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Evaluating Phytoremediation Approaches for the Restoration of Degraded Ecosystems in India

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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. On the other hand, stress brought on by heavy metal exposure significantly impairs plant development and output. These heavy metal contaminations are responsible for the harmful effects on biotic (plants and associated organisms) and the abiotic (soil, water, and air) environment. Mining operations are thought to be the main cause of heavy metal pollution in the environment if they are not adequately controlled. Phytoremediation provides an efficient, carbon-neutral, and environmentally friendly way to remove dangerous heavy metal contamination from various settings. It can efficiently treat a broad spectrum of heavy metal contaminants. Phytoremediation enhances the development and growth 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. Although phytoremediation has been extensively researched for the treatment of heavy metal stress in India's degraded ecosystems, where it is most needed, it has not yet reached economic viability. Through this article, we tried to minimize this gap by reviewing some important phytoremediation studies in India that successfully reduced the negative impacts of heavy metals in different degraded ecosystems. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) review principles were used to outline the selected studies giving a knowledge that most of the phytoremediation works in India have been performed on Shrubs (28.40%) closely followed by Tree species (26.28%) then in Herbs (17.65%), Grasses (17.25%) and Aquatic Plants (10.43%). Also, the trend has seen a spike after 2018 with most phytoremediation studies in the states of West Bengal. The studies reviewed in this article show us a pathway for implementing and managing remediation methods to reduce the heavy metal stress exerted on plants and enhance the metabolic and physiochemical processes of the plant.

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 unfavorable 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) (Fig. 1). 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). Heavy metal stress is crucial and has a noticeable negative impact on plant development and production despite all other stressors (Devi & Kumar 2020). Since the start of industrialization, the mining of minerals and precious metals has released many harmful compounds into the environment (Adnan et al. 2022a).

Heavy metals have the largest availability in soil (Chen et al. 2023, Li et al. 2022) and aquatic ecosystems (Boum-Nkot et al. 2023, Singh & Bajpai 2023) and a relatively smaller proportion in the atmosphere as particulate or vapors (Ulutaş 2022). The primary cause of heavy metal pollution in the environment is thought to be mining, which also produces very damaging waste metals and tailings if it is not managed effectively. 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. Although there are numerous disadvantages, there have previously been several physical and chemical approaches to heavy metal cleanup. The biological technique, or phytoremediation, is a relatively recent technology that has several benefits over conventional approaches for heavy metal cleanup. It is also cheap, easy to use, and environmentally benign (Rai et al. 2021).

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). It is impossible to fully transform heavy metals into non-toxic, innocuous forms, and they have a lasting detrimental effect on the environment in addition to being carcinogenic, mutagenic, and cytotoxic to living things that come into touch with them (Rahman et al. 2022, Yan et al. 2022, Dixit et al. 2015). They also have an adverse effect on the microbial community in the soil, which leads to the extinction of species that control the cycling of nutrients and impairs the ecosystem's ability to operate (Chen et al. 2023, Fashola et al. 2016, Zukauskaite et al. 2008).

Sources of Heavy Metals Contamination

There are different causes of heavy metal pollution, but mining (the process of removing valuable minerals and materials from the Earth's crust) is thought to be the main one (Shah et al. 2022, Zerizghi et al. 2022) (Fig. 2). Heavy metals are liberated from the ores during mining operations, deposited in the earth, or carried by air and water to other locations (Rashid et al. 2023). As a result, the surrounding region of mining sites has higher concentrations of heavy metals due to the release of waste products into the

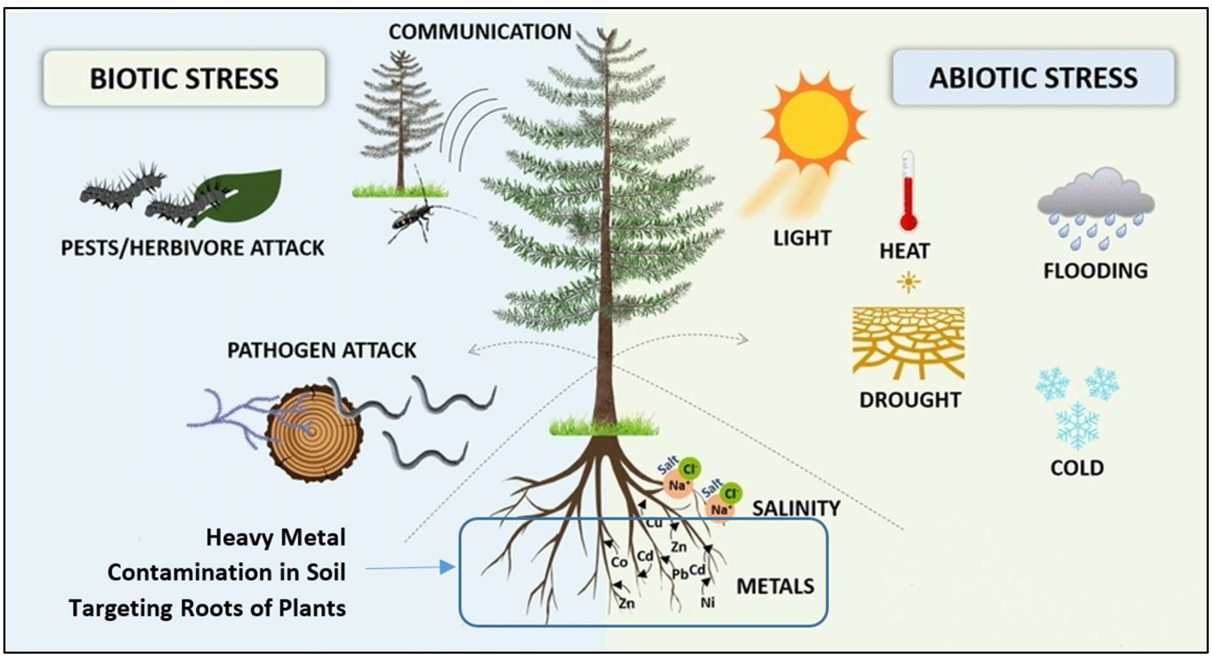

Fig. 1: Various abiotic and biotic stresses exerted on plants in the natural environment.

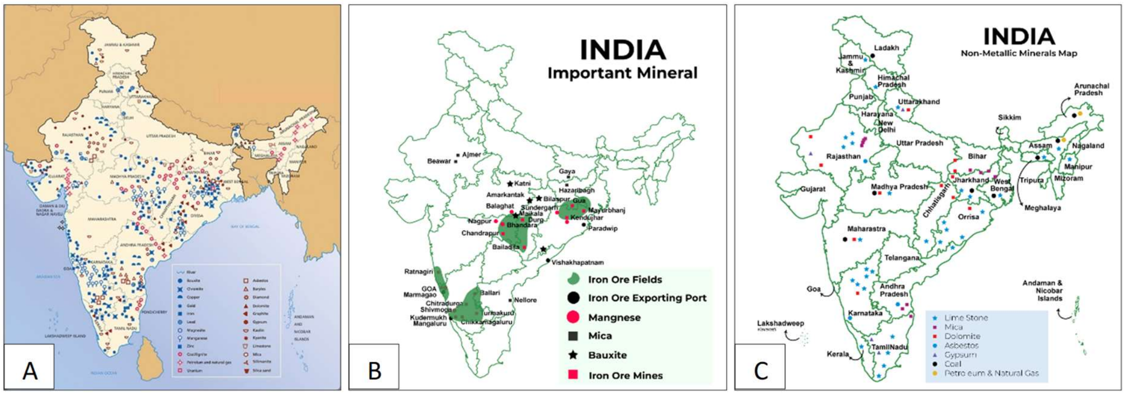

Fig. 2: A. Distribution pattern of various minerals in different regions of India showing the important zones for release of heavy metals in the environment, B. Metallic Minerals, C. Non-Metallic Minerals of India.

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 (US Department of Health and Human Services 2005).

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, Villiers et al. 2011). However, because various heavy metals have diverse sites of action inside plants, the overall hazardous visual reaction varies across them (Patil & Umadevi 2014). Plant mortality is frequently the consequence of heavy metal effects on leaves, which include chlorosis, necrosis, turgor loss, reduced seed germination, and photosynthetic failure (Dalcorso 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 associated with modifications in plant tissues and cells that are ultrastructural, biochemical, and molecular (Riyazuddin et al. 2022, Gamalero et al. 2009). High concentrations of heavy metals in the soil also have adverse effects on microorganisms (Patil & Faizan 2017), indirectly affecting the growth and development of the plants.

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. (2023), 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 intoxicating the environment greater than the environment can handle (Bhat et al. 2023, Zheng et al. 2023). Heavy metals discharged into the environment are reported to be mostly absorbed by soils and water sources (Gunwal et al. 2021), enter into the food chain, and can cause great damage to the well-being of 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 an imbalance of atmospheric composition.

Phytoremediation as Management Technique to Remove Heavy Metal Contamination

The creation of a healthy ecosystem for living things and the environment is the primary objective of remediation techniques (Saravanan et al. 2022). To prevent the spread of stress brought on by heavy metal contamination in soils and water bodies, a variety of remediation techniques can be applied (Adnan et al. 2022b, Bhat et al. 2022). Physical, chemical, and biological methods can be used to remove heavy metals, and each has advantages and disadvantages of its own (Yang et al. 2022) (Fig. 3). However, physical and chemical methods of heavy metal cleanup are expensive, labor-intensive, and result in permanent changes to the characteristics of the soil, as well as an increased risk of secondary pollution creation and the eradication of soil microflora (Sharma et al. 2023, Ali et al. 2013).

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

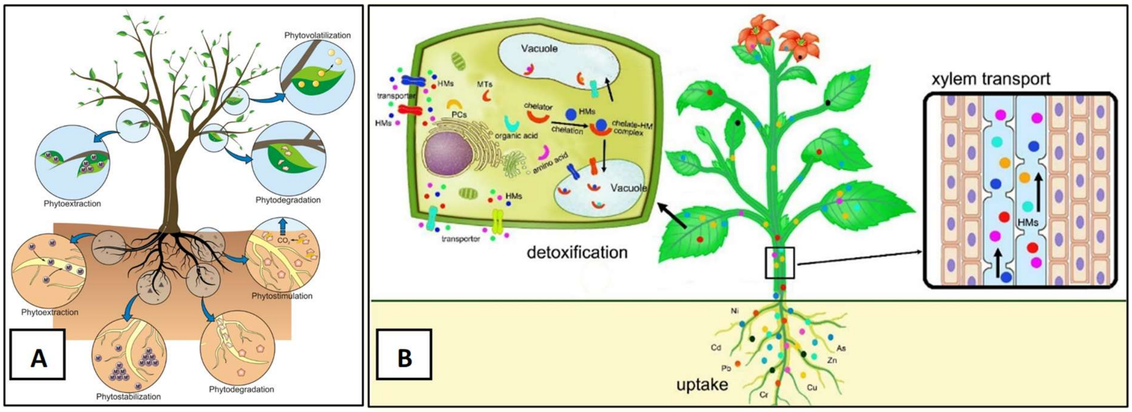

Fig. 3: A. Phytoremediation procedures through which the plant absorbs heavy metals from the soil, accumulates them into different parts, and releases them naturally through leaves; B. Accumulation of heavy metals in plants through phytoremediation.

microbes, and they also help to reduce metal bioavailability in the soil through various mechanisms (Rosyidah et al. 2023, Tiwari & Lata 2018). It can successfully remove a variety of heavy metal pollutants from various settings. Thus, phytoremediation provides an economical, carbon-neutral, long-lasting, efficient, and environmentally friendly way to get rid of dangerous pollutants from contaminated environments (Oladoye et al. 2022, Mandal et al. 2014).

MATERIALS AND METHODS

Information Sources and Literature Search

We conducted an extensive literature search and reviewed different online databases, Google Scholar, Scopus, ResearchGate, etc., for peer-reviewed publications of phytoremediation studies in India published between 1994 and June 2023. We used the following search string/keywords: [(phytoremediation*) OR (bioremediation*) OR (phyto*) OR (heavy metals*) OR (metal accumulation*) OR (degraded land*) OR (phytotoxicity) OR (phytoextraction*) OR (phytodegradation*) OR (phytostimulation*) OR (phytostabilization*)] AND (India). This combination of keywords allowed us to cover publications of phytoremediation research on the degraded lands of India. Additionally, a manual search was performed in the reference list of the review performed by Ghosh and Singh (2005a) since they were one of the first Indian researchers that introduced the term phytoremediation in their article and Mandal et al. (2014) as they provided necessary descriptions on phytoremediation in India till 2014 that is expanded in this review. We took the year 1994 as a starting point, the year when the term was popularized in developing nations of Southeast Asia. In this review, we have only focused on the phytoremediation work performed in India, and therefore, we excluded all the related works done in other countries and subcontinents, except for reviews/research based on secondary data from India.

Screening of Assessed Sources

We outlined the chosen studies in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) review principles (Fig. 4). The search turned up 1275 research and reviews. Based on relevance and subject specialization, we retained 246 articles after screening their titles and abstracts at stage 1. Then, to concentrate on the work done on the subject of phytoremediation, we evaluated the entire texts of 246 possibly pertinent research and omitted 102 articles at stage 2. Only 31 of the 144 relevant studies were kept at the final stage (stage 3) because of its deep information system and used in the analysis (Table 1). The remaining studies were disregarded due to their significant bias risk from underrepresenting the investigated bioremediating species, habitat distribution, or phyto-remediating indicators.

Data Extraction and Compilation

We extracted the following data from the 31 finalized articles: scientific and bioremediating species names, studied heavy metals, study site, publication year, and applications reported for each habitat/site (Table 1). Work done outside India was completely excluded from this review, as the focus was to highlight the applicability of phytoremediation in the Indian subcontinent. The extracted information was compiled in a database and grouped into plant categories based on degraded land type. Additionally, we classified the articles into one or more habitat categories according to the reported uses of plant species for the study. We also georeferenced each locality found in the studies and assigned it to a phytoremediation province based on the

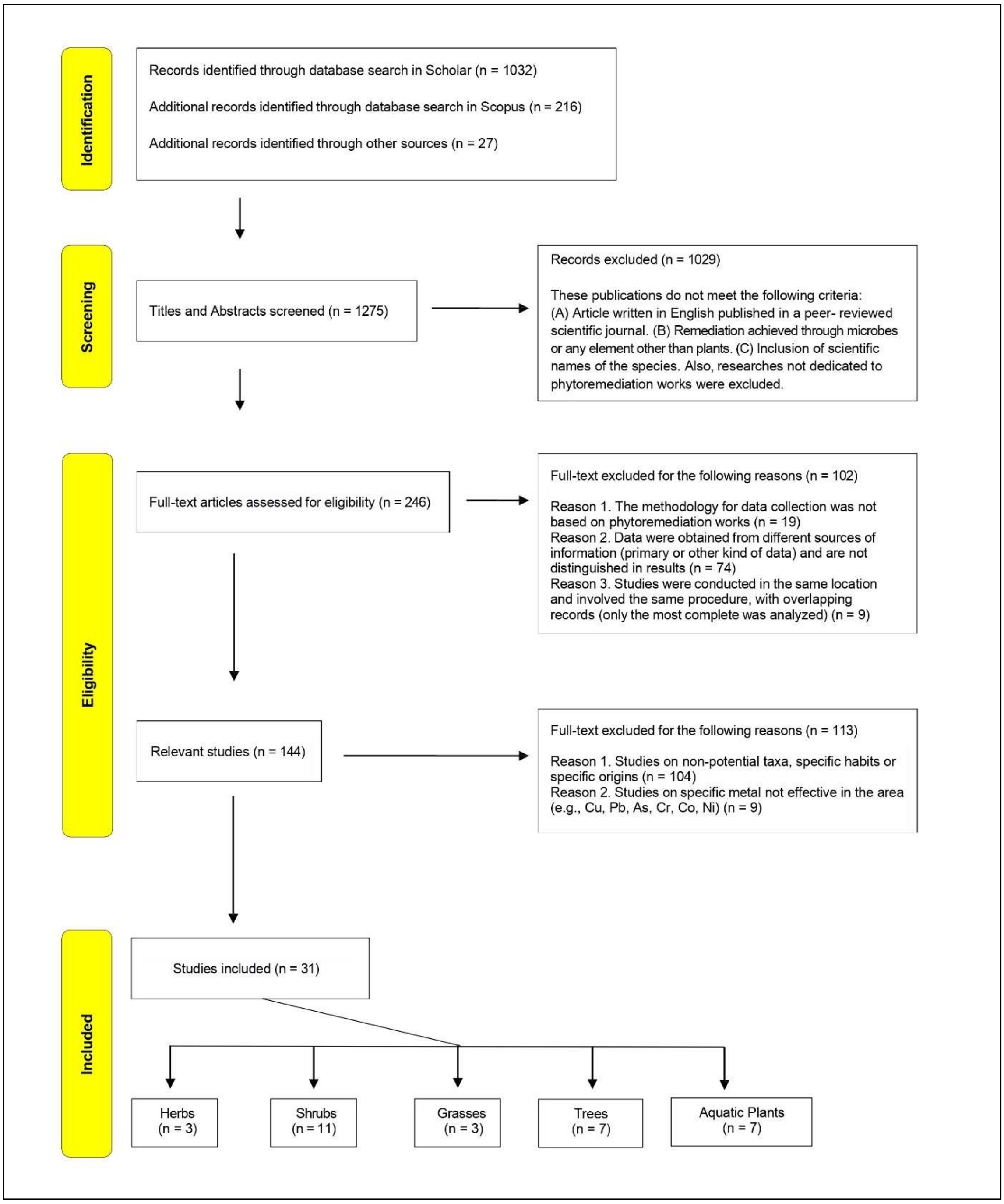

Fig. 4: PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow diagram of the study through the identification and selection process of important phytoremediation works in India.

intensity of phytoremediation works performed in that particular province/state of India. For the analysis of such phytoremediation provinces, we excluded articles in which the use of bioremediating plants was reported for more than one province without distinction between them.

Data Analysis

To evaluate the relationship between the applicability of phytoremediation on different habitat types and provinces in the country to date, we used generalized cluster analysis

Table 1: List of 31 studies included in the systematic review of phytoremediation works in India.

S. No.	Year	Title of the Article	Heavy Metal Studied	Species Studied	Scalability/Limitations
1.	**1999**	Physico-chemical characteristics and pollution level of Lake Nainital (U.P., India): role of macrophytes and phytoplankton in biomonitoring and phytoremediation of toxic metal ions.	**Cr, Cu, Fe, Mn, Ni, Pb and Zn**	*Salix acmophylla*	Applicable for large-scale water bodies with similar heavy metal contamination, but the scalability is limited by the plant's slow growth in colder climates.
2.	**2005**	Phytoremediation: a potential option to mitigate arsenic contamination in the soil-water-plant system.	**As**	*Ludwigia parviflora, Enhydra sp., Eleusine indica, Filmbristylis sp., Ageratum conyzoides, Croton sparsiflorus, Lantana camara, Vitis trifolia, Asteracantha longifolia*	Suitable for diverse contaminated environments, but the scalability is constrained by the weed's relatively low biomass production.
3.	**2005**	Phytoaccumulation of chromium by some multipurpose-tree seedlings.	**Cr**	*Tectona grandis, Leucaena luecocephala, Albizia amara, and Casuarina equisetifolia*	Limited by the long growth period of trees but scalable in afforestation projects.
4.	**2005**	A comparative study of cadmium phytoextraction by accumulator and weed species.	**Cd**	*Brassica campestris, Brassica juncea, Dhatura innoxia, Ipomoea carnea, Phragmytes karka*	It can be applied in agricultural fields with heavy Cd contamination, but biomass production is a limiting factor.
5.	**2007**	Phytoremediation in India.	**All**	*Trees*	Potential for large-scale deployment, but depends on specific plant species.
6.	**2008**	Extraction of cadmium and tolerance of three annual cut flowers on Cd-contaminated soils.	**Cd**	*Gladiolus grandiflorus, Tagetes erecta L and Chrysanthemum indicum L*	Not suitable for large-scale agricultural or industrial applications.
7.	2008	Cadmium uptake and tolerance of three aromatic grasses on the Cd-rich soil.	**Cd**	*Cymbopogan martini, Cymbopogonan flexuosus, and Vetiveria zizanoides*	Scalable for large land areas due to rapid growth and wide adaptability.
8.	**2008**	Bioaccumulation and translocation of metals in the natural vegetation growing on fly ash lagoons: a field study from Santaldih thermal power plant, West Bengal, India.	**Mn, Zn, Cu, Ni, Pb**	*Typha latifolia, Fimbristylis dichotoma, Amaranthus defluxes, Saccharum spontaenum and Cynodon dactylon*	High potential for large industrial sites, but depends on the establishment of wetland systems.
9.	**2008**	Phytoextraction of lead by marigold and chrysanthemum.	**Cd, Pb**	*Gladiolus grandifloras*	Not suitable for large-scale agricultural or industrial applications.
10.	**2008**	Tolerance and bioaccumulation of cadmium and lead by gladiolus.	**Cd**	*Tagetes erecta L and Chrysanthemum indicum L*	Not suitable for large-scale agricultural or industrial applications.
11.	**2009**	Screening of Brassica species for hyper-accumulation of zinc, copper, lead, nickel, and cadmium.	**Pb, Zn, Ni, Cu, Cd**	*Brassica juncea, Brassica campestris, Brassica carinata, Brassica napus, Brassica nigra*	Scalable for large land areas due to rapid growth and wide adaptability.
12.	**2009**	Phytoremediation of cadmium-contaminated soils by marigold and chrysanthemum.	**Pb**	*Tagetes erecta L and Chrysanthemum indicum L*	Not suitable for large-scale agricultural or industrial applications.
13.	**2010**	Phytoaccumulation of lead by selected wetland plant species.	**Pb**	*Typha angustifolia and Ipomoea carnea*	Suitable for deployment in lakes or other water systems, but large-scale application requires further research on biomass management.
14.	**2010**	Potential of Typha angustifolia for phytoremediation of heavy metals from aqueous solution of phenol and melanoidin.	**Cu, Pb, Ni, Fe, Mn, Zn**	*Typha angustifolia*	Suitable for deployment in lakes or other water systems, but large-scale application requires further research on biomass management.

Table Cont....

S. No.	Year	Title of the Article	Heavy Metal Studied	Species Studied	Scalability/Limitations
15.	**2010**	Wetland macrophytes as toxic metal accumulators.	**Cd, As, Pb**	*Hydrilla verticillata, Ipomoea aquatica*	Applicable for large-scale water bodies with similar heavy metal contamination.
16.	**2012**	Phytoremediation of chromium by tuberose.	**Cr**	*Polianthes tuberosa*	Scalable for large land areas due to rapid growth and wide adaptability.
17.	2012	Phytoremediation of cadmium-contaminated soils by tuberose.	**Cd**	*Polianthes tuberosa*	Scalable for large land areas due to rapid growth and wide adaptability.
18.	**2014**	Effect of Lead and Cadmium on the Fungal Population in Rhizosphere Soils of Eucalyptus species.	**Cd, Pb**	*E. tereticornis, E. camaldulensis, E. globulus and E. citriodora*	Potential for large-scale deployment, but depends on specific species variety. Limited by the long growth period of trees.
19.	**2015**	Removal of Lead and Chromium from Synthetic Wastewater Using Vetiveria zizanioides.	**Pb, Cr**	*Vetiveria zizanioides*	Scalable for large land areas due to rapid growth and wide adaptability.
20.	**2017**	Cadmium and lead effect on growth parameters of four Eucalyptus species.	**Cd, Pb**	*E. tereticornis, E. camaldulensis, E. globulus and E. citriodora*	Potential for large-scale deployment, but depends on specific species variety. Limited by the long growth period of trees.
21.	**2017**	Phytoremediation mechanism in Indian mustard (Brassica juncea) and its enhancement through agronomic interventions.	**Pb, Cr, Se, Hg, Ni**	*Brassica juncea*	Scalable for large land areas due to rapid growth and wide adaptability.
22.	**2020**	Phytoremediation of heavy metals/ metalloids by native herbaceous macrophytes of wetlands: Current research and perspectives.	**All**	*Macrophytes*	Applicable for large-scale water bodies with similar heavy metal contamination. Risk of uncontrolled invasion.
23.	**2020**	Phytoremediation efficiency of Helianthus annuus L. for reclamation of heavy metals-contaminated industrial soil.	**Pb, Cd, Zn, Cu, Fe, and As**	*Helianthus annuus L.*	Not suitable for large-scale agricultural or industrial applications.
24.	**2020**	Heavy metal fractions in rhizosphere sediment vis-à-vis accumulation in Phoenix paludosa (Roxb.) mangrove plants at Dhamra Estuary of India: assessing phytoremediation potential.	**Cd, Cu, Cr, Fe, Pb, Mn, Zn**	*Azolla pinnata*	Applicable for large-scale water bodies with similar heavy metal contamination.
25.	**2021**	Bioaccumulation of potentially toxic elements in three mangrove species and human health risk due to their ethnobotanical uses.	**Cd, Cr, Cu, Hg, Mn, Ni, Pb, and Zn**	*Avicennia officinalis, Porteresia coarctata, and Acanthus ilicifolius*	Not suitable for large-scale agricultural or industrial applications.
26.	**2021**	The potential of water fern (Azolla pinnata R. Br.) in phytoremediation of integrated industrial effluent of SIIDCUL, Haridwar, India: removal of physicochemical and heavy metal pollutants.	**Cu, Mn, Zn, Ni, Fe, Cr, Cd, Pb**	*Azolla pinnata R. Br., Phoenix paludosa (Roxb.)*	Applicable for large-scale water bodies with similar heavy metal contamination.
27.	2021	Application of Aztec Marigold (Tagetes erecta L.) for phytoremediation of heavy metal-polluted lateritic soil.	**Cd, Pb, Zn**	*Tagetes erecta L*	Not suitable for large-scale agricultural or industrial applications.
28.	**2021**	Phytoremediation of heavy metals by the dominant mangrove associate species of Indian Sundarbans.	**Zn, Cu, Pb**	*Suaeda maritima and Salicornia brachiata*	Not suitable for large-scale agricultural or industrial applications.

Table Cont....

S. No.	Year	Title of the Article	Heavy Metal Studied	Species Studied	Scalability/Limitations
29.	**2021**	Bioaccumulation potential of indigenous plants for heavy metal phytoremediation in rural areas of Shaheed Bhagat Singh Nagar, Punjab (India).	**Cd, Cr, Co, Cu, Fe, Mn, and Zn**	*Ageratum conyzoides (L.) L., Amaranthus spinosus L., Amaranthus viridis L., Brassica napus L., Cannabis sativa L., Dalbergia sissoo DC., Duranta repens L., Dysphania ambrosioides (L.) Mosyakin & Clemants, Ficus infectoria Roxb., Ficus palmata Forssk., Ficus religiosa L., Ipomoea carnea Jacq., Medicago polymorpha L., Melia azedarach L., Morus indica L., Malva rotundifolia L., Panicum virgatum L., Parthenium hysterophorus L., Dolichos lablab L., Ricinus communis L., Rumex dentatus L., Senna occidentalis (L.) Link, and Solanum nigrum L.*	Potential for large-scale deployment, but depends on specific plant/tree species.
30.	**2022**	Bioaccumulation Factor (BAF) of heavy metals in green seaweed to assess the phytoremediation potential.	**Zn, Cu, Pb**	*Enteromorpha compressa*	Applicable for large-scale water bodies with similar heavy metal contamination.
31.	**2022**	Heavy Metal Absorption and Phytoremediation Capacity of Macrophytes of Polachira Wetland of Kollam District, Kerala, India.	**Zn, Cu, Pb, Fe, Cd, Cr**	*Hydrilla verticillata, Salvinia minima, and Eichornia crassipes*	Applicable for large-scale water bodies with similar heavy metal contamination. Risk of uncontrolled invasion.

Abbreviations: As-Arsenic, Cd-Cadmium, Cr-Chromium, Cu-Copper, Fe-Iron, Hg-Mercury, Mn-Manganese, Ni-Nickel, Pb-Lead, Se-Selenium, Zn-Zinc.

models. Agglomerative hierarchical clustering was done using SPSS software (version 25.0) for classifying the states based on the quantity of work done in them, and vegetation types were enlisted based on their applicability in different habitats as well as provinces/states. The rest of the graphical works and analysis were performed using MS Excel 2021 version.

RESULTS AND DISCUSSION

Current Knowledge of Phytoremediation in India

The amount of article publications in the field of phytoremediation has increased severely from 1994 to 2023, and based on this trend and subject matter importance in the current world scenario, it is predicted to increase more rapidly in the near future, especially till 2030 (due to *Decade on Ecological Restoration*). Based on the current knowledge available in India, most of the phytoremediation works have been performed on Shrubs (28.40%), closely followed by Tree species (26.28%) then Herbs (17.65%), Grasses (17.25%), and Aquatic Plants (10.43%) respectively. Since 2018, the implementation of phytoremediation activities in tree species has gradually increased, possibly due to the introduction of new technologies, which has somewhat overshadowed the drawback of the long rotation period, cost-intensive practices, and low survivability of trees. Other than that, grasses have also shown a boost in the field of phytoremediation as they are one of the pioneer taxa that emerge and contribute to the initial and most important phytoremediation period of degraded land. Studies on the phytoremediation abilities of aquatic plants have also been taken into consideration in recent times to remediate heavy metals from water sources in different states of India (Fig. 5).

Geographical Patterns and Clustering of Priority Areas for Phytoremediation Work in India

The study sites of the articles included in our review were collected throughout all states/union territories of India. Most of the phytoremediation works were confined in the Eastern states like West Bengal (114) and Odisha (103) as these states have very high depository of metallic and non-metallic minerals. The Southern states of Karnataka (78), Kerala (92), and Tamil Nadu (96) also contributed to large phytoremediation works in India as they also have a large depository of minerals under their surface, falling in cluster 5. Similarly, states associated with the Central region of India, including Chhattisgarh (56), Jharkhand (83), Bihar (53), Maharashtra (66), and Madhya Pradesh (72), also have the bulk of articles published in the field of phytoremediation because of availability of more mining industries and release of a larger quantity of heavy metals in the environment confining themselves into cluster 2 and 4. North-eastern states also contribute a small amount of phytoremediation work, mainly on aquatic habitats, i.e., a total of 85 articles distributed among the North Eastern states of India in which the major contributors are Assam and Mizoram falling into

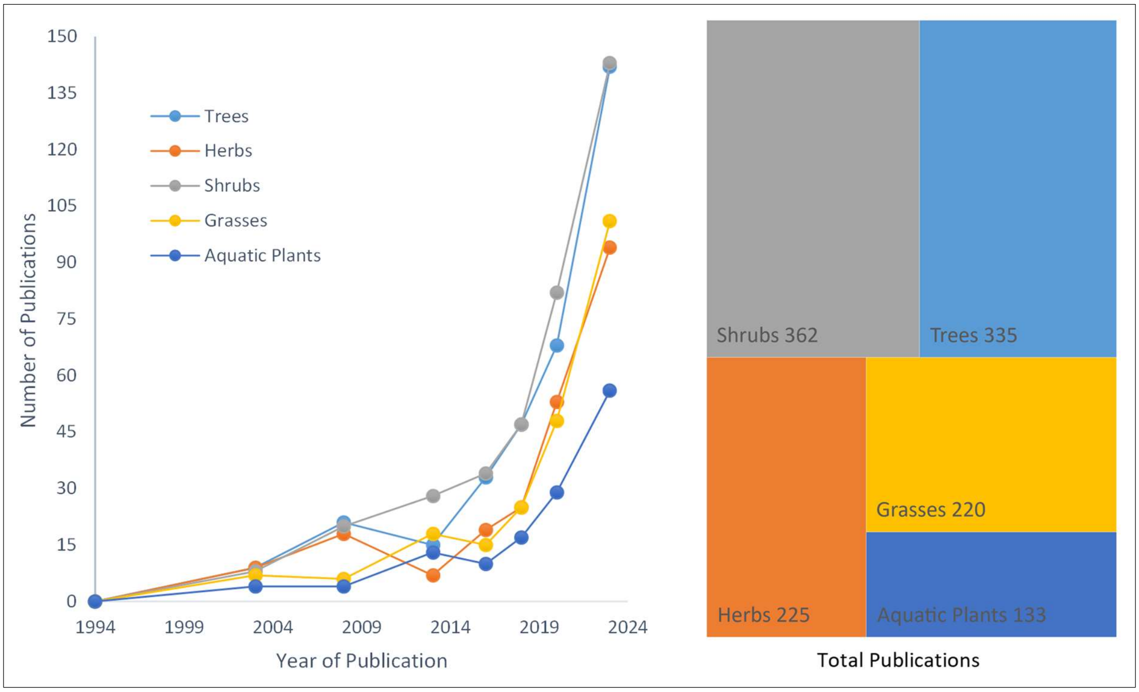

Fig. 5: Identified article publications from 1994 to June 2023 with reference to various plant types and their year-wise usage trend for the phytoremediation of heavy metals in India.

cluster 3 with some of the other North Indian states. The rest of the Indian states/Union territories (14) fall under cluster 1, which indicates the last article publications in such localities either due to low heavy metals availability in the environment or due to low research possibilities (Fig. 6).

Briefing the Important Works 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 & 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. (2021) in the rhizosphere accumulation of *Phoenix paludosa* (Roxb.). The main findings demonstrated *Phoenix paludosa*'s phyto-accumulation behavior for several heavy metals and demonstrated its comparatively higher remediation capability for Cd and Cr contamination. In a pot culture experiment, Shanker 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.

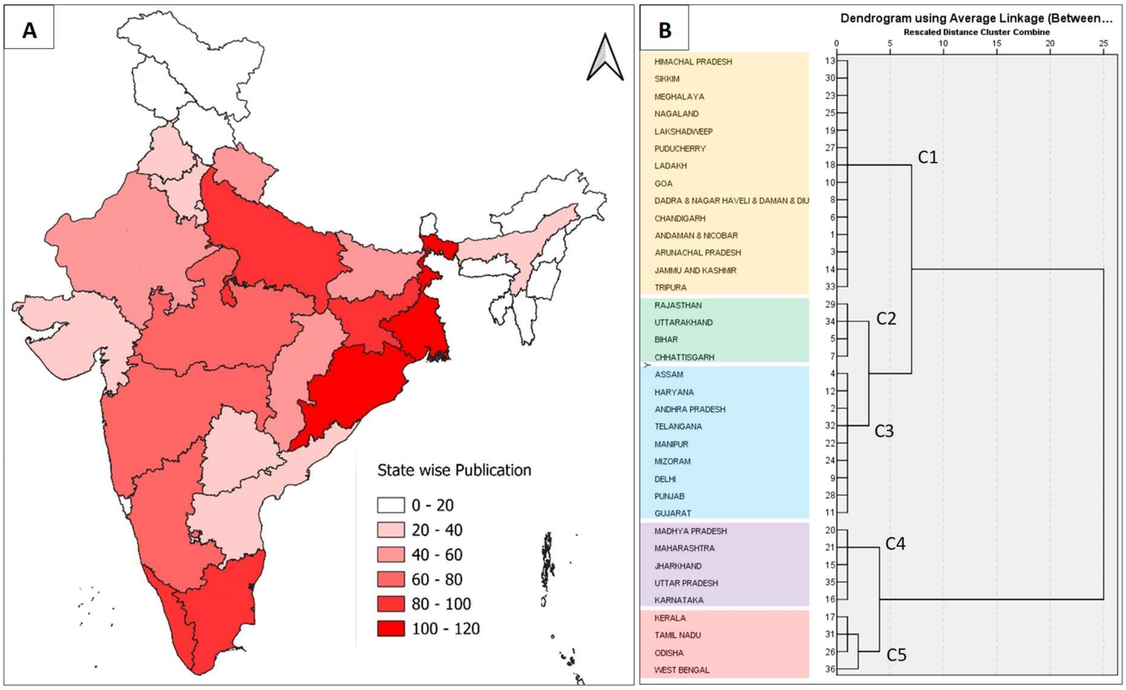

Fig. 6: A. State-wise heat map of India indicating the quantity of phytoremediation works done from 1994-June 2023, B. Hierarchical cluster analysis for classifying the phytoremediation works done in different states to identify the important zones of implementation of phytoremediation works and future possibilities in the zone.

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 phytoremediation 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 & 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 & 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. (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 & Yadav (2010). They concluded that under favorable circumstances, *T. angustifolia* can actively phytoremediation heavy metals from wastewater.

Maiti & Jaiswal (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. Mukherjee et al. (2021), in the high salinity supralittoral zone of the Indian Sundarbans, the phytoremediation capacity of two prominent mangrove association species, *Suaeda maritima* and *Salicornia brachiate*, was investigated for the remediation of zinc (Zn), copper (Cu), and lead (Pb). It was proposed that these halophytes may be employed as phytoremediation agents and that cultivating them would be beneficial for ecorestoration in relation to mild contaminants.

Similarly, Prasad (2007), reviewed various tree species and the type of heavy metals they can remediate based on the mining sites in the Indian subcontinent (Table 2). The study showed:

According to Singh et al. (2015), *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^{-1} 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, Purakavastha 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. (2017) 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.

Ramana 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 & Singh (2005b) 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 & Mathur (2020) used industrially polluted soil that was gathered from diverse areas of Jaipur (Rajasthan), Kashipur, Jaspur, and Bajpur

Table 2: Suitable plant species for different mining sites in India.

Mining Sites	Suitable Plant Species for Restoration
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)

(Uttrakhand), India. These industries included plastic, paper, dye, and textiles. 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 these three heavy metals, 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.

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. Phytoremediation is indeed a topic that intersects with various interdisciplinary research fields due to its potential to address environmental pollution. Phytoremediation's interdisciplinary nature allows researchers from various fields to collaborate and develop innovative solutions for addressing environmental pollution challenges (Fig. 7). Here are some of the interdisciplinary aspects of phytoremediation:

1. **Ecology:** Phytoremediation can impact local ecosystems.

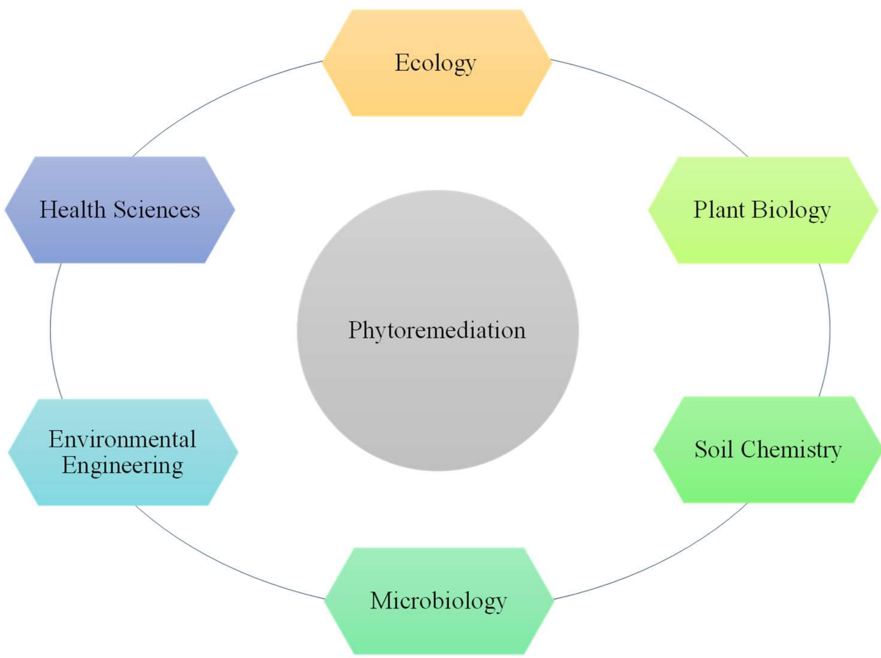

Fig. 7: Phytoremediation in interdisciplinary research fields allows researchers from various fields to collaborate and develop innovative solutions.

Ecologists study the ecological effects of introducing specific plant species for remediation and their interactions with local flora and fauna.

2. **Plant Biology:** Understanding the biology of plants, their physiological responses to contaminants, and their genetic traits for tolerance or accumulation of pollutants is crucial in phytoremediation research.
3. **Soil Chemistry:** Soil composition and chemistry play a significant role in phytoremediation. Soil scientists investigate how plants interact with soil properties and how these interactions affect pollutant removal.
4. **Microbiology:** Genetic modification of plants for enhanced pollutant tolerance or accumulation is an area of ongoing research. Biotechnologists work on developing engineered plants for more effective phytoremediation.
5. **Environmental Engineering:** Engineers design and implement phytoremediation systems, such as constructed wetlands or phytoextraction setups, to maximize pollutant removal.
6. **Health Sciences:** Some pollutants may pose health risks to humans and animals. Researchers in health sciences assess the impact of phytoremediation on reducing these risks.

CONCLUSIONS AND FUTURE PERSPECTIVES

Phytoremediation is yet in its infancy on a global scale, and its advantages and disadvantages in practical applications are still unclear. Compared to other treatments, bioremediation procedures, particularly phytoremediation, are generally simple to apply and don't require expensive equipment or highly skilled workers. Despite effectively lessening the harmful effects of heavy metals, phytoremediation is still not commercially viable in India. In parallel, efforts to find hyperaccumulation coding genes for certain heavy metals in plants are ongoing to create a "Superbug" plant that may be used in phytoremediation. Tree biomass production is impacted by the significant negative correlations that exist between heavy metals and tree physiology. The studies showed 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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