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Marine Plant-Based Phytoremediation of Heavy Metal Contamination: Insights from Scientometric Trends

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Abstract

Traditional remediation processes are resource-intensive and disruptive, whereas phytoremediation presents an environmentally better approach. Nonetheless, its scalability, efficiency, and species-specific potential in the marine ecosystem are being investigated. Utilizing Scientometric applications like VOSviewer, Scopus / WoS / PubMed databases, we analyze 651 articles (2016-2025) to visualize research development, network collaboration between countries and authors, and upcoming technologies such as genetic engineering and microbiome-associated phytoremediation. Hyperaccumulator plants are promising but inefficient, depending on the heavy metals and environmental conditions. Advances in CRISPR-edited plants optimization are driving progress. Asia dominates publication, but field-scale applications are lagging. Phytoremediation's potential for marine heavy metal cleanup is considerable, but it needs integration, policy support, and pilot-scale trials. Future research should focus on transgenic approaches, multi-metal resistance, and economic feasibility for global applicability.

Keywords: Heavy metal, phytoremediation, marine, bioremediation, phytoextraction

Introduction

Heavy metals are metallic elements with high atomic weight and high density. In general, some heavy metals are extremely toxic and lethal, even at low concentrations. Heavy metal pollution releases harmful components into the environment (1). Various modes of entry of heavy metals into the environment, *viz*., mining, smelting, foundries, untreated sewage sludge, traffic, combustion by-products from coal mining, and other industrial activities. Marine heavy metal pollution refers to the contamination of marine water with higher concentrations of heavy metals like lead, mercury, cadmium, arsenic, and copper (2). These heavy metals are posing a serious threat to living things in aquatic ecosystems and human health when people consume seafood. As heavy metals are non-biodegradable, they tend to accumulate in organisms throughout the food chain, reaching higher levels in predators that consume contaminated prey (3). Monitoring these marine ecosystems for the level of heavy metals is crucial, and reduction plans should include stricter regulations on industrial waste disposal and wastewater, as well as measures to reduce pollution from other water sources (4). Phytoremediation is a method that uses plants to fix environmental pollution. In the marine ecosystem, phytoremediation is used to absorb and accumulate pollutants like heavy metals, nutrients, and other contamination from that particular water source (5). In some cases, the plants break down the complex pollutants into simpler and less harmful substances, which is known as phytodegradation (6). Bioaugmentation is the introduction of microorganisms into the contaminated environment to enhance their bioremediation capabilities and shows

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promise in treating heavy metal pollution in marine ecosystems (7, 8). By adding microorganisms that can tolerate and even transform heavy metals, bioaugmentation can accelerate the natural degradation processes and reduce the toxicity of these pollutants (9).

Phytoremediation as a sustainable method

Several techniques have been developed to remove heavy metals from water sources, including physical, chemical, and biological processes. Even after the initial treatment, there is a need for subsequent advanced treatment techniques to bring heavy metal pollution to a safer level (10). Certain examples of physical treatment methods are adsorption, ion exchange, and membrane technology (11, 12). Chemical methods such as electrokinetic, chemical precipitation, and chemical oxidation, as well as approaches like biochar and phytoremediation in biological processes (13). Phytoremediation is considered a low-cost process as it primarily depends on plants to absorb and remove pollutants naturally (14). It also requires minimal infrastructure, and operational costs are also low compared to traditional methods of wastewater treatment. Phytoremediation is an environmentally friendly technique with long-term potential for use (15). The dual benefits of the phytoremediation method include pollutant removal and ecosystem restoration, such as habitat creation, carbon sequestration, environmental detoxification, and enhancement of native species diversity (16). There are 4 types of phytoremediation techniques generally used to treat heavy metals in all kinds of environments, which are as follows: (a) Phytoextraction, (b) Phytostabilization, (c) Rhizofiltration, and (d) Phytovolatilization (17).

Factors affecting phytoremediation

The plants, algae, bacterial types, root region, environmental conditions, root composition, and elemental species, as well as the soil physico-chemical and biological properties, all have an effect on the heavy metals bioaccumulation and distribution in plants (18). To improve the remediation, agricultural practices have been introduced. The pH of soil, organic matter, and phosphorus content are also important factors to consider (19). To minimize the absorption of pH by plants, the soil pH can be changed with the help of lime to 6.5 to 7.0 (20).

Adaptations of phytoremediation strategies in heavy metal

For this subtopic, the example chosen is the Sundarbans, located in the Bay of Bengal delta. This is more prone to the accumulation of inorganic toxic pollutants and also heavy metals (21). The heavy metal uptake by the mangrove roots occurs through passive diffusion across cell plasma membranes or sometimes through active transport, where metal ion transporters are influenced by concentration potential gradients (22). Mangrove utilizes different types of phytoremediation strategies like phytoextraction, phytostabilization, and physicochemical to avoid the uptake of heavy metals and toxic pollutants (23). Antioxidant response in mangroves depends upon the heavy metal concentration and its exposure duration (24). For the phytoremediation strategies in Mangrove processes, the usage of natural or genetically modified plants for their capability to accumulate, degrade, and eliminate heavy metals (25). Mangrove species like *Avicennia marina* and *Rhizophora mucronate* play a vital role in stabilizing sediments, reducing contamination through Rhizofiltration and phytostabilization, and improving water quality (26).

Bioaccumulation: It is a process where an organism absorbs a substance faster than it can be eliminated, leading to a build-up of the substance within its tissues over time. The bioaccumulation of elements in living organisms is vitally important from at least two points of view: the growth and development of the organisms themselves and the remediation of the polluted environment (27).

Bioaugmentation: It is the process of adding microorganisms to a contaminated environment to enhance the breakdown of

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pollutants. A promising long-term and sustainable solution to the growing scarcity of water worldwide is to recycle and reuse wastewater and marine water (28) (Tables 1 and 2).

Biosorption: It is the process where biological materials, or biomass, accumulate and bind pollutants, such as heavy metals, from a solution. This technique is considered to be low-cost and environmentally friendly, and it can be used to remove pollutants from aqueous solutions (29).

Phytoextraction: It is the process of using plants to remove contaminants, particularly heavy metals, from soil or water (30). It possesses considerable advantages over traditional techniques, especially due to its cost-effectiveness, potential treatment of multiple heavy metals simultaneously, and no need for excavation of the contaminated place (31).

Rhizofiltration: It is a type of phytoremediation that uses plant roots to remove pollutants from contaminated water. The rhizofiltration method that adsorbs, concentrates, and precipitates contaminants in or on a plant's rhizosphere is introduced (32).

Rhizo-degradation: It is the process where plants and their associated microorganisms break down pollutants in the soil and water, particularly within the rhizosphere. The plant takes up pollutants through the root systems, which can be further supported by endophytic microorganisms (33).

Phyto stabilization: It is a bioremediation technique that uses plants to stabilize and contain contaminants in soil, primarily by reducing their mobility and bioavailability. It focuses on immobilizing contaminants within the rhizosphere rather than removing them from the site (34).

Bibliometric Analysis

Bibliometric analysis is a statistical method of analyzing the data of book chapters, articles, reviews, and editorial papers. It's used to understand the trends, characteristics, and research status in that particular field. The purpose of this study method is to explore the structure, understand the evolution, sometimes assess the citation as an impact, and finally, to shed light on the emerging topics in a particular field.

The article collection related to the keyword-based search was performed. The keywords selected for the particular topic are "phytoremediation AND heavy metal AND marine", followed by the collection of relevant data from distinct databases such as Web of Science, PubMed, and Scopus. The search duration was fixed from 2016-2025, and Scopus data as .CSV file, PubMed data as a PubMed file, and Web of Science data as plain text (.txt) formats, respectively (Dated as 04-03-2025). The result of the search indicated that in SCOPUS, overall, 67 documents were found, whereas in Web of Science, there were 281 documents, and in PubMed, there were overall of 303 documents (Fig. 1).

The result of the data was analysed bibliometrically in VOSviewer and RStudio. VOSviewer 1.6.20 version, RStudio, and R 4.4.3 version were downloaded with all supporting tools suggested by Aria and Cuccurullo (2017). The following packages from the R bibliometrix were installed. The information regarding "co-occurrence, co-authorship, bibliographic analysis, document types, annual scientific production, tree map, countries' scientific production, and factorial analysis" was generated from the above-mentioned Biblioshiny package (52).

Results

This part of the paper explains how the searched database is distributed under various categories to understand the topic better. All the results presented in this section are obtained from Web of Science, Scopus, and PubMed, filtered, and run through VOSviewer and RStudio for Bibliometric analysis.

Publication Types

The scholarly output is dominated by original research articles, which make up 72%

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Table 1: Different types of marine organisms used for heavy metal removal in marine ecosystems

Marine organism	Heavy metal	Chemical used	Mechanism of action	How is heavy metal removed	Ref.
Brown algae (*Fucus vesiculosus*)	Copper Lead Zinc Cadmium	Phenolic acid	Chelation	Phenolic acid binds to the heavy metals on the surface and isolates them in the tissue.	(35)
Green algae (*Ulva Lactuca*)	Lead Mercury Cadmium Copper	Phytochelatins	Bioaccumulation	Phytochelatins bind to the heavy metals and store them in the vacuole.	(36)
Red algae (*Porphyra spp.*)	Chromium Copper Zinc Lead	Polysaccharides	Adsorption	Polysaccharides on the surface bind to the heavy metal and immobilize it.	(37)
Diatoms (*Navicula spp.*)	Arsenic Lead Mercury Cadmium	Organic Acids	Bioaccumulation	Heavy metals are absorbed by the diatoms and accumulated in the silica of the cell.	(38)
Cyanobacteria (*Anabaena spp.*)	Copper Cadmium Arsenic Lead	Amino Acids	Adsorption	Amino acids bind to the heavy metal and remove it from water through adsorption.	(39)
Microalgae (*Chlamydomonas reinhardtii*)	Zinc Copper Nickel Cadmium	Glutathione	Chelation	Heavy metal ions are isolated in the cell. The vacuole suppresses their bioavailability.	(40)
Sargassum fusiforme (Hikiji seaweed)	Lead Manganese	Sulfated polysaccharides	Ion exchange	Biosorption through surface binding of metal ions to cell wall components.	(41)
Enteromorpha prolifera (*Ulva Prolifera*)	Lead Manganese	Polysaccharides	Biosorption	Adsorption of metal ions onto the cell wall.	
Sargassum vulgaris (Brown seaweed)	Chromium	Alginic acid	Phytofiltration	Accumulation and uptake of metals within plants and removal through harvest	(42)
Azolla pinnata	Lead Chromium	Symbiotic bacteria	Bioaccumulation	Accumulation of metals within plants and removal through harvest	(43)
Chlorella vulgaris	Cadmium Lead	Polysaccharides	Biosorption	Adsorption of metal ions onto the cell wall	(44)
Fucus vesiculosus	Copper Cadmium	Alignates	Biosorption via a functional group	Binding of metal ions to the cell wall.	(45)

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Dunaliella salina	Zinc Cobalt Cadmium Copper	Polysaccharides	Bioaccumulation	Uptake and accumulation of metals within algal cells	(46)
Phormidium	Zinc Cadmium Lead Copper Nickel	Cell wall	Bioaccumulation	Uptake and accumulation of metals within cells	
Zostera marina (eelgrass)	Lead Mercury Arsenic	Natural uptake	Rhizofiltration	roots and rhizomes bind and accumulate metals from sediments. Accumulation in below-ground tissues	(47)
Halimeda opuntia (calcareous algae)	Cadmium Lead Zinc	None	Adsorption	Adsorption on calcium carbonate surface; partial intracellular accumulation	(48)
Mytilus edulis (blue mussel)	Mercury	Metallothionein proteins	Proteins	Intracellular binding by cysteine-rich peptides. Accumulation and immobilization inside tissues	(49)
Pseudomonas aeruginosa (marine bacteria)	Chromium	Biosurfactants	Redox reaction	converts Cr^{6+} to less toxic Cr^{3+}, then adsorbed by cell surfaces. Bio-reduction followed by biosorption	(50)
Marinobacter hydrocarbonoclasticus	Arsenic	Competitive inhibition	Phosphate	Competitive inhibition of arsenate uptake. Replacement of arsenate with phosphate and removal via microbial transformation	(51)

Table 2: Different types of marine organisms used for heavy metal removal in mangrove ecosystems

Organism Used	Heavy metal	Mechanism of action	How is heavy metal removed	Ref.
Rhizophora mucronata	Lead Cadmium Zinc	Phytoextraction	Absorb toxins through roots and store them in tissues.	(53)
Avicennia marina	Lead Zinc Cadmium Copper	Rhizofiltration	Uptake through pneumatophores and roots	(54)
Sonneratia alba	Lead	Rhizodegradation	Stimulates microbial degradation via root exudates	(55)
Bruguiera gymnorhiza	Chromium Nickel Cadmium	Phytoextraction	Accumulate in roots and stem tissues.	(56)
Kandelia candel	Arsenic Mercury Cadmium	Rhizofiltration	Roots uptake, limited translocation to shoots.	(57)

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Laguncularia racemosa	Copper Zinc Lead	Phytostabilization	Binds heavy metal in root zones	(58)
Excoecaria agallocha	Cadmium, Lead	Phytoextraction	Accumulates metals in roots and bark	(59)

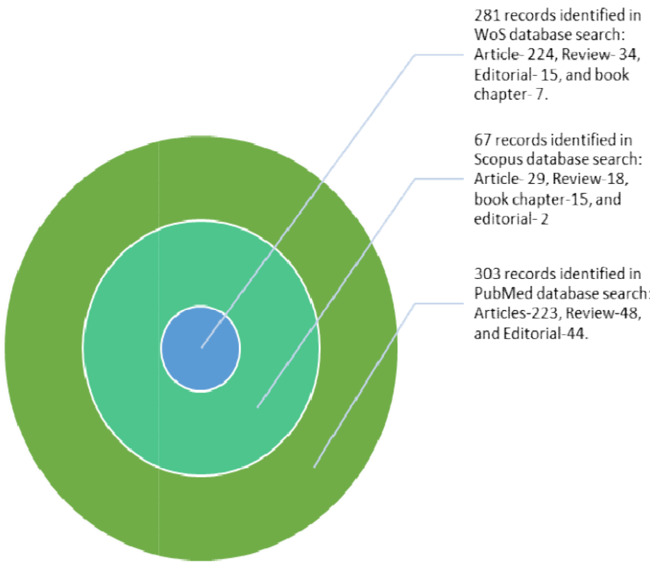

Fig. 1: Data collection from SCOPUS, WoS, and PubMed database

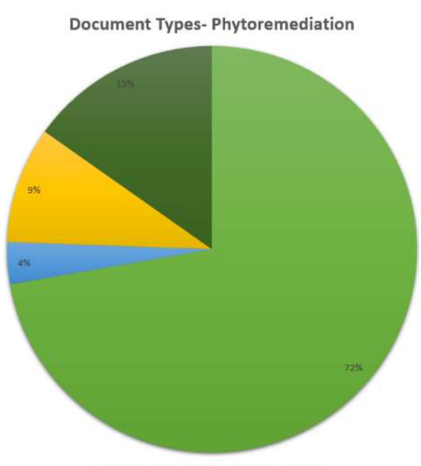

Fig. 2: Document Type

of all publications, according to an analysis of the publication types in the chosen dataset (Fig. 2).

This high percentage emphasizes how important it is to share new experimental results and case studies in the field. 15% are review articles, which represent attempts to compile and assess the body of existing literature. Contributions intended to discuss current issues, viewpoints, or policy-related topics make up 9% of editorials. Lastly, book chapters only make up 4%, indicating that they are not widely distributed through edited volumes or more comprehensive thematic compilations.

Annual Scientific Production

From 2016 to 2025, Fig. 3 illustrates the yearly publication trends for the chosen research topic in the top three scientific databases, including WoS, PubMed, and Scopus. Research activity keeps increasing gradually, especially in PubMed, which has seen a sharp increase from 13 publications in 2016 to a peak of 48 in 2024, suggesting that

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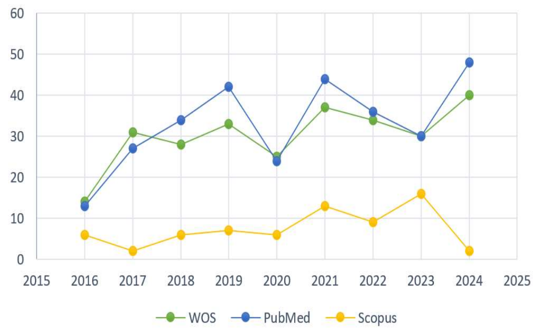

Fig. 3: Annual scientific production from exported data

interest in the topic is growing. Likewise, WoS exhibits a consistent upward trend, peaking at 40 publications in 2024, which reflects the platform's wider multidisciplinary scope.

On the other hand, Scopus displays comparatively lower publication volumes throughout the time frame, with a modest fluctuation and a peak of 16 publications in 2023. The database's selective indexing or coverage of subject areas could be the cause of this difference. Overall, the data shows a significant rise in research outputs over time, especially in PubMed and WOS, indicating that the topic has received more scientific attention and is becoming more relevant in recent years.

Co-occurrence of keywords

VOSviewer yielded a total of 10523 such keywords. The co-occurrence among these keywords was analyzed, and the analysis is as follows:

The keyword co-occurrence network image representations depicted above reflect the interdisciplinary and networked nature of phytoremediation, heavy metal pollution, and related environmental research.

In Fig. 4 (a), principal terms such as heavy metal, phytoremediation, bioremediation, bioaccumulation, and marine pollution are central nodes, suggesting that these are the key issues in the literature. They are surrounded by a wide range of related concepts, including soil, plant, and cosystem, as well as various metals such as lead, zinc, and cadmium, reflecting the interdisciplinary nature of research that spans environmental toxicology, plant biology, and microbial interactions. Fig. 4(b) further refines this structure, with keywords grouped into smaller thematic clusters. The keyword "phytoremediation" is strongly clustered, co-occurring with cadmium, zinc, accumulation, and tolerance, suggesting a research focus on plant processes related to metal uptake and stress tolerance. Fig. 4(c) illustrates the relationships between pollution, sediment, and surface sediments, with an emphasis on pollution sources. In contrast, biosorption, removal, and bioremediation form a distinct red cluster, indicating an interest in remediation technologies. In the third visualization, the prevalence of heavy metal biodegradation, phytoremediation, and soil pollution also provides evidence of biological and environmental restoration process synergy. Precisely, bacteria, biomass, biofilm, and adsorption are most directly engaged with water pollutants, and microbial communities and physicochemical interactions in detoxification processes are emphasized.

Co-authorship

The co-authorship network in the Fig. 5 represents co-authorship between researchers studying phytoremediation of heavy metals in marine ecosystems. Each node represents an individual author, with lines connecting the nodes indicating co-authored papers, which serve as a mark of academic collaboration. The visualization suggests a very dense web, which is testimony to the interdisciplinary and international nature of research in this field. Major contributors, such as “Neha Gupta”, Shiv Prasad, Krishna Kumar Yadav, and Amel Gacem, are located at the centre of the network, indicating their likely leadership in collaborative work and field building. The high rate of co-authorship among researchers such as Ahmed M. Fallatah, Marina M.S. Cabral-Pinto, and Omar Khulaif Rashed Alharbi suggests a high rate of knowledge and expertise exchange between geographical and institutional spaces. The

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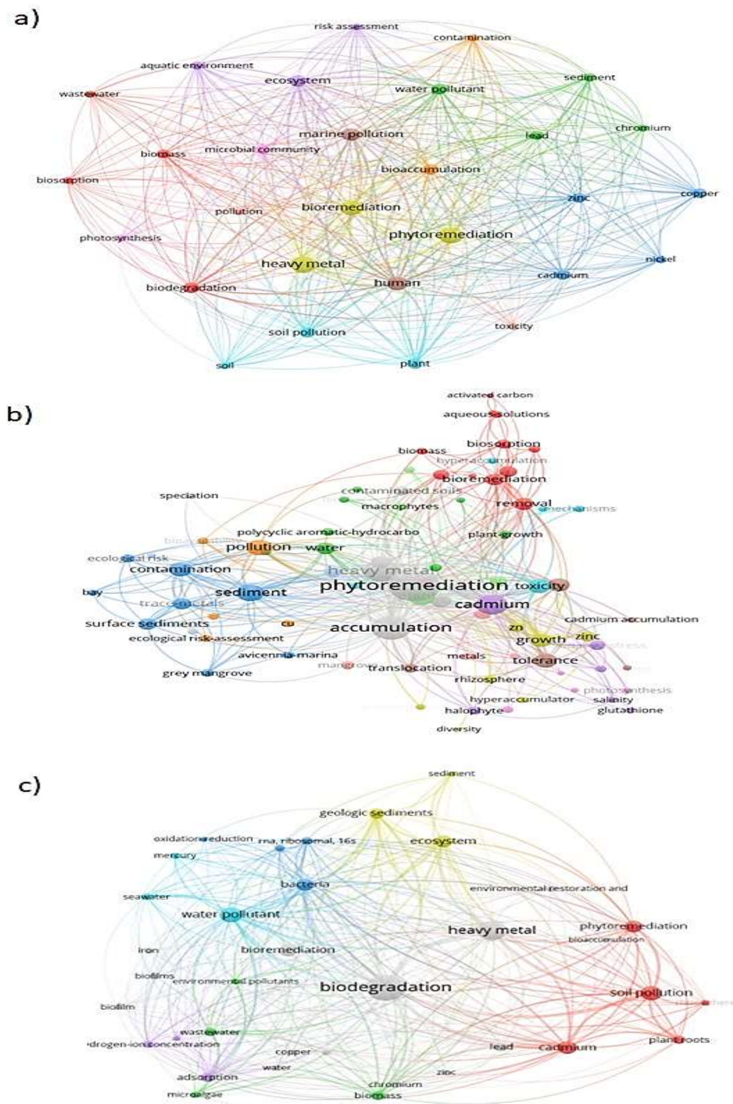

Fig. 4: Co-occurrence of keywords

highly interconnected nature of this structure not only facilitates innovation and knowledge dissemination but also reinforces the collective effort towards developing sustainable phytoremediation strategies to address marine heavy metal pollution. The present co-authorship analysis, VOSviewer, yielded 1053 such authors. The co-authorship among these researchers was analyzed using fractional counting of a minimum of 5 published papers and 5 citations per paper. Fig. 5 shows that 15 authors met the criteria.

Corresponding author's countries

Table 3 presents a comparative analysis of the top 10 countries contributing to the literature indexed in Scopus, Web of

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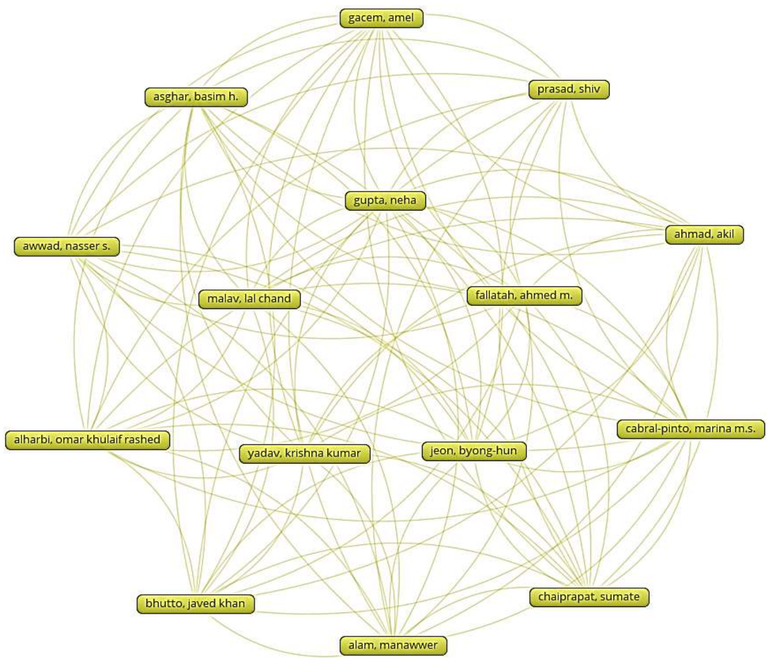

Fig. 5: Co-authorship analysis

Table 3: depicts the corresponding author's countries and Number of Articles (NOA) published in various database

Rank	Scopus		WoS		PubMed	
	Countries	NOA	Countries	NOA	Countries	NOA
1	India	11	China	72	China	109
2	China	6	India	38	India	37
3	Indonesia	3	Portugal	17	Egypt	14
4	Italy	3	Indonesia	14	Portugal	12
5	Japan	3	Australia	10	Italy	10
6	Korea	3	Italy	10	Japan	8
7	Spain	3	Spain	10	USA	8
8	Bangladesh	2	Korea	8	Korea	6
9	Egypt	2	Egypt	6	Bangladesh	5
10	Malaysia	2	Turkey	6	Brazil	5

Science, and PubMed, concerning the selected research domain. That data reveals a significant regional trend in active engagement in scholarly pursuits. China emerges as the heaviest contributor, particularly dominating the PubMed database with 109 publications and also leading in Scopus with 72 publications. This indicates China's substantial investment in research relevant to biomedical and environmental sciences. India ranks second in both PubMed (37 publications) and WoS (38 publications) and holds the top position in Scopus with 11 articles, underscoring its expanding role in global scientific discussion, especially in multidisciplinary and applied research

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contexts. Countries such as Portugal, Indonesia, Italy, Japan, and Egypt also appear across multiple databases, reflecting a diverse and geographically distributed research engagement in the research field.

Interestingly, Indonesia shows a strong presence in Scopus and WoS, suggesting a growing academic footprint in environmental sciences. Similarly, Portugal ranks high in WoS and PubMed, pointing to their involvement in scientific synthesis and research. While publications vary by database, likely due to their differing scope, interest, and indexing criteria, the analysis highlights the central role of Asian and European nations in advancing research within the scope of the study. These trends suggest the existence of a reliable research structure and organizational backing in these countries, facilitating both original investigations and literature integration through reviews and editorials.

Tree map

The tree map presented illustrates the frequency and thematic clustering of keywords in the domain of phytoremediation of heavy metals, based on a bibliometric dataset. The dominant keywords, such as phytoremediation, heavy metals, and bioremediation, represent the core focus of the research landscape. Other moderately frequent terms like microalgae, phytoremediation, remediation, and wastewater highlight specific biological agents and environmental contexts associated with remediation efforts. Smaller segments, including arsenic, bioaccumulation, macrophytes, microplastics, health risk assessment, and ecological risk indices, indicate emerging or specialized subtopics within the field. This distribution reveals a growing interdisciplinary interest involving plant biology, microbial processes, environmental toxicology, and ecological monitoring (Fig. 6). Overall, the tree map offers a visual synthesis of research priorities, highlighting both established and emerging areas in phytoremediation research related to heavy metal pollution.

Country's Scientific Production

The global trends of research on phytoremediation of heavy metals in marine systems, as represented by Fig. 7(a) PubMed, (b) Scopus, and (c) Web of Science data, show a clear clustering of scholarly research in a few lead countries, led by the biggest contributors, China and India.

In PubMed, with its biomedical and environmental health science skew, the top spot is taken by China with 109, followed by India with 37, and Egypt, Portugal, and Italy being significant contributors. In the WoS database, which indexes a broader set of multidisciplinary journals, China is the top contributor with 72, followed by India with 38, then Portugal, Indonesia, and Australia. In the

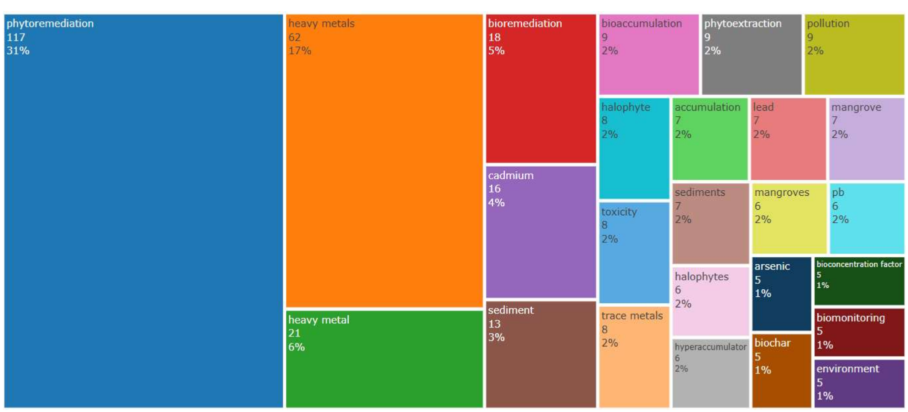

Fig. 6:Tree map illustrates the frequency and thematic clustering of keywords

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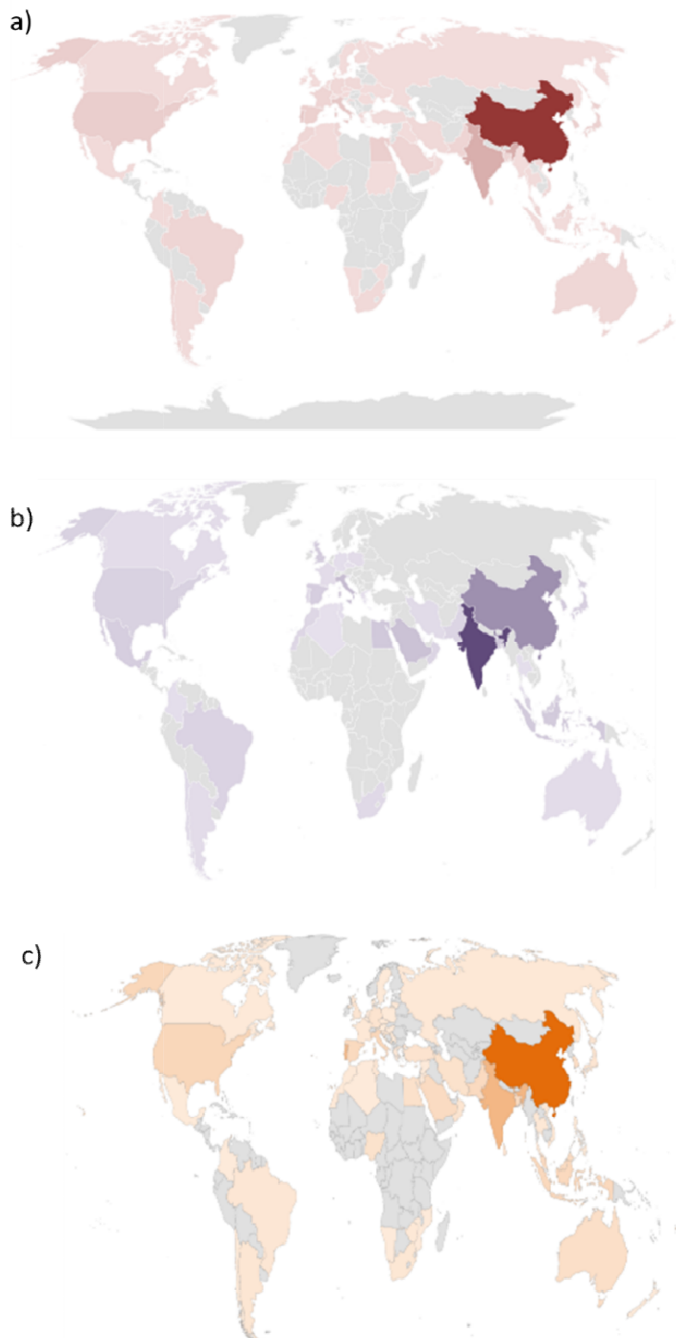

Fig. 7: Country's Scientific production (a) PubMed (b) Scopus (c) WOS

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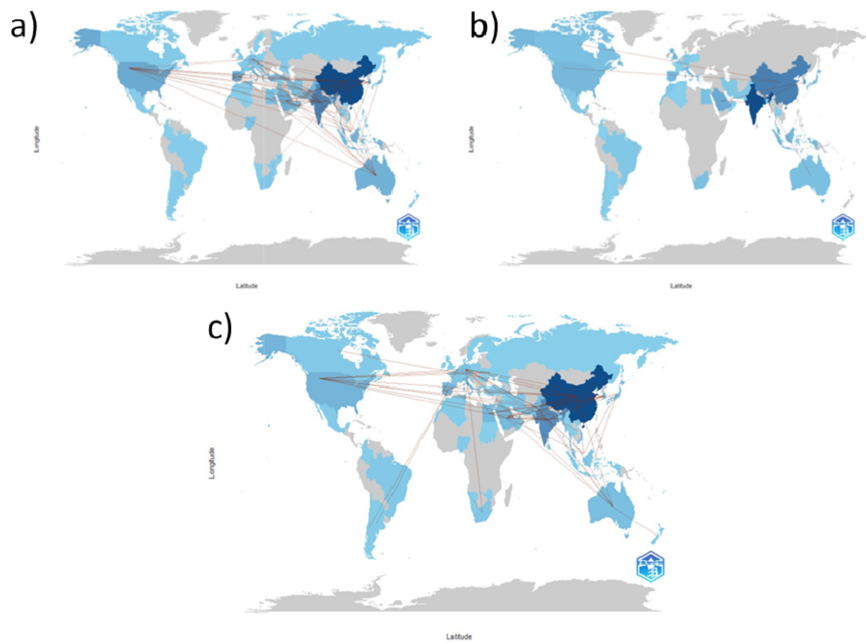

Fig. 8: Illustrates the international collaboration patterns for (a) WoS, (b) Scopus, (c) PubMed database

case of Scopus data, which also indexes conference proceedings and technical reports, India is at the top with 11, followed by China with 6, and Indonesia, Japan, Korea, and Malaysia making frequent appearances.

The world maps corresponding to these datasets visually validate these rankings, with the darker colors indicating higher research output from these countries. These differences among databases also reflect their scope of coverage and indexing parameters, with WoS aggregating larger interdisciplinary research, PubMed focusing on environmental and health impacts, and Scopus giving a balanced look at scientific and technical literature. Overall, the data show growing global interest in marine phytoremediation research, albeit with the research still led by a few Asian countries, pointing toward increased inclusive global cooperation and contributions from underrepresented countries. These geographical patterns underscore the increasing global interest in marine phytoremediation, while also reflecting the research priorities and indexing scope of each database.

World collaboration map

The world collaboration map illustrates the international research collaboration patterns within the field of phytoremediation and heavy metal removal. The map comprises three panels Fig. 8 (A, B, and C), each representing collaboration networks for different aspects of the research (such as phytoremediation, heavy metal, and related topics). The dark blue regions, predominantly in China, the USA, and India, reflect higher research output and collaboration activity. Lines connect these hubs to numerous other countries, indicating strong international collaborations and knowledge exchange. The lighter blue areas denote moderate collaboration, while grey regions reflect lower or no collaboration. This

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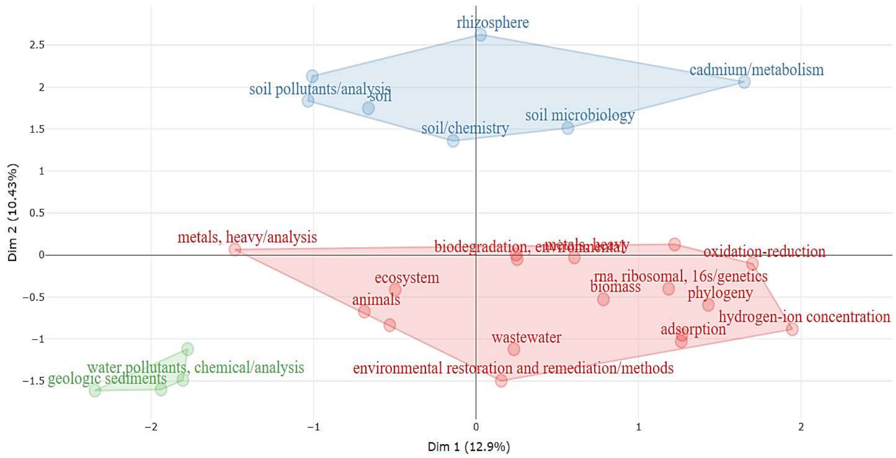

Fig. 9: Factorial analysis

pattern highlights a clear geographical concentration of expertise and joint research initiatives in Asia (China and India), North America (USA), and, to some extent, Australia and European countries. The visualization underscores the global nature of phytoremediation research and the key role of international partnerships in advancing knowledge and technology in this field.

Factorial Analysis

The factorial correspondence analysis illustrates thematic construction of environmental research, particularly the interrelationship of keywords across studies. From the plot, three clusters can be identified (Fig. 9). The blue cluster encompasses the study of soil ecosystems, touching on the rhizosphere, soil chemistry, and the effects of heavy metals like cadmium at the metabolic level, thereby indicating its emphasis on soil microbiology and interactions between pollutants. The red cluster is wider and includes bioremediation, microbial degradation, 16S rRNA phylogenetic analysis, adsorption, and wastewater treatment, thereby pointing to a heavy emphasis on microbial and biochemical mechanisms for environmental restoration. The green cluster, on the other hand, is a distinct and narrow cluster focusing on the aquatic environment, mainly the chemical

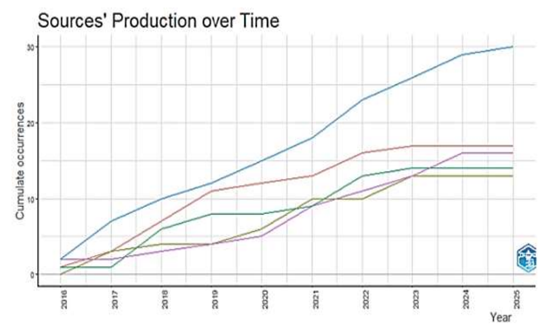

Fig. 10: Different journals in which the papers were published between 2016-2025

analysis of water pollutants and contamination in geologic sediments. The position and spread of the clusters indicate that bioremediation research is somewhat at the interface of soil and aquatic sides; in contrast, water pollution studies are narrowly defined and largely self-contained. In general, the plot exhibits an interdisciplinary nature.

Source production over time

The graph offers a cumulative view of publication activity of five major journals — Science of the Total Environment, Chemosphere, Environmental Science and Pollution Research, International Journal of Phytoremediation, and Marine Pollution Bulletin—between the years 2016 and 2025 (Fig. 10). The greatest increase is seen in

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Science of the Total Environment, which holds a persistently steep growth line, showing its frontline position in publishing studies on environmental remediation and pollution abatement.

By 2025, it will exceed 30 cumulative events, indicating its wide scope and high volume of research in the area. Chemosphere has a very high rising trend through 2022, then tapers off, possibly indicating stabilization or saturation in associated papers. Both Environmental Science and Pollution Research and the International Journal of Phytoremediation follow moderate and similar growth until approximately 2021, after which there is a plateau, suggesting steady but slow contributions. Marine Pollution Bulletin begins slowly but shows a steady rise, keeping pace with the publication rate of the other mid-ranking journals by 2023. Trends show an explosion of environmental studies publications, especially between 2018 and 2022, based on increased global fears of pollution, heavy metals, and remediation technology. The information also highlights the function of multidisciplinary journals in the capture of a broad range of topics within environmental science due to the complexity and integration of the research field.

Trend topics

The graph shows a visual representation of popular research themes in the area of environmental remediation between 2016 and 2024 (Fig. 11). Every term on the y-axis is a keyword widely applied in scientific publications, whereas the x-axis reflects the chronology of its usage. The size of bubbles relates to the frequency of every term, representing the intensity of research interest. Words like "phytoremediation," "heavy metals," "cadmium," "accumulation," and "soil" are most active in about 2019–2021, which corresponds to increased emphasis on metal pollution as well as plant-mediated cleanup processes during this time. Recent trends (2022 onward) indicate increasing usage of mechanistic terms like "transport," "root," "responses," and "ecological risk," indicating a change towards examining underlying processes and risk assessment. Generally, the graph reflects how the priorities of research have shifted over time.

Corresponding author's countries

The chart depicts the distribution of publications of research articles according to the country of the corresponding authors and

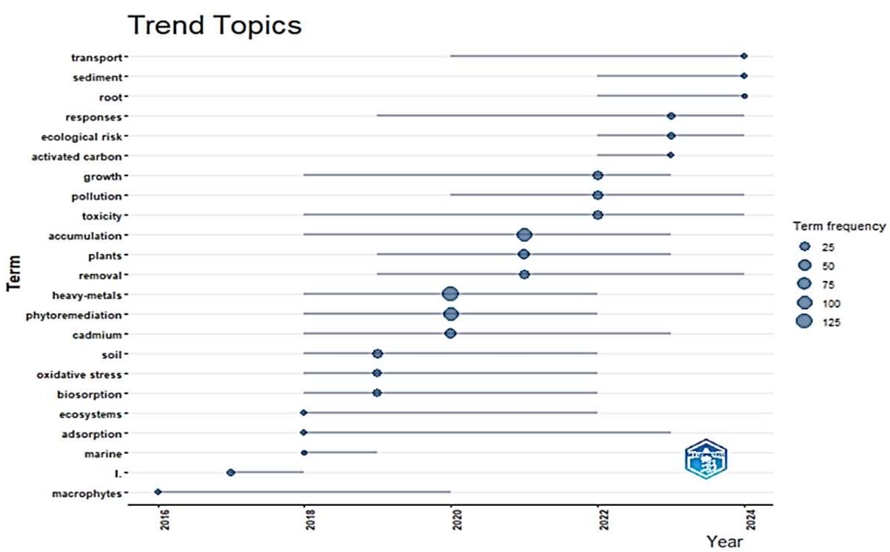

Fig. 11: Trend topics according to the keywords

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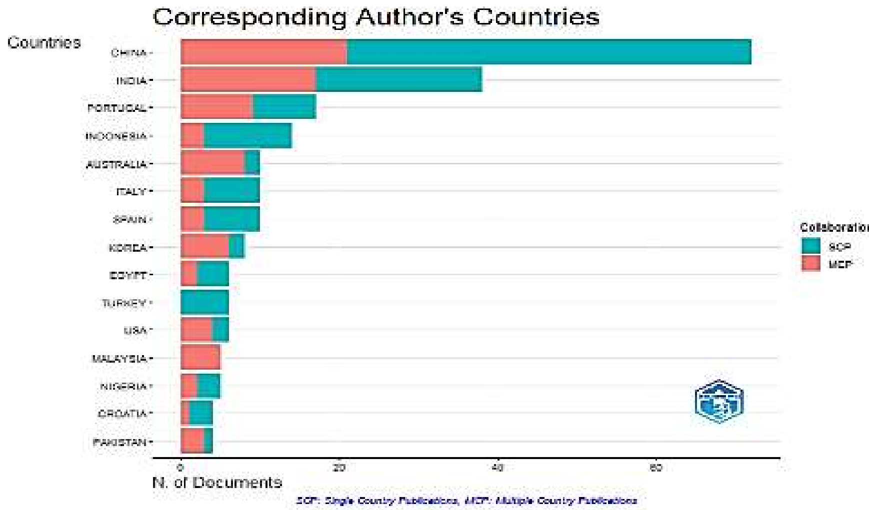

Fig. 12: Corresponding authors countries

their types of collaboration—Single Country Publications (SCP) and Multiple Country Publications (MCP). The largest number of documents is from China, with the majority being generated domestically, reflecting a robust national research base. India is close behind, with a similar percentage of single-country publications but with a proportionately larger amount of international collaboration than China. Portugal, Indonesia, and Australia have a more even split between national and collaborative research, with good activity in global scientific networks. Italy, Spain, and Korea make a moderate contribution with a decent amount of international co-authorship. While countries such as the USA, Malaysia, Nigeria, Croatia, and Pakistan are also less research-intensive but continue to contribute with both solo and collaborative work, total data cites the leading position of Asian nations in the area, with growing international collaboration in driving environmental research (Fig. 12).

Discussion

The scientific mapping of phytoremediation strategies highlights a growing interest in innovation and sustainable approaches to managing heavy metal pollution in marine ecosystems.

Limitations

Phytoremediation, though a promising green technology for the remediation of contaminated environments, continues to have significant limitations that hold it back from widespread adoption (60). Among the leading limitations is the lack of sufficient long-term environmental effects data regarding phytoremediation technologies, particularly in geographically and climatically varied regions (61). Most research is based on short laboratory or greenhouse experiments over a few days, weeks, or months, and they don't accurately reflect the ecological processes and sustainability of phytoremediation in actual outdoor field environments. This does not allow for meaningful evaluation of effectiveness, risk, and environmental trade-offs over long periods (62).

Another critical concern is the absence of standardized performance measures and evaluation protocols. No such system is in place at present to compare the effectiveness, rate of clean-up, or ecological safety of various phytoremediation approaches (63). As a result, investigations carried out in diverse environments across a range of plants, contaminants, and techniques have uneven and frequently

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incomparable outcomes. (64). In addition, phytoremediation is frequently contaminant-specific, and therefore, not all contaminants can be cleaned up effectively with plants. (65). For instance, strongly hydrophobic organic contaminants or tightly bound compounds to soil particles can be too non-bioavailable for plant acquisition. (66).

Challenges

Generally, the phytoremediation method faces certain challenges, such as uncertain phytoremediation lengths, which lead to uncertain land use times, and it also lacks representation of the impact and phytoremediation effectiveness (67). One major limitation is the slow rate of pollutant removal, which may not be suitable for urgent or heavily contaminated sites. (68). The survival and growth of plants in toxic environments can be difficult, and certain contaminants may not be bioavailable for uptake. Furthermore, a lack of public awareness and policy support hinders widespread adoption. (69). Sometimes, scaling up applications is also faced as a challenge. (70).

Consequences

Even though phytoremediation is a sustainable method, it has its consequences. Using aquatic plants or algae has potential drawbacks, like slow remediation, limited species to use, and proper post-treatment disposal of accumulated biomass. (71). Phytoremediation has both sustainability and consequences, but balancing them is a difficult job. (72). There are many ways to balance, such as thorough assessment, an integrated approach, community engagement, adaptive management, and research. These things all help us to balance the sustainability and consequences of phytoremediation. (73).

Phytoremediation is an emerging approach that has the potential to reduce water contamination. It is a cost-effective and environmentally friendly technique, offering advantages over conventional methods. The potential of phytoremediation is substantial and warrants further investigation. (13). The levels of several heavy metals in mangrove ecosystems have been observed to be higher compared to other mangroves globally. Copper (Cu) and Iron (Fe) levels exceed background values, indicating anthropogenic contamination. The plant species *E. agallochum, A. officinalis,* and *S. apetala* exhibited bioconcentration factors of less than one, reflecting a limited capacity for heavy metal uptake. However, the translocation factor values for all the studied plants were greater than one for the metals examined. The findings present several important insights: both of these selected plant species are nutritionally rich and possess a pleasant salty flavor, suggesting that their leaves could be utilized in the preparation of snacks and other food products, providing an additional source of livelihood. (59, 74).

Conclusion

Phytoremediation is an environmentally friendly and nature-based method that uses plants and their related microbial consortium to eliminate, immobilize, or change environmental pollutants, such as heavy metals, from water and soil environments. Phytoremediation is being considered for marine and coastal environments as a potential tool to mitigate growing levels of heavy metal contamination from industrial effluents, port operations, agricultural discharge, and aquaculture. The method depends on the utilization of salt-resistant plant species like halophytes, mangroves, and marine algae, which can tolerate salinity while absorbing and accumulating pollutants from sediments and water bodies (75). The phytoremediation process is affected by various ecological and environmental components such as the nature of the pollutant, plant species selection, sediment type, climatic conditions, and water dynamics. All these elements combined determine the efficiency of uptake and general remediation success. Research has established that *Avicennia marina* and *Rhizophora mucronata* are very efficient at absorbing and stabilizing cadmium, lead, and

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nickel metal in estuarine and mangrove systems (76).

Further, aquatic macrophytes like *Eichhornia crassipes* and *Lemna minor* are largely employed for phytoremediation of marine outfalls and brackish water bodies because they grow rapidly and possess huge metal uptake capabilities. (77). This paper provides an in-depth examination of phytoremediation strategies for addressing heavy metal pollution, particularly in marine ecosystems. Phytoremediation is a gradual process, and its effectiveness may be compromised if plant growth is slow. (78). Various factors influence the phytoremediation process, including the types of pollutants, waste disposal practices, flooding, selection of plant species, climatic conditions, and soil characteristics. Ongoing research aims to enhance phytoremediation techniques to mitigate these challenges, demonstrating their high effectiveness and potential benefits, with promising advancements anticipated in the future. However, phytoremediation may not be an ideal solution in areas with extensive contamination over prolonged periods. Inadequate management and care can lead to contamination within the food chain. (77).

Phytoremediation's future is in having intelligent, adaptive, and integrated systems that can function well in dynamic marine conditions. The integration of artificial intelligence (AI), remote sensing, and GIS-based modelling has great potential for enhancing the efficiency of phytoremediation. These technologies have the potential to aid in real-time tracking of pollutant concentrations, optimize plant choice depending on environmental parameters, and provide remediation outcome forecasts in changing marine conditions (79). For instance, satellite imagery combined with AI algorithms can detect contamination hotspots and track vegetation health over time, allowing for precision remediation strategies. Furthermore, genetic engineering and synthetic biology are being researched to improve the tolerance of contaminants and uptake potential of marine plants so that their usability can be diversified even under harsher environments, even when the climate is not in a favourable condition. (80). Another area with promising potential is the coupling of phytoremediation with circular economy principles. Plant biomass collected from phytoremediation can be processed into biochar, biogas, or other green commodities, reducing waste and providing economic benefit to remediation operations. (79).

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