumulator *Thlaspi caerulescens*. Although the exact genesis or destiny of these vesicles is unknown, they are thought to have a role in Cd vacuolar sequestration. In addition to sequestration into vacuoles; plants use a variety of other compartmentalization mechanisms. Heavy metal ion sequestration in the apoplast or specialised cell types, such as epidermal cells, mesophyll cells, and trichomes, are examples of these. Cd, Mn, and Pb, for example, were reported to be sequestered in trichomes (Leitenmaier and Kupper 2011).

Heavy metals can also be removed effectively by storing them in senescence leaves which subsequently fall off. Zn, for example, has been found to accumulate in leaves in the week leading to shedding of leaves resulting in leaf fall to reduce dangerous metal levels inside the plant body (Ernst *et al.*, 1992).

Chelation with appropriate ligands is another method used to detoxify HM ions inside plant tissues, and the chelate detoxification mechanism inside the cytosol involves amino acids and organic acids (such as histidine and other amino acids) and some thiol-containing substances like metallothioneins, glutathione and phytochelatins. Another mechanism to combat the toxicity of HMs is the greater production of free radicals and reactive oxygen species (ROS) in plant tissues, for example, the level of antioxidant enzymes increase in response to oxidative stress stimulated by amplified arsenic concentration as a secondary defence strategy (Figure 3) (Srivastava *et al.*, 2005).

Plants cope with HM stress by producing GSH, a precursor to phytochelatins, which functions as an

antioxidant that directly detoxifies HM by conjugating with them. (Lee *et al.*, 2003). It has been observed that in fungi and plants phytochelation plays an important role in the detoxification of HMs, particularly Cd. Tolerance to HMs is dependent on glutathione and organic acid metabolism (Prasad and Frietas, 2003). It has been seen that glutathione plays a function in heavy metal detoxification by its integration into PCs and not directly. Lee and coworkers (2003) observed and concluded that, in addition to increased PC synthesis, increased capacity for PC-metal complexes inside vacuoles is also required to boost Cd tolerance in plants.

Metallothioneins are another important class of chelating compounds. They are known to play a crucial part in the detoxification of metals, and heavy metal exposure to root cells induces the creation of these compounds in plants. Plants, mammals, and some prokaryotes all produce metallothioneins (MTs), which are 60–80 amino acid proteins rich in sulphur and known to include 9–16 cysteine residues. These cysteine-rich polypeptides take advantage of heavy metals' ability to bind to protein thiol groups and detoxify them. Participation in Cu homeostasis is another well-known characteristic of MTs (Rea *et al.*, 2004).

Polyamines are tiny, ubiquitous polycations that participate in a variety of plant growth and development processes and have anti-senescence and anti-stress properties. Their antioxidant and acid-neutralizing qualities, as well as their potential to stabilise membranes and cell walls, are accountable for these disturbing effects. Polyamines boost plants' immune systems and influence their function in response to a variety of environmental stresses, such as metal toxicity, oxidative stress, drought, salinity, and chilling stress (Jiang *et al.*, 2020). The precise function of polyamines discovered in plants under metal stress is yet unknown. The protection hypothesis is the most promising one regarding the role of polyamines in the protection and stabilization of biological membranes against HM toxicity (Jiang *et al.*, 2020).

Some significant polyamines that have shown an in vitro potential to neutralize free radicals include spermine, spermidine, putrescine, and cadaverine. Another effect of polyamines is the shutting of the fast vacuolar cation channel, one of the principal vacuolar channels. As these vacuolar channels build up, the ion conductance at the vacuolar membrane is reduced, enhancing the compartmentation of metal ions (Ashraf *et al.*, 2020).

Conclusion

Weed plant species in restoration of heavy metal contaminated environments forms the fundamental aspect in sustainable phytoremediation engineering. It further offers great commercial and economical opportunities. Bestowed with the potential to adapt, proliferate and survive in highly contaminated sites, these weeds can

act as a signature candidate as 'restoring assets for heavy metal contamination'. Phytoremediation aided by weeds offers a value-added, non-agricultural economical remedial asset which can be explored. Agricultural lands/crop lands are under continuous threat to toxic metals which limit their productivity and thus overall commercialization and economic growth. These weeds, thus can be used to restore/rehabilitate the contaminated sites by limiting the influx of toxic metals in the food chain and exposure of these toxic metals to economically important crops and to humans also. Further research in phytoremediation potential of weeds and its implication and perspectives needs to be researched and addressed upon. In addition, more inputs on Weed-HMs interactions needs to be worked out to efficiently design and execute phytoremediation processes and remediation schemes. This would achieve the purpose of phytoremediation coupled with sustainable development goals.

Conflict of Interest

There is no conflict of interest among the authors regarding the publication of the research paper.

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