Vol. 5 No. 1 (2026)

Pakistan Journal of Medical & Cardiological Review

https://pakjmcr.com/index.php/1/about

Online ISSN 3007-2387 | Print ISSN 3007-2379

Nasir et al., 2026

The Toxicity of Heavy Metals Contamination in Aquatic Environments: Review of Effective and Affordable Cleanup Techniques

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Received on 27 February, 2026
Accepted on 21 March, 2026
Published on 30 March, 2026

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Abstract

Rapid industrialization, urbanization and agricultural expansion has led to heavy metal contamination of aquatic environments, a major concern throughout the world as an environmental and health issue. Non-biodegradable, highly persistent and capable of bio accumulation in aquatic organisms, toxic metals like lead (Pb), mercury (Hg), cadmium (Cd) and arsenic (As) can enter the food chain and have serious impacts on human health. These metals can produce very serious toxic effects such as neurological, renal and developmental even at low levels. This review focuses on the major sources of heavy metal pollution, such as industrial effluents, mining activities, agricultural runoff and improper waste disposal. It also provides information on the chemical characteristics, mobility and transformation of these metals in aquatic systems that affect their toxicity and environmental effects. It is important to recognize these mechanisms to establish effective mitigation strategies. Moreover, the review critically assesses different methods of remediation including both physico-chemical and biological methods. The efficiency and limitations (including secondary pollution and cost) of conventional techniques like coagulation, precipitation, adsorption and membrane filtration are evaluated. Biological methods like phytoremediation and microbial bioremediation, which are considered more environmentally friendly and sustainable than traditional approaches, are highlighted for their potential applications. This study gives an overall insight of heavy metal pollution and the need to adopt integrated, affordable and environment compatible strategies for water treatment and long-term protection of the ecosystem.

Keywords: Heavy metals, Aquatic environments, Toxicity, Bioremediation, Chemical separation techniques, Precipitation, Coagulation, Flocculation, Industrial waste

1. Introduction

The availability of clean, potable water devoid of biotoxic components and substances is crucial to society's health and well-being [1,2]. Furthermore, a number of vital industries, such as food, electronics, and pharmaceuticals, depend heavily on clean water [3, 4]. Inorganic pollutants like heavy metals, arsenides, perchlorates, fluorides, nitrates, and phosphates are all harmful. Heavy metals are often defined as elements with relatively large atomic weights between 63.5 and 200.6 at. units that also exhibit a specific gravity greater than 5.0 [5]. Heavy metals are therefore naturally occurring elements that are identified by their high densities and large atomic masses. As a result of the rapid expansion of anthropogenic and heavy industrial processes, such as mining, metal-based surface plating, and the massive production of steel, paper, fertilizers, pesticides, and metal-based batteries [6], toxic inorganic pollutants have increased in a number of water sources. This pattern is especially prevalent in emerging areas [7, 8]

In contrast to many organic pollutants, such as food waste, organic dyes, and antibiotics, inorganic pollutants, particularly heavy metals, are not biodegradable [9]. This indicates that microorganisms do not naturally degrade them or transform them into species that are less or completely biotoxic [10]. As they accumulate in the environment, they become more dangerous. As a result, a number of inorganic pollutants are extremely toxic to humans and other living things. Heavy metal ions easily attach to live organisms due to their strong solubility in the aqueous phase, and then build up in their tissues [11].

There is a noticeable tendency for heavy metals to form complexes with biological substances, particularly those that include electron-rich elements such as nitrogen (N), oxygen (O), and sulfur (S) [12]. Though an excess of these metals can result in intoxication, important heavy metals are necessary for the body's main processes, including growth promotion, metabolic alterations, and the formation of key organs in living things.These vital heavy metals include, for example, copper (Cu), iron (Fe), manganese (Mn), cobalt (Co), zinc (Zn), and nickel (Ni). However, non-essential heavy metals like arsenic (As), cadmium (Cd), lead (Pb), mercury (Hg), chromium (Cr), and aluminum (Al) are not necessary for living things. [12]

These compounds are a major issue for environmental protection since they may have harmful and far-reaching effects on living things and the environment.[13, 14] A wide range of hazardous heavy metal contaminants are present in wastewater effluents from industrial processes, and the primary causes of elevated environmental toxicity are human and anthropogenic factors.[15] Natural activities including wind-driven soil erosion, forest fires, volcanic eruptions, biogenic processes, and the discharge of sea salt can all naturally deposit heavy metals into the ecosystem.[16] There are several ways that anthropogenic heavy metal poisoning of the environment can happen, including mining activities, the use of pesticides, fertilizers, and herbicides, as well as the irrigation of agricultural land with untreated sewage and industrial effluent.[16,17]

For instance, a variety of human activities, such as the manufacturing of chlorine and caustic soda, the preservation of paper and pulp, agricultural operations, and pharmaceutical manufacturing, can release mercury into the environment. Cadmium, a different heavy metal, is found in a lot of different geological materials, like rocks, coal, soil, and mineral fertilizers. Additionally, it is widely used in electroplating procedures for a variety of applications, such as the production of metal coatings, batteries, textiles, and pigments. An rise in heavy metal pollution in the environment is an inevitable consequence of these activities.[16,18]

Mercury, a potent neurotoxin, selectively damages nerve cells and seriously impairs the central and peripheral nervous systems' functionality [19]. Additionally, high levels of mercury accumulation in the body cause problems with the kidneys and respiratory system, which manifest as symptoms like shortness of breath and chest pain [20]. On the other hand, CD has also been shown to be a potential human carcinogen [21]. Human health may be seriously threatened by cadmium. Long-term exposure to cadmium has a negative effect on kidney function, and higher exposure levels may be lethal [22]. The central nervous system may be seriously harmed by Pb [23].

Pb may cause irreversible damage to the kidney, liver, and reproductive system as well as disrupt cellular and brain activities [24]. Among the symptoms that are most frequently associated with Pb poisoning's impairments in the functioning of living tissues are anemia, insomnia, migraines, vertigo, restlessness, muscle weakness, hallucinations, and kidney damage [24]. The two oxidation states of Cr(III) and Cr(VI) are the most prevalent forms of Cr in the aqueous phase [25]. Usually, exposure to Cr(VI) has more negative effects than Cr(III). Human physiology is impacted by Cr (VI), which also easily builds up in the food chain and causes major health issues that can range from slight skin irritation to potentially lethal lung tumors [26].

Because of heavy metals' toxicity, bioaccumulation, and persistence, which pose major risks to ecosystems, their effects on the environment are also a major issue. Heavy metal buildup in soils is a result of industrial processes, such as mining and manufacturing [27]. Runoff from mining sites, for instance, introduces significant quantities of metals like P and C into soils. This has a negative impact on soil fertility and disrupts important microbial populations that are necessary for the health of the soil [28]. Meanwhile, plankton, mollusks, and fish are put in danger by heavy metals like zinc and mercury that accumulate in sediments [29].

The effects of heavy metals on ecosystems are exacerbated by bioaccumulation and biomagnification, which result in their accumulation in the tissues of organisms, particularly in aquatic food chains. For instance, in aquatic settings, Hg undergoes biomagnification, which raises concentrations in species at higher trophic levels. This accumulation damages aquatic ecosystems, degrades water quality, and endangers recreational and drinking water safety. [30]

Heavy Metal Toxicity And Suppliers In Aquatic Environments

Heavy metal pollution in the environment has been primarily attributed to the rapid expansion of industry, the spread of agriculture, and the exponential growth of the human population. 31] Heavy metals have a major impact on the quality and safety of water because of their high toxicity, persistent presence, and bioaccumulation.[32] Heavy metals are a class of elements that can be harmful to the environment and human health due to their high density and atomic weight.

The public's concern for the environment and human health has been stoked by the fact that heavy metals are currently regarded as a major global issue and that they have recently become a significant issue with water contamination.[33, 34]

Therefore, to reduce the risk that heavy metals represent to the environment and human health, it is essential to understand their origins, chemical transformations, leaching processes, and modes of deposition. An overview of the global issue of heavy metal pollution in water bodies is provided in this section, with particular attention to the analysis of several man-made and natural sources . There are both natural and man-made reasons for the introduction of heavy metals into the environment. Heavy metal pollution is largely caused by human activities like mining, industrial operations, irrigation of agricultural fields with industrial water, industrialization, and agricultural practices,[35]

Natural phenomena, such as volcanic eruptions Weathering of rocks, biogenic processes, and wildfires all contribute to heavy metals entering the environment. 5 Modern industrial processes like electroplating, the production of electronic devices, mining, metallurgy, smelting, the production of fertilizer, the production of nuclear fuel, the production of paper, the emissions from power plants, and chemical etching are primarily responsible for the release of significant quantities of wastewater that contain harmful heavy metals into the environment.[7]

Industrial waste

According to research, agricultural and industrial activities that do not have an identified source, known as non-point source pollution, contribute significantly to the prevalence of cadmium, nickel, lead, zinc, arsenic, and mercury in the environment. Furthermore, considerable amounts of heavy metals can come from natural sources such as atmospheric deposits, which can be carried to the earth's surface through precipitation. It is known that industrial operations release heavy metal-contaminated wastewater into the environment, either directly into bodies of water or via leakage or runoff Heavy metal pollution of the aquatic environment is primarily caused by the sources listed above.[36-38]

Pakistan Journal of Medical & Cardiological Review
https://pakjmcr.com/index.php/1/about
Online ISSN Print ISSN
3007-2387 3007-2379

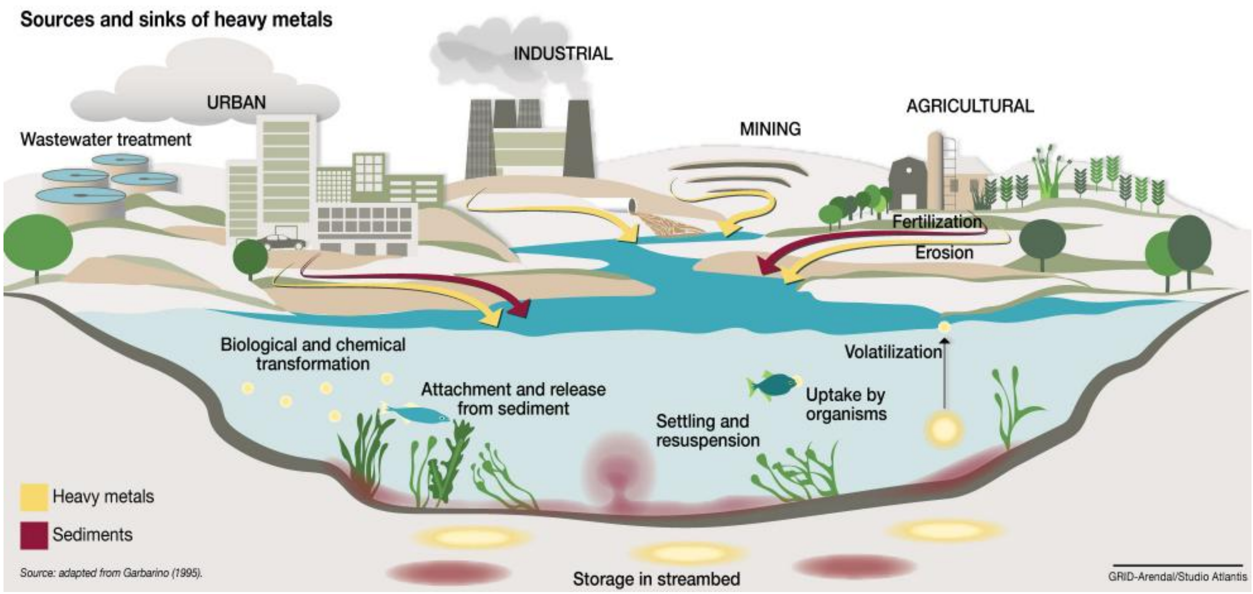

Fig:1. Source of heavy metals in water

Heavy metals can enter the human body in a variety of ways, including absorption, skin contact, and inhalation. These methods can lead to a variety of mild to severe health issues like loose intestines, anxiety, lung disease, fatigue, problems with the kidneys, stomach issues, skin infections, neurological issues, and malignant growth (Fig. 2). Some of these health concerns are caused by acute toxicity, whilst others are caused by persistent exposure to low levels of heavy metals.[39]

Aquaculture ponds have been shown to have water eutrophication and heavy metal contamination as a result of faulty aquaculture procedures, some of which are much more severe than safety guidelines allow.40,41High quantities of heavy metals in the food chain can induce severe ecotoxic stress in humans and aquatic creatures.42 Given the variable nature of heavy metal contamination in aquaculture environments, it is critical to understand how the ecological dangers of heavy metal exposure fluctuate during aquatic product growth

Soils contaminated with heavy metals restrict plant growth and survival, posing nutritional, ecological, and evolutionary challenges.43 The toxicity of heavy metals in plants is influenced by factors such as plant species, concentration, metal type, chemical form, and soil composition and pH. Heavy metals can affect the variety, amount, and function of microbial communities, as well as microorganisms' genetic composition. Heavy metal toxicity can alter the structure of nucleic acids, disrupt cell membranes, interfere with cellular functions, inhibit enzyme activity, and affect energy production. This can cause lipid oxidation and protein damage, altering the morphology,

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metabolism, and growth of microorganisms.44 Heavy metals in diet can accumulate in human bones and fatty tissues, resulting in nutritional shortages and reduced immunological responses. Several nations, including Japan, Iraq, and the United States, have reported situations in which thousands of people were ill or died. The most well-known of these is Minamata illness, which is caused by methylmercury toxicity. The outbreak was initially identified in 1956 at Minamata Bay in Kumamoto Prefecture, Japan, and a second epidemic occurred in 1965 along the Agano River in Niigata Prefecture, Japan.45 Various cases of food contamination induced by.

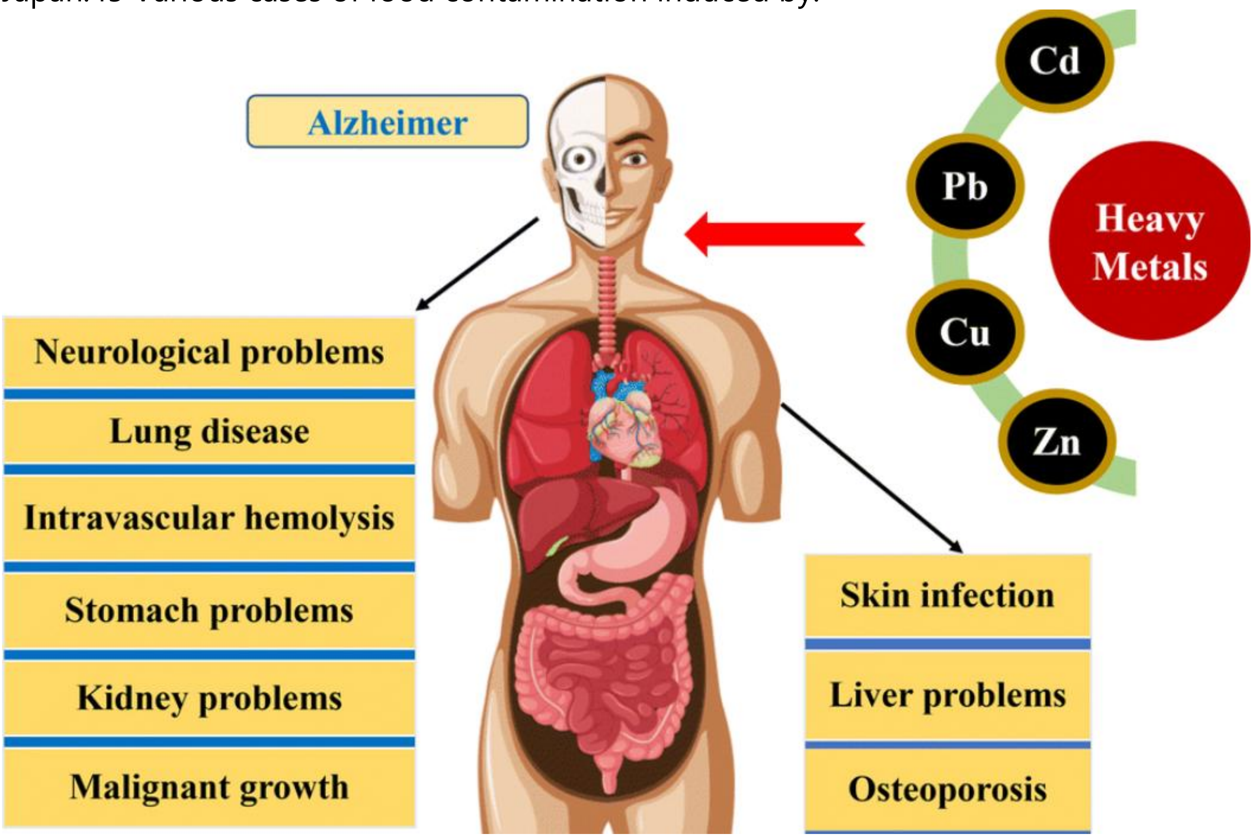

Fig:2. Disease that cause by heavy metals.

Sensory disruption, cerebellar ataxia, difficulties with speech and hearing, and a narrowing of the visual field were among the symptoms. Consumption of infected fish and shellfish, which absorbed the released methylmercury, caused the poisoning. Prior to 1960, the Jinzu river basin of Japan experienced an endemic illness called "itai-itai" caused by cadmium-contaminated rice. In 1961, an investigation found that Mitsui Mining and Smelting's Kamioka Mining Station was the source of cadmium pollution. The areas 30 kilometers downstream from the mine were the hardest hit. It wasn't until

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https://pakjmcr.com/index.php/1/about
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1968 that Japan's Ministry of Health and Welfare officially acknowledged that the symptoms of "itai-itai" sickness were caused by cadmium toxicity.

CHEMICALLY BASED SEPARATION

Heavy metal removal from wastewater by chemical techniques is well-established and widely utilized. This section covers the chemical-based Precipitation, coagulation, flocculation, and flotation are among the procedures covered.

Precipitation

Chemical precipitation, also known as coagulation precipitation, is a well-established and efficient process utilized in several sectors. The process makes solid particles out of dissolved metal ions, allowing for sedimentation. The reagent coagulant precipitates metal ions by pH changes, electro-oxidation potential, or co-precipitation [46]. Sediment removal is typically the next step. A simplified diagram of the chemical precipitation procedure can be found in Figure 4. Hydroxide precipitation is widely utilised because of its low cost, simplicity, and changeable pH [47]. The process involves adding a hydroxide to agitated wastewater, resulting in insoluble metal hydroxide precipitates. Metal ions may react with calcium hydroxide (lime) to form precipitates and calcium ions.

$$Metal^{n+} + Ca(OH)_2 \; e \; Metal(OH)_n \downarrow + Ca^{2+} \qquad (1)$$

pH ranges ranging from 9 to 11 were shown to boost process efficiency [48]. However, a high pH value is regarded a drawback of this procedure since it necessitates a huge amount of precipitates. Lime (CaO or $Ca(OH)_2$) is a highly effective hydroxide precipitate for the treatment of inorganic wastewater containing 1000 mg/L of heavy metals [49]. Supplementary Table 14 summarizes several investigations on hydroxide precipitation. This method primarily removes metals such as Zn^{2+}, Cu^{2+}, Ni^{2+}, Pb^{2+}, and Cr^{3+}. Even though a high dose is necessary for a proper pH, there are a few drawbacks, like a lot of sludge, dewatering, problems with disposal, amphoteric, and metal hydroxide precipitation when complexing agents are present. The sulfide participation approach outperforms the hydroxide method in terms of removal efficiency and dissolved solids. It has been demonstrated that this method eliminates harmful heavy metal ions [50]. Lower sulfide levels contribute to increased zinc concentrations in the effluent, whereas higher sulfide levels cause malodors from residual sulfide. Additionally, it has the potential to emit harmful and unpleasant hydrogen sulfide gas. To optimize results, sulfide precipitation should take place at a neutral pH (51). Metal sulfide precipitation reactions can follow Eq. (2).

$$Metal^{n+} + S^{2-} \; e \; MetalnS \downarrow \qquad (2)$$

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Supplementary Table 15 describes metal ion elimination using sulfite precipitation. The most significant disadvantages of sulfide are its toxicity and costly expense.

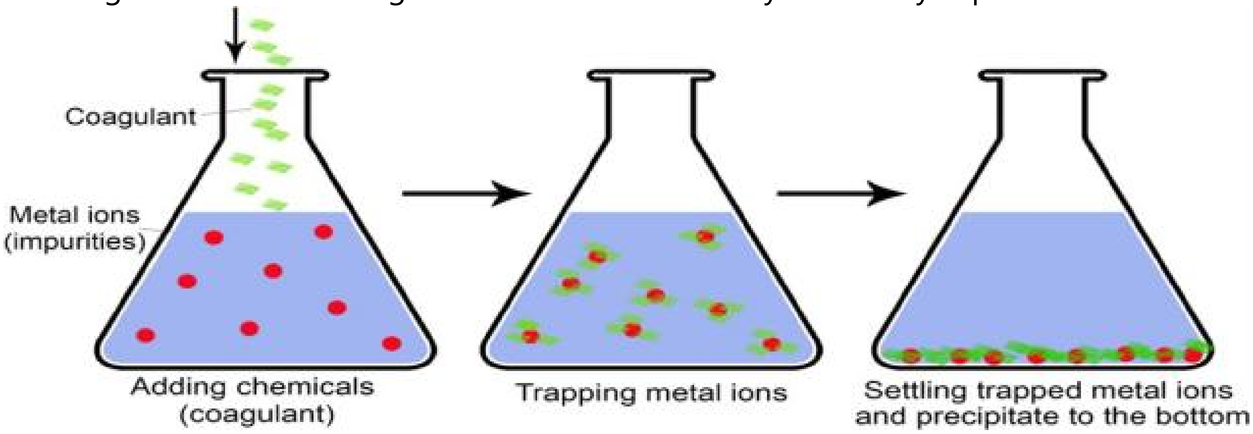

Figure 3 shows a simplified schematic of the chemical precipitation process.
Adding a coagulant to wastewater and stirring it helps trap metal ions that settle to the bottom of the container.

Carbonate precipitation is an excellent alternative to hydroxide precipitation, with optimal results at lower pH levels (52). This might be accomplished with sodium or calcium carbonate. Classical carbonates may be produced using Eq. (3 and 4)[53]:

$$Metaln++nNaCO3enMetal(CO3)+nNa+ \quad (3)$$

$$nMetal(CO3)+H2OeCO2\uparrow+(MeOH)nCO3\downarrow \quad (4)$$

While smaller sludge volume is possible, it may result in CO2 bubbles and require more reagents for effective precipitation [53].

Coagulation and Flocculation

Coagulation neutralizes the forces that keep colloids apart to destabilize them, whereas flocculation aggregates unstable particles [54]. Traditional coagulants include aluminum, ferrous sulfate, and ferric chloride, which are used to neutralize ions. Flocculation is the process by which particles are bound together to produce big agglomerates using a flocculant such as polyaluminum chloride (PAC), polyferric sulfate (PFS), polyacrylamide (PAM), or other macromolecule flocculants [55]. The PE was described as one of the most practical flocculations, although the resulting sludge might be toxic [54]. Most flocculants are synthetic and cannot be broken down by bacteria [56].

Figure 4 shows the process, including sedimentation. The use of inorganic coagulants comes with a number of drawbacks, some of which include the need for a significant amount of sludge, the fact that they are selective for particular metals, their ineffectiveness with new pollutants, the color of the effluent, their ineffectiveness with natural coagulants, and the difficulty of scaling up [57]. This process removes heavy metals such as Cu2+, Pb2+, and Ni2+. Other metals including As2+, Se2+, Cr2+, Sb3+, Sb5+, and Ag2+ can also be effectively removed.

Flotation

Diverse metal ions are removed through flotation. A general schematic for the flotation process is shown in Figure 5. Extensive research was conducted on dissolved air flotation, ion flotation, and precipitation flotation processes. Dissolved air flotation involves adding air (or gas) to wastewater to create micro-bubbles that adhere to metal ions, resulting in reduced density agglomerates and more flocs through the wastewater. Remove the slug that has collected on the top surface with ease [58].

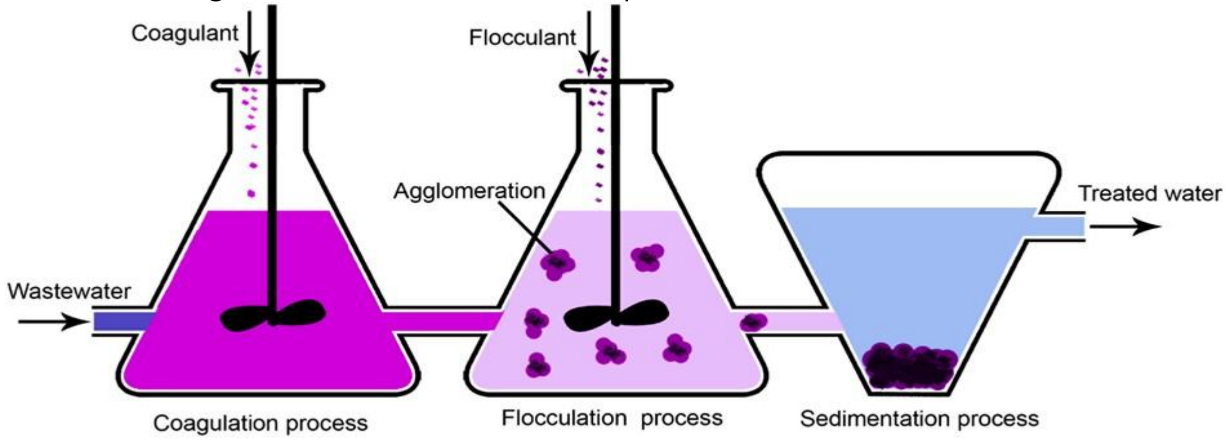

Figure 4 shows a schematic of the coagulation-flocculation treatment procedure. Coagulation and flocculation might occur sequentially or simultaneously. Filtration is a viable alternative to sedimentation.

Figure 5 depicts a schematic of the flotation treatment procedure. Chemicals like collectors attach to metal ions and microbubbles, resulting in lesser density agglomerates that float and are removed from the treatment column.

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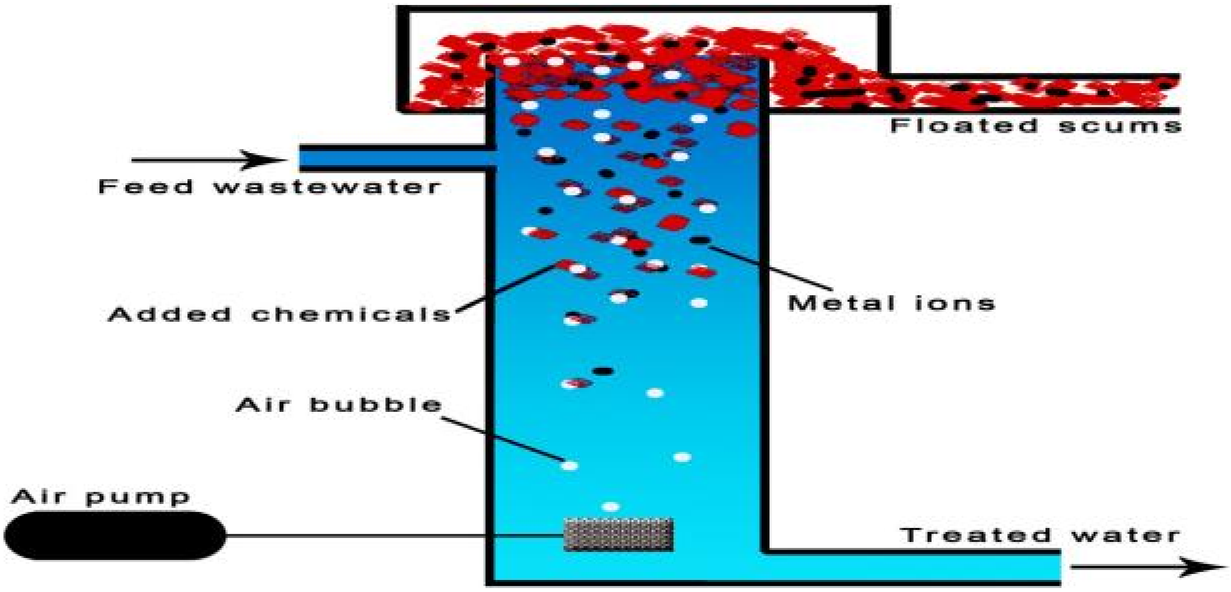

Surfactants are used to make metal species more hydrophobic during the ion flotation process. These species are then removed by air bubbles. Surfactants act as collectors and frothers influence ion flotation indices [59]. Ion flotation is inefficient for large amounts of wastewater with low metal ion concentrations [60]. The ion flotation technique is energy-efficient, requires less volume, produces less sludge, and provides selective treatment [61]. The precipitation flotation procedure uses chemical precipitates and microbubbles. The process of precipitation flotation is quick and efficient [62]. Techniques like flotation offer advantages like quick operation, compact design, and low cost. Efficient and non-toxic surfactants are essential for ion flotation, as they act as collectors. Chemical synthetic surfactants are versatile, selective, and simple to manufacture. However, cost and toxicity concerns restrict them. Biosurfactants may appear to be beneficial to the environment, but they are difficult to process, require a large dose, and have low removal rates [59]. With advantages comparable to those of synthetic and biosurfactants, nanoparticles have been suggested as a new collector [59].

Bioremediation

Since the 21st century, there has been an increasing awareness of the need to protect the natural environment. Alternatives to conventional physicochemical methods that make use of bacteria and plants to absorb metals are biotechnological approaches [63]. Bioremediation, especially phytoremediation, is a cost-effective and energy-efficient alternative technique [64]. To remove contaminants from soil and other environments, bioremediation makes use of enzymes, plants, and bacteria. It uses biological mechanisms in plants and microorganisms to remove contaminants and restore the

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environment to its natural condition [65]. Microbes remove metals from contaminated environments by chelation, leaching, redox transformation, and methylation. Because it has an effect on the material's oxidation state and makes it less harmful, metal ion elimination is not complete [66].

Plants play a crucial role in phytoremediation by breaking down contaminants through their leaves, roots, stomata, shoots, and cell walls [67]. Numerous factors, including nutrient deficiency (such as nitrogen and phosphorus) [68], temperature, pH, biomass contact time, biomass age, organism type, polluted site conditions, and pollutant concentration, influence bioremediation efficiency [69–70].

Bioremediation uses pH changes, redox reactions, and adsorption from contaminated areas to reduce pollutant solubility in the environment [71]. Hazardous contaminants are transformed by redox mechanisms into inactive, stable, and less toxic compounds [72, 73]. Pollutant adsorption is influenced by pH, with lowering pH leading to increased adsorptive capacity [74].

All microbial species have the ability to acquire and accumulate metals from aqueous solutions. Metal absorption occurs through a microbial process that uptakes necessary components for development and metabolism.

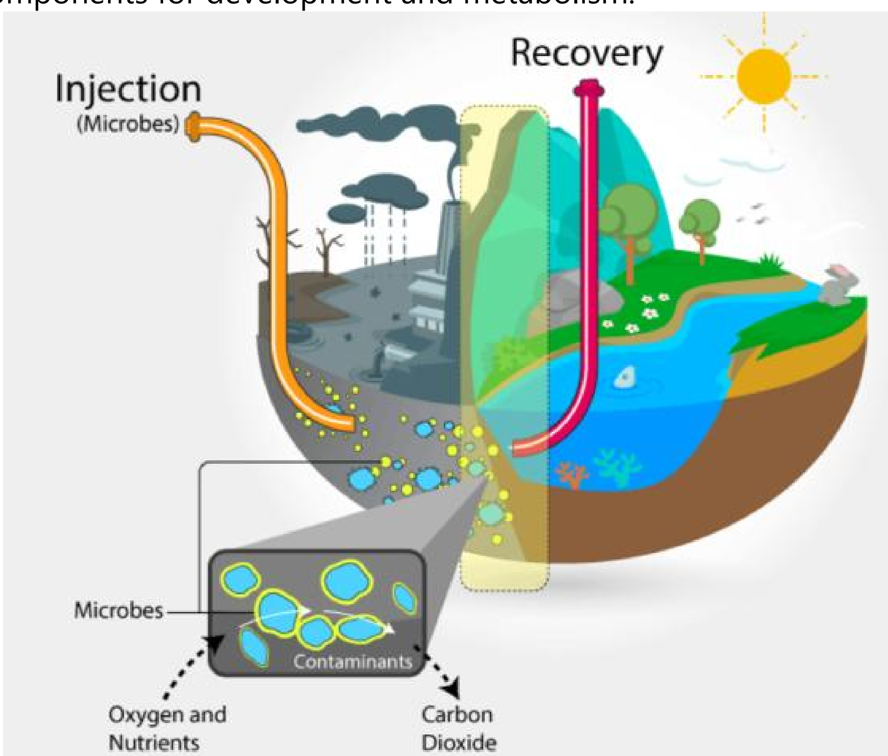

Fig:6. process of Bioremediation

Bioaccumulation

Pollutants are absorbed by living things either through direct contact with contaminated media or through indirect intake of pollutant-laden food [75]. When contaminant absorption rates exceed clearance rates, bioaccumulation takes place. Pollutants accumulate within organisms [76]. When harmful metals or chemical compounds bind within cells, this process is known as heavy metal bioaccumulation. Metal bioaccumulation is affected by exposure pathways (diet and solution), as well as geochemical factors that affect bioavailability. Since metals cannot be broken down, their bioaccumulation is a reliable indicator of exposure.

Bioaccumulation is an effective indication of chemical exposure in contaminated environments [77]. Bioactivity of biomass is critical in the process of bioaccumulation. Pollutants can only be absorbed by living cells via metabolic processes [78]. During bioaccumulation, metal ions are absorbed by the entire cell. Metals enter cells of living creatures through the same mechanisms as nutrition. Unicellular creatures absorb metals and vital minerals like calcium and magnesium.

Bioaccumulation occurs in two stages. Metal ions initially connect to the cell surface. The first stage has no metabolic activity. After that, metal ions are brought into the cell. The second stage of this technique requires metabolically active cells. The amount of biomass grows if ideal circumstances for organism growth are maintained in the second stage. This facilitates the binding of more significant numbers of metal ions [63].

Bioconcentration

Bioconcentration refers to an organism's capacity to concentrate chemicals from its environment [79] and the aggregation of materials during phase transitions [80]. Bioconcentration occurs when an organism has a higher concentration of a chemical than its surrounding environment (air or water). When a chemical or pollutant concentration rises as it moves from one trophic level to another, this phenomenon is known as biomagnification.

Phytoremediation

Innovative and friendly to the environment, phytoremediation is a method for removing heavy metals from water and soil [81,82]. Phytoremediation uses plants to gather, cleanse, and stabilize pollutants, making it an efficient and long-lasting remediation method. Heavy metals, such as Pb, Cd, Hg, As, and Cr, are commonly found in industrial wastewater, mining runoff, and agricultural runoff, posing a threat[83].

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Phytoremediation-Mechanisms

Phytoextraction. Phytoremediation using hyperaccumulator plants successfully eliminates heavy metals from contaminated environments [84]. Phytoextraction is a cost-effective and ecologically friendly alternative to traditional cleanup procedures, which are typically costly and intrusive. Hyperaccumulator plants have unique physiological and biochemical properties that allow them to collect high quantities of heavy metals in their tissues above ground. Plants have developed specialized mechanisms that efficiently absorb, transfer, and sequester heavy metals [85]. Hyperaccumulators use passive diffusion and active transport to absorb heavy metals from soilorwater.

Through xylem and phloem, heavy metals travel from the roots to aboveground plant components. Plants can concentrate heavy metals in shoots and leaves by translocation. To reduce heavy metal toxicity and protect cellular structures from sequestration, hyperaccumulator plants employ intracellular compartmentalization, organic ligand complexation, and ion detoxification pathways [86].

Several strategies can improve the efficacy of phytoextraction. Soil supplements including chelating agents, organic matter, and pH adjusters improve heavy metal solubility and availability for plant uptake. Genetic manipulation can increase the phytoextraction efficiency of hyper accumulator plants by increasing metal uptake, translocation, and sequestration capabilities [88]. Adopting appropriate agronomic methods can enhance metal extraction by encouraging plant growth and improving biomass yield. These practices include irrigation management, fertilization, and optimizing plant density. Phytoextraction holds enormous potential, but difficulties such as slow kinetics, poor metal selectivity, and continual maintenance require further attention [89]. Plants use many mechanisms to lower contamination levels during phytoremediation.

DOI: https://doi.org/10.5281/zenodo.20093486

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Pakistan Journal of Medical & Cardiological Review
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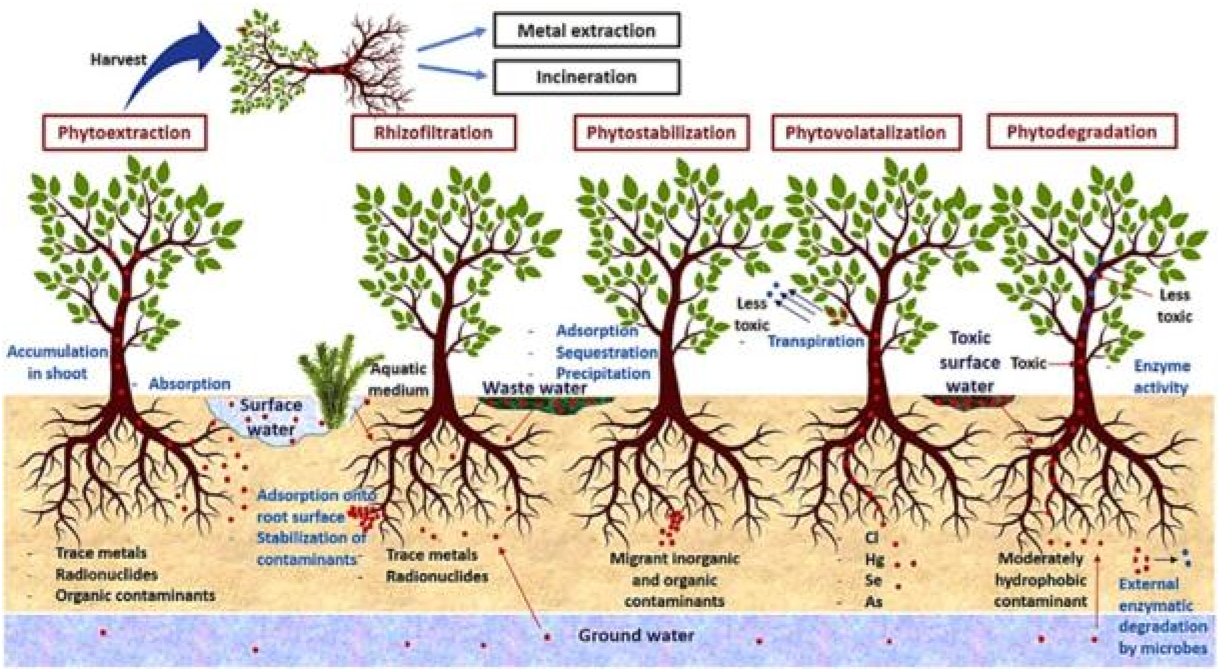

Fig. 7. Various processes used by plants to reduce the levels of pollutants in the phytoremediation process (modified with permission from Ref. [90].

Rhizofiltration

Plant roots are utilized in rhizofiltration, an innovative and environmentally friendly method for removing heavy metals from water sources [91]. Using the inherent capabilities of plants, rhizofiltration could be used to remove heavy metals from water sources. This approach relies on particular plant species with strong roots and high metal absorption ability [92]. The negatively charged surfaces of plant roots attract and bind heavy metal ions through electrostatic interactions (adsorption), which are the primary mechanisms by which this process operates. Ion exchange, or the absorption of heavy metal ions by plant roots, may occur [82]. Plants discharge organic chemicals, such as acids and chelators, into the rhizosphere. Heavy metals' absorption and elimination from water are facilitated by these chemicals' formation of complexes with them (complexation). Effective rhizofiltration projects need careful selection of plant species. The selected species should have high metal absorption capabilities, quick growth rates, and tolerance to different water conditions [93]. Commonly used plants include Salix (willows) [94], Typha (cattails) [95], and Phragmites australis (common reed) [96]. Rhizofiltration systems can be installed in several designs, including built wetlands, floating treatment wetlands, and biofiltration units. Heavy metal removal efficiency can only be maximized by carefully considering things like hydraulic loading rates, plant density, and residence time.

Rhizofiltration's efficacy can be affected by a number of factors [97]. The chemical forms and concentrations of heavy metals in water can affect how well-suited certain species of plants are for the elimination of particular metals. Heavy metal solubility and speciation can be influenced by pH and redox potential, leading to plant root uptake and removal. Organic matter and competing ions can reduce heavy metal uptake and rhizofiltration effectiveness.

Rhizofiltration can be incorporated into existing water treatment systems and is energy- and cost-effective [98]. Rhizofiltration is a sustainable approach that enhances biodiversity and aids ecosystem restoration. However, it may have limits when treating high metal concentrations or certain kinds of metals, requiring extra treatment stages for best outcomes.

Phytostabilization

A phytoremediation technique called Phytostabilization is used to immobilize heavy metals in polluted water and soil. Their bioavailability and diffusion to other environmental compartments are diminished as a result [97]. This strategy uses plant species that can store heavy metals in their root systems without causing major transfer to above-ground areas [82]. Metal-tolerant plants, or metallophytes, are ideal for Phytostabilization [99]. Plants have evolved protections to flourish in metal-contaminated ecosystems. They can produce compounds that assist in the immobilization of metals in soil and have extensive root systems as well as a high tolerance for metals. Indian mustard (Brassica juncea) and ferns are two examples of commonly used plants for Phytostabilization [100, 101].

Phytostabilization involves plants absorbing heavy metals from soil and water through their roots. Rather than transferring metals to shoots and leaves, plants store them in their root systems. Heavy metals are efficiently trapped by the roots, which function as a sink and prevent them from moving into the plant's aboveground sections. This process lowers metal absorption by grazing animals, insects, and plants in the ecosystem. Phytostabilization has several benefits for heavy metal removal compared to other remediation methods. It is frequently inexpensive, green, and requires little upkeep. This method can improve soil and water quality in contaminated places over time. The selection of plant species, the conditions of the site, and the concentration of heavy metals all influence the success of phytostabilization [87]. The long-term efficacy of phytostabilization projects is dependent on regular monitoring.

Methodology

A systematic and comprehensive literature survey was done as a review article to assess the toxicity of heavy metals in aquatic environment and adopt effective and economical remediation techniques. Sources of relevant scientific literature were selected from well-established academic databases such as National Center for Biotechnology Information, Google Scholar, ScienceDirect and SpringerLink.

1. Literature Search Strategy

Peer-reviewed research articles, review papers and reports from 2000 to 2025 were included. The keywords used in searching were heavy metal toxicity, aquatic pollution, bioremediation, phytoremediation, adsorption techniques and wastewater treatment. Boolean operators such as AND and OR were used to narrow down the search result and ensure it was relevant.

2. Inclusion and Exclusion Criteria

Articles that were published in English and with aquatic environments were selected. Research related to the heavy metals including lead (Pb), mercury (Hg), cadmium (Cd) and arsenic (As) was given preference. To ensure the quality and relevance of the papers, those with no experimental validation, outdated data, and unrelated to remediation techniques were excluded.

3. Data Extraction and Analysis

Extracted and classified relevant information on sources, toxicity, environmental behavior and remediation. Physiochemical methods (coagulation, precipitation, and adsorption) and biological methods (microbial and plant based remediation methods) were critically examined with respect to their efficiency, cost-effectiveness, and environmental sustainability.

4. Comparative Evaluation

The selected studies were compared to find the most feasible and economical treatments. Techniques appropriate for a developing country, taking into account economic and environmental limitations, were emphasised.

5. Synthesis of Findings

The information gathered was then systematically synthesized and presented in a coherent manner to get a clear understanding of the heavy metal contamination and promising eco-friendly remediation strategies for future research and application.

Discussion

The problem of aquatic pollution by heavy metals continues to be an important environmental problem as they are persistent, toxic and bioaccumulate in food chains. As seen in this review, the levels of metals like lead (Pb), mercury (Hg), cadmium (Cd) and arsenic (As) are still a serious threat for aquatics and human health even at lower levels. Not being biodegradable makes them capable of bio-concentrating within sediments and in the living tissues, causing long-term ecological damage and raising risks of chronic diseases.

The results show that the conventional physicochemical treatment techniques (coagulation, precipitation and adsorption) can effectively and quickly decrease the metal levels in the wastewater. But, these methods are also accompanied with many disadvantages such as high operating cost, need for energy and production of toxic sludge that will need extra treatment and disposal. Furthermore, their effectiveness might be reduced for low concentration of metal ions or complicated composition of wastewaters.

Biological methods like phytoremediation and microbial bioremediation, on the other hand, have been the subject of significant attention because of their eco-friendly and cost-effective nature. Natural processes are used to remove or stabilize the contaminants, and they are especially well suited for large scale, low resource situations. But, they tend to run slower and may need to be monitored diligently if they're to perform at their best.

One of the critical facts to be noted from this review is that there exists no single remediation technique that works out for each and every student. Rather, integrated or hybrid methods, which are the combination of both physicochemical and biological methods, may provide more efficient and sustainable solutions. In addition, the choice of remediation options should take into account site-specific elements including type of pollutant, pollutant concentration, the environmental context, and the economic viability. In conclusion, the treatment of heavy metal is a complex process that should be carefully managed to ensure that the technology is efficient and sustainable for the environment. More work is needed to enhance the effectiveness of less expensive methods and to create new and innovative hybrid systems for long-term water quality management.

Conclusion

Heavy metal contamination in aquatic environments continues to be a severe problem in the environment because of its toxicity, persistence and bio accumulative nature. Traditional chemical approaches are effective, but are typically expensive with negative environmental effects. Biological methods like phytoremediation and microbial treatment, however, offer a cheap, sustainable and environmentally friendly alternative. Looking ahead, there is a need for more research to combine these techniques and create more efficient and scalable solutions for long-term environmental protection.

Pakistan Journal of Medical & Cardiological Review
https://pakjmcr.com/index.php/1/about
Online ISSN Print ISSN
3007-2387 3007-2379

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