Heavy Metal Stress Management through Phytoremediation in Degraded Ecosystems of India to Mitigate Climate Change Impacts: An Overview

Abstract

Plant stresses are the conditions that adversely affect the growth, development, or productivity of plants/trees and can be caused by various physical, chemical, and biological factors. However, stress caused by the influence of heavy metals has a notable adverse effect on plant growth and productivity. These heavy metal contaminations are responsible for the harmful effects on biotic (plants and associated organisms) and the abiotic (soil, water, and air) environment. If not properly managed, mining activities are considered to be the prime source of heavy metal contamination in the surrounding environment. Phytoremediation may effectively remediate a wide range of heavy metal contaminants in different environments and hence offers an effective, carbon-neutral, and ecologically beneficial method for the removal of hazardous heavy metal contaminants. Phytoremediation enhances the growth and development of plants and nourishes the environment resulting in the ill effects of climate extremes in disturbed areas and hence mitigating the impacts of climate change. Phytoremediation has been widely studied for the remediation of heavy metal stress but it hasn't yet achieved commercial viability in degraded ecosystems of India where it is required the most. Through this review article, we tried to minimize this gap by reviewing some important phytoremediation studies in India which successfully reduced the negative impacts of heavy metals in different degraded ecosystems.

Keywords: climate change, degradation, heavy metals, phytoremediation, stress.

Introduction

Stress can be defined as any conditions that adversely affect the growth, development, or productivity of plants/trees. Plant stress usually reflects some sudden changes in environmental conditions which create unfavourable conditions for the growth and development of the plants (Verma et al., 2013). Stress occurring in plants can be divided into two primary categories namely abiotic stress and biotic stress (Bhandari et al., 2023). Abiotic stress is imposed on plants by either physical or chemical factors of the environment (Yang et al., 2023), while biotic stress exposed to the plants are biological entities like weeds, pathogens, insects, pests, etc. (García-Montelongo et al., 2023, Gull et al., 2019). Despite all other stresses, heavy metal stress is of great importance and has notable adverse effects on plant growth and productivity (Devi and Kumar, 2020). Since the beginning of industrialization, numerous hazardous elements have been introduced into the environment by the extraction of precious metals and minerals (Adnan et al., 2022). Heavy metals have the largest availability in soil (Chen et al., 2023, Li et al., 2022) and aquatic ecosystems (Boum-Nkot et al., 2023) and a relatively smaller proportion in the atmosphere as particulate or vapours (Ulutaş, 2022). Mining is considered the prime source of heavy metal contamination in the surrounding environment and if not properly managed, they produce highly polluting waste metals and minerals along with tailings (Karn et al., 2021). The heavy metal stress exerted on the plants in and around the mining areas directly inhibits their growth and development which decreases the vegetative capacity of such areas leading to land degradation. These land degradations are causing major contributions to climate change as the mining sector in India is distributed over an area of approx. 312645 hectares (Ministry of Mines, GOI - Annual Report 2021-22). This chapter briefly summarizes the heavy metal impacts on plants, studies on their management techniques, and their benefits in mitigating climate change impacts. There have already been various physical and chemical methods of heavy metal remediation but have many drawbacks. As a new technology, the biological approach i.e., phytoremediation for heavy metal remediation is a clean, inexpensive, environment-friendly method and has more advantages than others (Rai et al., 2021).

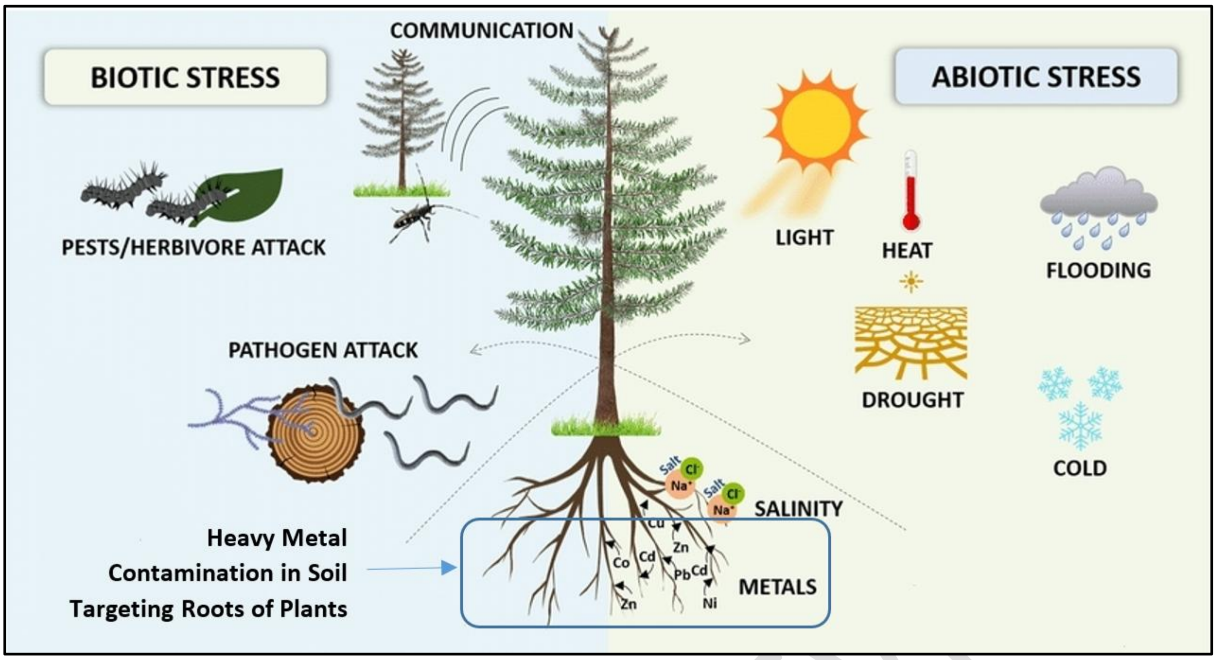

Figure 1. Illustration showing various abiotic and biotic stresses exerted on plants.

Heavy Metal Contamination

Heavy metal term was coined for any metallic element that has a relatively high atomic weight and density, and in the field of biology, heavy metals are referred to the metals that are toxic to organisms even in small amounts (Lenntech Water Treatment and Air Purification, 2004). Heavy metals include lead (Pb), cadmium (Cd), nickel (Ni), cobalt (Co), iron (Fe), zinc (Zn), chromium (Cr), iron (Fe), arsenic (As), silver (Ag) and the platinum group elements and can be categorized into important and toxic heavy metals (Geleta, 2023). Heavy metals cannot be reduced into non-toxic harmless forms completely and they leave an enduring negative impact on the environment and are also carcinogenic, mutagenic, and cytotoxic harming the living organisms that are in contact with it (Rahman et al., 2022, Yan, et al., 2022, Dixit et al., 2015). They also affect the microbial population within the soil which ends up in the loss of species that manages the nutrient cycling resulting in a negative impact on the ecosystem functioning of the soil (Chen et al., 2023, Fashola et al., 2016, Zukauskaite et al., 2008).

Source of Heavy Metals Contamination

Heavy metal contamination comes from different sources and mining (extraction of precious minerals and materials from the crust of the Earth) is considered the major source (Shah et al., 2022, Zerizghi et al., 2022). During mining activities, heavy metals are released from the ores, dumped in the soil, or transported to other areas through air and water (Rashid et al., 2023). Therefore, there is an increased volume of heavy metals within the encircling area of mining sites because of the disposal of waste materials into the environment (Singh et al., 2023). Four heavy metals namely Cd, Pb, As, and Hg based on their occurrence, toxicity level, and exposure to living organisms, are identified as the most toxic metals released from mining among numerous other heavy metals (ATSDR, 2003).

Effects of Heavy Metal Contamination

Effects of Heavy Metal Contamination on Plants

The exposure of plants to toxic levels of heavy metals triggers a wide range of physiological and metabolic alterations (Ahmad et al., 2023, Sharma et al., 2022, Dubey, 2011, Villiers et al., 2011). However, the overall visual toxic response differs between heavy metals as different heavy metals have different sites of action within the plant (Patil and Umadevi, 2014). Effects of heavy metals on plants including leaf chlorosis, necrosis, turgor loss, decreased rate of seed germination, and photosynthetic dysfunction often correlated with result in plant death (Dalcarso et al., 2010). Cellular organelles and components of the cell such as the mitochondria, nuclei, lysosomes, cell membrane, and enzymes are reported to be affected by heavy metals (Collin et al., 2022). Metal ions also interact with DNA and nuclear proteins, thus damaging the DNA. These effects are related to ultra-structural, biochemical, and molecular changes in plant tissues and cells (Riyazuddin et al., 2022, Gamalero et al., 2009). High concentrations of heavy metals in the soil also have adverse effects on micro-organisms (Patil and Faizan, 2017) indirectly affecting the growth and development of the plants too.

Effects of Heavy Metal Contamination on the Environment

Due to their harmful character, environmental chemists have given heavy metals the most attention among all pollutants (Zaynab et al., 2022). According to Triassi et al. 20223, heavy metals are typically present in small quantities in natural watercourses, although many of them are dangerous even at very low concentrations. Metals such as lead, cadmium, mercury, arsenic, nickel, cobalt, zinc, chromium, and selenium are highly toxic even in minor quantities (Geleta, 2023). There is currently more concern about the number of heavy metals in our resources since they are intoxication the environment greater than the environment can handle (Bhat et al., 2023, Zheng et al., 2023). Heavy metals discharged into the environment have been reported to be mostly absorbed by soils and water sources (Gunwal et al., 2021) that enter into the food chain and can cause great damage to the well-being of the living organisms (Sharma et al., 2023, Triassi et al., 2023). A relatively smaller proportion of heavy metals are released into the air and can result in a misbalance of atmospheric composition.

Phytoremediation as Management Technique for Heavy Metal Contamination

The main goal of remediation strategies is to create an ecosystem that is healthy for living organisms and the environment (Saravanan et al., 2022). Various methods of treatment can be practiced to avoid the spread of stress caused by heavy metal contaminants in soils and water bodies (Adnan et al., 2022, Bhat et al., 2022). Removal of heavy metals can be accomplished by physical, chemical, and biological processes and each technique has its benefits and limitations (Yang et al., 2022). However, physical and chemical approaches to heavy metal remediation are of high cost, labour-intensive, cause irreversible alterations in soil properties, chances of production of secondary pollutants, and destruction of soil microflora (Sharma et al., 2023, Ali et al., 2013).

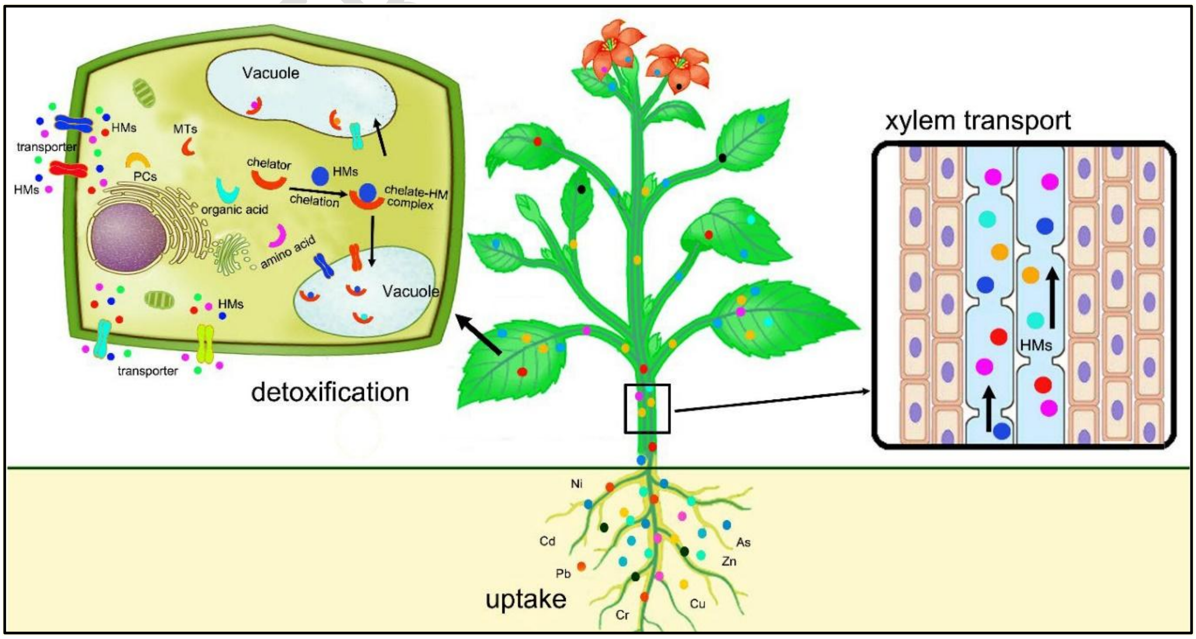

Figure 2. Accumulation of heavy metals in plants as a method of phytoremediation.

On the other hand, bioremediation techniques do not require any expensive equipment or highly-specialized personnel and thus, it is relatively easy to implement. Metal accumulation in plant tissues is decreased by plant-associated microbes and they also help to reduce metal bioavailability in the soil through various mechanisms (Tiwari et al., 2018). It can effectively remediate a wide range of heavy metal contaminants in different environments. Therefore, phytoremediation offers a low-cost, carbon-neutral, permanent, effective, and ecologically beneficial method for the removal of hazardous contaminants in the contaminated environment (Oladoye et al., 2022, Mandal et al., 2014).

Studies on Phytoremediation of Heavy Metals in India

Parihar et al. (2021) explored the bioaccumulation potential of 23 plant species via bioaccumulation factor (BAf), metal accumulation index (MAI), translocation potential (Tf), and comprehensive bioconcentration index (CBCI) for seven heavy metals (cadmium, chromium, cobalt, copper, iron, manganese, and zinc). Although, high bioaccumulation of individual metals was observed in herbs like *C. sativa*, *M. polymorpha,* and *Amaranthus spp*., cumulatively, trees were found to be the better bioaccumulation of heavy metals. Heavy metals Zn, Cu, and Pb were examined by Agarwal et al. (2022) in the thallus body tissue of *Enteromorpha compressa* collected from 10 different sites in the lower Gangetic delta. Pb, followed by Zn and Cu, has the greatest value of all the studied heavy metals' bioaccumulation factors (BAF). Pb's higher BAF is a cause for serious concern because, in comparison to Zn and Cu, it is a more poisonous metal. The application of heavy metals had a substantial impact on the eucalyptus species (*E. tereticornis, E. camaldulensis, E. globulus, and E. citriodora*) because it hindered the growth of seedlings' shoot and root lengths, total dry biomass, and germination percentage (Patil and Umadevi, 2014). In a pot culture experiment conducted by Patil and Faizan (2017), three different concentrations of the metals lead and cadmium were imposed in the rhizosphere and non-rhizosphere soils. As a result of the toxicity of the various metal concentrations, the fungal population was significantly reduced.

By using pot tests, Madanan et al. (2021) investigated the potential of *Tagetes erecta* L. for phytoremediation of lateritic soil contaminated with cadmium (Cd), lead (Pb), and zinc (Zn). The total amount of heavy metals absorbed by the plant increased with increasing heavy metal concentration in the soil. Eight heavy metals (Cu, Mn, Zn, Ni, Fe, Cr, Cd, and Pb) were examined by Kumar et al. (2020) in the rhizosphere accumulation of *Phoenix paludosa* (Roxb.). The main findings demonstrated *Phoenix paludosa*'s phyto-accumulation behaviour for several heavy metals and demonstrated its comparatively higher remediation capability for Cd and Cr contamination. In a pot culture experiment, Shankar et al. (2005) examined the ability of four different tree species—*Tectona grandis, Leucaena luecocephala, Albizia amara*, and *Casuarina equisetifolia*—to accumulate Cr in soils. *Albizia amara* has the potential to absorb Cr pollutants from soil, according to the experimental data. *Salix acmophylla* can be utilized successfully as a tool for biomonitoring of different metal contaminations in soil and water bodies, according to research by Ali et al. (1999). According to the investigations, *S. acmophylla* has a great capacity for phytoremediating metal contamination in soils and water.

To determine the number of heavy metals, present in the water and aquatic macrophytes (*Hydrilla verticillata*, *Salvinia minima*, and *Eichornia crassipes*) gathered from the Polachira wetland in the Kollam district of Kerala, Najila and Anila (2022) conducted research. The findings showed that the mean levels of heavy metals in aquatic macrophytes were in the following order: Fe>Zn>Pb>Cu>Cr>Cd. *Salvinia minima* were shown to be the hyperaccumulator of zinc, copper, lead, and cadmium among the three aquatic macrophytes, while *Hydrilla verticillata* exhibits the hyperaccumulation of iron and chromium, according to their research. The phytoremediation capacity of macrophytes found in the marshes of Assam, India, was investigated by Bora and Sarma (2020). The study claimed that some macrophytes are known to be hyperaccumulators of one or more metals or metalloids and that many native macrophytes are distributed globally, indicating a global interest in the field of phytoremediation research. The potential of water fern (*Azolla pinnata* R.Br.) for phyto-treating Integrated Industrial Effluent (IIE) was examined by Kumar et al. in 2020. The findings of this study indicated that *A. pinnata* was useful for the environmentally friendly treatment of SIIDCUL IIE and might reduce potential wastewater management concerns. According to that, this was the first report on the phytoremediation of IIE.

For the phytoremediation of As, Cd, and Pb-contaminated water bodies, Ghosh (2010) researched a few aquatic plants. His research revealed that *Ipomoea aquatica* is a potential Cd accumulator but a little less prospective As and Pb accumulator. Similar to this, another aquatic species, *Hydrilla verticillata*, has a high potential for phytoremediation of both As and Cd. It is also an efficient accumulator of As and Cd from contaminated water, but it is less effective at doing so for Pb. Adhikari et al. (2010) assessed the potential of *Typha angustifolia* and *Ipomoea carnea*, two kinds of aquatic plants, for phytoextraction of lead. They noticed that both plants are demonstrating promise for removing Pb from contaminated water sources. The phytoremediation capacity of Typha angustifolia against various heavy metals was also examined by Chandra and Yadav (2010). They concluded that under the right circumstances, *T. angustifolia* can actively phytoremediation heavy metals from wastewater.

Maiti et al. (2008) studied five dominant vegetation namely, *Typha latifolia*, *Fimbristylis dichotoma*, *Amaranthus defluxes*, *Saccharum spontaenum*, and *Cynodon dactylon* in West Bengal (India). The study infers that natural vegetation removed Mn by phytoextraction mechanisms ($TF > 1$), while other metals like Zn, Cu, Pb, and Ni were removed by rhizofiltration mechanisms ($TF < 1$). The field study revealed that *T. latifolia* and *S. spontaenum* plants could be used for bioremediation of fly ash lagoon. *Suaeda maritima* and *Salicornia brachiate*, two dominant mangrove associate species, were studied for their phytoremediation potential in the high salinity supralittoral zone of the Indian Sundarbans for the remediation of zinc (Zn), copper (Cu), and lead (Pb). It was suggested that these halophytes could be used as agents of phytoremediation and that their farming would be effective in the ecorestoration in context to conservative pollutants.

Table 1. Suitable plant species for different mining sites in India

Mining Sites	**Suitable Plant Species**
Coal mine spoils of Central India	*Acacia auriculiformis, Acacia nilotica, Dalbergia sissoo, Pongamia pinnata, Eucalyptus hybrid, Eucalyptus camaldulensi, etc.*
Limestone mine spoils of Northern areas	*Acacia catechu, Ipomea carnea, Eulaliopsis binata, Salix tetrasperma, Leucaena leucocephala, Bauhinia retusa, Pennisetum purpureum, Agave americana, Erythrina subersosa, etc.*
Bauxite mine spoils of Central India	*Eucalyptus camaldulensis, Shorea robusta, Grevillea pteridifolia, etc.*
Lignite mine spoils of Tamil Nadu	*Acacia sp., Eucalyptus species, Leucaena leucocephala, and Agave sp.*
Rock-phosphate mine spoils of Uttrakhand	*Acacia catechu, Dalbergia sissoo, Leucaena leucocephela, Pennisetum purpureum, Saccharum spontaneum, Vitex negundo, and Salix tetrasperma etc.*
Iron ore spoils of Orissa	*Albizia lebbeck, Leucaena leucocephala, etc.*
Mica, copper, dolomite, and limestone mine spoils of Rajasthan	*Prosopis juliflora, Salvadora oleiodes, Tamarix articulata, Ziziphus nummularia, Acacia tortilis, Acacia senegal, Acacia catechu, Cynodon dactylon, D. annulatum, Cenchrus setigerus, Cymbopogon sp., etc*

Source: Prasad (2007)

According to Singh et al. (2014), *Vetiveria zizanioides* was able to remove 77–78% of Cr and 80–94% of Pb from synthetic wastewater samples with concentrations of 5–20 mg/L of Cr and Pb, demonstrating the aromatic plant's potential for phytoremediation. The phytoremediation capacity for Cd contaminations of three fragrant types of grass, *Cymbopogan martini*, *Cymbopogonan flexuosus*, and *Vetiveria zizanoides*, was investigated by Lal et al. (2008b). They concluded that *V. zizanoides* can repair Cd-contaminated soils up to a specific degree during their studies.

To explore the hyperaccumulation of heavy metals, Purakayastha et al. (2009) looked at five varieties of mustard: *Brassica juncea* (Indian mustard), *Brassica campestris* (Yellow mustard), *Brassica carinata* (Ethiopian mustard), *Brassica napus*, and *Brassica nigra*. *Brassica carinata* of the cv. DLSC1 variety was shown to reduce the metal load for Pb by 12%, Zn by 15%, and Ni by 11%. Lal et al. (2008a) investigated the phytoremediation capacity of three flower crops in Karnal for Cd-contaminated soils: chrysanthemum (*Chrysanthemum indicum*), marigold (*Tagetes erecta*), and gladiolus (*Gladiolus grandiflorus*). They discovered during their research that *G. grandiflorus* had the highest concentration of Cd and may be able to remediate moderately contaminated soils. Rathore et al. (2019) studied the phytoremediation process for removing toxic metals from soil using metal-accumulating plants like Brassica sp., including Indian mustard (*Brassica juncea*). They discovered that the addition of organic matter, organic chelates, soil amendments, use of suitable cropping systems, intercrops, and fertilizer choice can improve Indian mustard's phytoremediation capacity.

Gna et al. (2008a, 2008b, 2009, 2012a, 2012b) carried out significant research employing xerophytes (such as *Agave angustifolia, Euphorbia milli, Furcraea gigantea*, etc.) and flowering shrubs (aster, tuberose, rose marigold, chrysanthemum, dahlia, gladioulus, etc.). Chrysanthemum phytostabilizes Cd-contaminated soils, but marigold and tuberose can hyper-accumulate in Cd-contaminated soils with moderate to medium degrees of contamination, according to the study. To determine their capacity for Cd phytoextraction, Ghosh and Singh (2005a) compared the high biomass-producing weeds *Dhatura innoxia, Ipomoea carnea,* and *Phragmytes karka* to the indicator species *Brassica campestris* and *Brassica juncea*. According to them, *B. juncea* and *I. carnea* accumulated the most Cd, whereas *P. karka* and *D. innoxia* were the best species for phytoextraction of Cd affected soil.

To grow *H. annuus* plants, Chauhan and Mathur (2020) used industrially polluted soil that was gathered from diverse areas of Jaipur (Rajasthan), Kashipur, Jaspur, and Bajpur (Uttrakhand), India. These industries included plastic, paper, dye, and textile. As evidenced by the reduction in growth characteristics compared to the standard, the results showed that industrial-contaminated soil had a considerable negative impact on the plantlets of *H. annuus*. This information was useful for decontaminating industrial soil that had been severely impacted. Chowdhury et al. (2021) studied the usage of *Avicennia officinalis*, *Porteresia coarctata*, and *Acanthus ilicifolius* for bioaccumulation of potentially toxic elements (Cd, Cr, Cu, Hg, Mn, Ni, Pb, and Zn). Mercury showed the highest but Pb has the lowest bioaccumulation potential in all three plants. Among the toxic trio, Hg showed the highest bioaccumulation in *A. officinalis*, and Cd in *P. coarctata*. For the phytoremediation of As-contaminated soils, Das et al. (2005) found the utilization of weed species including *Lantana camara, Vitis trifolia, Ludwigia parviflora, Eleusine indica, Enhydra*, and *Filmbristylis sp.* They noticed enhanced arsenic accumulation with 2–14 mg As kg-1 in the above-ground sections of these weeds growing in polluted soils, and the weed species has a strong potential to behave as a hyperaccumulator for arsenic.

Phytoremediation for Mitigating Climate Change Impacts

Phytoremediation offers a nature-based solution (NBS) for heavy metal contamination. It is an in-situ technology that requires less energy input than traditional technologies. An important consideration in phytoremediation is the selection of tree species. Local species are usually preferred (Baretha et al., 2022, Pradeep et al., 2023) because they can better adapt to the conditions, and are sometimes required by local regulatory agencies due to concerns over invasive species (David et al, 2019). These species show the best growth in the stressed regions too as they are susceptible to the accumulation of heavy metals without degrading their physiological processes. They capture atmospheric CO_2 and convert it into organic compounds, act as a windbreaker to minimize the transportation of air pollutants, and also improve the micro-climate of the area (Govindaraju et al, 2021). Phytoremediation is the best practice for the development of a sustainable environment and to rejuvenate degraded lands. Thus, mitigating the impacts of climate change.

Limitations of Phytoremediation

According to the current study, phytoremediation can be said as the best technique for the remediation of heavy metal but still suffers the following limitations as a management technique for heavy metal contamination:

1. Due to some hyperaccumulators having a slow growth rate and less production of biomass the efficiency of phytoremediation is less.
2. The process of phytoremediation is time-consuming as the time required for the removal of heavy metal from contaminated soil or water is long.
3. Chances of risk creation in the food chain as mismanagement and improper techniques can lead to contamination of the food chain.
4. Low mobilization effect due to some tightly bound metal ions that act as heavy metals for plants.

Phytoremediation in Interdisciplinary Research Fields

The phytoremediation technique requires knowledge of ecology, plant biology, soil chemistry, microbiology, and environmental engineering. The current state and trajectory in these fields of scientific knowledge integration approach support a successful future resolution of this issue.

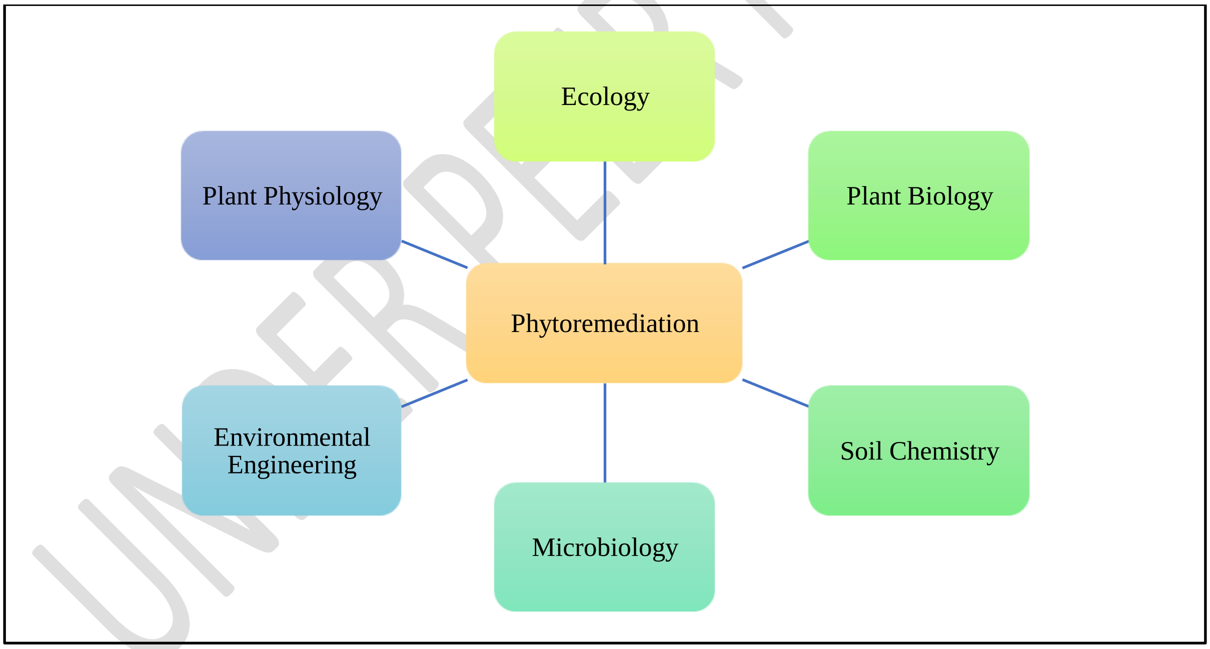

Figure 3. Phytoremediation in interdisciplinary research fields

Conclusion and Future Perspectives

Globally, phytoremediation is still in the evolving stage and the pros and cons of this technology at the field level are not clearly understood (Mandal A et al., 2014). Bioremediation techniques especially phytoremediation is relatively easy to implement and do not require any more expensive equipment or highly-specialized personnel than other techniques. Although phytoremediation successfully reduces the negative impacts of toxic heavy metals, it hasn't yet achieved commercial viability in India. Simultaneously, the quest for hyperaccumulation coding genes for specific heavy metals in plants is constantly progressing for the development of a 'Superbug' plant for phytoremediation (Devi and Kumar, 2020). The strong negative relationships between tree physiology and heavy metals affect tree biomass productivity. The studies show us a pathway for the implementation and management of remediation methods to reduce the heavy metal stress exerted on plants and enhance the metabolic and physiochemical processes of the plant. Reduced heavy metal stress increases the growth and developmental characteristics of plants as well as nourishes the environment resulting in better carbon sequestration ability, restricting land degradation, preventing erosion, purifying the water, and modifying the temperature against the effects of climate extremes in disturbed areas and hence mitigates the impact of climate change.

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