Bioscene

Bioscene
Volume- 21 Number- 04
ISSN: 1539-2422 (P) 2055-1583 (O)
www.explorebioscene.com

A Comprehensive Study on Heavy Metal Phytotoxicity and Bioremediation Strategies for Ecological Sustainability

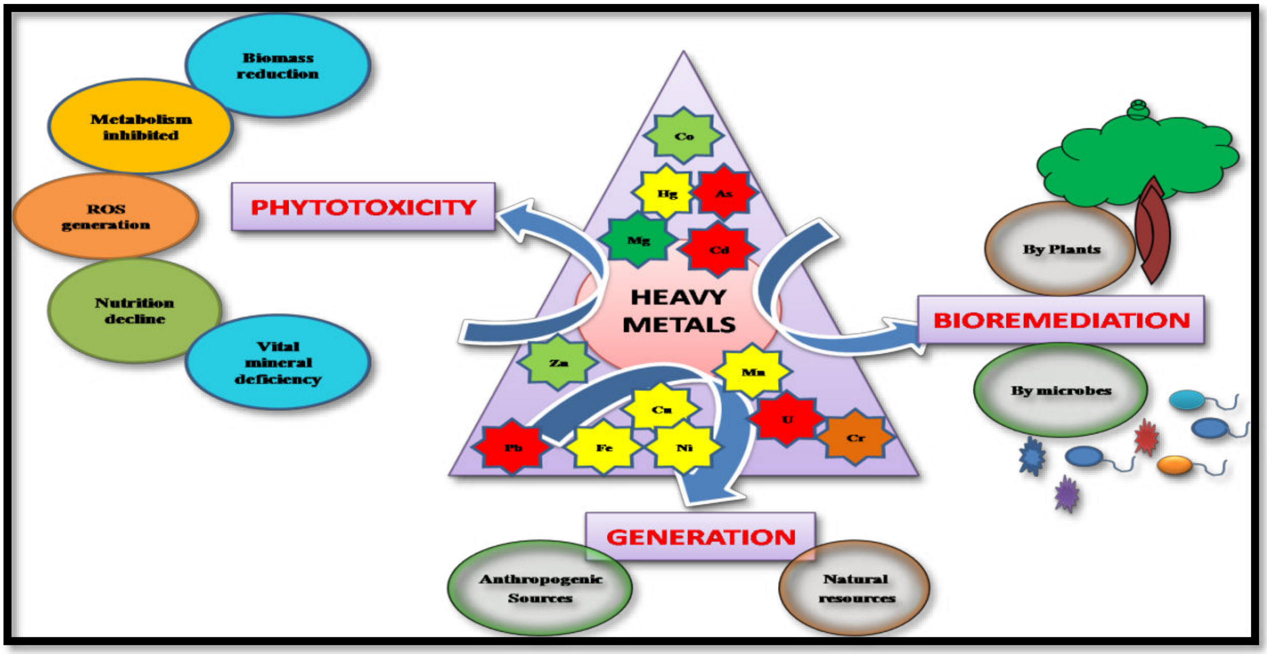
Nupur & Ashok Kumar
Research Scholar & Professor
Department of Botany, CCS University, Meerut, India

Corresponding Author: **Ashok Kumar**

Abstract: Heavy metals are environmental contaminants that threaten our ecosystems and pose health concerns to living beings through their continuous persistence and magnification in the environment as a result of natural as well as anthropogenic sources. The bulk of these contaminants are exceedingly potent for all life forms, due to which their thorough elimination from the environment is necessary, but existing treatment methods are unable to offer a practical and sustainable approach. Researchers now consider using microbes and plants forheavy metal mitigation as one of the most viable approaches. This review is focused on the general account of heavy metals and their toxicity symptoms in plants. It also states the different bioremediation approaches of plants and microbial cells for a sustainable ecosystem.

Keywords: bioremediation**,** environment, heavy metal, mitigation, pollutant, toxicity

Graphical abstract



1. Introduction

Heavy metals (HMs) are naturally occurring elements or metals possessing a high atomic mass of more than 23, a high atomic number larger than 20, a high atomic weight ranged within 63.5–200.6 g/moland a high atomic density of at least 5 g/cm^3. HMs are characterized by the phenomenon of recalcitration, which shows resistance against biodegradation (Figlioli et al.2019**).**Bishop, P. L. (2000) categorized heavy metals into three classes: precious metals (Ag, Au), radionuclides (U, Th, Ra, Ce), and toxic metals (Hg, Cr, Pb, Zn, Cu, Ni, Cd, As, Co, and Sn). HMs can also be further classified into essential and non-essential. Essential HMs serve a significant role in several oxidation-reduction reactionsand influence the biochemistry and physiology of living organisms for proper growth and nutrition, but their higher amounts can be toxic. On the other hand, non-essential HMs are often associated with different serious concerns in both ecology and human health. Based on their toxicity, HMs can further be classified into extremely toxic and moderately toxic (Fig 1).

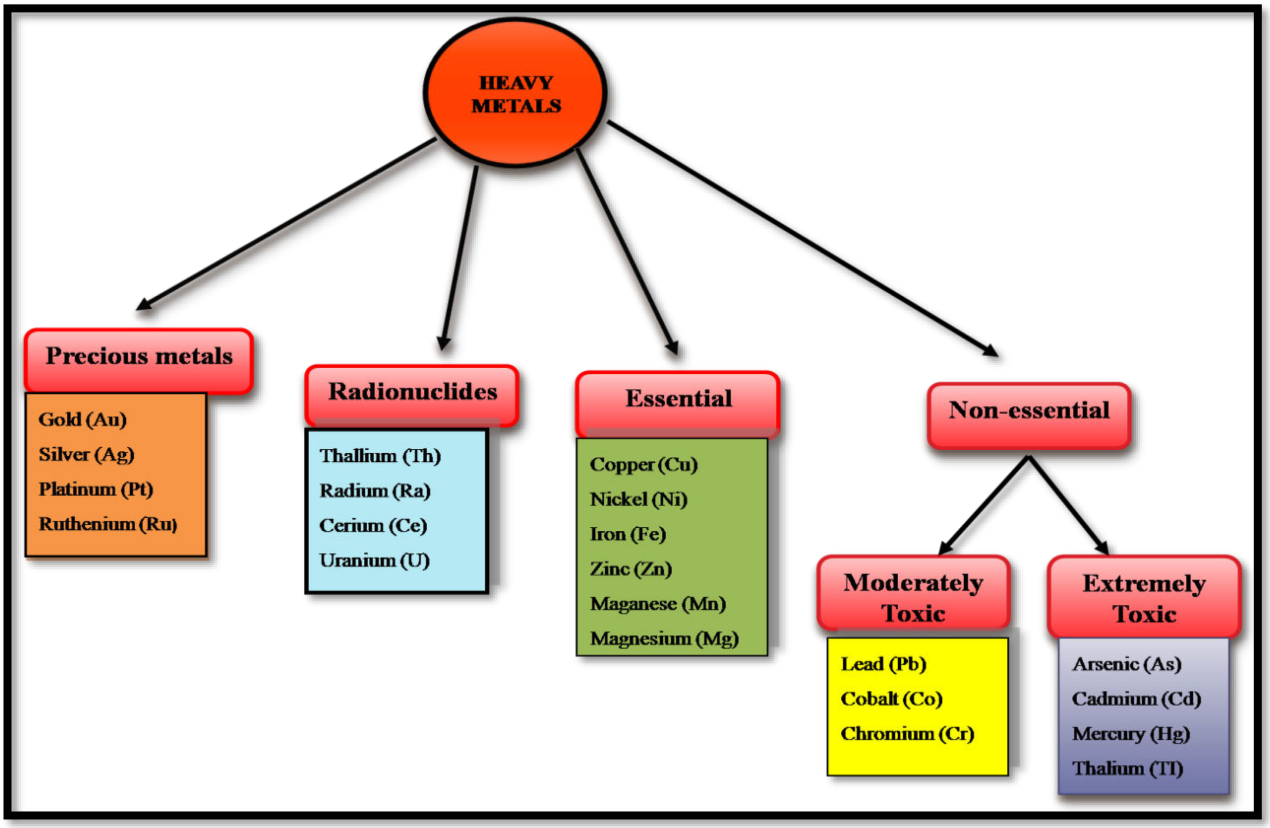


Fig. 1: Classification of heavy metals.

2. Origin of Heavy Metals

Heavy metals are naturally distributed in nature, but some anthropogenic activities are also responsible for their persistence in the surroundings. Natural sources are recognized as weathering of metal-bearing rocks, soil erosion, and volcanic eruptions (Seaward and Richardson, 1989), while anthropogenic sources include mining, tailings (ore residues) activities, and wastes generated from geogenic operations and pharmaceutical industries. Repeated use of agrochemicals during agricultural practice also causes heavy metal magnification in the soil; from there, they get into the water during leaching. Emissions from fossil fuels (coal products, crude oil, and petroleum products) cause fluctuations in the natural level of HMs, making them persistent in the atmosphere (Tchounwouet al. 2012). Major sources of heavy metal pollution are given in Fig 2.

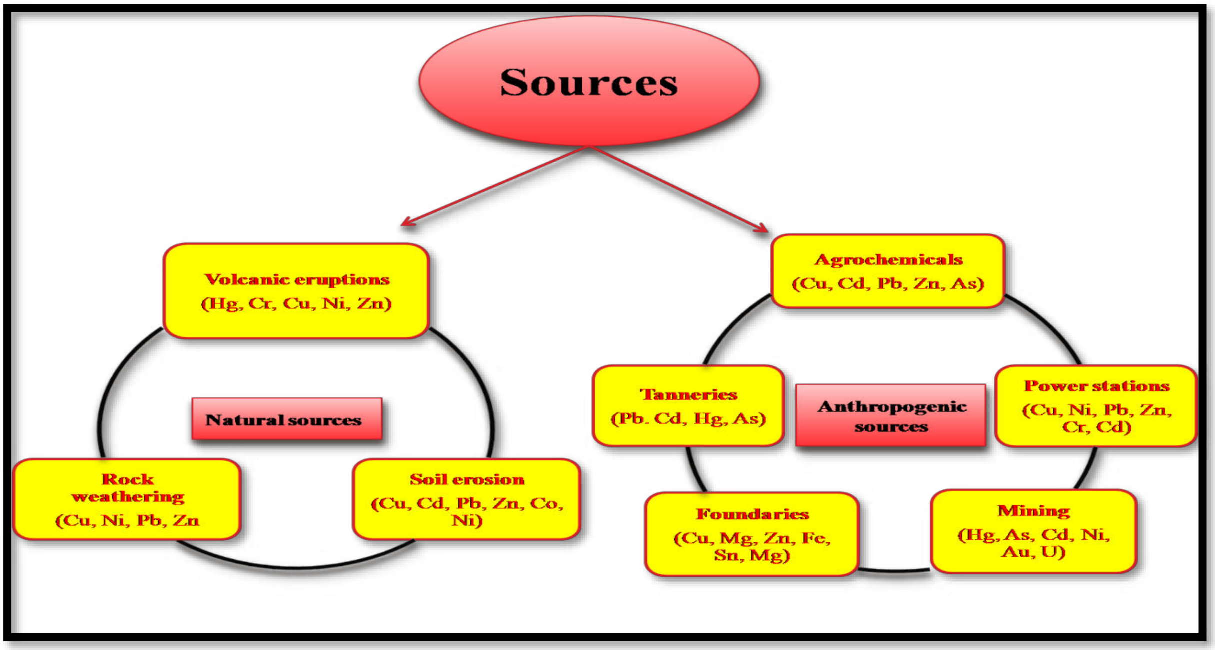


Fig. 2: Emerging heavy metals (HMs) concentration in the environment from major sources.

3. Heavy metals phytotoxicity

Potentially toxic levels of HMs can cause a variety of deleterious impacts on plant growth, photosynthetic& respiratory rates, mineral nutrition, and antioxidant activity. The details of the toxic effects of some important HMs on plants are given below.

Zinc (Zn) is an essential heavy metal that serves as an enzyme catalyst in various metabolic pathways such as chlorophyll production, auxin formation, and conversion of starch to sugar. It also helps the plant survive in the winter (Ghori et al. 2019). However, it is phytotoxic at higher concentrations and interferes with the other minerals uptake by plants (P, Fe, Mn, Cu), causing mineral deficiencies in plant tissues (White and Pongrac, 2017).

Chromium (Cr) alone makes up about 0.1 to 0.3 mg kg^{-1} of the rocks and is considered the seventh most abundant element on earth (Cervantes et al. 2001). Cr toxicity in plants include reduced seed germination, slow growth, low yields, suppression of enzyme activity, photosynthesisimpairment, imbalances in nutritional availability &oxidative mechanisms, and gene alteration (Kumar et al. 2016).

Copper is naturally distributed in the earth's crust at an average concentration of 60 mg/kg (Alloway, B. J. 2013). It is needed in a trace amount to maintain proper functioning. However, an excess of Cu may have negative consequences on overall productivity and survival of plants (Printz et al. 2016). Mir et al.(2021) outlined the detrimental consequences of excessive copper in plants, such as delayed germination, photosynthesis inhibition, ROS (reactive oxygen species) generation, and poor nutritional availability.

Cadmium (Cd) is listed 7th among the 20 most pernicious toxic metals due to its carcinogenic nature (Jaishankar et al. 2014). Plants exposed to cadmium toxicity suffer from reduced germination to decreased productivity. It also impairs the physiological processes (water exchanges, other vital minerals deficiency, and photosynthetic activity) by altering plant metabolism (enzymes/metabolites inhibition, ROS generation, oxidative stress) (Zulfiqar et al. 2022).

Nickel (Ni) is the 5th most abundant (0.08% of the earth's crust) metal used in manufacturing of utensils, coins, and electronics items (batteries) (Genchi et al. 2020). In plants, it interrupts mineral ion uptake and causes oxidative stress. Moreover, Ni poisoning also results in chlorosis, necrosis, and inhibition of many physiological processes (photosynthesis, transpiration) (Hassan et al. 2019).

Arsenic (As) is the 20thmost abundant element on earth (Garbinski et al. 2019), with extreme toxicity and carcinogenicity (WHO, 2018). Arsenic phytotoxicity is not only limited to reducing plant biomass and nutritional quality (Hu et al. 2013), but also causes physiological changes in plants by disrupting a number of metabolic processes (Tripathi et al. 2015).

WHO/FAO (1988) listed iron (Fe) as the 2ndmost abundant metal on the earth's crust. In plants, Fe is essential for a number of vital biological processes, including photosynthesis, mitochondrial respiration, metabolism (nitrogen&sulphur), and biomolecule synthesis (hormones &DNA) (Ibanez et al. 2020). However, high levels of Fe can generate oxidative stress by upsetting the cell’s redox equilibrium and leading to alterations in the plants' morphology, metabolism, and physiological characteristics (de Oliveira Jucoskiet al. 2013).

Manganese (Mn) is considered as crucial cofactor for photosystem II's (PSII) water-splitting activity (Andresen et al. 2018) in plants. However, prolonged exposure can lead to oxidative stress and photosynthetic disruption. As a result, young leaves suffer from interveinal chlorosis, while mature leaves have necrosis with black patches and wrinkles. Browning of roots also occurs to hinder the absorption and transfer of other mineral elements, causing their deficiency in the respective plant (Li et al. 2019).

Magnesium (Mg) regulates numerous enzyme-linked metabolic functions such as photosynthesis, glycolysis, genome regulation, protein formation and enzyme activation for CO_2fixation&assimilation, etc. ((Chen et al. 2018; Lu et al. 2021) in plants and has been known to enhance biomass along with nutritional quality and fruit yield (Yan and Hou, 2018)but an excess amount can lead to bacterial spots on tomatoes and peppers due to interference with calcium ion regulation (Huber and Jones, 2013).

Cobalt (Co)occurs in a combined form with other HMs (Fe, Ni, Ag, Pb, Cu, and Mn) and in rock carbonates and minerals (Maheyet al. 2020). In plants, Co is a crucial part of cobalamin (vitamin B_{12}), which is necessary for the functioning of various N_2 fixation-related enzymes. Conversely, elevated levels of cobalt show detrimental effects on plant physiology andmetabolism, resulting in pale leaves, discoloured veins, and leaf loss due to iron deficiency (Asatiet al. 2016; Hu et al. 2021).

Lead (Pb) is extremely poisonous as it can disrupt cellular membranes, enzymatic activities, and DNA synthesis (Marzan et al. 2017). Plants accumulate Pb within their roots, where it causes inhibition of different physiological and biochemical processes specifically germination period, CO_2 and nitrate assimilation, photosynthesis, and plant growth&advancement (Naveed et al. 2020; Aqeel et al. 2021).

Mercury (Hg) is a persistent and volatile contaminant due to which it shows vast mobility in nature (Pacyna, J. M. 2020). Mercury interacts with plants either by direct application as an antifungal agent (seed disinfectant) or foliar spraying as herbicide (Patra and Sharma, 2000). Mercury phytotoxicity is associated with inhibition of photosynthetic rate, impermeability of cell membranes, disrupting protein structure, causing oxidative damage, and replacing other vital mineral elements such as Mg (Patra et al. 2004; Israr et al. 2006).

Uranium (atomic number: 92; atomic density: 19.1 g/cm^3) is one of the most toxic pollutants, posing mutation, carcinogenicity, and DNA alteration due to its radioactive properties (Qi et al. 2019; Gudkov et al. 2016). Rapid advancement in nuclear technology generates enormous amounts of uranium waste (Iltonet al.2008), causing significant danger to our ecosystem **(**Chen et al. 2021). In plants, nitrogen and protein metabolisms are hampered by uranium activity (Chen et al. 2023). Expression of photosynthetic genes is also hampered, which alters the photosynthetic metabolism and inhibits ETC, resulting in unusual energy supply and a slowed respiration rate (Zhang et al. 2020).

4. Acceptable level of heavy metals (HMs) (Table 1).

The acceptable limit for each HM in the environment varies according to its toxicity, affected medium, exposure time, etc. Hence, the World Health Organization (WHO) has mandated permissible concentrations of heavy metals in plants, drinking water, and soil to minimize their noxious effects on ecosystems (Table 1).

Table 1: Acceptable levels (ppm) of heavy Metals in plants, water and soil.

Heavy metal	**Plants(per kg)**	**Drinking water (per litre)**	**References**
Cd	0.02	0.01	Hasan et al. 2012
Pb	2	0.05	Hasan et al. 2012
Hg	-	0.001	WHO, 2004
Cr	1.30	0.1	Hasan et al. 2012
Ni	10	0.2	Hasan et al. 2012
Cu	10	2	Hasan et al. 2012
Fe	20	1.0	Shah et al. 2013 Patil and Ahmed, 2011
Zn	50	5	Shah et al. 2013
As	-	0.05	WHO, 2004
Co	-	0.01	WHO, 2004
Agricultural soil (per kg)			
Cd	0.003		Chiromaet al. 2014, Aneyoet al. 2016
Pb	0.1		Chiromaet al. 2014
Hg	0.05		World Bank, 1998
Cr	0.1		Chiromaet al. 2014, Aneyoet al. (2016)
Ni	0.05		Chiromaet al. 2014, Aneyoet al. (2016)
Cu	36		WHO, 1996

5. Heavy metal remediation: plants and microorganisms

Cleaning up of environment by removing toxic chemicals/pollutants by living organisms is termed bioremediation. When microorganisms are employed to treat the contaminants, it is termed microbial remediation, but in the case of plants, it is called phytoremediation.

5.1 Plants defense mechanisms (Fig 3).

Plants remediate HMs-polluted environments by utilizing two general approaches (a) Site stabilization: in-situ techniques that reducing HM's acute toxicity through decreasing their mobility &bioavailability such asphytoimmobilization, which is also known as phyto-stablization or phyto-sequestration and (b) Direct removal of heavy metals by "clean-up" strategiesinvolving phyto-degradation, phyto-extraction,phyto-volatilization, and phyto-accumulation to combat heavy metal stress (Table 3).

a. Site Stabilization: In-situ technique

Phytostabilization/Phytoimmobilization/Phytosequestration

Phytoimmobilization entails plants to immobilize pollutants (heavy metals)in the soil or root portion rather than in aerial or above-ground parts preventing their entry into food chain (Gil-Loaiza et al. 2016). Such plants include Festuca rubra (red fescue) and Dactylis glomerata (orchard grass) (Kacprzak, 2014). Some studies also conclude that F. rubra is efficient enough to immobilize Cu, Pb, Mn, and Zn from metal-contaminated sites emerging via industrial activities such as mining, energy, and fuel emissions (Yin et al. 2014).

b. Clean-up Strategies

Phytodegradation

Enzymes secreted from plant roots are employed in phytodegradation to break down pollutants. These enzymes (nitroreductases and dehalogenases) are uniquely able to break down hazardous pollutants such as pesticides and chlorinated solvents. For phytodegradation, poplar trees are frequently utilized to degrade copper (Cu), cadmium (Cd), and zinc (Zn) (Greipsson, S. 2011).

Phytoextraction

This tactic depends on a plant's capacity to absorb and store large amounts of hazardous contaminants (heavy metals) that get detoxified in their above-ground parts or aerial sections (leaves), which can be later harvested and processed further (Rascio and Navari-Izz, 2011). Some examples of plants with efficient phytoextraction capacity include Elsholtzia splendens for copper (Cu), Thlaspi caerulescens (alpine pennygrass), Pteris vittata (Chinese brake) for arsenic (As), Brassica carinata and Halianthus annuus for lead (Pb), Brassica juncea for mercury (Hg), Astragalus bisulcatus (the two-grooved milkvetch), and Stanleya pinnata for selenium (Se) (Favas et al. 2014; Freeman et al. 2006; Tangahuet al. 2011; Furiniet al. 2015).

Phytovolatilization

Some plants can absorb toxic substances from the soil, and then release their volatile forms into the atmosphere by transforming them into less harmful forms. Many inorganic chemicals (Se, As, and Hg) can be volatilized by different plant species, such as selenium (Se) by Brassica juncea (Banuelos et al. 1993) and mercury (Hg) by Nicotiana tabacum(Rayuet al. 2012; Mukhopadhyay and Maiti, 2010). Further, Limmer and Burken (2016) categorized phytovolatilization into two types.

1. **Indirect phytovolatilization:** Plant roots usually burrow deeply into large regions of soil, which ultimately increases the flux of volatile pollutants from the subsurface (belowground).
2. **Direct phytovolatilization:** When volatilization of contaminants occurs from leaves (stomatal opening, cuticle) or stems (trunk), it is termed direct phytovolatilization, involving uptake,translocation, and volatilization of the toxicants.

Phytoaccumulation

Plants that grow naturally on contaminated sites are termed excluders and hyperaccumulators based on their survival strategies (Baker, 1981). Excluders can tolerate high levels of heavy metals and limit their toxicity to the roots, where they get detoxified into less harmful ionic forms. However, hyper-accumulators are known to accumulate toxic heavy metals in their shoots(Van der Ent et al. 2013). A hyperaccumulator can uptake HMs up to 100–1000 times faster than non-hyperaccumulators, as stated by Reeves (2006) and Rascio and Navari (2011). The maximum allowed concentration of different heavy metals in dry biomass for plants to qualify as hyperaccumulators is given (Table 2).

Table 2: Criteria to be known as hyperaccumulators (AjM, B. 1989)

Heavy metals	**mg/kg dry mass**
Cadmium (Cd)	100
Selenium (Se)	100
Cobalt (Co)	1000
Copper (Cu)	1000
Nickel (Ni)	1000
Lead (Pb)	1000
Zinc (Zn)	10000
Manganese (Mn)	10000

Phytofiltration

Rhizofiltration, caulofiltration, and blastofiltration are the three subtypes of phytofiltration processes where contaminants are removed from liquid systems (sewage water, industrial effluents, wastewater, and wetlands) via plant roots, shoots, and seedlings, respectively (Mesjasz-Przybyowiczet al. 2004). Rhizofiltration is the pollutant's adsorption or absorption on the root surface due to exudate secretions that facilitate the binding of pollutants (by changing rhizospheric pH) and further reduce the metal leaching (Timalsinaet al. 2022). Aquatic species such as Hyacinthus orientalis (hyacinth), Lemna minor (duckweed), Typha latifolia (cattail), and Populas alba (poplar) are frequently utilized for remediation of contaminated water as they possess high accumulation and tolerance capacities towards heavy metals, with rapid growth producing high biomass (Hooda, 2007).

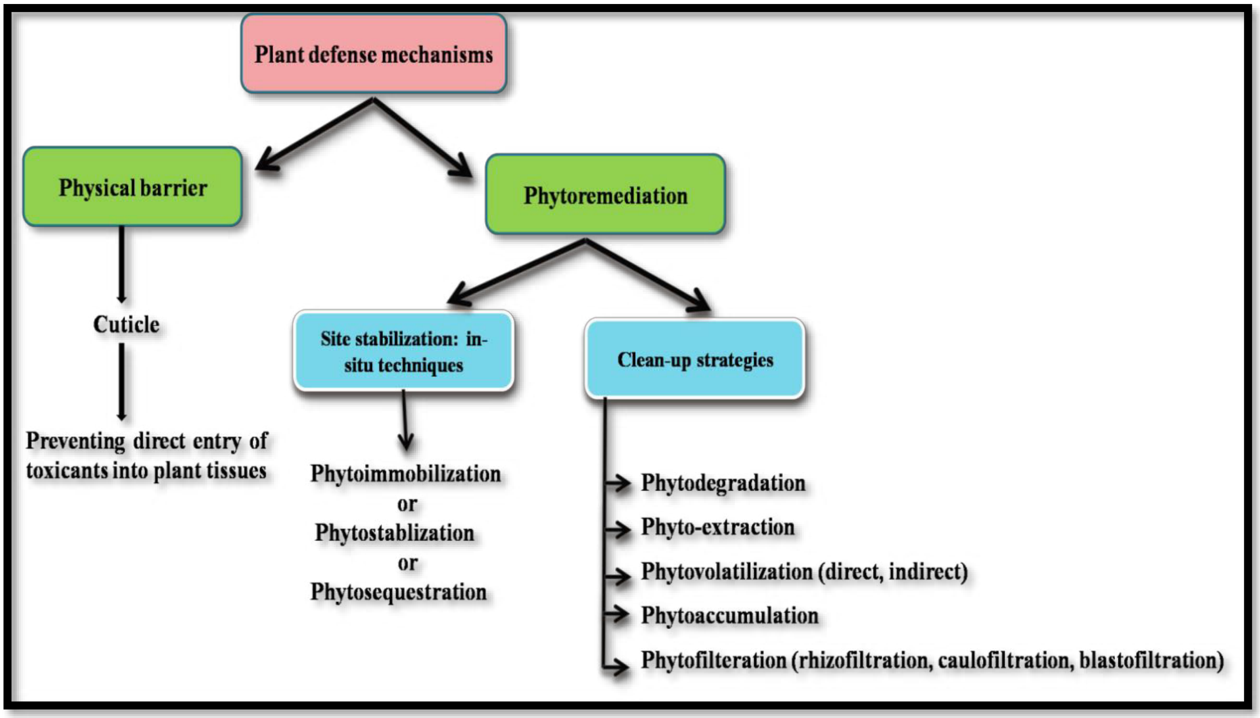


Fig. 3: Different strategies adopted by plants to cope up toxicant's effects.

5.2Microbial strategies for heavy metal mitigation

The process of utilizing microorganisms to reduce heavy metals from the contaminated site is termed "microbial remediation" (Su, C. 2014). Microorganisms have evolved a variety of mechanisms for maintaining homeostasis and resistance in order to accommodate to HMs' toxicity because of their distinctive degradative enzymes for a particular contaminant (Wei et al. 2014. The microbial capability of flourishing in adverse conditions (extremely hot & cold environments) also makes them suitable agents for performing bioremediation, and aerobic (Pseudomonas, Acinetobacter, Sphingomonas, Nocardia, Flavobacterium, Rhodococcus) as well as anaerobic ones can be utilized for pollutants degradation(Sharma, I. 2020). Different microbial approaches for heavy metal mitigation are discussed further.

Table 3: Tabular representation of different plants species' defence mechanism under heavy metal stress with suitable examples (Kafle et al. 2022).

Strategies	**Heavy Metals**	**Plantspecies**	**References**
Phytoextraction	Cd, Zn	Thlaspi caerulescens Arabdidopsis helleri	Cosio et al. (2004)
	Cu	Commelina communis	Wang et al. (2004)
	Pb	Pelargonium hortorum	Manzoor et al. (2019)
		Sedum alfredii	Ning et al. (2019)
	Cd, Pb, Ni, Zn	Xanthium strumarium	Khalid et al. (2019)
	Ni, Co, Fe	Lolium perenne Lactuca sativa	Hernandez et al. (2019)
Phytostablization	As	Eupatorium cannabinum	Gonzalez et al. (2019)
	Cd, Zn	Kosteletzkyapentacarpos	Zhou et al. (2019)
	Cu, Zn, Cd	Solanum nigrum	Li et al. (2019)
	Cd	Salix sps	Yang et al. (2019a)
Phytovolatilization	Se	Brassica juncea	Banuelos et al. 1997
		Scirpus robustus	Arthur et al. 2005
	As	Polypogonmonspeliensis	Ruppert et al. 2013
Phytodegradation	Cu, Cd, Zn	Populus	Guerra et. al., 2011
Rhizodegradation	Pb	Sesbania cannabina	Maqbool et al. 2012
Rhizofilteration	As	Azolla caroliniana Callitriche lusitanica Callitriche brutia	Favas et al. 2012
	Fe, Cr, Cu, Cd,	Eichhornia crassipes	Rai, 2019

5.2.1 Bioaccumulation

It is the migration of heavy metals from the cell's surfaceinto its cytoplasm (Ramasamy et al. 2007), comprising two steps: adsorption (metal ions becoming adsorbed on the cell surface) and heavy metal entry into the cytoplasm, due to which metallic ions become immobilized within the cytoplasm of the cell, termed as metal sequestration (Mishra and Malik 2013).

5.2.2 Biotransformation

Microbes reclaim the polluted environment by acting as detoxifiers and converting the toxic pollutant into soluble and less toxic forms. Complexation, precipitation, and solubilization of are some examples of metal resistance mechanisms performed by microbes during transformation (Roane et al. 2015). Agrobacterium sp. and Pseudomonasaeruginosaare some identified metal-reducing specieswhich transform the toxic hexavalent chromium (Cr^{+6}) to (Cr^{+3}) (Kamaludeenet al. 2003). Mercury (Hg) has also been reported to be converted from its dangerous form into a harmless form by Hymenoscyphusericae,Neocosmosporavasinfecta, and Verticillium terrestre (Kelly et al. 2006). Aspergillus parasitica and Cephalosporiumaphidicolaalso aggressively remediate lead (Pb) from contaminated sites (Akar et al. 2007).

5.2.3 Biosorption

Some microorganisms release extracellular polymeric substances (EPS) such as polysaccharides, glycoproteins, lipopolysaccharides, and soluble peptides for self-defence under unfavourable conditions (Sedarat and Taylor-Robinson, 2022). Microbial exopolysaccharides (EPS) lead to biofilm formation during heavy metal exposure, which acts as a protective sheath and enables the heavy metal tolerance of microbial cells. Rhizobial EPS (succinoglycan, galactoglucan) can remove Cd, As and Hg by bioabsorption (Gupta and Diwan, 2017). Gemella, Micrococcus, and Hafnia sp. can be used for the bioremediation of Cr, Cd and Pb from tannery effluents (Marzan et al. 2017). Microbial groups with biosorption of different heavy metals are also illustrated further (Table 4).

Table 4: Different microbial groups performing heavy metal biosorption (Ayangbenroand Babalola, 2017)

Heavy Metal	Bacteria	Fungi	Algae
Cd	Bacillus. laterosporus, Bacillus. Licheniformis	Asparagopsis armata	Codium vermilar, Cystoseirabarbata
Cu	Micrococcus luteus,	Aspergillus niger,	Codium

	Desulfovibriodesulfuricans	Phanerochaetechrysosporium	vermilara
Pb	Enterobacter cloacae, Micrococcus luteus	Botrytis cinereal, Asparagopsis armata	Cystoseirabarbata, Spirogyra sp.
As	Sulphate-reducing bacteria	---	---
Ni	Desulfovibriodesulfuricans, Pseudomonas aeruginosa	Asparagopsis armata	Codium vermilara Cystoseirabarbata
Zn	Pseudomonas sp.	Phanerochaetechrysosporium	Codium vermilara
Hg	Bacillus cereus	---	---
Sb	---	---	Sargassum muticum

5.2.4 Biomineralization

It is the natural capacity of microorganisms to bind the metal and create minerals to efficiently collect heavy metal in a stable solid phase, preventing heavy metal from leaching. Microbial cells produce urease enzymes, leading to an increase in pH and encouraging carbonate production, aiding in the mineralization of heavy metal ions (Li et al. 2013). Bacillus sp. KK1 has been identified as Pbbioremediation agent using induced calcite precipitation (Govarthananet al. 2013). SporosarcinaginsengisoliCR5's remove As by generating the urease enzyme throughout the biomineralization process (Achal et al. 2012).

5.2.5 Volatilization

It is the direct release of ionic forms of heavy metals into the atmosphere after turning into a volatile state. For e.g., in mercury-resistant bacteria, the enzyme organomercurial lyase is the product of the mer B gene responsible for the conversion of methyl mercury to mercuric ions, which are further converted into 100-fold less toxic elemental mercury by mercuric reductase, a product of the mer A gene' (Fig 4).Metal-binding peptides, phytochelatin, and metallothein are some examples of chelator molecules used for metal binding. In addition to facilitating microbial uptake and the transit of heavy metals, these chelators bind to ionic forms of metals.

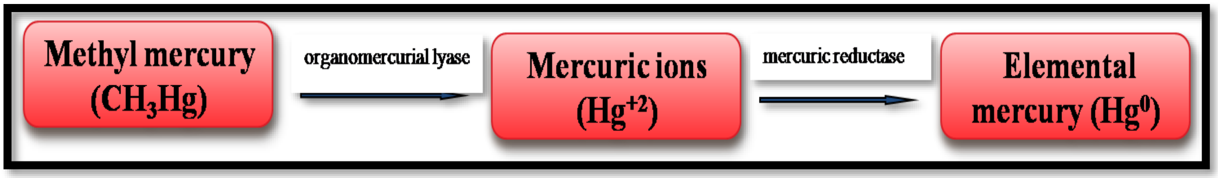


Fig. 4: Conversion of toxic mercury ionic form into less harmful elemental mercury by mercury-resistant bacteria (Krout et al. 2022).

6. Conclusion

Bioremediation is a slow process that takes years to complete. On the other hand, the remediation of polluted soils is also a laborious operation. High quantities of heavy metals may be hazardous to livestock if they eat vegetation growing on remediation sites. The process of bioremediation is intriguing and demonstrates that there is still much to learn about the special skills of microorganisms and plants concerning the mitigation of polluted sites. Researchers are constantly seeking hybrid methods to enhance and use this more successfully. Therefore, to take the necessary measures against extended exposure to them, a thorough awareness of heavy metals is essential.

Conflict of Interest : None

References

- Achal, V, Pan, X, & Zhang, D. (2012). Bioremediation of strontium (Sr) contaminated aquifer quartz sand based on carbonate precipitation induced by Sr resistant Halomonas sp. Chemosphere, 89(6), 764-768.
- AjM, B. (1989). Terrestrial higher plants which hyperaccumulate metallic elements-a review of their distribution, ecology and photochemistry. Biorecovery, 1, 81-126.
- Akar, T, Tunali, S, & Çabuk, A. (2007). Study on the characterization of lead (II) biosorption by fungus Aspergillus parasiticus. Applied biochemistry and biotechnology, 136(3), 389-405.
- Alloway, B. J. (2013). Sources of heavy metals and metalloids in soils. Heavy metals in soils: trace metals and metalloids in soils and their bioavailability, 11-50.
- Andresen, E, Peiter, E, & Küpper, H. (2018). Trace metal metabolism in plants. Journal of Experimental Botany, 69(5), 909-954.
- Aneyo, I. A, Doherty, F. V, Adebesin, O. A, & Hammed, M. O. (2016). Biodegradation of pollutants in waste water from pharmaceutical, textile and

local dye effluent in Lagos, Nigeria. Journal of Health and Pollution, 6(12), 34–42.

- Aqeel, M, Khalid, N, Tufail, A, Ahmad, R. Z, Akhter, M. S, Luqman, M, Javed, M. T, Irshad, M. K, Alamri, S, Hashem, M, & Noman, A. (2021). Elucidating the distinct interactive impact of cadmium and nickel on growth, photosynthesis, metal-homeostasis, and yield responses of mung bean (Vigna radiata L.) varieties. Environmental Science and Pollution Research International, 28(21), 27376–27390.
- Arthur, E. L., Rice, P. J., Rice, P. J., Anderson, T. A., Baladi, S. M., Henderson, K. L., & Coats, J. R. (2005). Phytoremediation—an overview. Critical Reviews in Plant Sciences, 24(2), 109-122.
- Asati, A, Pichhode, M, & Nikhil, K. (2016). Effect of heavy metals on plants: an overview. International Journal of Application or Innovation in Engineering & Management, 5(3), 56-66.
- Ayangbenro, A. S, & Babalola, O. O. (2017). A new strategy for heavy metal polluted environments: a review of microbial biosorbents. International journal of environmental research and public health, 14(1), 94.
- Baker, A.J.M. (1981). Accumulators and excluders - strategies in the response of plants to 634 heavy-metals. Journal of Plant Nutrition 3(1-4).
- Banuelos, G. S, Cardon, G, Mackey, B, Ben-Asher, J, Wu, L, Beuselinck, P. &Zambrzuski, S. (1993). Boron and selenium removal in boron-laden soils by four sprinkler irrigated plant species (Vol. 22, No. 4, pp. 786-792). American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.
- Banuelos, G. S., Ajwa, H. A., Terry, N. O. R. M. A. N., & Zayed, A. (1997). Phytoremediation of selenium laden soils: A new technology. Journal of Soil and Water Conservation, 52(6), 426-430.
- Bishop, P. L. (2000). Pollution prevention: fundamentals and practice. Singapore: McGraw-Hill; ISBN 0-07-366147-3.
- Cervantes, C, Campos-García, J, Devars, S, Gutiérrez-Corona, F, Loza-Tavera, H, Torres-Guzmán, J. C, & Moreno-Sánchez, R. (2001). Interactions of chromium with microorganisms and plants. FEMS Microbiology Reviews, 25(3), 335–347.
- Chen, L, Liu, J, Zhang, W, Zhou, J, Luo, D, & Li, Z. (2021). Uranium (U) source, speciation, uptake, toxicity and bioremediation strategies in soil-plant system: a review. Journal of Hazardous Materials, 413, 125319.
- Chen, P, Culbreth, M, & Aschner, M. (2016). Exposure, epidemiology, and mechanism of the environmental toxicant manganese. Environmental Science and Pollution Research International, 23(14), 13802–13810.

- Chen, X, Dang, Y. X, Li, Q. L, Li, W, Xie, M. T, Wang, M. X, ... & Wu, G. (2023). Uranium affects nitrogen metabolism and endoplasmic reticulum protein homeostasis in plants. Environmental and Experimental Botany, 105444.
- Chen, Z. C, Peng, W. T, Li, J, & Liao, H. (2018, February). Functional dissection and transport mechanism of magnesium in plants. In Seminars in cell & developmental biology (Vol. 74, pp. 142-152). Academic Press.
- Chiroma, T. M, Ebewele, R. O, & Hymore, F. K. (2014). Comparative assessment of heavy metal levels in soil, vegetables and urban grey waste water used for irrigation in Yola and Kano. International refereed journal of engineering and science, 3(2), 01-09.
- Cosio, C., Martinoia, E., & Keller, C. (2004). Hyperaccumulation of cadmium and zinc in Thlaspi caerulescens and Arabidopsis halleri at the leaf cellular level. Plant physiology, 134(2), 716-725.
- de Oliveira Jucoski, G, Cambraia, J, Ribeiro, C, de Oliveira, J. A, de Paula, S. O, & Oliva, M. A. (2013). Impact of iron toxicity on oxidative metabolism in young Eugenia uniflora L. plants. Acta physiologiae plantarum, 35, 1645-1657.
- Favas, P. J, Pratas, J, Varun, M, D'Souza, R, & Paul, M. S. (2014). Phytoremediation of soils contaminated with metals and metalloids at mining areas: potential of native flora. Environmental risk assessment of soil contamination, 3, 485-516.
- Favas, P. J., Pratas, J., & Prasad, M. N. V. (2012). Accumulation of arsenic by aquatic plants in large-scale field conditions: opportunities for phytoremediation and bioindication. Science of the total Environment, 433, 390-397.
- Figlioli, F, Sorrentino, M. C, Memoli, V, Arena, C, Maisto, G, Giordano, S, Capozzi, F, & Spagnuolo, V. (2019). Overall plant responses to Cd and Pb metal stress in maize: Growth pattern, ultrastructure, and photosynthetic activity. Environmental Science and Pollution Research International, 26(2), 1781–1790.
- Freeman et al (2006) Spatial imaging, speciation, and quantification of selenium in the hyperaccumulator plants Astragalus bisulcatus and Stanleya pinnata. Plant Physiology 142: 124-134.
- Furini, A, Manara, A, &DalCorso, G. (2015). Environmental phytoremediation: plants and microorganisms at work. Frontiers in plant science, 6, 520.
- Garbinski, L. D, Rosen, B. P, & Chen, J. (2019). Pathways of arsenic uptake and efflux. Environment international, 126, 585-597.
- Genchi, G, Carocci, A, Lauria, G, Sinicropi, M. S, & Catalano, A. (2020). Nickel: Human health and environmental toxicology. International Journal of Environmental Research and Public Health, 17(3), 679.

- Ghori, N. H, Ghori, T, Hayat, M. Q, Imadi, S. R, Gul, A, Altay, V, & Ozturk, M. (2019). Heavy metal stress and responses in plants. International journal of environmental science and technology, 16, 1807-1828.
- Gil-Loaiza, J, White, S. A, Root, R. A, Solís-Dominguez, F. A, Hammond, C. M, Chorover, J, & Maier, R. M. (2016). Phytostabilization of mine tailings using compost-assisted direct planting: translating greenhouse results to the field. Science of the Total Environment, 565, 451-461.
- González, H., Fernández-Fuego, D., Bertrand, A., & González, A. (2019). Effect of pH and citric acid on the growth, arsenic accumulation, and phytochelatin synthesis in Eupatoriumcannabinum L., a promising plant for phytostabilization. Environmental Science and Pollution Research, 26, 26242-26253.
- Govarthanan, M, Lee, K. J, Cho, M, Kim, J. S, Kamala-Kannan, S, & Oh, B. T. (2013). Significance of autochthonous Bacillus sp. KK1 on biomineralization of lead in mine tailings. Chemosphere, 90(8), 2267-2272.
- Greipsson, S. (2011). Phytoremediation. Nature Education Knowledge, 3(10), 7.
- Gudkov, S. V, Chernikov, A. V, &Bruskov, V. I. (2016). Chemical and radiological toxicity of uranium compounds. Russian Journal of General Chemistry, 86, 1531-1538.
- Guerra, F, Gainza, F, Pérez, R, & Zamudio, F. (2011). Phytoremediation of heavy metals using poplars (Populus spp.): a glimpse of the plant responses to copper, cadmium and zinc stress. Handbook of phytoremediation. Nova Science, New York, 387-413.
- Gupta, P, & Diwan, B. (2017). Bacterial exopolysaccharide mediated heavy metal removal: a review on biosynthesis, mechanism and remediation strategies. Biotechnology Reports, 13, 58-71.
- Hasan, Z, Anwar, Z, Khattak, K. U, Islam, M, Khan, R. U, & Khattak, J. Z. K. (2012). Civic pollution and its effect on water quality of river Toi at district Kohat, NWFP. Research Journal of Environmental and Earth Sciences, 4(3), 334-339.
- Hassan, M. U, Chattha, M. U, Khan, I, Chattha, M. B, Aamer, M, Nawaz, M, ... & Khan, T. A. (2019). Nickel toxicity in plants: reasons, toxic effects, tolerance mechanisms, and remediation possibilities—a review. Environmental Science and Pollution Research, 26, 12673-12688.
- Hernández, A., Loera, N., Contreras, M., Fischer, L., & Sánchez, D. (2019). Comparison Between Lactuca sativa L. and Lolium perenne: Phytoextraction Capacity of Ni, Fe, and Co from Galvanoplastic Industry. In Energy

Technology 2019: Carbon Dioxide Management and Other Technologies (pp. 137-147). Springer International Publishing.

- Hooda, V. (2007). Phytoremediation of toxic metals from soil and waste water. Journal of Environmental Biology, 28(2), 367.
- Hu, H, Zhang, J, Wang, H, Li, R, Pan, F, Wu, J, & Liu, Q. (2013). Effect of silicate supplementation on the alleviation of arsenite toxicity in 93-11 (Oryza sativa L. indica). Environmental Science and Pollution Research, 20, 8579-8589.
- Hu, X, Wei, X, Ling, J, & Chen, J. (2021). Cobalt: an essential micronutrient for plant growth?. Frontiers in plant science, 12, 768523.
- Huber, D. M, & Jones, J. B. (2013). The role of magnesium in plant disease. Plant and soil, 368, 73-85.
- Ibanez, T. B, Santos, L. F. D. M, Lapaz, A. D. M, Ribeiro, I. V, Ribeiro, F. V, Reis, A. R. D, ... & Heinrichs, R. (2020). Sulfur modulates yield and storage proteins in soybean grains. Scientia Agricola, 78.
- Israr, M, Sahi, S, Datta, R, & Sarkar, D. (2006). Bioaccumulation and physiological effects of mercury in Sesbania drummondii. Chemosphere, 65(4), 591-598.
- Jaishankar, M, Tseten, T, Anbalagan, N, Mathew, B. B, &Beeregowda, K. N. (2014). Toxicity, mechanism and health effects of some heavy metals. Interdisciplinary toxicology, 7(2), 60.
- Kacprzak (2014) Efficacy of biosolids in assisted phytostabilization of metalliferous acidic sandy soils with five grass species. International Journal of Phytoremediation. 16:593-608.
- Kafle, A., Timilsina, A., Gautam, A., Adhikari, K., Bhattarai, A., & Aryal, N. (2022). Phytoremediation: Mechanisms, plant selection and enhancement by natural and synthetic agents. Environmental Advances, 8, 100203.
- Kamaludeen, S. P, Megharaj, M, Juhasz, A. L, Sethunathan, N, & Naidu, R. (2003). Chromium-microorganism interactions in soils: remediation implications. Reviews of Environmental Contamination and Toxicology, 93-164.
- Kelly, D. J, Budd, K, & Lefebvre, D. D. (2006). The biotransformation of mercury in pH-stat cultures of microfungi. Botany, 84(2), 254-260.
- Khalid, N., Noman, A., Aqeel, M., Masood, A., & Tufail, A. (2019). Phytoremediation potential of Xanthium strumarium for heavy metals contaminated soils at roadsides. International Journal of Environmental Science and Technology, 16, 2091-2100.
- Kinuthia, G. K, Ngure, V, Beti, D, Lugalia, R, Wangila, A, & Kamau, L. (2020). Levels of heavy metals in wastewater and soil samples from open drainage

channels in Nairobi, Kenya: Community health implication. Scientific Reports, 10(1), 8434.

- Krout, I. N., Scrimale, T., Vorojeikina, D., Boyd, E. S., & Rand, M. D. (2022). Organomercurial lyase (merB)-mediated demethylation decreases bacterial methylmercury resistance in the absence of mercuric reductase (merA). Applied and Environmental Microbiology, 88(6), e00010-22.
- Kumar, V, Suryakant, P, Kumar, S, & Kumar, N. (2016). Effect of chromium toxicity on plants: A review. Agriways, 4(1), 107-120.
- Li, J, Jia, Y, Dong, R, Huang, R, Liu, P, Li, X, & Chen, Z. (2019). Advances in the mechanisms of plant tolerance to manganese toxicity. International Journal of Molecular Sciences, 20(20), 5096.
- Li, M, Cheng, X, & Guo, H. (2013). Heavy metal removal by biomineralization of urease producing bacteria isolated from soil. International Biodeterioration & Biodegradation, 76, 81-85.
- Li, X., Zhang, X., Wang, X., & Cui, Z. (2019). Phytoremediation of multi-metal contaminated mine tailings with Solanum nigrum L. and biochar/attapulgite amendments. Ecotoxicology and Environmental Safety, 180, 517-525.
- Limmer, M, & Burken, J. (2016). Phytovolatilization of organic contaminants. Environmental Science & Technology, 50(13), 6632-6643.
- Lu, M, Liang, Y, Lakshmanan, P, Guan, X, Liu, D, & Chen, X. (2021). Magnesium application reduced heavy metal-associated health risks and improved nutritional quality of field-grown Chinese cabbage. Environmental Pollution, 289, 117881.
- Mahey, S, Kumar, R, Sharma, M, Kumar, V, & Bhardwaj, R. (2020). A critical review on toxicity of cobalt and its bioremediation strategies. SN Applied Sciences, 2(7), 1-12.
- Manzoor, M., Gul, I., Ahmed, I., Zeeshan, M., Hashmi, I., Amin, B. A. Z., Kallerhoff, J., & Arshad, M. (2019). Metal tolerant bacteria enhanced phytoextraction of lead by two accumulator ornamental species. Chemosphere, 227, 561-569.
- Maqbool, F., Wang, Z., Xu, Y., Zhao, J., Gao, D., Zhao, Y. G., Bhatti, Z.A.,& Xing, B. (2012). Rhizodegradation of petroleum hydrocarbons by Sesbania cannabina in bioaugmented soil with free and immobilized consortium. Journal of hazardous materials, 237, 262-269.
- Marzan, L. W, Hossain, M, Mina, S. A, Akter, Y, & Chowdhury, A. M. M. A. (2017). Isolation and biochemical characterization of heavy-metal resistant bacteria from tannery effluent in Chittagong city, Bangladesh: Bioremediation viewpoint. Egyptian Journal of Aquatic Research, 43(1), 65–74.

- Mesjasz-Przybyłowicz, J. O. L. A. N. T. A, Nakonieczny, M. I. R. O. S. Ł. A. W, Migula, P. A. W. E. Ł, Augustyniak, M. A. R. I. A, Tarnawska, M. O. N. I. K. A, Reimold, W. U, Koeberl, C.H.R.I.S.T.I.A.N, Przybyłowicz, W.O.J.C.I.E.C.H, & Głowacka, E. L. Ż. B. I. E. T. A. (2004). Uptake of cadmium, lead nickel and zinc from soil and water solutions by the nickel hyperaccumulator Berkheyacoddii. Acta Biol. Cracoviensia Ser. Bot, 46, 75-85.
- Mir, A. R, Pichtel, J, & Hayat, S. (2021). Copper: uptake, toxicity and tolerance in plants and management of Cu-contaminated soil. Biometals, 34(4), 737-759.
- Mishra A, Malik A (2013) Recent advances in microbial metal bioaccumulation. Crit Rev Environ Sci Technol 43:1162–1222.
- Mukhopadhyay, S, & Maiti, S. K. (2010). Phytoremediation of metal mine waste. Applied Ecology and Environmental Research, 8(3), 207-222.
- Naveed, M, Mustafa, A, Qura-Tul-Ain Azhar, S. Q, Kamran, M, Zahir, Z. A, & Núñez-Delgado, A. (2020). BurkholderiaphytofirmansPsJN and tree twigs derived biochar together retrieved Pb-induced growth, physiological and biochemical disturbances by minimizing its uptake and translocation in mung bean (Vigna radiata L.). Journal of Environmental Management, 257, 109974.
- Ning, Y., Liu, N., Song, Y., Luo, J., & Li, T. (2019). Enhancement of phytoextraction of Pb by compounded activation agent derived from fruit residue. International Journal of Phytoremediation, 21(14), 1449-1456.
- Pacyna, J. M. (2020). Recent advances in mercury research. The Science of the total environment, 738, 139955.
- Patil, G, & Ahmed, I. (2011). Heavy metals contamination assesment of Kanhargaon Dam water near Chhindwara city. Acta Chimica and Pharmaceutica Indica, 1(1), 7-9.
- Patra, M, & Sharma, A. (2000). Mercury toxicity in plants. The Botanical Review, 66, 379-422.
- Patra, M, Bhowmik, N, Bandopadhyay, B, & Sharma, A. (2004). Comparison of mercury, lead and arsenic with respect to genotoxic effects on plant systems and the development of genetic tolerance. Environmental and experimental botany, 52(3), 199-223.
- Pratas, J., Favas, P. J., Paulo, C., Rodrigues, N., & Prasad, M. N. V. (2012). Uranium accumulation by aquatic plants from uranium-contaminated water in Central Portugal. International Journal of phytoremediation, 14(3), 221-234.
- Printz, B, Lutts, S, Hausman, J. F, & Sergeant, K. (2016). Copper trafficking in plants and its implication on cell wall dynamics. Frontiers in plant science, 7, 601.
- Qi, X, Gou, J, Chen, X, Xiao, S, Ali, I, Shang, R, ... & Luo, X. (2021). Application of mixed bacteria-loaded biochar to enhance uranium and cadmium

immobilization in a co-contaminated soil. Journal of Hazardous Materials, 401, 123823.

- Rai, P. K. (2019). Heavy metals/metalloids remediation from wastewater using free floating macrophytes of a natural wetland. Environmental Technology & Innovation, 15, 100393.
- Ramasamy, K, Kamaludeen, & Banu, S. P. (2007). Bioremediation of metals: microbial processes and techniques. Environmental bioremediation technologies, 173-187.
- Rascio, N, & Navari-Izzo, F. (2011). Heavy metal hyperaccumulating plants: how and why do they do it? And what makes them so interesting?. Plant science, 180(2), 169-181.
- Rayu, S, Karpouzas, D. G, & Singh, B. K. (2012). Emerging technologies in bioremediation: constraints and opportunities. Biodegradation, 23(6), 917-926.
- Reeves, R. (2006). "Hyperaccumulation of trace elements by plants," in Phytoremediation of Metal-Contaminated Soils, eds. J.L. Morel, G. Echevarria & N. Goncharova. (Dordrecht: Springer), 25-52.
- Roane, T. M, Pepper, I. L, & Gentry, T. J. (2015). Microorganisms and metal pollutants. In Environmental microbiology (pp. 415-439). Academic Press.
- Ruppert, L., Lin, Z. Q., Dixon, R. P., & Johnson, K. A. (2013). Assessment of solid phase microfiber extraction fibers for the monitoring of volatile organoarsinicals emitted from a plant–soil system. Journal of hazardous materials, 262, 1230-1236.
- Seaward, M. R. D, & Richardson, D. H. S. (1989). Atmospheric sources of metal pollution and effects on vegetation. Heavy metal tolerance in plants: Evolutionary aspects, 75-92.
- Sedarat, Z, & Taylor-Robinson, A. W. (2022). Biofilm formation by pathogenic bacteria: applying a staphylococcus aureus model to appraise potential targets for therapeutic intervention. Pathogens, 11(4), 388.
- Shah, A, Niaz, A, Ullah, N, Rehman, A, Akhlaq, M, Zakir, M, & Suleman Khan, M. (2013). Comparative study of heavy metals in soil and selected medicinal plants. Journal of Chemistry, 2013.
- Sharma, I. (2020). Bioremediation techniques for polluted environment: concept, advantages, limitations, and prospects. In Trace Metals in the Environment-New Approaches and Recent Advances. IntechOpen.
- Song, J, Shen, Q, Wang, L, Qiu, G, Shi, J, Xu, J, ... & Liu, X. (2018). Effects of Cd, Cu, Zn and their combined action on microbial biomass and bacterial community structure. Environmental pollution, 243, 510-518.

- Su, C. (2014). A review on heavy metal contamination in the soil worldwide: Situation, impact and remediation techniques. Environmental Skeptics and Critics, 3(2), 24.
- Tangahu, B. V, Sheikh Abdullah, S. R, Basri, H, Idris, M, Anuar, N, &Mukhlisin, M. (2011). A review on heavy metals (As, Pb, and Hg) uptake by plants through phytoremediation. International Journal of Chemical Engineering, 2011.
- Tchounwou, P. B, Yedjou, C. G, Patlolla, A. K, & Sutton, D. J. (2012). Heavy metal toxicity and the environment. Molecular, clinical and environmental toxicology: volume 3: environmental toxicology, 133-164.
- Timalsina, H, Gyawali, T, Ghimire, S, & Paudel, S. R. (2022). Potential application of enhanced phytoremediation for heavy metals treatment in Nepal. Chemosphere, 306, 135581.
- Tripathi, P, Singh, P. C, Mishra, A, Tripathi, R. D, & Nautiyal, C. S. (2015). Trichoderma inoculation augments grain amino acids and mineral nutrients by modulating arsenic speciation and accumulation in chickpea (Cicer arietinum L.). Ecotoxicology and Environmental Safety, 117, 72-80.
- Van der Ent, A, Baker, A.J.M, Reeves, R.D, Pollard, A.J, and Schat, H. (2013). Hyperaccumulators of metal and metalloid trace elements: Facts and fiction. Plant and Soil 362(1-2), 319-334.
- Wang, H., Shan, X. Q., Wen, B., Zhang, S., & Wang, Z. J. (2004). Responses of antioxidative enzymes to accumulation of copper in a copper hyperaccumulator of Commoelina communis. Archives of Environmental Contamination and Toxicology, 47, 185-192.
- Wei, W, Liu, X, Sun, P, Wang, X, Zhu, H, Hong, M, Mao, Z.W,& Zhao, J. (2014). Simple whole-cell biodetection and bioremediation of heavy metals based on an engineered lead-specific operon. Environmental science & technology, 48(6), 3363-3371.
- White, P. J, & Pongrac, P. (2017). Heavy-metal toxicity in plants. In Plant stress physiology (pp. 300-331). Wallingford UK: Cabi.
- World Health Organization. (1988). Requirements of Vitamin A, Iron, Folate, and Vitamin B12: Report of a Joint FAO/WHO Expert Consultation (No. 23). Food & Agriculture Org.
- World Health Organization. (1996). Trace elements in human nutrition and health. World Health Organization.
- World Health Organization. (2004). Guidelines for drinking-water quality (Vol. 1). World Health Organization.

- Yan, B, & Hou, Y. (2018). Effect of soil magnesium on plants: a review. In IOP Conference Series: Earth and Environmental Science (Vol. 170, p. 022168). IOP Publishing.
- Yang, W., Yang, Y., Ding, Z., Yang, X., Zhao, F., & Zhu, Z. (2019). Uptake and accumulation of cadmium in flooded versus non-flooded Salix genotypes: Implications for phytoremediation. Ecological Engineering, 136, 79-88.
- Yin, L, Ren, A, Wei, M, Wu, L, Zhou, Y, Li, X, & Gao, Y. (2014). Neotyphodiumcoenophialum-infected Tall fescue and its potential application in the phytoremediation of saline soils. International Journal of Phytoremediation, 16(3), 235-246.
- Zhang, Y, Lai, J. L, Ji, X. H, & Luo, X. G. (2020). Unraveling response mechanism of photosynthetic metabolism and respiratory metabolism to uranium-exposure in Vicia faba. Journal of Hazardous Materials, 398, 122997.
- Zhao, X, Sun, Y, Huang, J, Wang, H, & Tang, D. (2020). Effects of soil heavy metal pollution on microbial activities and community diversity in different land use types in mining areas. Environmental Science and Pollution Research, 27, 20215-20226.
- Zhou, M., Ghnaya, T., Dailly, H., Cui, G., Vanpee, B., Han, R., & Lutts, S. (2019). The cytokinin trans-zeatine riboside increased resistance to heavy metals in the halophyte plant species Kosteletzkyapentacarpos in the absence but not in the presence of NaCl. Chemosphere, 233, 954-965.
- Zulfiqar, U, Ayub, A, Hussain, S, Waraich, E. A, El-Esawi, M. A, Ishfaq, M, Ahmad, M, Ali, N, & Maqsood, M. F. (2022). Cadmium toxicity in plants: Recent progress on morpho-physiological effects and remediation strategies. Journal of soil science and plant nutrition, 1-58.