Egyptian Journal of Aquatic Biology & Fisheries
Zoology Department, Faculty of Science,
Ain Shams University, Cairo, Egypt.
ISSN 1110 – 6131
Vol. 29(2): 1307 – 1335 (2025)
www.ejabf.journals.ekb.eg

Bioremediation vs. Traditional Methods: A Comparative Review of Heavy Metal Removal Techniques from Aquatic Environment

Ahmed M. Khalifa[1*], Khaled Z. ElBaghdady[2], Sameh B. El Kafrawy[1], Ahmed M. El-Zeiny[3]

[1] Marine Sciences Department, National Authority for Remote Sensing and Space Sciences (NARSS), Cairo, Egypt
[2]Microbiology Department, Faculty of Science, Ain Shams University
[3]Environmental Studies Department, National Authority for Remote Sensing and Space Sciences (NARSS), Cairo, Egypt

***Corresponding Author :** ahmed.khalifa@narss.sci.eg

ARTICLE INFO

Article History:
Received: Jan. 21, 2025
Accepted: March 16, 2025
Online: March 29, 2025

Keywords:
Bioremediation,
Phytoremediation,
Bacteria,
Remote sensing,
Spatial analyses,
Heavy metal

ABSTRACT

Heavy metals, while naturally occuring, become toxic when concentrated in water. There has been a significant increase in industrial waste entering the environment which affects the soil and water. This is largely due to industrial expansion, resulting in the accumulation of heavy metals. The elimination of heavy metals from wastewater has presented a considerable challenge for a prolonged duration. An assortment of methods have been developed for the removal of toxic metal ions from wastewater, including chemical precipitation, ion exchange, membrane filtration, reverse osmosis, and electrodialysis. Nonetheless, these traditional technologies incur significant costs attributed to the utilization of non-regenerable materials, elevated expenses, and the production of hazardous sludge. Bioremediation is a biotechnological process that effectively and economically removes heavy metals from aqueous solutions. This illustrates a conventional approach to employing economical alternative biological materials for the specified objective. Bioremediation is a critical component of environmental and bioresource technology, with increasing attention on the use of microorganisms specifically bacteria, algae, yeasts, and fungi as biosorbents for the removal of heavy metals. This review outlines the contributions of microorganisms and plants in the biotransformation of heavy metals into non-toxic forms, highlighting the superiority of green technologies over traditional methods for heavy metal remediation. This review juxtaposes the efficiency of bioremediation and traditional methods for the removal of heavy metals. It also presents the role of remote sensing and spatial analyses in enhancing bioremediation strategies by enabling precise detection, monitoring, and assessment of contaminated sites.

INTRODUCTION

There has been a major rise in industrial waste in the environment, primarily soil and water, due to the growth of industry, leading to the buildup of heavy metals which originate from the weathering of parent materials, as well as through human activities **(Shaaban *et al.*, 2016)**. Toxic metals have received worldwide attention because of their abundance polluting the environment, affected by significant growth in industrialization and urbanization, the accumulation of heavy metals in water and sediments causes damage to all aquatic life, and exposing fish to a high concentration of trace elements in a polluted aquatic system forces them to directly absorb metals from the environment **(Farombi *et al.*, 2007)**. Heavy metals and trace elements must be removed from polluted water and soil to return them to an appropriate state. Chemical precipitation, oxidation or reduction, filtration, ion exchange, reverse osmosis, membrane technology, evaporation, and electrochemical treatment are all ineffective ways to get rid of heavy metals **(Ahluwalia & Goyal, 2007)**. Due to the fact that the bulk of heavy metal salts are water-soluble and dissolve in wastewater, they cannot be separated via physical separation techniques **(Hussein *et al.*, 2004)**. In addition, at very low concentrations of heavy metals, physicochemical methods are either inefficient or too expensive. One attractive alternative to physicochemical approaches for heavy metal removal is biological methods, which include biosorption and bioaccumulation **(Kapoor & Viraraghvan, 1995)**. Bioremediation is less harmful, cleaner, less expensive, and more environmentally friendly than other approaches when it comes to cleaning up polluted regions. The process of bioremediation involves using living or decomposing biomass to promote the transformation of pollutants into non-toxic substances that ultimately mineralize into carbon dioxide, nitrogen, and water **(Kapahi & Sachdeva, 2019)**.

Heavy metal bioremediation involves the study and use of plants, fungi, bacteria, algae, and cyanobacteria. The job is best suited to microorganisms since they are simple to work with, cultivate, and implement. Bacteria in particular have come into the spotlight in recent years due to their ability to adsorb (biosorption), bioaccumulate (bioaccumulation), bioleach (bioleaching), and bioprecipitate (bioprecipitation) heavy metals. Bacteria are ideal candidates for bioremediation due to their widespread presence, abundance, diversity, small size, and ability to survive and propagate in unregulated and environmentally difficult circumstances **(Srivastava *et al.*, 2015)**. Bacteria depend mostly on adsorption on their cell surface when it comes to bioremediating heavy metals in solution. It is the bacteria's first line of defence in cases of metal toxicity.

Traditional methods such as adsorption, chemical precipitation, and membrane separation yield rapid results; however, they frequently exhibit lower efficiency and higher costs compared to biological approaches **(Razzak *et al.*, 2022)**. Bioremediation employs the metabolic capabilities of diverse organisms, including bacteria, fungi, plants, and algae, to eliminate heavy metals via mechanisms such as bioaccumulation, biosorption, and biotransformation **(Das & Osborne, 2018; Jacob *et al.*, 2018)**. Biological methods provide benefits related to sustainability and decreased generation of secondary waste **(Verma & Sharma, 2017)**. With an eye toward their efficacy, benefits, constraints, and uses in a variety of settings, this review contrasts conventional techniques with bioremediation for heavy metal removal. Fig. (1) presents a comparison between bioremediation techniques and conventional methods for heavy metal extraction. Conventional methods, while accepted, may exhibit issues related to efficiency and environmental impact. Bioremediation employs biological processes for the treatment of heavy metals, presenting an environmentally sustainable and innovative alternative.

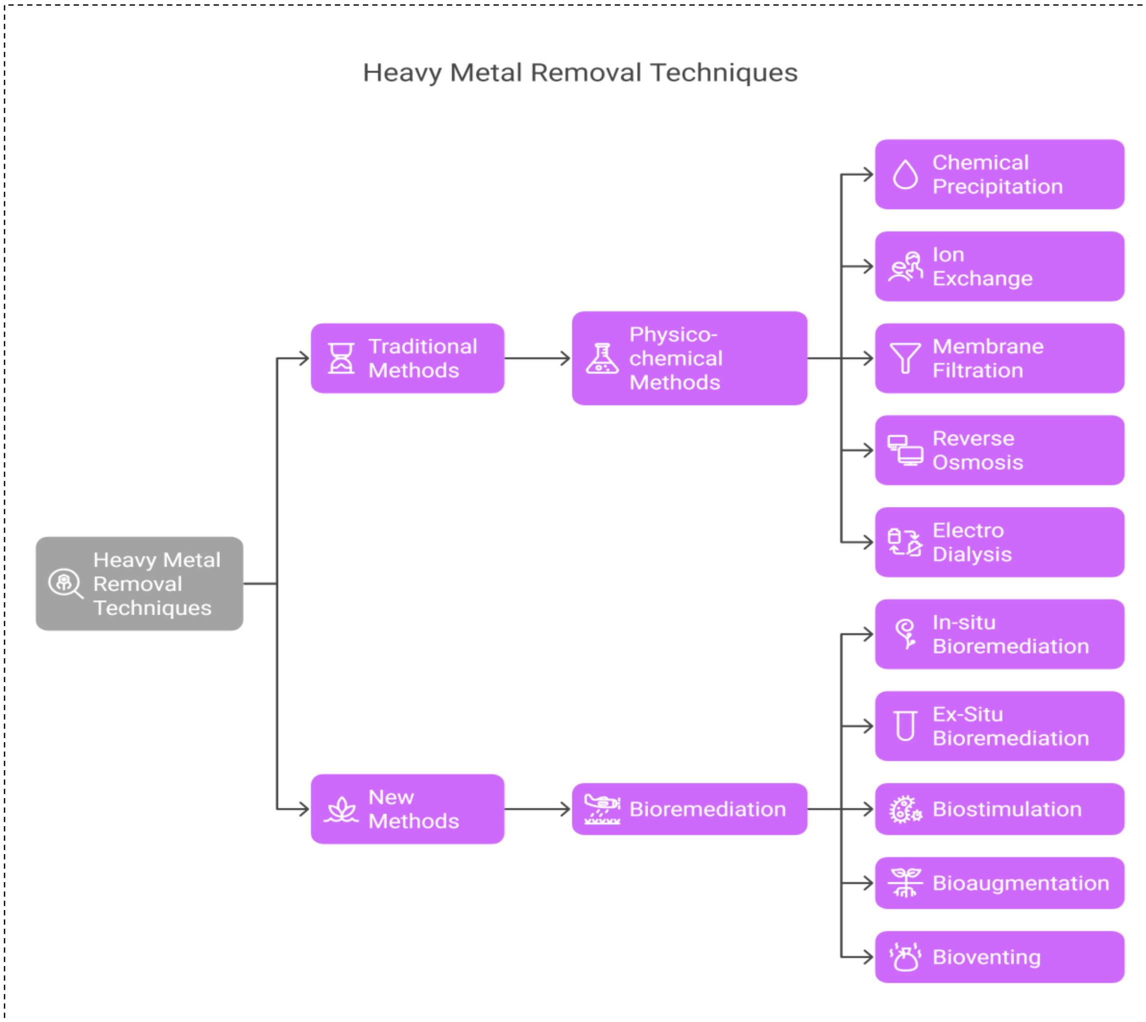

Fig. 1. Comparative overview of heavy metal removal methods

Traditional methods used for removal of heavy metals

1. Physico-chemical methods

An efficient and widely used approach for purifying wastewater that is polluted with metals is the physicochemical treatment method. It uses specialized adsorbents to discriminate, is cost-effective at low and high pollution concentrations, and can be regenerated after use. The process of adsorption involves the physical and/or chemical interactions between substances and solid surfaces, leading to a transfer of mass. Several new inexpensive adsorbents have been developed and implemented to purify metal-polluted water. These adsorbents may be derived from agricultural detritus, industrial scraps, natural materials, or biopolymers that have been modified. Utilizing agricultural byproducts as adsorbents through the biosorption process has recently been the focus of research regarding the removal of heavy metals from industrial wastewater. After undergoing chemical processing, waste materials such as hazelnut shells, rice husks, pecan shells, jackfruit, maize stalk or husk, rice straw, rice husk, coconut shell, etc., can be used as a heavy metal adsorbent **(Igwegbe *et al.*, 2013)**.

2. Chemical precipitation

Chemical precipitation is a widely used method for eliminating heavy metals from inorganic sewage in both laboratory and industrial settings, owing to its simplicity of implementation **(Lou *et al.*, 2007)**. The common chemical precipitation processes yield insoluble precipitates of heavy metals, namely hydroxide, sulphide, carbonate, and phosphate. Heavy metals in the wastewater solution that the chemistry lab releases into the environment react to set in motion the process. Insoluble metal precipitation is produced by this process. Sludge may be more easily removed from a system that uses chemical precipitants, coagulants, and flocculation methods to increase the size of the very small particles that are produced during precipitation. Metals may be safely discharged, even in minute concentrations, when they precipitate and solidify into particles (Fig. 2), **(Barakat, 2011)**.

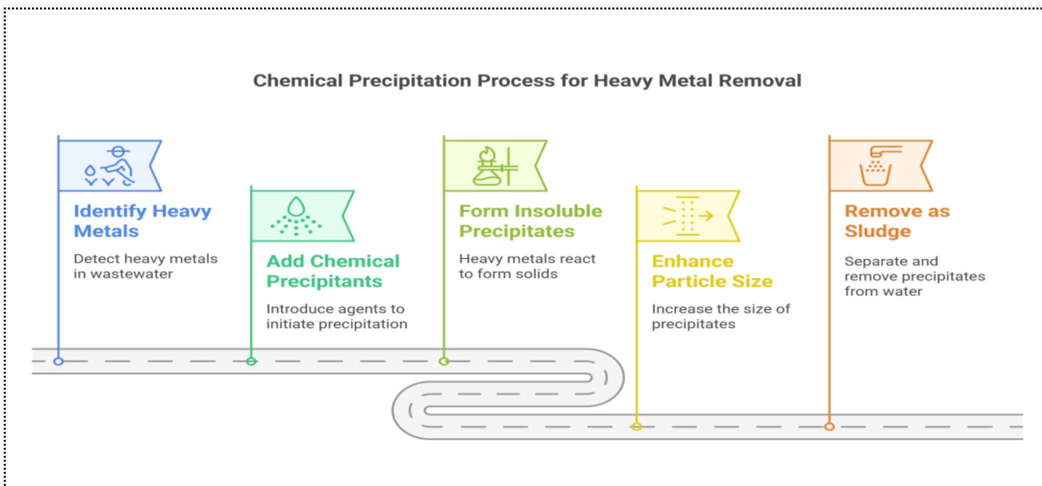

Fig. 2. The chemical precipitation process for heavy metal removal entails a systematic method that includes the detection of heavy metals, the introduction of chemical precipitants, the formation of insoluble precipitates, the increase of particle size, and the subsequent removal of sludge to achieve successful wastewater decontamination

3. Ion exchange

The chemical reaction described as ion exchange is one that may be reversed. An ion, a charged atom or molecule that has acquired or lost an electron, is exchanged from a wastewater solution for another one. An ion with a comparable charge that is bound to a stationary solid particle undergoes this exchange. Solid ion exchange resins are not soluble in water. They have the ability to adsorb ions that are positively or negatively charged from a solution containing electrolytes. These resins can then release other ions that have the same charge into the solution in an amount that is equivalent to the number of ions that were adsorbed. Cationic resins, which contain positively charged ions such as hydrogen and sodium, undergo an exchange process with other positively charged ions, including but not limited to nickel, copper, zinc, silver, cadmium, gold, mercury, lead, chromium, iron, tin, arsenic, selenium, molybdenum, cobalt, manganese, and aluminium ions present in the solutions. The negatively charged ions present in resins, such as hydroxyl and chloride ions, can be substituted by negatively charged ions, including chromate, sulphate, nitrate, cyanide, and dissolved organic carbon (DOC) (Fig. 3), **(Chaemiso, 2019)**.

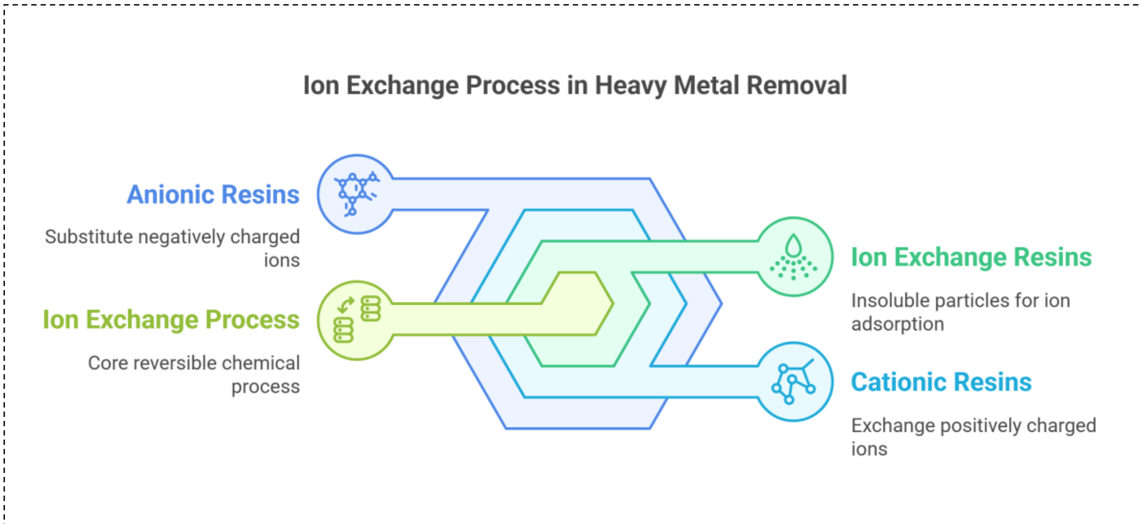

Fig. 3. Schematic representation of the ion exchange mechanism for the elimination of heavy metals, demonstrating the function of anionic and cationic resins in replacing negatively and positively charged ions, respectively. The procedure involves reversible adsorption on ion exchange resins, enabling the extraction of heavy metals from polluted water

4. Membrane filtration

Various contaminants such as heavy metals, suspended solids, inorganic pollutants, and organic substances can be effectively removed through filtration. Membrane filtration techniques such as ultra-filtration, nano-filtration, and reverse osmosis have been employed for the purpose of eliminating heavy metals from wastewater. The selection of a specific filtration method is contingent upon the particle size that can be feasibly sustained. Ultrafiltration (UF) is a technique employed to eliminate impurities from an inorganic solution. This method involves the use of a membrane with pore sizes ranging from 5 to 20nm and a molecular weight cutoff that is commensurate with the solutes being extracted. Ultrafiltration (UF) can effectively remove more than 90% of metals from solutions with concentrations between 10 and 112mg/ L, depending on the membrane characteristics, pH levels ranging from 5 to 9.5, and pressures between 2 and 5 bar. The use of UF provides benefits including decreased driving force and necessary area owing to its high packing density (Fig. 4), **(Barakat, 2011)**.

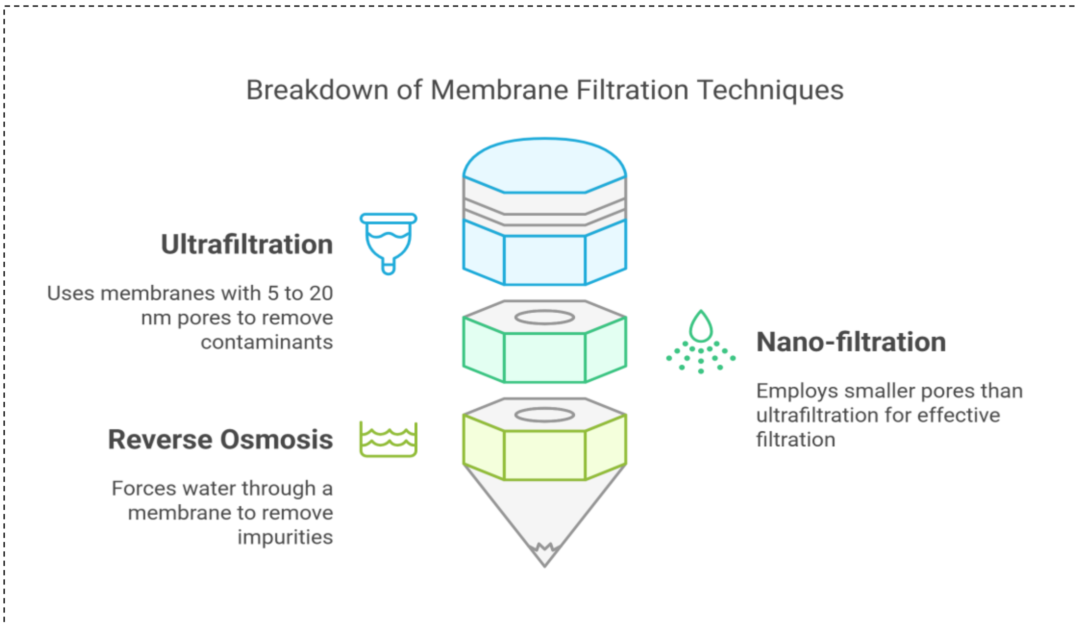

Fig. 4. Depiction of diverse membrane filtration methodologies for the extraction of heavy metals, encompassing ultrafiltration, nanofiltration, and reverse osmosis, categorised by pore dimensions and filtration efficacy

5. Reverse osmosis (RO)

In reverse osmosis, the solvent is allowed to flow through a membrane while the solute is retained on one side. This separation technique makes use of pressure. Semipermeable membranes like this one let solvents through but block metal ions. The reverse osmosis membranes are characterized by a thick barrier layer inside the polymer matrix, which is responsible for the majority of the separation. Bacteria are only one of several chemicals and ions that reverse osmosis and may filter out of a solution. Solute concentration, pressure, and water flow rate determine the separation efficiency in reverse osmosis, which is a diffusive process (Fig. 5) **(Bakalár *et al.*, 2009)**.

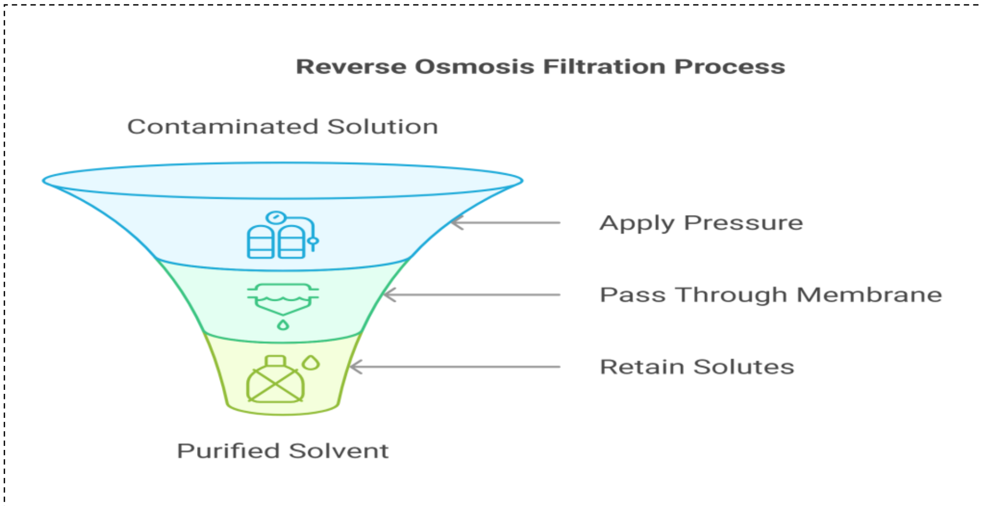

Fig. 5. Reverse osmosis filtration orocess for water purification

6. Electro dialysis

One method of separating ions in a solution from one another is electrodialysis (ED), which makes use of an electric potential to move the ions over an ion exchange membrane. Membranes are made of thin plastic sheets that have anionic or cationic characteristics. If ionic species in a solution want to move from one part of a cell to another, they have to cross two membranes: the anion exchange membrane and the cation exchange membrane (Fig. 6) **(Mungray *et al.*, 2012)**.

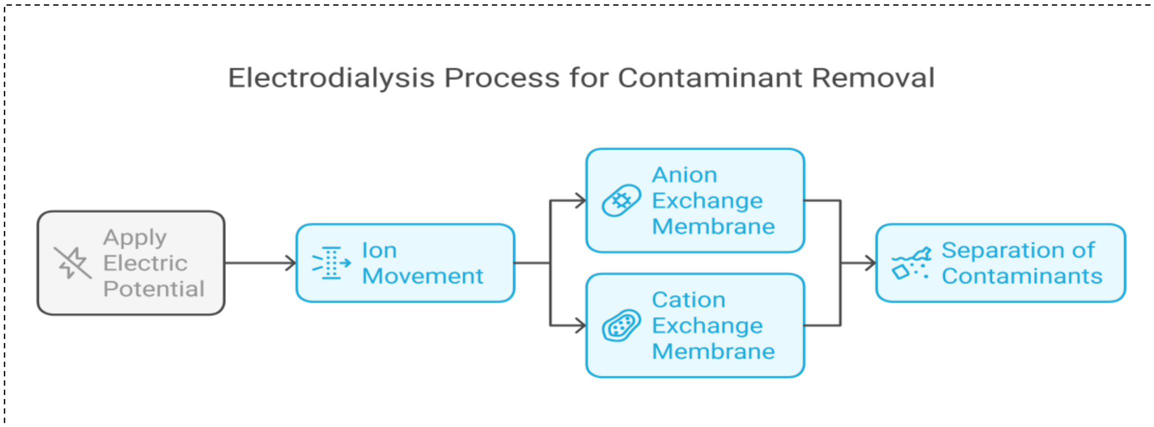

Fig. 6. A schematic representation of the electrodialysis process for contaminant extraction. This method involves the application of an electric potential to promote ion migration via anion and cation exchange membranes, resulting in the segregation of pollutants from the solution

New methods for removal of heavy metals

1. Phytoremediation

In phytoremediation, plants and related microorganisms are utilized to remove certain pollutants from soil, detritus, sediments, effluent, and groundwater. It is capable of removing radionuclides, organic contaminants and heavy metals **(Ali *et al.*, 2013)**. Phytoremediation is a technique for decontaminating polluted areas that employ diverse plant processes and plant properties. Recently, phytoremediation has received a great deal of attention because this attribute may be utilized in the remediation of heavy metal-contaminated soils **(Robinson *et al.*, 1997; Martinez *et al.*, 2006)**. The phytoremediation strategy consists of several techniques, including phytoextraction, phytofiltration, phytostabilization, phytovolatilization, and phytodegradation **(Alkorta *et al.*, 2004)**. The first phase of phytoremediation is phytoextraction, which involves the roots of a plant absorbing contaminants from the surrounding environment and transporting them to the seedlings, where they will accumulate **(Sekara *et al.*, 2005)**. A desirable biochemical phase for efficient phytoextraction is metal translocation to stems. Phytofiltration, which can include rhizofiltration (using plant roots), blastofiltration (using seedlings), or caulofiltration (using excised plant shoots) **(Mesjasz *et al.*, 2004)**, is the next crucial process in phytoremediation because it inhibits the metals' mobility in the groundwater. Phytostabilization and phytoimmobilization reduce the mobility and bioavailability of metals in the environment and prevent their migration into groundwater or the food chain **(Erakhrumen, 2007)**. Plants immobilize heavy metals in soils via root absorption, precipitation, complex formation, and metal valence reduction in the rhizosphere **(Pinto**

***et al.*, 2015)**. Phytovolatilization, however, causes certain heavy metals absorbed by plants to be converted into volatile forms and then released into the atmosphere. Volatile heavy metals, such as Hg and Se, were extracted from damaged soils utilizing this method (Fig.7), **(Karami & Shamsuddin, 2010)**. This approach has limitations, as it does not completely eliminate metals; it only transfers them from one medium (soil or water) to another (atmosphere), from which they may eventually return to soil and water.

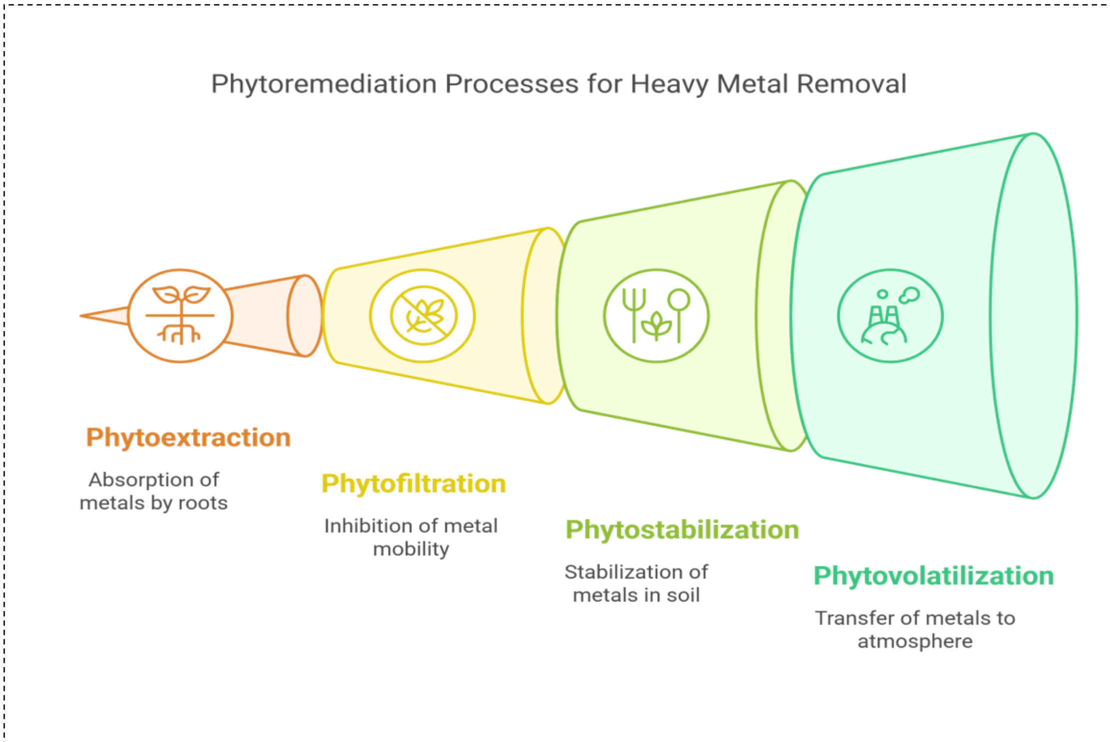

Fig. 7. Phytoremediation techniques for heavy metal extraction: A biological method using plants to extract (phytoextraction), filter (phytofiltration), stabilise (phytostabilization), or volatilize (phytovolatilization) heavy metals from polluted environments

2. Bioremediation

The concept of bioremediation has been coined to refer to the use of living organisms to eliminate hazardous pollutants from the surroundings. The utilization of bioremediation represents a highly efficacious approach to the management of environmental pollution and the restoration of soil that has been contaminated. Bioremediation is a technique that employs a range of agents, including bacteria, fungi, algae, and higher plants, as primary tools for the treatment of heavy metals found in the environment. The scientific advancement of bioremediation, encompassing both *in-situ* and *ex-situ* methods, has been notable. This can be attributed, in part, to the heightened utilization of natural attenuation, which is primarily driven by biodegradation. The utilization of bioremediation and natural attenuation has been identified as a potential resolution for the issue of emerging contaminants, therefore microbes play a crucial role in the remediation of contaminated environments **(Kulshreshtha *et al.*, 2014)**. During bioremediation procedures, microorganisms are utilized to convert organic contaminants into end-products, including carbon dioxide and water, or metabolic intermediates that serve as primary substrates for cell growth. Microorganisms exhibit a dual defence mechanism, which involves the production of degradative enzymes that target pollutants, as well as resistance to heavy metals that are relevant to the pollutants **(Dixit *et al.*, 2015)**.

According to **Sreedevi *et al.* (2022)**, the process of bioremediation is predominantly dependent on bacteria, in addition to other microorganisms and plant species. Bacteria have developed both inherent and adaptive mechanisms to counteract the harmful effects of metal toxicity. These mechanisms include bioadsorption (biosorption), bioaccumulation, bioprecipitation, and bioleaching. Bacterial strains that are resistant to heavy metals can be easily cultured and sustained. Additionally, even the biomass of deceased cells exhibits significant potential for remediating heavy metals in a solution. The utilization of bacterial remediation techniques for heavy metals offers a dual advantage of metal retrieval and water purification, while also presenting opportunities for the reuse of both metal and water resources. Table (1) shows some examples of a certain types of native biomass that have been employed in the bioremediation process.

Types of Bioremediation

Sachan *et al.* (2022) mentioned two types of bioremediation :

1. *In-situ* bioremediation: The remediation of contamination at the site of the incident. There are two primary forms of *in situ* bioremediation: intrinsic and accelerated. Intrinsic bioremediation decomposes toxic substances using microorganisms already present in the environment. In accelerated bioremediation, either substrate or nutrients are introduced to the environment to promote the rapid growth of microorganisms, thereby aiding in the breakdown of the toxic discharge.

2. *Ex-Situ* bioremediation: The application of *ex-situ* bioremediation is typically reserved for situations where it is deemed necessary due to the associated costs and potential harm to the surrounding environment, as the process involves the physical removal of contaminated soil or water.

Sachan *et al.* (**2022**) discussed both the benefits and drawbacks associated with bioremediation. The objective is to minimize the level of exposure of workers present on the site to the contaminant, ensure the sustained safeguarding of public health over an extended period, and use the most cost-effective approach to eliminating pollutants. The procedure is conducted at the location of interest with limited spatial and equipment requirements. The primary benefit of bioremediation is its utilization of natural processes and the absence of waste generation. It should be noted that not all organic compounds possess the ability to undergo biodegradation. One of the primary drawbacks of bioremediation is that the resulting products of biodegradation may occasionally exhibit toxicity that surpasses that of the original parental form.

Table 1. The categories of native biomass implemented in bioremediation processes, accompanied by specific species examples. The table is designed to emphasize the targeted contaminants and the mechanisms of action as identified in prior studies

Biomass Type	Species Example	Contaminants Remediated	Mechanism	References
Bacteria	*Pseudomonas aeruginosa*	Hydrocarbons, heavy metals (Cr, Cd, Pb)	Enzymatic degradation, biosorption	**Olukanni *et al.*, (2014)**
	Bacillus subtilis	Petroleum hydrocarbons, pesticides	Biofilm formation, metabolic degradation	**Kusdini *et al.*, (2024)**
	Bacillus cereus	Heavy metals (Pb, Ni, Cd)	Bioaccumulation & Biosorption	**Khalifa *et al.*, (2023); Murthy *et al.*, (2012)**
	Geobacillus thermodenitrificans	Heavy metals (Fe, Pb,Cr,Co,Cu,Zn,Ag)	Biosorption	**Chatterjee *et al.*, (2010)**
Fungi	*Aspergillus niger*	Heavy metals (As, Cu), dyes	Biosorption, chelation	**Darwesh *et al.*, (2023); Neethu *et al.*,(2023); Ekanayake & Manage, (2022)**
	Phanerochaete chrysosporium	Polycyclic aromatic hydrocarbons (PAHs)	Ligninolytic enzyme production (laccases)	**Das, (2014)**
	Trichoderma viride	Pesticides (organophosphates)	Enzymatic hydrolysis	**Jayaraman *et al.*, (2012)**
Actinomycetes	*Streptomyces spp.*	Pesticides, plastics (polyethylene)	Extracellular enzyme secretion	**Rodríguez-Fonseca *et al.*, (2021)**
	Nocardia spp.	Petroleum sludge, chlorinated compounds	Hydrocarbon oxidation	**Hocinat *et al.*, (2019)**
Algae	*Chlorella vulgaris*	Heavy metals (Cd, Zn)	Phycoremediation, bioaccumulation	**El-Naggar,& Sheikh, (2014)**
	Spirulina platensis	Textile dyes	Adsorption, metabolic assimilation	**Selvaraj & Arivazhagan, (2024)**
Plants	*Helianthus annuus* (Sunflower)	Heavy metals (Pb, Ni)	Phytoextraction, rhizofiltration	**Rizwan *et al.*, (2016)**
	Brassica juncea (Mustard)	Selenium, petroleum hydrocarbons	Rhizodegradation, hyperaccumulation	**Sharma & Pathak, (2014)**
	Populus deltoides (Poplar)	Trichloroethylene (TCE), chlorinated solvents	Phytovolatilization, rhizosphere degradation	**Chappell, (1997);Doty *et al.*, (2017)**

Bioremediation techniques

1. Biostimulation

This particular approach involves the introduction of particular nutrients into the soil or water to enhance the performance of indigenous microorganisms. The primary objective is to induce the proliferation of indigenous microbial populations, including bacteria and fungi. Initially, the provision of fertilizers, growth supplements, and trace minerals is essential. Additionally, it has been suggested that the acceleration of metabolic rate and pathways in microorganisms can be facilitated by the provision of various environmental conditions, such as pH, temperature, and oxygen **(Adams *et al.*, 2015)**. The existence of trace quantities of contaminants may also function as a stimulatory agent by activating the operons responsible for bioremediation enzymes. Typically, this strategic approach involves the supplementation of nutrients and oxygen to support autochthonous microorganisms. The aforementioned nutrients serve as fundamental constituents of life and enable microorganisms to generate essential prerequisites, such as energy, cellular biomass, and enzymes for pollutant degradation. All of these entities will require nitrogen, phosphorus, and carbon **(Madhavi & Mohini, 2015)**.

2. Bioaugmentation

Bioaugmentation is a technique that involves the application of pollutant-degrading microorganisms, which can be natural, exotic, or engineered, to enhance the biodegradative potential of the indigenous microbial populations in a contaminated environment. The objective is to expedite the proliferation of indigenous microorganisms and augment the biodegradation of pollutants at the location. Microorganisms are retrieved from the remediation location, cultured individually, genetically altered, and subsequently reintroduced to the site. The purpose of this approach is to guarantee the complete removal and modification of these contaminants into non-toxic by the *in-situ* microorganisms **(Niu *et al.*, 2009)**.

Bioaugmentation refers to the introduction of genetically modified microorganisms into a given system, with the aim of serving as bioremediators that can efficiently degrade complex pollutants. Furthermore, it has been demonstrated that genetically modified microorganisms have the ability to enhance the degradation efficacy of various environmental contaminants.

Malik and Ahmed (2012) suggested that the ability to convert into less complex and innocuous end products is attributed to the presence of varied metabolic profiles. To enhance the process of breaking down certain compounds, genetic modification through DNA manipulation is often employed as natural species may not possess sufficient speed. Genetically engineered microbes are utilized to expedite the breakdown of pollutants, exhibiting a higher rate of efficacy compared to their natural counterparts. These modified microbes are known to outcompete indigenous species, predators, and various abiotic factors. The utilization of genetically modified microorganisms has demonstrated promise in the field of bioremediation, specifically in the remediation of soil, groundwater, and activated sludge. These microorganisms have exhibited an increased capacity to degrade a wide range of chemical and physical pollutants **(Thapa *et al.*, 2012)**.

3. Bioventing

The condition of microbial growth and activity is triggered by the act of oxygen venting through the contaminated medium. The prevalent *in situ* remediation technique is bioventing, which entails the provision of air and nutrients via wells to polluted soil to activate the autochthonous microbial population. The bioventing technique uses a low rate of airflow, supplying the required amount of oxygen for biodegradation, while simultaneously reducing the emission of contaminants into the atmosphere through volatilization. This method is effective for uncomplicated hydrocarbons and should be applied in cases where the pollution is situated at a significant depth beneath the surface. The effective diffusion of oxygen for bioremediation purposes is limited to a range of several centimetres to approximately 30cm in numerous soil types. However, there have been instances where depths of 60cm or more have been successfully treated. Numerous researchers have demonstrated the efficacy of bioventing as a means of achieving successful bioremediation of soil contaminated with petroleum **(Vidali, 2001)**.

4. Bioremediation by actinobacteria

Actinobacteria, one of the most diverse Gram-positive filamentous bacteria, are distinguished by their ability to generate diverse secondary metabolites of enormous biotechnological significance, in addition to their efficient use in the biological treatment of toxic heavy metals from wastewater **(Hozzein *et al.*, 2012)**. **Remenár *et al.* (2014)** reported that the actinobacteria were evaluated for their capacity to produce biosurfactants, in addition to their potential for heavy metal resistance and biodegradation of dyes. Actinobacteria have been observed to produce various chemical compounds to survive during circumstances of stress **(Chiaki *et al.*, 2007)**. Microbial organisms can produce a diverse array of surface-active compounds, commonly referred to as biosurfactants. The molecules in controversy may exhibit varying characteristics, including but not confined to lipopeptides, glycolipids, proteins, polysaccharides, lipopolysaccharide proteins, or lipoproteins **(Banat *et al.*, 2010)**. *Streptomyces* spp., known for their biosurfactant production, were obtained from soil and marine sediment **(Suthindhiran & Kannabiran, 2009; Deepika & Kannabiran, 2010)**. **Amoroso *et al.* (1998)** reported that actinobacteria tolerant of heavy metals have been isolated from polluted regions of the

Sali River in Argentina. **Joseph *et al.* (2009)** have documented similar studies on the resistance of marine microorganisms associated with the marine sponge *Fasciospongia cavernosa* to heavy metals.

Streptomycetes are a promising candidate for bioremediation of metals and have the potential for future biotechnological applications. This is due to their metabolic versatility, capacity to form spores in adverse environmental conditions, ability to create mycelia, and relatively rapid growth **(El-Baz *et al.*, 2015)**. Actinobacteria that thrive in contaminated environments may possess extensive biosorption capacity and metal tolerance **(Polti *et al.*, 2007)**. The subsequent sections delineate research discoveries pertaining to streptomycetes and their capacity for bioremediation of heavy metals, Streptomycetes are of interest due to their ability to survive in metal-contaminated environments by producing a diverse array of metal ion chelators, such as siderophores, which provide protection from the harmful effects of heavy metals or specific uptake for specialised metabolic processes. Resistance to elevated concentrations of heavy metals is a characteristic shared by numerous strains **(Timková *et al.*, 2018)**.

Actinobacteria genera originating from environments with significant heavy metal contamination may exhibit resistance to multiple metals. The development of resistance may ensue from prolonged exposure to high concentrations of heavy metals in the surrounding environment, thereby conferring a potential benefit for bioremediation purposes **(Hassanein *et al.*, 2012)**.

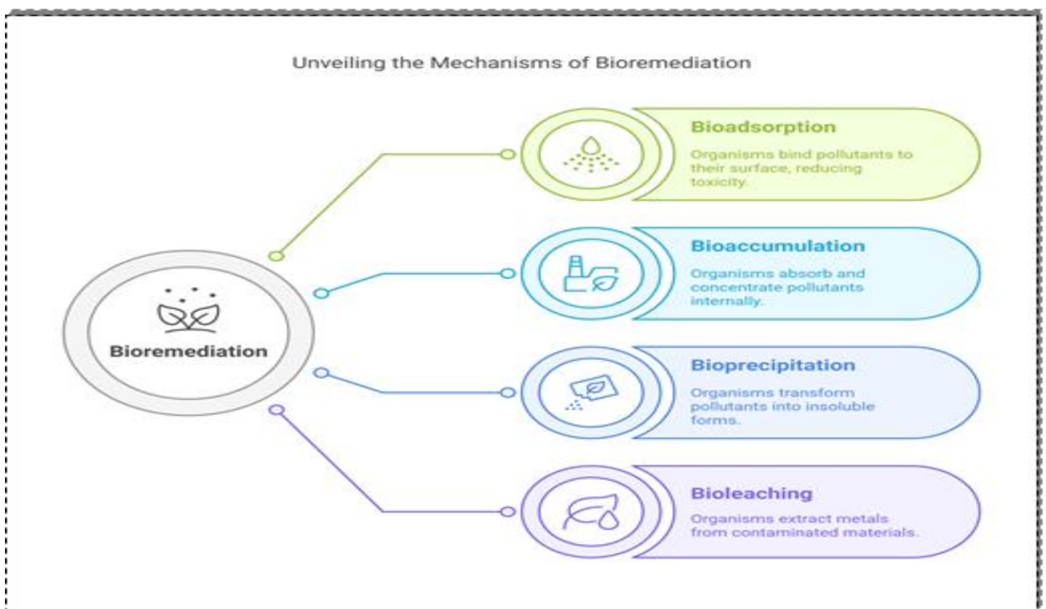

Fig. 8. Exploring the mechanisms of bioremediation: A depiction of several bioremediation methods used for the removal of heavy metals, including bioadsorption, bioaccumulation, bioprecipitation, and bioleaching

Why is bioremediation a superior option than other conventional methods of treatment?

The process of using biological materials to remove metal or metalloid species, compounds, and particles from solution is known as bioremediation. Bioremediation is increasingly acknowledged as a more effective alternative to traditional treatment methods for mitigating environmental contamination. This method utilizes the inherent detoxifying properties of microorganisms, rendering it both economically viable and environmentally sustainable.

The primary advantages of bioremediation compared to traditional methods include lower operational costs associated with bioremediation relative to chemical treatments and physical excavation, which can be excessively costly **(Ganesan *et al.*, 2024; Koushal *et al.*, 2025)**. This approach reduces the requirement for extensive infrastructure and equipment, thereby enhancing its feasibility for large-scale applications **(Ganesan *et al.*, 2024)**. Bioremediation employs natural processes to minimize environmental impact, in contrast to conventional methods that may produce secondary pollutants **(Thirumalaivasan *et al.*, 2024)**. This practice enhances soil health and biodiversity, thereby supporting sustainable agricultural methods **(Koushal *et al.*, 2025)**. Bioremediation may efficiently address a diverse array of pollutants, such as heavy metals and organic contaminants, via many microbial pathways **(Akinola *et al.*, 2024; Patil & Tarfe, 2024)**. Recent breakthroughs, including the use of genetically engineered organisms, improve the efficacy of pollution breakdown **(Patil & Tarfe, 2024)**.

Because of its technological innovation and possible industrial application, bioremediation has been demonstrated to be a viable strategy **(Beni & Esmaeili, 2020)**. However, there are a number of benefits to using microbial-based biosorption for the removal of metal ions, including a high metal removal efficiency due to the specific metals' selectivity **(Arief *et al.*, 2018)**. A small quantity of microbial biomass offers a high surface area to volume ratio for adsorption because of the tiny size of the microorganisms **(Zouboulis *et al.*, 2004)**. Most notably, there is a good likelihood of both metal recovery and revival with the microbial biosorbent, making it both economical and environmentally beneficial **(Yu *et al.*, 2020)**. Additionally, biosorption is a reversible, independent process that can be exploited to absorb metals from both living and dead biomass **(Vijayaraghavan & Yun, 2008)**.

Conversely, while bioremediation has certain benefits, it may not be appropriate for all forms of pollution, especially in situations when prompt cleanup is essential. Therefore, a balanced strategy that incorporates both bioremediation and traditional approaches may be essential in some situations. Table (2) and Fig. (9) present a comparison between conventional procedures and biological approaches.

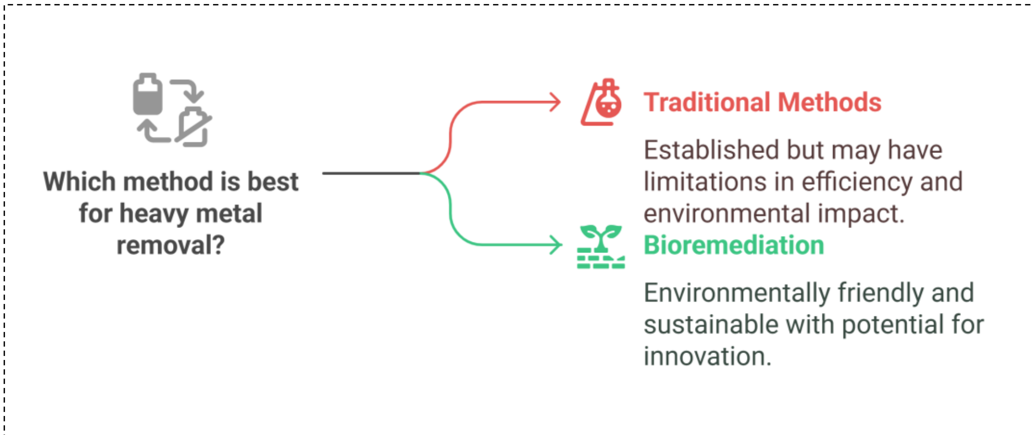

Fig. 9. Comparative analysis of heavy metal removal techniques: traditional methods vs. bioremediation – evaluating efficiency, environmental impact, and sustainable potential

Challenges to meet

Many issues related to the bioremediation of heavy metals compromise its effectiveness and wider use. The challenges come from biological, technological, and environmental aspects that complicate remediation. Developing more successful bioremediation methods depends on an awareness of these challenges. Environmental variability relates to the variations in chemical composition wherein heavy metals show different degrees of toxicity and persistence, therefore hindering the effective breakdown by microorganisms. Additionally, nutrient limitations can impede microbial activity due to inadequate nutrient availability, thereby requiring supplementation to improve degradation rates **(Singh *et al.*, 2024)**.

Biological constraints refer to microbial resistance, whereby particular bacteria exhibit resistance to certain heavy metals, hence limiting their bioremediation capabilities. Along with toxicity consequences where tailored or genetically modified strains may be required **(Singh *et al.*, 2024; Mandal *et al.*, 2024)**, high quantities of heavy metals might be harmful to microorganisms, therefore reducing their effectiveness in bioremediation **(Singh *et al.*, 2024)**. Technological and monitoring challenges highlight the prolonged nature of bioremediation processes, which may not keep pace with conventional methods and may not meet immediate remedial requirements.

Furthermore, complicating the assessment of remedial success are conventional monitoring methods often lacking the capacity for real-time evaluations of microbial activity **(Singh *et al.*, 2024)**.

Table 2. Comparison between traditional methods and biological methods

Parameter	Traditional methods	Biological methods
Principle	Based on electrochemical, solvent extraction, evaporation, reverse osmosis, adsorption, ion exchange, membrane filtration, and precipitation techniques.	Based on transforming toxic metals into less toxic form using bacteria, fungi, algae or plants.
Efficiency	❖ 70–99% removal (rapid) ❖ Efficiency drops for low-concentration metals.	❖ 60–95% removal (species-dependent). ❖ Slower but sustainable.
Cost	❖ High capital/operational costs (e.g., membrane replacement, chemical reagents)	❖ Low operational cost ❖ Requires minimal infrastructure
Environmental Impact	❖ Toxic sludge/byproducts (e.g., chemical sludge from precipitation) ❖ High energy/water use	❖ Eco-friendly (no secondary pollution) ❖ Produces biodegradable biomass
Scalability	❖ Easily scalable for industrial applications ❖ Standardized processes	❖ Limited to moderate scales (field trials ongoing) ❖ Site-specific optimization needed
Limitations	❖ High waste generation ❖ Non-selective (removes all ions) ❖ Cost-prohibitive for large volumes	❖ Slow kinetics ❖ -Sensitive to extreme pH/temperature ❖ Metal specificity
Mechanism	❖ Biosorption, bioaccumulation, enzymatic transformation, rhizofiltration	❖ Precipitation, chelation, electrostatic attraction, physical sieving
Advantages	❖ Simple ❖ Economically viable ❖ Efficient when confronting with certain heavy metals ❖ Good removal	❖ Applicable to both *in-situ* and *ex-situ* ❖ Efficient when confronting with certain heavy metals ❖ Lessened secondary pollutant accumulation ❖ Cost effectiveness ❖ Specificity and ability to operate in low concentrations. ❖ Environmental friendly.
Disadvantages	❖ Many of these methods were unable to clean up the contaminated environment. ❖ Operational intricacy and maintenance costs ❖ secondary waste production ❖ Solvent loss ❖ Phase separation difficulty ❖ Emulsion formation ❖ High energy requirements ❖ Incomplete metal removal ❖ Generate large amounts of sludge, and produce harmful waste.	❖ Microbial activity has consequences ❖ Changes in hydrological and geochemical conditions may result in the remobilization of pollutants ❖ The bioremediation process takes a lot longer than other forms of treatment ❖ The degradation products, may be more hazardous than the parent molecule.

The Role of Remote Sensing and GIS in Heavy Metal Bioremediation

Heavy metal pollution is a significant environmental concern due to its persistence, toxicity, and bio-accumulative nature. Conventional remediation methods, such as excavation, chemical leaching, and solidification, are often expensive and environmentally disruptive. Bioremediation, which employs microorganisms, plants, and fungi to remove or stabilize heavy metals, has gained attention as a sustainable and cost-effective alternative. Recent advancements in Remote Sensing (RS) and Geographic Information Systems (GIS) have enhanced bioremediation strategies by enabling precise detection, monitoring, and assessment of contaminated sites. These geospatial technologies provide real-time data, spatial analysis, and predictive modeling, which significantly improve the efficiency and scalability of bioremediation techniques. Remote sensing technologies, including multispectral and hyperspectral imaging, play a crucial role in detecting heavy metal contamination in soil and water. Satellite-based sensors such as Landsat, Sentinel-2, MODIS, and Hyperion can detect spectral changes associated with heavy metal stress in vegetation and soil composition **(Shi *et al.*, 2018; El-Zeiny & Abd El-Hamid, 2022)**.

Spectral indices like the Normalized Difference Vegetation Index (NDVI) and Chlorophyll Content Index (CCI) are widely used to assess plant health, which is directly impacted by heavy metal toxicity **(Chatterjee, 2024)**. These indices help evaluate the effectiveness of phytoremediation, a bioremediation technique that utilizes plants to absorb and stabilize heavy metals in contaminated areas. Additionally, thermal infrared remote sensing can monitor microbial activity in bioremediation processes by detecting temperature variations associated with metabolic processes **(Gholizadeh *et al.*, 2018)**.

Geographic Information Systems (GIS) facilitate spatial analysis and modeling of heavy metal contamination patterns, providing valuable insights for bioremediation planning and management. GIS-based interpolation techniques, such as kriging and inverse distance weighting (IDW), help in mapping pollution hotspots and predicting contamination spread over time **(Anthony, 2023)**. This spatial information is essential for selecting appropriate bioremediation strategies, as different microbial and plant species exhibit varying efficiencies depending on the type and concentration of heavy metals present. Furthermore, GIS can integrate multiple datasets, including soil properties, hydrology, and land use patterns, to develop decision support systems (DSS) for optimizing bioremediation efforts **(Khalifa *et al.*, 2023; Gheibi *et al.*, 2024)**. These DSS platforms use artificial intelligence (AI) and machine learning algorithms to predict remediation efficiency and recommend site-specific bioremediation techniques.

One of the major advantages of using RS and GIS in heavy metal bioremediation is their ability to provide cost-effective, large-scale, and real-time monitoring of contaminated sites. Traditional field-based sampling methods are time-consuming and require extensive laboratory analysis, whereas remote sensing allows for rapid and non-invasive assessment of contamination levels **(Xu *et al.*, 2023)**. Moreover, temporal analysis using satellite imagery enables continuous monitoring of remediation progress, allowing researchers and policymakers to make data-driven decisions regarding remediation interventions. UAV (Unmanned Aerial Vehicle) based remote sensing has also gained popularity for localized contamination assessment, providing high-resolution data for targeted bioremediation applications **(Gan *et al.*, 2023)**.

Despite these advantages, certain challenges exist in the integration of RS and GIS for heavy metal bioremediation. The accuracy of remote sensing data depends on factors such as sensor resolution, atmospheric interference, and calibration with ground-based measurements. Additionally, while GIS models can predict contamination trends, they require extensive validation with field data to ensure reliability. Future advancements in hyperspectral imaging, AI-driven geospatial analysis, and sensor fusion techniques will further enhance the application of RS and GIS in bioremediation. The integration of Internet of Things (IoT) sensors with GIS platforms is also expected to improve real-time monitoring capabilities, providing a more comprehensive approach to managing heavy metal pollution **(Pamula *et al.*, 2022; Aziz *et al.*, 2024)**.

Future prospects

Heavy metals are considered pollutants in the soil and water environment posing a significant hazard to the environment, because they are persistently toxic and resistant to biodegradation and bioaccumulation. Bioremediation is recognized as an environmentally sustainable and effective approach for the removal of heavy metals from contaminated environments. Via processes including bioaccumulation, biosorption, and biotransformation **(Verma & Sharma, 2017; Leong & Chang, 2020)**, microorganisms, plants, and microalgae demonstrate tremendous potential for heavy metal remediation. Recent technological developments have improved microbial enzyme ability to more effectively breakdown heavy metals **(Ojuederie & Babalola, 2017)**. Microalgae offer high availability, economic feasibility, and efficient metal removal, among other advantages **(Leong & Chang, 2020)**. Biosurfactants and genetically modified organisms offer complementary advantages in the removal of heavy metals **(Jeyakumar *et al.*, 2022).** A sustainable substitute for conventional approaches, bioremediation continues to pose difficulties in developing economically feasible technologies **(Leong & Chang, 2020).** Future studies should look at latent ability of biological species to bring environmental uniqueness back **(Verma & Sharma, 2017)**.

CONCLUSION

This study aimed to compare bioremediation with conventional heavy metal removal techniques, evaluating their effectiveness, cost-efficiency, and environmental impact. Though traditional methods are widely used, they often involve high costs and generate significant waste, underscoring the need for more sustainable alternatives. Bioremediation presents a promising solution due to its ability to leverage microorganisms for pollutant degradation in an eco-friendly and cost-effective manner. Microorganisms, with their remarkable metabolic adaptability, can thrive in diverse environmental conditions, making them highly effective in breaking down contaminants. Engineered *in situ* bioremediation further enhances this process by optimizing physicochemical conditions to accelerate microbial activity and pollutant degradation. However, its success depends on environmental factors that support microbial growth and activity. Despite variability in outcomes, the advantages of bioremediation—such as lower costs, reduced environmental impact, and sustainability—often outweigh its limitations. Rather than replacing traditional remediation methods, bioremediation can serve as a complementary strategy, making it an attractive and viable alternative for heavy metal removal in environmental cleanup efforts.

Remote sensing and geographic information systems have revolutionized heavy metal bioremediation by offering efficient, scalable, and cost-effective monitoring solutions. Their capacity to identify contamination, evaluate remediation progress, and enhance site selection renders them essential instruments in environmental management. The evolution of geospatial technologies is anticipated to enhance their application in bioremediation, thereby advancing sustainable remediation strategies. Future research must prioritize enhancing sensor accuracy, incorporating AI-driven predictive models, and broadening the application of UAV-based remote sensing for localised bioremediation efforts.

REFERENCES

Adams, G.O.; Fufeyin, P.T. and Okoro, S.E. (2015). Biostimulation and Bioaugmention: A Review. Int. J. Environ. Bioremediat. Biodegrad., 3(1): 28–39.

Ahluwalia, S.S. and Goyal, D. (2007). Microbial and plant derived biomass for removal of heavy metals from wastewater. Bioresour. Technol., 98(12): 2243–2257.

Ali, H.; Khan, E. and Sajad, M.A. (2013). Phytoremediation of heavy metals-Concepts and applications. Chemosphere, 91: 869–881.

Alkorta, I.; Hernández-Allica, J.; Becerril, J.M.; Amezaga, I.; Albizu, I. and Garbisu, C. (2004). Recent findings on the phytoremediation of soils contaminated with environmentally toxic heavy metals and metalloids such as zinc, cadmium, lead, and arsenic. Rev. Environ. Sci. Biotechnol., 3: 71–90.

Amoroso, M.J.; Castro, G.R.; Carlino, F.J.; Romero, N.C.; Hill, R.T. and Oliver, G. (1998). Screening of heavy metal-tolerant actinomycetes isolated from the Sali River. J. Gen. Appl. Microbiol., 44(2): 129–132.

Anthony, T. (2023). Assessment of Heavy Metal Contamination in Wetlands Soils Around an Industrial Area Using Combined GIS-Based Pollution Indices and Remote Sensing Techniques. Air Soil Water Res., 16: 11786221231214062.

Arief, V.O.; Trilestari, K.; Sunarso, J.; Indraswati, N. and Ismadji, S. (2008). Recent progress on biosorption of heavy metals from liquids using low cost biosorbents: characterization, biosorption parameters and mechanism studies. CLEAN–Soil Air Water, 36(12): 937–962.

Aziz, M.A.; El-Zeiny, A.; Hassan, F.M. and Naguib, D.M. (2024). Coastal water quality dynamics of the Red Sea, southeast coast of Egypt using GeoAI and ChatGPT. J. Afr. Earth Sci., 219: 105409.

Bakalár, T.; Búgel, M. and Gajdošová, L. (2009). Heavy metal removal using reverse osmosis. Acta Montan. Slovaca, 14(3): 250.

Banat, I.M.; Franzetti, A.; Gandolfi, I.; Bestetti, G.; Martinotti, M.G.; Fracchia, L.; Smyth, T.J. and Marchant, R. (2010). Microbial biosurfactants production, applications and future potential. Appl. Microbiol. Biotechnol., 87: 427–444.

Barakat, M.A. (2011). New trends in removing heavy metals from industrial wastewater. Arab. J. Chem., 4(4): 361–377.

Beni, A.A. and Esmaeili, A. (2020). Biosorption, an efficient method for removing heavy metals from industrial effluents: a review. Environ. Technol. Innov., 17: 100503.

Chaemiso, T.D. and Nefo, T. (2019). Removal methods of heavy metals from laboratory wastewater. J. Nat. Sci. Res., 9(2): 36–42.

Chappell, J. (1997). Phytoremediation of TCE using Populus. US Environ. Prot. Agency, Technol. Innov. Off., 38.

Chatterjee, S. (2024). Site assessment, suitability, and strategy references for in-situ phytoremediation: a case study of Asansol-Pandabeswar mining region. Environ. Dev., 50: 100992.

Chatterjee, S.K.; Bhattacharjee, I. and Chandra, G. (2010). Biosorption of heavy metals from industrial waste water by Geobacillus thermodenitrificans. J. Hazard. Mater., 175(1-3): 117–125.

Chiaki, I.; Naoko, K.; Masazumi, K.; Takeshi, K. and Naoko, H.S. (2007). Isolation and characterization of antibacterial substances produced by marine actinomycetes in the presence of seawater. Actinomycetologica, 21: 27–31.

Darwesh, O.M.; Shalaby, M.; Gharieb, M.M. and Matter, I.A. (2023). Application of the Novel Cu-Resistant Fungus *Aspergillus niger* A3 in Bioremoval of Cu-NPs from its Aqueous Solutions. OpenNano.

Das, A. and Osborne, J.W. (2018). Bioremediation of heavy metals. In: "Nanotechnology, Food Security and Water Treatment." Springer, pp. 277–311. https://doi.org/10.1007/978-3-319-70166-0_9.

Das, S. (Ed.). (2014). Microbial biodegradation and bioremediation. Elsevier, Amsterdam.

Deepika, L. and Kannabiran, K. (2010). Biosurfactant and heavymetal resistance activity of *Streptomyces* spp. isolated from saltpan soil. Br. J. Pharm. Toxicol., 1: 33–39.

Dixit, R.; Wasiullah, X.; Malaviya, D.; Pandiyan, K.; Singh, U.B.; Sahu, A. and Paul, D. (2015). Bioremediation of heavy metals from soil and aquatic environment: an overview of principles and criteria of fundamental processes. Sustainability, 7(2): 2189–2212.

Doty, S.L.; Freeman, J.L.; Cohu, C.M.; Burken, J.G.; Firrincieli, A.; Simon, A. and Blaylock, M.J. (2017). Enhanced degradation of TCE on a superfund site using endophyte-assisted poplar tree phytoremediation. Environ. Sci. Technol., 51(17): 10050–10058.

Ekanayake, M. and Manage, P.M. (2022). Mycoremediation Potential of Synthetic Textile Dyes by *Aspergillus niger* via Biosorption and Enzymatic Degradation. Environ. Nat. Resour. J., 20(3): 1–12.

El Baz, S.; Baz, M.; Barakate, M.; Hassani, L.; El Gharmali, A. and Imziln, B. (2015). Resistance to and accumulation of heavy metals by actinobacteria isolated from abandoned mining areas. Sci. World J., 2015.

El-Naggar, A.H. and Sheikh, H.M. (2014). Response of the green microalga *Chlorella vulgaris* to the oxidative stress caused by some heavy metals. Life Sci. J., 11(10): 1349–1357.

El-Zeiny, A.M. and Abd El-Hamid, H.T. (2022). Environmental and human risk assessment of heavy metals at northern Nile Delta region using geostatistical analyses. Egypt. J. Remote Sens. Space Sci., 25(1): 21–35.

Erakhrumen, A.A. (2007). Phytoremediation: An environmentally sound technology for pollution prevention, control and remediation in developing countries. Educ. Res. Rev., 2: 151–156.

Farombi, E.O.; Adelowo, O.A. and Ajimoko, Y.R. (2007). Biomarkers of oxidative stress and heavy metal levels as indicators of environmental pollution in African cat fish (Clarias gariepinus) from Nigeria Ogun River. Int. J. Environ. Res. Public Health, 4: 158–165.

Gan, W.; Zhang, Y.; Xu, J.; Yang, R.; Xiao, A. and Hu, X. (2023). Spatial distribution of soil heavy metal concentrations in road-neighboring areas using UAV-based hyperspectral remote sensing and GIS technology. Sustainability, 15(13): 10043 .

Ganesan, S.; Padmapriya, G.; Arya, S.N. and Kudva, S. (2024). A Review of Bioremediation of Soil Contaminated with Heavy Metals. Adv. Technol. Sci. Eng., 219–226. https://doi.org/10.2174/9789815165586124020021

Gheibi, M.; Masoomi, S.R.; Magala, M.U.; Fathollahi-Fard, A.M.; Ghazikhani, A. and Behzadian, K. (2024). The Application of Artificial Intelligence (AI) in Adsorption Process of Heavy Metals: A Systematic Review. Environ. Ind. Lett., 2(2): 57–78.

Gholizadeh, A.; Saberioon, M.; Ben-Dor, E. and Borůvka, L. (2018). Monitoring of selected soil contaminants using proximal and remote sensing techniques: Background, state-of-the-art and future perspectives. Crit. Rev. Environ. Sci. Technol., 48(3): 243–278.

Hassanein, N.M.; El-Gendy, M.M.; Ibrahim, H.A.E.-H. and El Baky, D.H.A. (2012). Screening and evaluation of some fungal endophytes of plant potentiality as low-cost adsorbents for heavy metals uptake from aqueous solution. Egypt. J. Exp. Biol., 8: 17–23.

Hocinat, A.; Ali-Khodja, H. and Boudemagh, A. (2019). Capability of *Nocardia nova* found in activated sludge to use synthetic BTEX as sole source of carbon and energy. Int. J. Environ. Stud.

Hozzein, W.N.; Ahmed, M.B. and Tawab, M.S.A. (2012). Efficiency of some actinomycete isolates in biological treatment and removal of heavy metals from wastewater. Afr. J. Biotechnol., 11(5): 1163–1168.

Igwegbe, A.O.; Agukwe, C.H. and Negbenebor, C.A. (2013). A survey of heavy metal (lead, cadmium and copper) contents of selected fruit and vegetable crops from Borno State of Nigeria. Int. J. Eng. Sci., 2(1): 01–05.

Jacob, J.M.; Karthik, C.; Saratale, R.G.; Kumar, S.S.; Prabakar, D.; Kadirvelu, K. and Pugazhendhi, A. (2018). Biological approaches to tackle heavy metal pollution: a survey of literature. J. Environ. Manage., 217: 56–70. https://doi.org/10.1016/j.jenvman.2018.03.077

Jayaraman, P.; Naveen Kumar, T.; Maheswaran, P.; Sagadevan, E. and Arumugam, P. (2012). In vitro studies on biodegradation of chlorpyrifos by Trichoderma viride and T. harzianum. J. Pure Appl. Microbiol., 6: 1465–1474.

Jeyakumar, P.; Debnath, C.; Vijayaraghavan, R. and Muthuraj, M. (2023). Trends in bioremediation of heavy metal contaminations. Environ. Eng. Res., 28(4). https://doi.org/10.4491/eer.2021.631

Joseph, S.; Shanmugha, P.S.; Seghal, K.G.; Thangavelu, T. and Sapna, B.N. (2009). Sponge-associated marine bacteria as indicators of heavy metal pollution. Microbiol. Res., 164: 352–363.

Kapahi, M. and Sachdeva, S. (2019). Bioremediation options for heavy metal pollution. J. Health Pollut., 9(24): 191203.

Kapoor, A. and Viraraghvan, T. (1995). Fungal biosorption - An alternative treatment option for heavy metal bearing wastewater: A review. Bioresour. Technol., 53: 195–206.

Karami, A. and Shamsuddin, Z.H. (2010). Phytoremediation of heavy metals with several efficiency enhancer methods. Afr. J. Biotechnol., 9(25): 3689–3698.

Khalifa, A.M.; ElBaghdady, K.Z.; El Kafrawy, S.B. and El-Zeiny, A.M. (2023). Bioaccumulation of Pb, Ni and Cd by *Bacillus cereus* isolated from Lake Qarun, Egypt, using the spatial technique. Egypt. J. Aquat. Biol. Fish., 27 (4).

Koushal, S.; Kanagalabavi, A.C.; Kumar, A.; Arya, D.S.; Nehul, J.N.; Panigrahi, C.K.; Haloi, D.; Chauhan, N. and Muhilan, G. (2025). Bioremediation of Soil

Pollution: An Effective Approach for Sustainable Agriculture. Int. J. Plant Soil Sci., 37(1): 400–410. https://doi.org/10.9734/ijpss/2025/v37i15282

Kulshreshtha, A.; Agrawal, R.; Barar, M. and Saxena, S. (2014). A review on bioremediation of heavy metals in contaminated water. IOSR J. Environ. Sci. Toxicol. Food Technol., 8(7): 44–50.

Kusdini, K.; Kastilon, K.; Gumanti, R.; Reflis, R. and Utama, S.P. (2024). Kajian Penggunaan Bakteri *Bacillus subtilis* dalam Penanganan Tumpahan Minyak Mentah. Insologi J. Sains Teknol., 3(3): 262–270.

Leong, Y.K. and Chang, J.S. (2020). Bioremediation of heavy metals using microalgae: Recent advances and mechanisms. Bioresour. Technol., 303: 122886.

Lou, J.C. and Chang, C.K. (2007). Completely treating heavy metal laboratory waste liquid by an improved ferrite process. Sep. Purif. Technol., 57(3): 513–518.

Madhavi, G.N. and Mohini, D.D. (2015). Review paper on Parameters affecting bioremediation. Int. J. Life Sci. Pharm. Res., 2(3): 77–80.

Malik, Z.A. and Ahmed, S. (2012). Degradation of petroleum hydrocarbons by oil field isolated bacterial consortium. Afr. J. Biotechnol., 11(3): 650–658.

Mandal, S.H.; Halder, P. and Panigrahi, A.K. (2024). Bioremediation of Heavy Metals by Microbial Process. https://doi.org/10.52756/lbsopf.2024.e01.005

Martinez, M.; Bernal, P.; Almela, C.; Vélez, D.; García-Agustín, P.; Serrano, R. and Navarro-Aviñó, J. (2006). An engineered plant that accumulates higher levels of heavy metals than *Thlaspi caerulescens*, with yields of 100 times more biomass in mine soils. Chemosphere, 64: 478–485.

Mesjasz-Przybylowicz, J.; Nakonieczny, M.; Migula, P.; Augustyniak, M.; Tarnawska, M.; Reimold, W.U.; Koeberl, C.; Przybylowicz, W. and Glowacka, E. (2004). Uptake of cadmium, lead, nickel and zinc from soil and water solutions by the nickel hyperaccumulator *Berkheya coddii*. Acta Biol. Cracov. Ser. Bot., 46: 75–85.

Mungray, A.A.; Kulkarni, S.V. and Mungray, A.K. (2012). Removal of heavy metals from wastewater using micellar enhanced ultrafiltration technique: A review. Cent. Eur. J. Chem., 10: 27– 46.

Murthy, S.; Bali, G. and Sarangi, S.K. (2012). Biosorption of lead by *Bacillus cereus* isolated from industrial effluents. Br. Biotechnol. J., 2(2): 73.

Neethu, T.M.; Dubey, P.K.; Patel, K.G.; Karmakar, N. and Mishra, A. (2023). Bio-sorbents: A Novel Technology to Mitigate Heavy Metal Pollution. Int. J. Plant Soil Sci., 35(19): 1481–1487.

Niu, G.L.; Zhang, J.J.; Zhao, S.; Liu, H.; Boon, N. and Zhou, N.Y. (2009). Bioaugmentation of a 4-chloronitrobenzene contaminated soil with *Pseudomonas putida* ZWL73. Environ. Pollut., 157(3): 763–771.

Ojuederie, O.B. and Babalola, O.O. (2017). Microbial and plant-assisted bioremediation of heavy metal polluted environments: a review. Int. J. Environ. Res. Public Health, 14(12): 1504. https://doi.org/10.3390/ijerph14121504

Olukanni, D.O.; Agunwamba, J.C. and Ugwu, E.I. (2014). Biosorption of heavy metals in industrial wastewater using microorganisms (*Pseudomonas aeruginosa*). Am. J. Sci. Ind. Res., 5(2): 81–87.

Pamula, A.S.; Ravilla, A. and Madiraju, S.V.H. (2022). Applications of the internet of things (IoT) in real-time monitoring of contaminants in the air, water, and soil. Eng. Proc., 27(1): 26.

Patil, D.P. and Tarfe, K. (2024). An overview of bioremediation. In: "Bioremediation and Biotechnology," Vol. 3, pp. 75–103. https://doi.org/10.58532/v3bbbt14p1ch7

Pinto, A.P.; De Varennes, A.; Fonseca, R. and Teixeira, D.M. (2015). Phytoremediation of soils contaminated with heavy metals: techniques and strategies. Phytoremediation: Management of Environmental Contaminants, Vol. 1, pp. 133–155.

Razzak, S.A.; Faruque, M.O.; Alsheikh, Z.; Alsheikhmohamad, L.; Alkuroud, D.; Alfayez, A. and Hossain, M.M. (2022). A comprehensive review on conventional and biological-driven heavy metals removal from industrial wastewater. Environ Adv 7: 100168.https://doi.org/10.1016/j.envadv.2022.100168.

Remenár, M.; Karelová, E.; Harichová, J.; Zámocký, M.; Krčová, K. and Ferianc, P. (2014). Actinobacteria occurrence and their metabolic characteristics in the nickel-contaminated soil sample. Biologia, 69, 1453-1463.

Rizwan, M.; Ali, S.; Rizvi, H.; Rinklebe, J.; Tsang, D.C.; Meers, E. and Ishaque, W. (2016). Phytomanagement of heavy metals in contaminated soils using sunflower: a review. Crit. Rev. Environ. Sci. Technol., 46(18), 1498-1528.

Robinson, B.H.; Brooks, R.R.; Howes, A.W.; Kirkman, J.H. and Gregg, P.E.H. (1997). The potential of the high-biomass nickel hyperaccumulator *Berkheya coddii* for phytoremediation and phytomining. J. Geochem. Explor., 60(2), 115-126.

Rodríguez-Fonseca, M.F.; Sánchez-Suárez, J.; Valero, M.F.; Ruiz-Balaguera, S. and Díaz, L.E. (2021). Streptomyces as potential synthetic polymer degraders: a systematic review. Bioengineering, 8(11): 154.

Sachan, R.; Yadav, A. and Verma, H. (2022). Bioremediation of Heavy Metals. Vigyan Varta, SP1: 24–27.

Sekara, A.; Poniedzialeek, M.; Ciura, J. and Jedrszczyk, E. (2005). Cadmium and lead accumulation and distribution in the organs of nine crops: implications for phytoremediation. Pol. J. Environ. Stud., 14(4): 509–516.

Selvaraj, D. and Arivazhagan, M. (2024). Synergistic effects of *Spirulina platensis* cultivation in textile wastewater towards nutrient removal and seed germination study. Environ. Pollut., 357: 124435.

Shaaban, T.M.; Ibrahim, H.A.H. and Hanafi, M.A.A. (2016). Distribution of bacteria in Lake Qarun, AL Fayoum, Egypt (2014 -2015) in relation to its physical and hydrochemical characterization. J. Biosci. Appl. Res., 2: 601– 615.

Sharma, S. and Pathak, H. (2014). Basic techniques of phytoremediation. Int. J. Sci. Eng. Res., 5(4): 584–604.

Shi, T.; Guo, L.; Chen, Y.; Wang, W.; Shi, Z.; Li, Q. and Wu, G. (2018). Proximal and remote sensing techniques for mapping of soil contamination with heavy metals. Appl. Spectrosc. Rev., 53(10): 783–805.

Singh, H.; Kumar, S. and Arya, A. (2024). Challenges in Bioremediation: Overcoming Environmental and Technological Barriers. In: Challenges and Sustainable Solutions in Bioremediation, pp. 143–162. CRC Press.

https://doi.org/10.1201/9781003407317-9

Sreedevi, P.R.; Suresh, K. and Jiang, G. (2022). Bacterial bioremediation of heavy metals in wastewater: A review of processes and applications. J. Water Process Eng., 48: 102884.

Srivastava, S.; Agrawal, S.B. and Mondal, M.K. (2015). A review on progress of heavy metal removal using adsorbents of microbial and plant origin. Environ. Sci. Pollut. Res., 22: 15386–15415.

Suthindhiran, K. and Kannabiran, K. (2009). Hemolytic activity of *Streptomyces* spp VITSDK1. isolated from marine sediments in Southern India. J. Mycol. Méd., 19: 77–86.

Thapa, B.; Kumar, A.K.C. and Ghimire, A. (2012). A review on Bioremediation of petroleum hydrocarbon contaminants in soil. Kathmandu Univ. J. Sci. Eng. Technol., 8(1): 164–170.

Thirumalaivasan, N.; Gnanasekaran, L.; Kumar, R.S.S.; Rajesh, D.; Thanigaivel, S.; Rajendran, S.; Nangan, S. and Kanagaraj, K. (2024). Utilization of fungal and bacterial bioremediation techniques for the treatment of toxic waste and biowaste. Front. Mater., 11. https://doi.org/10.3389/fmats.2024.1416445

Timková, I.; Sedláková-Kaduková, J. and Pristaš, P. (2018). Biosorption and Bioaccumulation Abilities of Actinomycetes/Streptomycetes Isolated from Metal Contaminated Sites. Separations, 5: 54.

Verma, N. and Sharma, R. (2017). Bioremediation of toxic heavy metals: a patent review. Recent Pat. Biotechnol., 11(3): 171–187.

https://doi.org/10.2174/1872208311666170111111631

Vidali, M. (2001). Bioremediation. An overview. Pure Appl. Chem., 73: 1163–1172.

Xu, Z.; dos Muchangos, L.S.; Ito, L. and Tokai, A. (2023). Cost and health benefit analysis of remediation alternatives for the heavy-metal-contaminated agricultural land in a Pb–Zn mining town in China. J. Clean. Prod., 397: 136503.

Zouboulis, A.I.; Loukidou, M.X. and Matis, K.A. (2004). Biosorption of toxic metals from aqueous solutions by bacteria strains isolated from metal-polluted soils. Process Biochem., 39(8): 909–916.