ECOLOGICAL ENGINEERING
& ENVIRONMENTAL TECHNOLOGY

Ecological Engineering & Environmental Technology, 2026, 27(2), 326–344
https://doi.org/10.12912/27197050/217564
ISSN 2719–7050, License CC-BY 4.0

Received: 2025.12.30
Accepted: 2026.01.30
Published: 2026.02.07

Decision-oriented evaluation and conceptual framework of bioremediation strategies for heavy metal contamination in aquatic ecosystems

Nuning Irnawulan Ishak[1,2], Hasanuddin Ishak[3*], Anwar Daud[3], Yahya Thamrin[4], Hasnawati Amqam[3], Gemini Alam[5], Agus Bintara Birawida[3], Al Asyary[6], Ermayanti Ishak[7], Anwar Mallongi[3]

[1] Doctoral Program, Faculty of Public Health, Hasanuddin University, Makassar, 90245, Indonesia
[2] Department of Environmental Health, Faculty of Public Health, Islamic University of Kalimantan, Banjarmasin, 70123, Indonesia
[3] Department of Environmental Health, Faculty of Public Health, Hasanuddin University, Makassar, 90245, Indonesia
[4] Department of Occupational Health and Safety, Faculty of Public Health, Hasanuddin University, Makassar, 90245, Indonesia
[5] Department of Pharmacognosy-Phytochemistry Laboratory, Faculty of Pharmacy, Hasanuddin University, Makassar, 90245, Indonesia
[6] Department of Environmental Health, Faculty of Public Health, University of Indonesia, Depok, 16424, Indonesia
[7] Department of Aquatic Resources Management, Faculty of Fisheries and Marine Sciences, Halu Oleo University, Kendari, 93132, Indonesia
* Corresponding author's e-mail: hasanuddin.ishak@gmail.com

ABSTRACT

Heavy metal contamination in aquatic environments represents a persistent global challenge due to the toxicity, mobility, and bioaccumulative behaviour of metals such as Pb, Cr, Hg, As, and Cd. Although a wide range of bioremediation approaches has been investigated, the translation of laboratory-scale removal efficiencies into reliable field-scale applications remains limited. This review critically synthesises recent advances in biosorption, microbial remediation, phytoremediation, and nanotechnology-assisted strategies, with emphasis on bridging the gap between experimental performance and operational applicability. Rather than comparing technologies based solely on removal efficiency, the analysis adopts a systems-based perspective that evaluates remediation strategies in relation to environmental heterogeneity, technological readiness, and sustainability-related constraints. The synthesis highlights that biomass- and microbe-based systems often exhibit high removal performance under controlled conditions, while facing challenges associated with scalability, process stability, and biosafety in complex aquatic environments. To address these limitations, the review introduces a decision-oriented evaluation framework and an integrated conceptual architecture that incorporate adaptive monitoring and enabling tools, including omics-informed assessment and Artificial intelligence of things (AIoT)-based sensing, as system-level support mechanisms. By reframing bioremediation assessment from a technology-centred to a context-dependent decision process, this study provides a structured basis for interpreting existing evidence and supporting environmentally defensible remediation planning in real-world aquatic systems.

Keywords: heavy metals, aquatic ecosystems, bioremediation, sustainable remediation, decision-oriented evaluation.

INTRODUCTION

Human life and biodiversity sustainability are highly dependent on the aquatic environment, which is one of the most critical ecosystems (Kamal, 2024). Water quality studies are widely conducted, given the increasing incidence of water pollution, which poses a threat to the ecosystem, human health, economy, development, and social welfare (Puari et al., 2025). Around 50% of global child fatalities and 80% of illnesses are caused by poor water quality (Dr. Amit Krishan et al., 2023). Heavy metals are a category of environmental contaminants from contaminated water sources (Abubakar et al., 2024). Increased concentrations of heavy metals in water that are above permissible limits result in environmental issues and pose risks to public health due to their toxic, persistent, bioaccumulative, and bioconcentrative characteristics (Mekuria et al., 2021).

Heavy metals are elements characterized by atomic weights ranging from 63.5 to 200.6 and densities above 5 g/cm³ (Chahal et al., 2023). Currently, more than 50 heavy metals may pose a threat to human health. Heavy metals recognised as dangerous to humans include lead (Pb), mercury (Hg), copper (Cu), chromium (Cr), arsenic (As), and cadmium (Cd) (Tandel et al., 2024). Heavy metal pollutants are inherently found in the atmosphere, aquatic environments, and the Earth's crust, and they can accumulate in biological systems, including plants and animals (Ethaib et al., 2022). Additionally, human activities like farming, manufacturing, urbanisation, and mining create large amounts of heavy metals (Bargah, 2024). These metals are subsequently discharged into aquatic ecosystems and biomagnified through the food web (Kumar et al., 2020). Humans may encounter heavy metal ions via contaminated drinking water, resulting in considerable health issues (Roy et al., 2024).

Various technologies have been developed to minimise the presence of heavy metal ions in water environments (Li et al., 2023). Although they have been used for a long time, conventional methods such as chemical precipitation, adsorption, ion exchange, reserve osmosis, and precipitation are often limited by high operating costs, poor performance at low metal concentrations, and a tendency to generate secondary waste, which requires more care and disposal (Nurmustaqimah et al., 2025). Conventional method limitations highlight the need for more economical and ecological approaches to heavy metal treatment (Pathak et al., 2024). The development of economical and environmentally sustainable remediation technology is crucial for addressing heavy metal contamination, while also enhancing water and soil quality to ensure sustained environmental protection and public health (Md Isa, 2022). Environmentally friendly remediation techniques such as phytoremediation, biosorption using plant biomass or organic waste, and microorganism-based bioremediation that are efficient and cost-effective in adsorbing heavy metals (Ayach et al., 2024). Additionally, methods based on nanotechnology can remove heavy metals from contaminated settings in a highly focused and efficient manner (Sah et al., 2024). These alternative remediation techniques possess the capacity to mitigate heavy metal contamination in a cost-effective and sustainable way.

Despite the proliferation of research on various bioremediation techniques, existing literature predominantly focuses on isolated laboratory-scale removal efficiencies, often overlooking the complex environmental heterogeneity and operational stability required for large-scale aquatic restoration. Furthermore, integrative analyses that systematically connect biological remediation mechanisms with emerging digital-enabling technologies, such as bionanotechnology and artificial intelligence of things (AIoT), remain limited (Alakkari and Ali, 2025).

To address these limitations, this review critically synthesises existing evidence on heavy metal toxicity, sources, and remediation strategies, and advances a decision-oriented analytical framework that links technological readiness, environmental compatibility, and sustainability constraints. Rather than prescribing future research directions, the framework provides a structured basis for interpreting comparative evidence and identifying trade-offs relevant to real-world remediation contexts, particularly within sustainability and circular economy considerations.

THE SOURCES AND TOXICITY OF HEAVY METALS POLLUTION

Anthropogenic activity shows a significant contribution to waterways polluted by heavy metals (Ahmad, 2025). The most harmful heavy metals that negatively affect aquatic ecosystems include Pb, Cr, Hg, As, and Cd (Rajan and Nandimandalam, 2024). Industrial waste, such as that from battery factories, electroplating, metal smelting, and chemical industries, contains waste that is often high in heavy metals (Khan et al., 2021). An alarming 80% of industrial and municipal wastewater is released into aquatic habitats globally without any pre-treatment, according to the United Nations World Water Development

Report for 2021(Visvanathan et al., 2024). The disposal of waste from petrochemical plants that produce As and Cd contaminates drinking water sources (Mokarram et al., 2020). Mining activities increase the release of Pb and Cr metals (Addo-Bediako et al., 2021). The agricultural sector, with its use of fertilisers and pesticides containing As, Pb, Cd, and Cr metals, can leach these metals into groundwater (Choudhury et al., 2024). Domestic waste disposal and urbanisation contribute to Hg metal pollution in aquatic environments (Adewumi and Ogundele, 2024).

The existence of heavy metals in aquatic environments degrades water quality (Rekha, 2023). Water is an indispensable natural resource, crucial for the sustenance of life on Earth (Jung et al., 2023). Access to potable and secure water has emerged as a governmental priority initiative within the worldwide framework known as the sustainable development goals (SDGs) (Basuki et al., 2024). The United Nations World Water Development Report, published by UNESCO in 2018, indicates that approximately 47% of the global population lacks access to safe, clean drinking water. This proportion is expected to increase to 57% by 2050 in direct proportion to the human population, anticipated to rise between 9.4 billion and 10.2 billion, predominantly comprising individuals from Africa and Asia (Ismail et al., 2024). In many regions globally, the average concentrations of heavy metals in surface water substantially surpass the permissible limits for potable water (Kumar et al., 2020).

The United States Environmental Protection Agency (US-EPA) and the World Health Organization (WHO) have established maximum allowable limits for heavy metals in potable water. The allowable amounts in potable water are enumerated in Table 1. Heavy metals cause toxic effects if they exceed the maximum tolerable limits. Heavy metal contamination in drinking water has diverse health implications, affecting multiple organ systems and posing both non-carcinogenic and carcinogenic risks (Radfard et al., 2023). Figure 1 shows the mechanism of heavy metal migration within the drinking water contamination chain and its effects on human health.

Table 1. Maximum tolerable concentrations of heavy metals in potable water (EPA 822-F-18-001, 2018; World Health Organization (WHO), 2022)

Heavy metals	US EPA, 2018 (mg/L)	WHO, 2022 (mg/L)
Pb	0.015	0.01
Cr	0.10	0.05
Hg	0.0003	0.006
As	0.0003	0.01
Cd	0.005	0.003

Lead (Pb) is a harmful environmental contaminant that has severe toxic effects on numerous bodily organs (Alisha et al., 2018). Lead exposure can induce neurological, respiratory, urinary tract, and cardiovascular disorders via immunomodulatory, oxidative, and inflammatory pathways (Balali-Mood et al., 2021). Skin discoloration, and paralysis are the results of excessive exposure to lead in water (Rerknimitr et al., 2019). Children with elevated blood lead levels may encounter growth delays, auditory impairment, anemia, behavioral and cognitive difficulties, diminished IQ, and hyperactivity (Embirsh, 2022). Lead exposure in adults may lead to reproductive complications, hypertension, and impaired kidney function (Ushurhe et al., 2024).

Chromium (Cr), particularly Cr (VI), is infamous for its mutagenic and carcinogenic characteristics (Kotyk and Iskra, 2024). Contact to chromium (VI) elements in various forms can result in lung cancer and other health detriments (Shi et al., 2022). The liver is the principal organ impacted by Cr (VI) exposure, and such exposure through oral consumption of water has increased the prevalence and mortality rates of liver cancer (Yang et al., 2022). The development of allergic contact dermatitis due to Cr exposure has also been found in large numbers (Mitra et al., 2022). Chromium (VI) induces DNA damage, gastric cancer, cutaneous tumors, pulmonary cancer, and adversely impacts the immune system, gastrointestinal tract, liver, and kidneys contributes to cancer mortality (Aklilu et al., 2024).

Mercury (Hg) is a prevalent pollutant in natural water bodies and is highly toxic to human health (Pant et al., 2024). Methylmercury (Me-Hg), one of the many chemical forms of mercury, is highly neurotoxic and has been linked to Minamata sickness (Mallongi et al., 2022). The food chain is one way for this metal to enter the human body and cause neurodevelopmental disorders and severe immune reactions (Grandjean, 2024). Inside cells, mercury can lead to oxidative stress and neurological disorders because it is extremely toxic to mitochondria (Dong and Li, 2024).

Arsenic (As) is an extremely poisonous metalloid with an atomic number of 33, existing

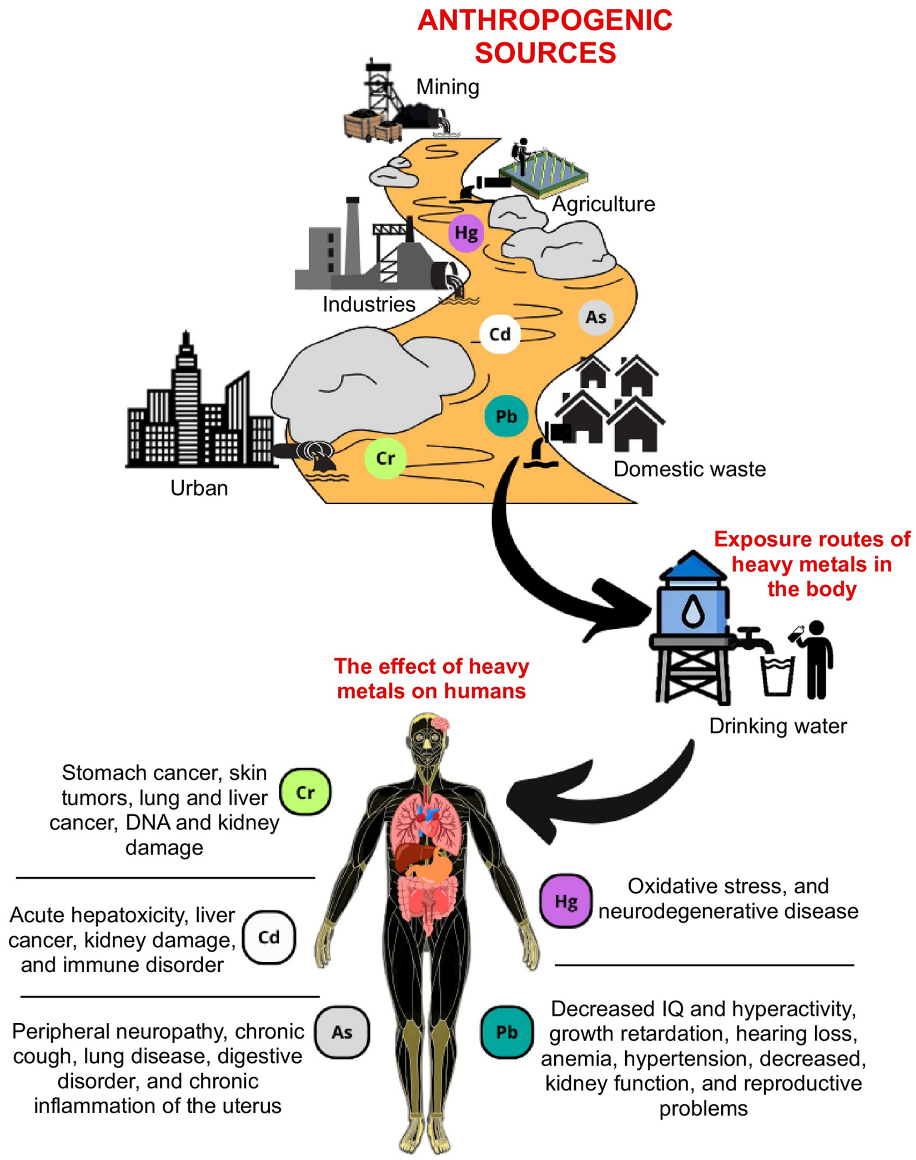

Figure 1. Heavy metal contamination in drinking water and health effects

in inorganic and organic forms (Ganie et al., 2024). The danger of the inorganic form entering the body, primarily through drinking water, is much greater than the organic form (Ahmed et al., 2022). It has adverse health effects, including disorders related to the neurological, respiration, and gastrointestinal systems (Fowler et al., 2022). Contaminated drinking water can result in peripheral neuropathy, sleep disturbances, cognitive impairments, persistent cough, pulmonary diseases, gastroenteritis, and gastrointestinal illnesses (Akhavan and Golchin, 2021). A notable correlation exists between elevated arsenic levels in potable water and the incidence and mortality of kidney cancer (Jaafarzadeh et al., 2023).

Cadmium (Cd) is a toxic heavy metal that poses a considerable threat to human health. Cd enters the body through water with a half-life (10–30 years)(Genchi et al., 2020), accumulating mainly in the liver, kidneys, bones, and other organs, harming the target organs irreparably (Purushottam and Reddy, 2024). Consumption of Cd-contaminated water hurts various tissues, the cardiovascular system, and the immune system (Rezaei et al., 2019). The kidney is the primary target organ and exhibits the highest sensitivity to cadmium pollution, resulting in a diminished glomerular reabsorption rate (Qing et al., 2021). The findings indicated that doses of As and Cd in water sources may significantly correlate with incidence rates of stunting (Oginawati et al., 2023).

Acute and chronic hepatotoxicity from cadmium can lead to liver failure, hence elevating the risk of cancer (Mitra et al., 2022).

REMOVAL OF HEAVY METALS

The limitations of conventional methods for eliminating heavy metals from water have prompted researchers to develop sustainable, cost-effective, and environmentally friendly techniques. These alternatives aim to minimise energy consumption, chemical use, and secondary waste (Singh et al., 2024). Bioremediation utilises biological agents to restore and rehabilitate contaminated environments, including aquatic ecosystems. This technique uses the inherent metabolic functions of microbes, plants, and animals to transform hazardous chemicals into less or non-toxic forms (Mahanayak, 2024). Furthermore, nanotechnology contributes to enhancing sustainability and efficacy in the extraction of heavy metals from aquatic ecosystems (Olawade et al., 2024).

Biosorption using plant biomass and agricultural waste

Biosorption is a bioremediation technique whose development is increasingly recognised as the method of choice in the process of removing heavy metals from aquatic environments (Nguyen et al., 2025). Biosorption is the passive physicochemical binding of various substances to a biological matrix, one example of which is the use of plant-based products and agricultural waste as biosorbents (Paranjape and Sadgir, 2023). Cellulose and lignin, present in plant materials, are proficient at biosorbing heavy metal ions (Kaur et al., 2022). The process of selecting biosorbents is important, especially those derived from abundant, renewable, non-toxic, and cost-effective raw materials, as this directly impacts efficiency, cost-effectiveness, environmental compatibility, and biomass absorption capacity (Phan and Phan, 2023).

The efficacy of biosorption is affected by various parameters, including pH, temperature, adsorbent dosage, biomass concentration, contact duration, and concentrations of other pollutants (Kumar et al., 2023). The pH parameter influences the intensity of electrostatic interactions between metal ions and the biosorbent surface. Low pH levels cause interactions with metal cations to decrease due to protonation of active groups, while high pH levels cause groups to tend to deprotonate and reduce their affinity for metal ions (Ali Redha, 2020). Temperature affects the increase in ion kinetic energy and the rate of diffusion. In endothermic systems, temperature increases sorption capacity, and in exothermic systems, temperature decreases sorption capacity (Singh et al., 2024). The biosorption mechanism depends on the biomass concentration, which affects how efficiently metal ions are removed from aqueous solutions (Vishan et al., 2019). Contact time correlates with sorption equilibrium; the initial rate will slow down as saturation approaches (Jain et al., 2016). Target pollutants can form complexes with various other metals that compete for binding sites, thereby reducing the effectiveness of target metal ion removal (Harshala and Wagh, 2022).

The form and classification of biomass greatly influence surface area, pore-size distribution, and the concentration of active functional groups (Madhavi et al., 2021). Diverse functional groups in plants, including amino, carboxylate, phenolic, and hydroxyl groups, serve as metal-binding agents (Nobahar et al., 2021). The morphological characteristics of the surface and functional groups of biosorbents can be determined using scanning electron microscopy (SEM), energy dispersive x-ray spectroscopy (EDX), Brunauer–Emmett–Teller (BET) analysis, and Fourier transform infrared spectroscopy (FTIR) (Sebayang et al., 2023). The pH point of zero charge can be measured to elucidate the biosorption mechanism by identifying the pH at which the biosorbent exhibits a neutral surface charge, reflecting the analogous adsorption of H^+ and OH^- ions (Stadnik et al., 2023). Biosorption is a viable alternative to traditional heavy metal removal techniques; however, the problems related to its implementation must be addressed (Karnwal, 2024). Table 2 shows the capacity of various plant biomass and agricultural waste to remove heavy metals Pb, Cr, Hg, As, and Cd from the aquatic environment.

Despite the high efficiency reported in many studies, the practical deployment of plant-based biosorbents faces several engineering bottlenecks. These challenges range from the mechanical fragility of raw biomass to the difficulties associated with post-treatment recovery. Table 3 synthesizes these critical limitations and proposes strategic solutions, emphasizing the transition from raw biological materials to functionalized hybrid systems to enhance field-scale applicability.

Microbial remediation

Microbial remediation is a novel strategy for environmental conservation that is essential for removing contaminants, including nutrients, petroleum hydrocarbons, and hazardous metals (Wang et al., 2025). Bacterial bioremediation provides an environmentally sustainable and cost-effective approach for treating metal-contaminated industrial wastewater (Patil et al., 2024). Bacterial cells are generally between 0.5 to 5 µm in size and are curved rod-shaped, which can be observed singly, in pairs, or even in chains. Their prevalence, broad enzyme activity, and ability to adapt to extreme conditions make bacteria highly useful in wastewater treatment worldwide (Nascimento et al., 2018).

Bacteria employ biosorption and bioaccumulation mechanisms (Patil et al., 2024). Biosorption is highly effective for heavy metals such as lead, as bacteria can sequester metal ions, thereby reducing their environmental bioavailability and toxicity. This process entails the passive adhesion of contaminants to bacterial cell surfaces, which can be enhanced by cell wall constituents such as polysaccharides, proteins, and lipids (Sevak et al., 2021). Unlike biosorption, bioaccumulation is an active process in which pollutants are absorbed and internalized by bacterial cells. This process often requires energy in the form of ATP and necessitates specialized transport proteins that enable the translocation of contaminants across cellular membranes (Kumar et al., 2024).

Bacteria can utilize heavy metal ions for metabolic processes and detoxify them via soluble enzymes synthesized by the bacteria (Alotaibi et al., 2021). Bacteria absorb metals into their cells, frequently sequestering them in less harmful forms (Hernandez-Guerrero et al., 2025). The intracellular and extracellular pathways involved in these processes are illustrated in Figure 2. For instance, some bacterial cells, such as *Bacillus* sp. convert Cr (VI) into Cr (III), which is significantly less toxic to aquatic environments. The reduction processes illustrated in Figure 2 demonstrate that *Bacillus* sp. is a viable bioremediation agent for mitigating chromium toxicity in wastewater (Seragadam et al., 2021).

Microbial remediation is both environmentally sustainable and cost-effective, with the ability to degrade a range of organic and inorganic contaminants, including heavy metals (Chatterjee et al., 2022). Advances in genetic engineering have enabled the enhancement of microbial capabilities by introducing specific genes for metal chelation and detoxification, thereby improving bioremediation efficiency (Kumar and Chakraborty, 2024). However, several operational limitations persist, including high sensitivity to environmental fluctuations, the risk of toxic intermediate formation, and challenges in field-scale scalability. These engineering bottlenecks, along with their corresponding strategic solutions, are summarized in Table 4, highlighting the transition from conventional biotreatment to smart, technology-driven microbial systems.

The reported bioremediation efficacy of numerous heavy metal-tolerant bacterial strains is described in Table 5, complementing these strategic strategies.

Table 2. Heavy metal removal by plant biomass and agricultural waste

Plant biomass and agricultural waste	Target metal	pH	Biosorption capacity (mg/g)	Reference
Banana (*Musa sapientum*) peel	Pb (II)	5	2.1	(Nurain et al., 2021)
Schleichera oleosa bark	Pb (II)	6	69.44	(Khatoon et al., 2018)
Lavandula pubescens Decne	Pb (II)	≤ 7	91.32	(Alorabi et al., 2020)
Sunflower waste	Pb (II)	5	91.8	(Radenkovic et al., 2024)
Eichhornia crassipes	Cr (VI)	3	41.53	(Tri et al., 2024)
Sambucus nigra L	Cr (VI)	2	6.389	(Mancilla et al., 2022)
Water hyacinth	Hg (II)	5	123.5	(Murmu et al., 2024)
Camellia oleifera shell	Hg (II)	2	57.6	(Chen et al., 2023)
Corn bract	Hg (II)	4	332.50	(Xu et al., 2022)
Pine needles	As (III)	4	3.27	(Jain et al., 2016)
Jamun seed	Cd (II)	6	3.88	(Giri et al., 2021)
Corn husk fiber	Cd (II)	6	23.0	(Zhang et al., 2024)

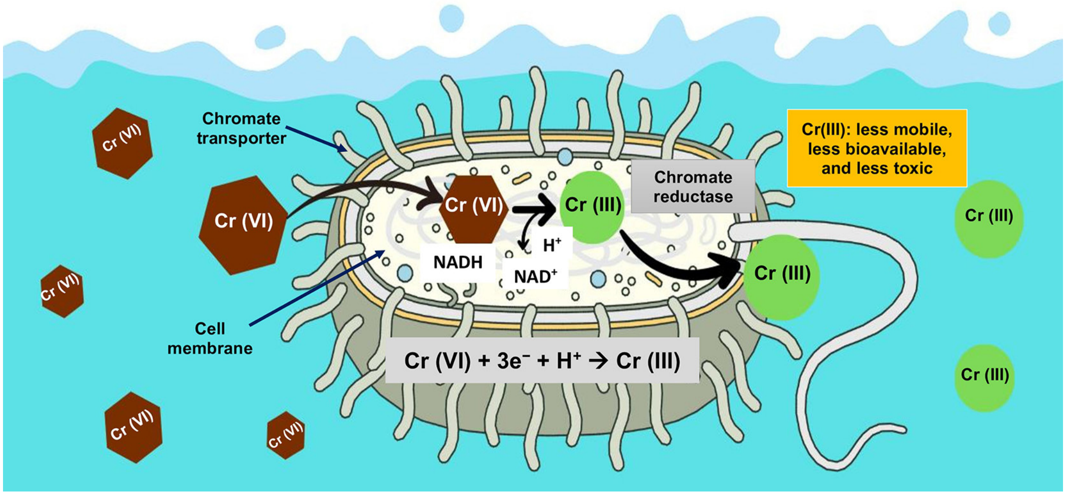

Figure 2. Bacterial-mediated bioremediation of Cr (VI) and reduction mechanisms within cells

Table 3. Critical limitations and strategic solutions for plant-based biosorption in aquatic systems

Limitation category	Technical constraint	Potential solutions (strategic improvements)	Reference
Operational separation	Difficulty in separating and recovering biomass from treated effluent.	Immobilization & Magnetization: Employing biomass immobilization within polymer matrices (e.g., alginate/chitosan) or synthesizing magnetic bio-nanocomposites to facilitate rapid phase separation using external magnetic fields.	(Ramrakhiani et al., 2016)
Environmental sensitivity	Efficiency is significantly influenced by pH, temperature, and the presence of competing ions.	Surface Functionalization: Applying chemical modifications (acid/base activation or grafting chelating agents) to enhance site-specific affinity and buffering capacity against fluctuating field conditions.	(Srivastava et al., 2023)
Structural integrity	Biological materials lack the mechanical strength and rigidity required for continuous use.	Hybrid Composites: Integrating biomass with robust support materials like carbon nanotubes, graphene oxide, or synthetic polymers to increase mechanical durability in large-scale fixed-bed or fluidized-bed reactors.	(Srivastava et al., 2023)
Scalability gap	Performance drop-off when transitioning from controlled laboratory settings to industrial scales.	Pilot-Scale Optimization & AIoT: Conducting rigorous pilot-scale studies and integrating Artificial Intelligence of Things (AIoT) for real-time monitoring and autonomous control of operational parameters to ensure stability.	(Ramrakhiani et al., 2016)

Phytoremediation – plant-based removal

Phytoremediation is an environmentally friendly and economical technology that utilises the natural ability of certain plants known as hyperaccumulators to extract, decompose, or bind environmental pollutants, including heavy metals in aquatic environments, thereby sustainably rehabilitating contaminated ecosystems (Kumar et al., 2024). Phytoremediation mechanisms encompass phytoextraction, phytodegradation, phytostabilization, phytovolatilization, and rhizodegradation (Rout et al., 2024). Hyperaccumulator plants can store large amounts of heavy metals without causing toxic effects. Phytoremediation is a better alternative to conventional methods. However, the main challenges include the generally slower rate of remediation, as it depends on plant growth and metabolic processes (Kafle et al., 2022), Choosing appropriate plants, as not all species are efficient in eliminating contaminants (LM et al., 2025), Pest factors, and environmental stress can also reduce the effectiveness of phytoremediation (Singh et al., 2024). Table 6 illustrates the extraction of heavy metals Pb, Cr, Hg, As, and Cd through phytoremediation in aquatic ecosystems.

Table 4. Engineering bottlenecks and strategic solutions in microbial bioremediation

Limitation category	Technical constraint	Potential solutions (strategic improvements)	Reference
Environmental sensitivity	Effectiveness is highly dependent on specific pH, temperature, and nutrient availability.	Adaptive Process Control: Integrating AIoT-based sensors for real-time monitoring and automated adjustment of environmental parameters to maintain optimal microbial activity.	(Patil et al., 2024)
Metabolic by-products	Potential for incomplete breakdown, leading to the generation of more hazardous intermediate metabolites.	Metabolic Engineering & Omics: Utilizing genomics and proteomics to map metabolic pathways, ensuring complete detoxification or sequestration of metals into stable, non-toxic forms.	(Wang et al., 2025)
Field-scale stability	Microorganisms often fail to compete with indigenous species or survive environmental fluctuations in the field.	Microbial Immobilization & Consortia: Using robust microbial consortia (multi-strain) and immobilizing cells in protective bio-carriers (e.g., biochar or hydrogels) to enhance resilience and survivability.	(Kumar and Chakraborty, 2024)
Kinetics and duration	Bioremediation typically requires a significantly longer time to reach target levels compared to chemical methods.	Bionanotechnology Synergy: Integrating microbes with metal-oxide nanoparticles to accelerate electron transfer and catalytic rates, thereby enhancing the kinetics of metal reduction (e.g., Cr(VI) to Cr(III)).	(Seragadam et al., 2021)

Table 5. Bacterial species and removal efficiency

Bacteria	Target metal	Initial concentration (mg/L)	Removal efficiency (%)	Reference
Bacillus subtilis	Pb (II)	500	100	(Rocco et al., 2024)
Shewanella oneidensis	Hg (II)	50	73	(Fang et al., 2024)
Zhihengliuella alba sp. T2.2	Hg (II)	162	39.5	(Fernandez-F et al., 2022)
Bacillus sp.	Cr (VI)	40	95.24	(Seragadam et al., 2021)
Microbacterium paraoxydans strain VSVM IIT (BHU)	Cr (VI)	50	99.96	(Singh and Mishra, 2021)
Bacillus sp.	As (III)	4500	50	(Dey et al., 2024)
Bacillus cereus	As (III)	1000	50	(Dey et al., 2024)
Bacillus subtilis	Cd (II)	100	92.3	(Rocco et al., 2024)
Serratia bozhouensis CdIW2	Cd (II)	10	65.79	(Rezaee and Ahmady-Asbchin, 2023)

Nanotechnology-based approaches

At present, nanoparticle technology is garnering considerable interest in the domain of metal ion extraction from aquatic ecosystems (Mohanapriya et al., 2023). Nanomaterials are characterized as substances including particles with dimensions ranging from 1.0 to 100 nm in at least one dimension (Korkmaz and Baykal, 2024). Nanomaterials are primarily categorized into two types: carbon-based and inorganic (Sune et al., 2024). Nanomaterials function as effective adsorbents and catalysts for environmental remediation owing to their elevated chemical reactivity, substantial adsorption surface area, capacity for low-temperature alteration, and atomic-level activity (Kamble, 2024). All these properties of nanoparticles are beneficial for the biosorption of heavy metals from polluted environments (Al-Amrani and Onaizi, 2024). Nevertheless, several drawbacks exist with some widely utilised nanomaterials, including their high cost, potential toxicity, difficulty in recycling, and ease of interaction with other media (Perez-Hernandez et al., 2021). Despite these limitations, the development of nanomaterials continues through rigorous research and regulation to develop safer nanomaterials, improve recycling methods, and conduct comprehensive risk assessments to reduce potential health and environmental impacts (Kumar et al., 2024). To remove metal ions, a variety of nanoparticles have been created. Table 7 illustrates instances of nanomaterials and their capacity to adsorb Pb, Cr, Hg, As, and Cd in aquatic ecosystems.

Table 6. Heavy metal removal by phytoremediation

Plant-based	Target metal	Monitoring time (day)	Average removal (%)	Reference
Eichhornia crassipes	Pb (II)	12	45.81	(Adelodun et al., 2020)
Pistia stratiotes	Pb (II)	21	79.6	(Khambali et al., 2024)
Salvinia natans (L.) All.	Hg (II)	21	94	(Sitarska et al., 2023)
Echinodorus palaefolius	Hg (II)	3	91.84	(Prasetya et al., 2020)
Portulaca oleracea	Cr (VI)	7	29.4	(Banik et al., 2025)
Eichhornia crassipes (Water Hyacinth)	Cr (VI)	7	81.1	(Banik et al., 2025)
Azolla pinnata	As (III)	10	88.06	(Kumar and Banerjee, 2018)
Lemna minor	As (III)	10	82.56	(Kumar and Banerjee, 2018)
Ceratophyllum demersum L.	Cd (II)	15	97.9	(Abdulwahid, 2023)
Ipomoea aquatica (Water Spinach)	Cd (II)	20	82.20	(Badrul Hisam et al., 2022)

DECISION-ORIENTED EVALUATION OF BIOREMEDIATION STRATEGIES

From efficiency-centred assessment to decision-oriented evaluation

Most studies on heavy metal bioremediation have traditionally assessed remediation performance using laboratory-scale removal efficiencies under controlled conditions (Ali Redha, 2020). Although such metrics are essential for understanding fundamental mechanisms, they provide limited guidance for decision-making in complex aquatic environments where environmental heterogeneity, operational constraints, and biosafety considerations are decisive (Ramrakhiani et al., 2016). For example, biosorption systems based on agricultural waste often achieve high Pb or Cd removal under optimised pH, yet their performance rapidly declines under fluctuating hydrodynamics or competitive ion conditions typical of natural waters (Harshala and Wagh, 2022; Jain et al., 2016).

Synthesis across Tables 2–7 reveals a consistent pattern: technologies demonstrating high experimental efficiency frequently encounter substantial barriers during scale-up, including limited regeneration capacity, environmental instability, elevated operational costs, or unresolved ecological risks (Ayach et al., 2024; Md Isa, 2022). These findings indicate that removal efficiency alone is an insufficient indicator of field applicability (Paranjape and Sadgir, 2023). Accordingly, this review advances a shift from efficiency-centred assessment towards

Table 7. Nano materials and heavy metal adsorption capacity

Nanomaterials	Target metal	Adsorption capacity (mg/g)	References
Nanocomposite graphene oxide	Pb (II)	142.9	(Akhdhar and Yakout, 2023)
Nanofibers of polyvinyl alcohol	Pb (II)	444.2	(Turan and Kalfa, 2022)
Imogolite with nanoscale zero-valent iron (Imo-nZVI)	Pb (II)	73.8	(Martinis et al., 2022)
Carbonaceous nanomaterial (N, S-HFC-180)	Cr (VI)	164,29	(Li et al., 2024)
nano-scale zerovalent iron (S-nZVI)	Cr (VI)	75	(Wang et al., 2024)
Poly-2-mercapto-1,3,4-thiadiazole nanoparticles	Hg (II)	186.9	(Huang et al., 2018)
CMC/Fe3O4 nanocomposite	Hg (II)	243.52	(Zirpe and Thakur, 2023)
Imogolite with nanoscale zero-valent iron (Imo-nZVI)	Hg (II)	62.3	(Martinis et al., 2022)
Magnetic carbon-based nanocomposite	As (III)	10.1	(Jokic Govedarica et al., 2024)
A Ca-carbonate layered double-hydroxide nanosheet	As (III)	452	(Zahir et al., 2021)
Nanocomposite graphene oxide	Cd (II)	125.0	(Akhdhar and Yakout, 2023)
Carbon nanotubes (SWCNTs/Fe_3O_4 @PDA)	Cd (II)	186.48	(Ghasemi et al., 2020)
Nano zero valent iron (nZVI)	Cd (II)	213	(Tarekegn et al., 2021)

a decision-oriented evaluation paradigm that accounts for real-world implementation constraints.

This transition is operationalised through the decision-oriented evaluation matrix (Table 8), which explicitly links bioremediation strategies with environmental conditions, technological readiness, and sustainability-related constraints. Rather than ranking technologies based on isolated performance indicators, the matrix integrates system controllability, scalability, biosafety requirements, and long-term operational feasibility. For instance, microbial remediation may exhibit lower nominal removal efficiencies than nanomaterial-based approaches, yet its adaptability through biological regulation and omics-assisted monitoring can confer greater suitability for controlled in situ applications (Ali Redha, 2020; Ayach et al., 2024). Table 8 thus represents a core analytical contribution, demonstrating that remediation effectiveness emerges from alignment between environmental complexity and technological maturity rather than intrinsic method efficiency alone.

Operationalising environmental heterogeneity and technological readiness

The decision-oriented synthesis highlights environmental heterogeneity as a critical determinant of remediation feasibility. Aquatic systems exhibit dynamic physicochemical conditions, including variations in pH, temperature, salinity, redox potential, and contaminant speciation (Radfard et al., 2023). Evidence summarised in Tables 2–7 consistently shows that remediation strategies optimised under stable laboratory conditions often lose robustness under such variability.

By embedding environmental complexity alongside indicators of technological readiness, Table 8 clarifies trade-offs that are often obscured in method-centric reviews. Technologies at lower readiness levels may achieve high efficiencies

Table 8. Decision-oriented evaluation matrix linking bioremediation strategies, environmental conditions, technological readiness, and sustainability constraints

Bioremediation strategy	Target environmental conditions	Sustainability & Circular economy potential	Smart integration (AIoT & Omics)	Decision-oriented strategic implications	Strengths and limitations
Plant-based biosorption (agricultural waste, biomass residues)	Low-to-moderate metal concentrations; relatively stable pH; low hydrodynamic disturbance; small-scale or decentralised systems	High potential for waste valorisation and low-cost resource reuse; limited material regeneration	Limited applicability; sensor-based monitoring feasible for influent quality	Suitable for low-cost, short-term mitigation or pre-treatment stages; not recommended as a standalone solution for long-term remediation	Low cost and environmentally benign; limited selectivity, regeneration capacity, and scalability
Microbial remediation	Dissolved or speciated metals; biologically active environments; controlled redox and nutrient conditions	Moderate potential through metal immobilisation or recovery; biosafety management required	High relevance; omics tools for community stability assessment and AIoT for adaptive process control	Appropriate for in situ remediation where biological stability can be maintained; requires regulatory oversight and biosafety protocols	High specificity and adaptability; sensitive to environmental stressors and operational instability
Phytoremediation	Shallow water bodies; low-to-moderate contamination; long residence time systems	Moderate-to-high potential via biomass harvesting and ecosystem restoration	Limited real-time integration; monitoring mainly indirect	Best suited for long-term ecological restoration rather than rapid contaminant removal	Ecologically beneficial and low energy demand; slow kinetics and land-use constraints
Nanotechnology-based approaches	High metal concentrations; complex matrices; industrial or point-source pollution	Variable potential; depends on nanoparticle recovery and reuse strategies	High compatibility with smart sensing and automation	Effective for targeted, high-efficiency removal; best applied in controlled or hybrid systems	High removal efficiency and selectivity; cost, recovery, and ecotoxicity concerns
Hybrid and integrated systems	Heterogeneous environments; fluctuating contamination profiles; field-scale applications	High potential through combined efficiency and material recovery	Strong relevance; AIoT enables real-time optimisation and system learning	Most suitable for complex, real-world aquatic systems requiring adaptive management	Enhanced robustness and flexibility; higher design and operational complexity

under narrowly defined conditions but remain constrained by limited scalability and environmental sensitivity (Ali Redha, 2020). Conversely, approaches with greater operational maturity – such as biologically mediated systems supported by adaptive monitoring – may exhibit lower peak efficiencies yet offer enhanced stability and controllability in heterogeneous environments (Ayach et al., 2024; Paranjape and Sadgir, 2023). This synthesis reframes technological readiness as a function of environmental compatibility rather than developmental stage alone.

Biosafety constraints and the role of adaptive monitoring

Biosafety considerations emerge as a central decision constraint when transitioning bioremediation strategies from laboratory to field applications (Radfard et al., 2023). Risks associated with microbial dissemination, nanoparticle persistence, and unintended ecological interactions are insufficiently captured by efficiency-based metrics (Ali Redha, 2020; Ramrakhiani et al., 2016). Table 8 explicitly incorporates these constraints, highlighting their influence on strategy selection and operational feasibility.

To translate matrix-based synthesis into an operational decision process, Figure 3 presents a flowchart-based architecture integrating site characterisation, functional applicability, biosafety thresholds, and technological readiness. Within this system, adaptive monitoring enabled by AIoT-based sensing and omics-informed biological assessment functions as a regulatory feedback mechanism rather than an auxiliary enhancement (Akeem 2024; Chrobak et al., 2023). Bidirectional feedback loops support continuous performance evaluation, early risk detection, and iterative optimisation, thereby strengthening biosafety management and system resilience under dynamic environmental conditions.

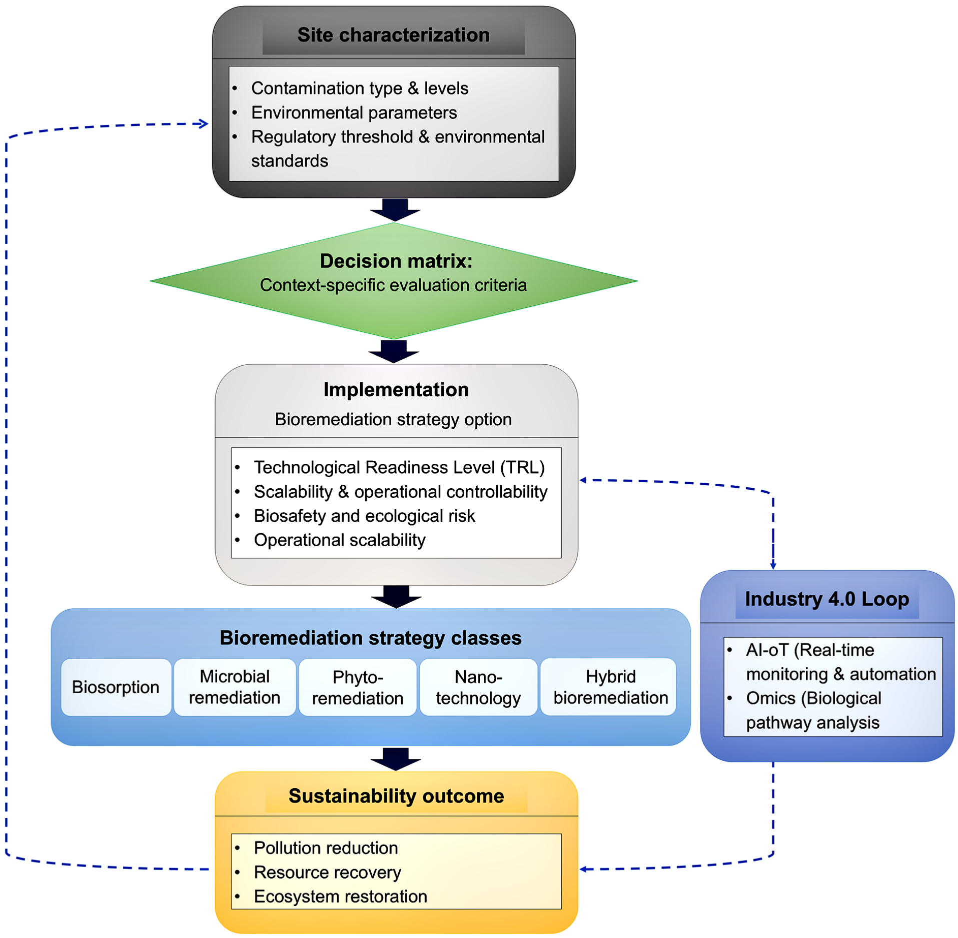

Figure 3. Decision-oriented flowchart for the selection and implementation of heavy metal bioremediation strategies in aquatic ecosystem

Implications of the decision-oriented evaluation architecture for real-world remediation

The integrated use of Table 8 and Figure 3 reconceptualises heavy metal bioremediation as a context-dependent decision process rather than a technology-centred optimisation exercise. By jointly considering environmental variability, technological readiness, and biosafety constraints, the framework enables more realistic assessments of operational feasibility and environmental defensibility.

This architecture demonstrates that technologies with superior laboratory-scale performance may not constitute optimal field solutions when scalability, ecological risk, and regulatory considerations are evaluated concurrently (Poonam et al., 2021). Through transparent trade-off analysis and adaptive feedback integration, the proposed decision-oriented framework bridges the gap between evidence synthesis and field-level decision support. In doing so, it advances existing bioremediation research from descriptive comparison towards system-level interpretation aligned with environmental health protection, sustainability objectives, and regulatory accountability.

CONCLUSIONS

The objective of developing a decision-oriented perspective for heavy metal bioremediation is achieved in this study through a systematic reorganisation of existing evidence beyond technology-specific efficiency reporting. Unlike prior reviews that predominantly catalogue removal performances under controlled laboratory conditions, this work demonstrates that such an approach is insufficient to support real-world remediation decisions in environmentally heterogeneous aquatic systems.

The principal scientific contribution of this review is the formulation of a structured decision-oriented evaluation architecture, operationalised through a comparative evaluation matrix (Table 8). This matrix represents a previously unavailable synthesis that explicitly links bioremediation strategies with environmental conditions, technological readiness levels, and sustainability-related constraints. By integrating these dimensions, the study reveals that the suitability of bioremediation technologies is fundamentally context-dependent and cannot be inferred from removal efficiency metrics alone.

Through this synthesis, the review fills a critical gap between descriptive assessments of bioremediation performance and implementation-relevant decision support. The analysis clarifies why technologies demonstrating high laboratory efficiency frequently encounter limitations at field scale, particularly when biosafety requirements, system controllability, and long-term operational feasibility are considered. The accompanying decision flowchart (Figure 3) formalises this evaluative logic into a transparent selection pathway, serving as an operational abstraction of the matrix rather than an illustrative concept.

The evaluation framework presented herein opens a pathway for translating accumulated experimental knowledge into structured, context-aware remediation planning. By enabling systematic comparison across environmental, technological, and sustainability dimensions, the study provides a reproducible basis for evidence-informed decision-making in aquatic heavy metal remediation, supporting regulatory assessment and practical implementation without prescribing specific technological outcomes.

Acknowledgements

Acknowledgement is extended to the Indonesian Educational Scholarship (BPI), the Center for Higher Education Funding and Assessment (PPAPT), and the Indonesian Endowment Fund for Education (LPDP) for their financial support for the Doctoral Program, which facilitated the funding of this research (Grant number: 202231103778).

REFERENCES

1. Abdulwahid, K. D. (2023). Phytoremediation of cadmium pollutants in wastewater by using Ceratophyllum demersum l. As an aquatic macrophytes. *Water Conservation & Management*, *7*(2), 83–88. https://doi.org/10.26480/wcm.02.2023.83.88
2. Abubakar, M. Y., Ahmad, K. B., Mathew, T. S., Haladu, M., Adam, A. B. (2024). Heavy metal pollution in aquatic ecosystems: A review of toxic impacts and remediation strategies. *Journal of Sciences and Technology*, *1*(1), 416–427. https://doi.org/http://doi.org/10.58578/KIJST.v1i1.3621
3. Addo-Bediako, A., Nukeri, S., Kekana, M. B. (2021). Heavy metal and metalloid contamination in the sediments of the Spekboom River, South Africa. *Applied Water Science*, *11*(7), 1–9. https://doi.org/10.1007/S13201-021-01464-8

4. Adelodun, A. A., Afolabi, N. O., Chaúque, E. F. C., Akinwumiju, A. S. (2020). The potentials of Eichhornia crassipes for Pb, Cu, and Fe removal from polluted waters. *SN Applied Sciences*, *2*(10), 1646. https://doi.org/10.1007/s42452-020-03392-9
5. Adewumi, A. J., Ogundele, O. D. (2024). Hidden hazards in urban soils: A meta-analysis review of global heavy metal contamination (2010-2022), sources and its Ecological and health consequences. *Sustainable Environment*, *10*(1). https://doi.org/10.1080/27658511.2023.2293239
6. Ahmad, O. A. (2025). The effect of anthropogenic activities on soil quality (Shafa Badran watercourse) in the Al Zarqa River basin. *Journal of Ecological Engineering*, *26*(3), 108–118. https://doi.org/10.12911/22998993/199570
7. Ahmed, S. F., Kumar, P. S., Rozbu, M. R., Chowdhury, A. T., Nuzhat, S., Rafa, N., Mahlia, T. M. I., Ong, H. C., Mofijur, M. (2022). Heavy metal toxicity, sources, and remediation techniques for contaminated water and soil. *Environmental Technology and Innovation*, *25*, 102114. https://doi.org/10.1016/j.eti.2021.102114
8. Akeem Akinkunmi Akintola. (2024). AI-driven monitoring systems for bioremediation: real-time data analysis and predictive modelling. *World Journal of Advanced Research and Reviews*, *24*(1), 788–803. https://doi.org/10.30574/wjarr.2024.24.1.3099
9. Akhavan, A., Golchin, A. (2021). Environmental risk assessment of arsenic in Zn-Pb mine tailings. *Journal of Water and Soil Conservation*, *27*(6), 1–26.
10. Akhdhar, A., Yakout, A. A. (2023). Enhanced simultaneous sequestration of Cd(II) and Pb(II) ions from industrial wastewater samples based on poly-(2-aminothiophenol) functionalized graphene oxide. *Journal of Dispersion Science and Technology*, *44*(14), 2700–2710. https://doi.org/10.1080/01932691.2022.2122495
11. Aklilu, T., Sahilu, G., Ambelu, A. (2024). Public health risks associated with drinking water consumption in the upper Awash River sub-basin, Ethiopia, sub-Saharan Africa. *Heliyon*, *10*(3). https://doi.org/10.1016/j.heliyon.2024.e24790
12. Al-Amrani, W. A., Onaizi, S. A. (2024). Adsorptive removal of heavy metals from wastewater using emerging nanostructured materials: A state-of-the-art review. *Separation and Purification Technology*, *343*, 127018. https://doi.org/10.1016/j.seppur.2024.127018
13. Alakkari, K., Ali, B. (2025). Artificial intelligence of things: A review. *Babylonian Journal of Internet of Things*, *2025*, 113–120. https://doi.org/10.58496/BJIoT/2025/006
14. Ali Redha, A. (2020). Removal of heavy metals from aqueous media by biosorption. *Arab Journal of Basic and Applied Sciences*, *27*(1), 183–193. https://doi.org/10.1080/25765299.2020.1756177
15. Alisha, Paul, V., Gupta, P. (2018). A comprehensive review of environmental exposure of toxicity of lead. *Journal of Pharmacognosy and Phytochemistry*, *7*(4), 1991–1995.
16. Alorabi, A. Q., Alharthi, F. A., Azizi, M., Al-Zaqri, N., El-Marghany, A., Abdelshafeek, K. A. (2020). Removal of Lead(II) from synthetic wastewater by lavandula pubescens decne biosorbent: insight into composition–adsorption relationship. *Applied Sciences*, *10*(21), 7450. https://doi.org/10.3390/app10217450
17. Alotaibi, B. S., Khan, M., Shamim, S. (2021). Unraveling the underlying heavy metal detoxification mechanisms of *Bacillus* Species. *Microorganisms*, *9*(8), 1628. https://doi.org/10.3390/microorganisms9081628
18. Ayach, J., El Malti, W., Duma, L., Lalevée, J., Al Ajami, M., Hamad, H., Hijazi, A. (2024). Comparing conventional and advanced approaches for heavy metal removal in wastewater treatment: an in-depth review emphasizing filter-based strategies. *Polymers*, *16*(14), 1959. https://doi.org/10.3390/polym16141959
19. Badrul Hisam, N. I., Zakaria, M. Z., Azid, A., Abu Bakar, M. F., Samsudin, M. S. (2022). Phytoremediation process of water spinach (*Ipomoea aquatica*) in Absorbing heavy metal concentration in wastewater. *Journal Of Agrobiotechnology*, *13*(1S), 131–144. https://doi.org/10.37231/jab.2022.13.1S.322
20. Balali-Mood, M., Naseri, K., Tahergorabi, Z., Khazdair, M. R., Sadeghi, M. (2021). Toxic mechanisms of five heavy metals: mercury, lead, chromium, cadmium, and arsenic. *Frontiers in Pharmacology*, *12*. https://doi.org/10.3389/fphar.2021.643972
21. Banik, B. K., Islam, M. M., Kabir, M. I., Azizul Hoque, M. (2025). Phytoremediation of Cr(VI)-rich wastewater using water hyacinth, water lettuce and duckweed. *Environmental Research and Technology*, *8*(1), 88–96. https://doi.org/10.35208/ert.1491794
22. Bargah, R. K. (2024). Heavy metals: environmental pollution and impact on human health. In *Futuristic Trends in Chemical Material Sciences & Nano Technology Volume 3 Book 18*, 461–482. Iterative International Publishers, Selfypage Developers Pvt Ltd. https://doi.org/10.58532/V3BDCS18CH37
23. Basuki, T. M., Indrawati, D. R., Nugroho, H. Y. S. H., Pramono, I. B., Setiawan, O., Nugroho, N. P., Nada, F. M. H., Nandini, R., Savitri, E., Adi, R. N., Purwanto, Sartohadi, J. (2024). Water pollution of some major rivers in indonesia: the status, institution, regulation, and recommendation for its mitigation. *Polish Journal of Environmental Studies*, *33*(4), 3515–3530. https://doi.org/10.15244/pjoes/178532
24. Chahal, M. K., Mittan, S., Dhaliwal, A. K., Sran, A. S., Mittal, D., Kumari, A., Sidhu, O. S., Pahil, V. S. (2023). Heavy metals in various components of the environment – a review. *Pollution Research*, *42*(2), 209–212. https://doi.org/10.53550/pr.2023.v42i02.006

25. Chatterjee, S., Kumari, S., Rath, S., Das, S. (2022). Prospects and scope of microbial bioremediation for the restoration of the contaminated sites. In *Microbial Biodegradation and Bioremediation* 3–31. Elsevier. https://doi.org/10.1016/B978-0-323-85455-9.00011-4
26. Chen, F., Ma, N., Peng, G., Xu, W., Zhang, Y., Meng, F., Huang, Q., Hu, B., Wang, Q., Guo, X., Cheng, P., Jiang, L. (2023). *Camellia oleifera* shell biochar as a robust adsorbent for aqueous mercury removal. *Fermentation*, *9*(3), 295. https://doi.org/10.3390/fermentation9030295
27. Choudhury, T. R., Acter, T., Alam, M. A., Sowrav, S. F. F., Rahman, M. S., Chowdhury, A. M. S., Quraishi, S. B. (2024). Appraisal of heavy metal contamination and their source apportionment identification in five river water systems of the coastal areas in Bangladesh. *Regional Studies in Marine Science*, *70*, 103378. https://doi.org/10.1016/j.rsma.2024.103378
28. Chrobak, D., Kołodzieczak, M., Kozlovska, P., Krzemińska, A., Miller, T. (2023). Leveraging random forest techniques for enhanced microbiological analysis: a machine learning approach to investigating microbial communities and their interactions. *InterConf*, *32(151)*, 386–398. https://doi.org/10.51582/interconf.19-20.04.2023.040
29. Dey, U., Mondal, N. K., Chatterjee, S., Das, K., Raj, D., Kumar, P., Meraj, G. (2024). The isolation and identification of novel arsenic-resistant bacteria from an arsenic-contaminated region—A study to understand the efficiency of bacteria for arsenic removal from aqueous media. *Water*, *16*(17), 2401. https://doi.org/10.3390/w16172401
30. Dong, T., Li, H. (2024). Neurological risks arising from the bioaccumulation of heavy metal contaminants: A focus on mercury. *Environmental Toxicology*, *39*(5), 2692–2705. https://doi.org/10.1002/tox.24119
31. Dr. Amit Krishan, Dr. Shweta Yadav, Ankita Srivastava. (2023). Water pollution's global threat to public health: A mini-review. *International Journal of Scientific Research in Science, Engineering and Technology*, 321–334. https://doi.org/10.32628/IJSRSET2310643
32. Embirsh, M. (2022). Lead toxicity in children: A public health issue. *Libyan Journal of Medical Research*, *16*(1), 80–88. https://doi.org/10.54361/ljmr.152003
33. EPA 822-F-18-001. (2018). *Edition of the Drinking Water Standards and Health Advisories* (Issue March).
34. Ethaib, S., Al-Qutaifia, S., Al-Ansari, N., Zubaidi, S. L. (2022). Function of nanomaterials in removing heavy metals for water and wastewater remediation: A review. *Environments - MDPI*, *9*(10). https://doi.org/10.3390/environments9100123
35. Fang, Y., Yang, Q., Mu, K., Wang, Q., Liu, K., Wang, J. (2024). A promotion strategy of enhancing the mercury removal in Shewanella oneidensis MR-1 based on the mercury absorption and electronic consumption via mer operon. *Journal of Environmental Chemical Engineering*, *12*(3), 112993. https://doi.org/10.1016/j.jece.2024.112993
36. Fernandez-F, F., Lopez-C, P., Febres-Molina, C., Gamero-Begazo, P. L., Gómez, B., Bernabe-Ortiz, J. C., Cáceres-Huambo, A., Aguilar-Pineda, J. A. (2022). Identification and characterization of peruvian native bacterial strains as bioremediation of Hg-polluted water and soils due to artisanal and small-scale gold mining in the Secocha Annex, Arequipa. *Sustainability*, *14*(5), 2669. https://doi.org/10.3390/su14052669
37. Fowler, B. A., Chou, C.-H. S. J., Jones, R. L., Costa, M., Chen, C.-J. (2022). Arsenic. In *Handbook on the Toxicology of Metals* 41–89. Elsevier. https://doi.org/10.1016/B978-0-12-822946-0.00037-4
38. Ganie, S. Y., Javaid, D., Hajam, Y. A., Reshi, M. S. (2024). Arsenic toxicity: sources, pathophysiology and mechanism. *Toxicology Research*, *13*(1). https://doi.org/10.1093/toxres/tfad111
39. Genchi, G., Sinicropi, M. S., Lauria, G., Carocci, A., Catalano, A. (2020). The effects of cadmium toxicity. *International Journal of Environmental Research and Public Health*, *17*(11), 3782. https://doi.org/10.3390/ijerph17113782
40. Ghasemi, S. S., Mohammadnia, E., Hadavifar, M., Veisi, H. (2020). Cadmium Removal from aqueous solution by magnetized and polydopamine surface functionalized single-walled carbon nanotubes. *AUT Journal of Civil Engineering*, *4*(3), 315–322. https://doi.org/10.22060/AJCE.2020.17477.5635
41. Giri, D. D., Jha, J. M., Tiwari, A. K., Srivastava, N., Hashem, A., Alqarawi, A. A., Abd_Allah, E. F., Pal, D. B. (2021). Java plum and amaltash seed biomass based bio-adsorbents for synthetic wastewater treatment. *Environmental Pollution*, *280*, 116890. https://doi.org/10.1016/j.envpol.2021.116890
42. Grandjean, P. (2024). Mercury. In *Textbook of Children's Environmental Health*, 427–436. Oxford University PressNew York. https://doi.org/10.1093/oso/9780197662526.003.0032
43. Harshala, K., Wagh, N. D. (2022). Use of agricultural waste-based biosorbents for the removal of heavy metals from aqueous solution: A review. *Nature Environment and Pollution Technology*, *21*(3), 1003–1014. https://doi.org/10.46488/NEPT.2022.v21i03.007
44. Hernandez-Guerrero, A. A., Castrejon-Godinez, M. L., Mussali-Galante, P., Tovar-Sanchez, E., Rodriguez, A. (2025). In vitro removal of cd and pb through the bacterial strain Burkholderia zhejiangensis CEIB S4-3: Efficiency and cellular mechanisms implicated in the process. *Processes*, *13*(1), 276. https://doi.org/10.3390/pr13010276

45. Huang, S., Ma, C., Li, C., Min, C., Du, P., Xia, Y., Yang, C., Huang, Q. (2018). Facile synthesis, characterization of Poly-2-mercapto-1,3,4-thiadiazole nanoparticles for rapid removal of mercury and silver ions from aqueous solutions. *Polymers*, *10*(2), 150. https://doi.org/10.3390/polym10020150
46. Ismail, U. M., Vohra, M. S., Onaizi, S. A. (2024). Adsorptive removal of heavy metals from aqueous solutions: Progress of adsorbents development and their effectiveness. *Environmental Research*, *251*, 118562. https://doi.org/https://doi.org/10.1016/j.envres.2024.118562
47. Jaafarzadeh, N., poormohammadi, A., Almasi, H., Ghaedrahmat, Z., Rahim, F., Zahedi, A. (2023). *Arsenic in drinking water and kidney cancer: A systematic review*. *38*(2), 255–263. https://doi.org/doi:10.1515/reveh-2021-0168
48. Jain, C. K., Malik, D. S., Yadav, A. K. (2016). Applicability of plant based biosorbents in the removal of heavy metals: a review. *Environmental Processes*, *3*(2), 495–523. https://doi.org/10.1007/s40710-016-0143-5
49. Jokic Govedarica, J., Pesic, J., Simetic, T., Votson, M., Molnar-Jazic, J., Agbaba, J., Nikic, J. (2024). The utilization of magnetic carbon-based nanocomposite for removing arsenic and selected heavy metals in water treatment. *45. Međunarodna Konferencija "Vodovod i Kanalizacija '24" - Zbornik Radova - Zbornik Radova*, 107–114. https://doi.org/10.5937/VIK24107J
50. Jung, M. S., Da Silva, J. A. G., Fachinetto, J. M., Carvalho, I. R., Lucchese, O. A., Basso, N. C. F., Copetti, C. M., Da Silva, L. G. (2023). Water: A fundamental resource for ensuring sustainability. *Revista de Gestao Social e Ambiental*, *17*(7), e03661. https://doi.org/10.24857/rgsa.v17n7-013
51. Kafle, A., Timilsina, A., Gautam, A., Adhikari, K., Bhattarai, A., Aryal, N. (2022). Phytoremediation: Mechanisms, plant selection and enhancement by natural and synthetic agents. *Environmental Advances*, *8*, 100203. https://doi.org/10.1016/j.envadv.2022.100203
52. Karnwal, A. (2024). Unveiling the promise of biosorption for heavy metal removal from water sources. *Desalination and Water Treatment*, *319*, 100523. https://doi.org/10.1016/j.dwt.2024.100523
53. Kaur, M., Rattan, G., Kaushik, A., Singhal, S. (2022). Effectiveness of major plant components, cellulose and lignin, for removal of heavy metal ions from industrial wastewater. In *Environmental Studies and Climate Change* 189–212. CRC Press. https://doi.org/10.1201/9781003220824-14
54. Khambali, K., Anwar, T., Wardoyo, S. (2024). Innovation in utilisation of Apu-apu (Pistia stratiotes) for phytoremediation of heavy metal contaminants in industrial wastewater: a case study on local biodiversity. *Journal of Ecological Engineering*, *25*(12), 333–339. https://doi.org/10.12911/22998993/194952
55. Khan, R., Saxena, A., Shukla, S., Sekar, S., Senapathi, V., Wu, J. (2021). Environmental contamination by heavy metals and associated human health risk assessment: a case study of surface water in Gomti River Basin, India. *Environmental Science and Pollution Research*, *28*(40), 56105–56116. https://doi.org/10.1007/s11356-021-14592-0
56. Khatoon, A., Uddin, M. K., Rao, R. A. K. (2018). Adsorptive remediation of Pb(II) from aqueous media using Schleichera oleosa bark. *Environmental Technology & Innovation*, *11*, 1–14. https://doi.org/10.1016/j.eti.2018.04.004
57. Korkmaz, A. D., Baykal, A. (2024). Nanomaterials: properties and characterization. In *Molecular Impacts of Nanoparticles on Plants and Algae* 1–29. Elsevier. https://doi.org/10.1016/B978-0-323-95721-2.00006-3
58. Kotyk, B., Iskra, R. (2024). Influence of Chromium(VI) on the environment and metabolic processes in the body. *Current Chemical Biology*, *19*(1), 2–16. https://doi.org/10.2174/0122127968319843241207142638
59. Kumar, A., Dadhwal, M., Mukherjee, G., Srivastava, A., Gupta, S., Ahuja, V. (2024). Phytoremediation: Sustainable approach for heavy metal pollution. *Scientifica*, *2024*(1). https://doi.org/10.1155/2024/3909400
60. Kumar, A., Rani, M., Thakur, A. K. (2024). Microbial remediation of heavy metals in polluted soil. *Contemporary Advances in Science and Technology*, *7*(1), 135–148. https://doi.org/10.70130/CAST.2024.7110
61. Kumar, R., Banerjee, T. K. (2018). Phytoremediation of arsenic contaminated water. In *Heavy Metals*. InTech. https://doi.org/10.5772/intechopen.72238
62. Kumar, R., Kumar Joshi, H., Vishwakarma, M. C., Sharma, H., Joshi, S. K., Bhandari, N. S. (2023). Biosorption of copper and lead ions onto treated biomass Myrica esculenta: Isotherms and kinetics studies. *Environmental Nanotechnology, Monitoring & Management*, *19*, 100775. https://doi.org/10.1016/j.enmm.2022.100775
63. Kumar, S., Khan, S. I., Neidhe, M. M. R., Islam, M., Hasan, M. M. (2024). Nanomaterials in industry: A review of emerging applications and development. *Control Systems and Optimization Letters*, *2*(3), 342–348. https://doi.org/10.59247/csol.v2i3.135
64. Kumar, V., Chakraborty, P. (2024). Microbial bioremediation of metal and radionuclides: approaches and advancement. In *Microbiome-Based Decontamination of Environmental Pollutants* 269–292. Elsevier. https://doi.org/10.1016/B978-0-443-21781-4.00004-9

65. Kumar, V., Sharma, A., Kumar, R., Bhardwaj, R., Kumar Thukral, A., Rodrigo-Comino, J. (2020). Assessment of heavy-metal pollution in three different Indian water bodies by combination of multivariate analysis and water pollution indices. *Human and Ecological Risk Assessment*, *26*(1), 1–16. https://doi.org/10.1080/10807039.2018.1497946
66. L. Kamble, V. (2024). Enhanced carbon-based nanomaterials for superior environmental contaminant separation. *Ecology, Environment and Conservation*, *30*(4), 1611–1617. https://doi.org/10.53550/EEC.2024.v30i04.025
67. Li, Y., Huang, Y., Pan, Z., Ni, J., Yang, W., Zhang, Y., Li, J., Chen, X., Yuan, X., Li, C. (2024). Fabrication of hierarchically porous "Fish Cage"-like carbonaceous nanomaterials via soft template-assisted strategy for Cr removal: Accelerated stepped adsorption and enhanced coordination effect. *European Journal of Inorganic Chemistry*, *27*(33). https://doi.org/10.1002/ejic.202400328
68. Li, Y., Huang, Z., Lyu, C., Yan, Y., Zhu, S. (2023). Exploration of Treatment Technology for Heavy Metal Wastewater. *E3S Web of Conferences*, *393*, 03031. https://doi.org/10.1051/e3sconf/202339303031
69. LM, K., Askarova Shinar, K., Zhaksybayeva Gulzhan, S., Zh.E., S., Sultangaziy Eva Gulbaram, S. (2025). Utilising phytoremediation in green technologies: Exploring natural means of environmental clean-up. *IgMin Research*, *3*(1), 5–8. https://doi.org/10.61927/igmin276
70. Madhavi, A., Srinivasulu, M., Chandra, M. S., Rangaswamy, V. (2021). Detoxification of heavy metals using marine metal resistant bacteria: A new method for the bioremediation of contaminated alkaline environments. In *Innovations in Biotechnology for a Sustainable Future* 297–332. Springer International Publishing. https://doi.org/10.1007/978-3-030-80108-3_15
71. Mahanayak, B. (2024). Environmental restoration through bioremediation: methods, advantages, and challenges. *International Journal of Research Publication and Reviews*, *5*(6), 6661–6664. https://doi.org/10.55248/gengpi.5.0624.1637
72. Mallongi, A., Rauf, A. U., Daud, A., Hatta, M., Al-Madhoun, W., Amiruddin, R., Stang, S., Wahyu, A., Astuti, R. D. P. (2022). Health risk assessment of potentially toxic elements in Maros karst groundwater: a Monte Carlo simulation approach. *Geomatics, Natural Hazards and Risk*, *13*(1), 338–363. https://doi.org/10.1080/19475705.2022.2027528
73. Mancilla, H. B., Cerrón, M. R., Aroni, P. G., Paucar, J. E. P., Tovar, C. T., Jindal, M. K., Gowrisankar, G. (2022). Effective removal of Cr (VI) ions using low-cost biomass leaves (*Sambucus nigra* L.) in aqueous solution. *Environmental Science and Pollution Research*, *30*(49), 106982–106995. https://doi.org/10.1007/s11356-022-24064-8
74. Martinis, E. M., Denardin, J. C., Calderón, R., Flores, C., Manquián-Cerda, K., Maldonado, T., Arancibia-Miranda, N. (2022). Enhanced removal of mercury and lead by a novel and efficient surface-functionalized imogolite with nanoscale zero-valent iron material. *Environmental Science and Pollution Research*, *29*(14), 20221–20233. https://doi.org/10.1007/s11356-021-17242-7
75. Md Isa, Z. (2022). Remediation technology inventions for soil and groundwater contamination. *Medicine & Health*, *17*(1), 13–30. https://doi.org/10.17576/MH.2022.1701.02
76. Mekuria, D. M., Kassegne, A. B., Asfaw, S. L. (2021). Assessing pollution profiles along Little Akaki River receiving municipal and industrial wastewaters, Central Ethiopia: implications for environmental and public health safety. *Heliyon*, *7*(7), e07526. https://doi.org/10.1016/j.heliyon.2021.e07526
77. Mitra, S., Chakraborty, A. J., Tareq, A. M., Emran, T. Bin, Nainu, F., Khusro, A., Idris, A. M., Khandaker, M. U., Osman, H., Alhumaydhi, F. A., Simal-Gandara, J. (2022). Impact of heavy metals on the environment and human health: Novel therapeutic insights to counter the toxicity. *Journal of King Saud University - Science*, *34*(3), 101865. https://doi.org/10.1016/j.jksus.2022.101865
78. Mohanapriya, V., Sakthivel, R., Pham, N. D. K., Cheng, C. K., Le, H. S., Dong, T. M. H. (2023). Nanotechnology- A ray of hope for heavy metals removal. *Chemosphere*, *311*, 136989. https://doi.org/10.1016/j.chemosphere.2022.136989
79. Mokarram, M., Saber, A., Sheykhi, V. (2020). Effects of heavy metal contamination on river water quality due to release of industrial effluents. *Journal of Cleaner Production*, *277*, 123380. https://doi.org/10.1016/j.jclepro.2020.123380
80. Murmu, R., George, S. M., P, Y., Bhatnagar, P., K, A., S., K. M. (2024). Sustainable solutions for heavy metal contamination: characterization and regeneration of water hyacinth biosorbent in wastewater treatment. *Global NEST Journal*, *26*(6), 1–8. https://doi.org/10.30955/gnj.05910
81. Mustafa Kamal, A. H. (2024). Navigating the waters of innovation: advancing in aquatic research and sustainability. *Journal of Aquatic Research and Sustainability*, *1*(1), 01–02. https://doi.org/10.69517/jars.2024.01.01.0001
82. Nascimento, A. L., Souza, A. J., Andrade, P. A. M., Andreote, F. D., Coscione, A. R., Oliveira, F. C., Regitano, J. B. (2018). Sewage sludge microbial structures and relations to their sources, treatments, and chemical attributes. *Frontiers in Microbiology*, *9*, 1–11. https://doi.org/10.3389/fmicb.2018.01462
83. Nguyen, V. D., Nguyen, M. T., Vu, A.-T. (2025). Production of green biosorbent from chemically

modified moringa leaves for enhanced removal of heavy metal in aqueous environment. *Biomass Conversion and Biorefinery*, *15*(9), 13933–13953. https://doi.org/10.1007/s13399-024-06164-2

84. Nobahar, A., Carlier, J. D., Miguel, M. G., Costa, M. C. (2021). A review of plant metabolites with metal interaction capacity: a green approach for industrial applications. In *BioMetals* (Vol. 34, Issue 4). https://doi.org/10.1007/s10534-021-00315-y
85. Nurain, A., Sarker, P., Rahaman, M. S., Rahman, M. M., Uddin, M. K. (2021). Utilization of banana (*Musa sapientum*) peel for removal of Pb2+ from aqueous solution. *Journal of Multidisciplinary Applied Natural Science*, *1*(2), 117–128. https://doi.org/10.47352/jmans.v1i2.89
86. Nurmustaqimah, Z. M., Jamilatun, S. (2025). Evaluation of conventional methods in reducing heavy metal concentrations in industrial waste. *Indonesian Journal of Chemical Engineering*, *3*(1), 22–31. https://doi.org/10.26555/ijce.v3i1.1413
87. Oginawati, K., Yapfrine, S. J., Fahimah, N., Salami, I. R. S., Susetyo, S. H. (2023). The associations of heavy metals exposure in water sources to the risk of stunting cases. *Emerging Contaminants*, *9*(4), 100247. https://doi.org/10.1016/j.emcon.2023.100247
88. Olawade, D. B., Wada, O. Z., Egbewole, B. I., Fapohunda, O., Ige, A. O., Usman, S. O., Ajisafe, O. (2024). Metal and metal oxide nanomaterials for heavy metal remediation: novel approaches for selective, regenerative, and scalable water treatment. *Frontiers in Nanotechnology*, *6*. https://doi.org/10.3389/fnano.2024.1466721
89. Pant, R., Mathpal, N., Chauhan, R., Singh, A., Gupta, A. (2024). A review of mercury contamination in water and its impact on public health. In *Earth and Environmental Sciences Library* 93–115. Springer International Publishing. https://doi.org/10.1007/978-3-031-48817-7_4
90. Paranjape, P., Sadgir, P. (2023). Heavy metal removal using plant origin biomass and agricultural waste-derived biomass from aqueous media: A review. *Water Conservation Science and Engineering*, *8*(1), 9. https://doi.org/10.1007/s41101-023-00177-0
91. Pathak, S., Kumar, A., Khan, S. U. (2024). An overview of physical and chemical methods of heavy metal removal from wastewater. In *Heavy Metal Contamination in the Environment* 203–216). CRC Press. https://doi.org/10.1201/9781032685793-13
92. Patil, A., Chakraborty, S., Yadav, Y., Sharma, B., Singh, S., Arya, M. (2024). Bioremediation strategies and mechanisms of bacteria for resistance against heavy metals: a review. *Bioremediation Journal*, 1–33. https://doi.org/10.1080/10889868.2024.2375204
93. Perez-Hernandez, H., Perez-Moreno, A., Sarabia-Castillo, C. R., Garcia-Mayagoitia, S., Medina-Perez, G., Lopez-Valdez, F., Campos-Montiel, R. G., Jayanta-Kumar, P., Fernandez-Luqueno, F. (2021). Ecological drawbacks of nanomaterials produced on an industrial scale: collateral effect on human and environmental health. *Water, Air, & Soil Pollution*, *232*(10), 435. https://doi.org/10.1007/s11270-021-05370-2
94. Phan, H. H., Phan, A. N. (2023). Carbon nanostructures with the ultra-high surface area and porosity derived from biomass. In *Biomass-Based Functional Carbon Nanostructures for Supercapacitors* 99–125. https://doi.org/10.1007/978-981-99-0996-4_4
95. Poonam, Rani, A., Sharma, P. K. (2021). Biosorption: Principles, and Applications. In L. M. Gupta, M. R. Ray, & P. K. Labhasetwar (Eds.), *Advances in Civil Engineering and Infrastructural Development* 501–510. Springer Singapore.
96. Prasetya, A., Prihutami, P., Warisaura, A. D., Fahrurrozi, M., Murti Petrus, H. T. B. (2020). Characteristic of Hg removal using zeolite adsorption and Echinodorus palaefolius phytoremediation in subsurface flow constructed wetland (SSF-CW) model. *Journal of Environmental Chemical Engineering*, *8*(3), 103781. https://doi.org/10.1016/j.jece.2020.103781
97. Prathamesh R. Sune, Kajal S. Jumde, Pooja R. Hatwar, Ravindra L. Bakal, Samiksha D. More, Atharv V. Korde. (2024). Nanoparticles: Classification, types and applications: A comprehensive review. *GSC Biological and Pharmaceutical Sciences*, *29*(3), 190–197. https://doi.org/10.30574/gscbps.2024.29.3.046
98. Puari, A. T., Anandika, A., Apriani, I. I., Azora, A., Maida, S. P. (2025). Contamination level of heavy metals and assessment of the ecologic risk in the surface water and sediments of Batanghari river Dharmasraya, Indonesia. *Journal of Ecological Engineering*, *26*(4), 182–197. https://doi.org/10.12911/22998993/199978
99. Purushottam, B., Reddy, R. A. (2024). Cadmium Toxicity: Sources, Mechanisms and Human Health Implications: A Comprehensive Review. *Uttar Pradesh Journal of Zoology*, *45*(15), 442–450. https://doi.org/10.56557/upjoz/2024/v45i154260
100. Qing, Y., Yang, J., Zhu, Y., Li, Y., Zheng, W., Wu, M., He, G. (2021). Dose–response evaluation of urinary cadmium and kidney injury biomarkers in Chinese residents and dietary limit standards. *Environmental Health: A Global Access Science Source*, *20*(1), 1–9. https://doi.org/10.1186/s12940-021-00760-9
101. Radenkovic, M., Petrovic, J., Pap, S., Kalijadis, A., Momcilovic, M., Krstulovic, N., Zivkovis, S. (2024). Waste biomass derived highly-porous carbon material for toxic metal removal: Optimisation, mechanisms and environmental

implications. *Chemosphere*, *347*, 140684. https://doi.org/10.1016/j.chemosphere.2023.140684

102. Radfard, M., Hashemi, H., Baghapour, M. A., Samaei, M. R., Yunesian, M., Soleimani, H., Azhdarpoor, A. (2023). Prediction of human health risk and disability-adjusted life years induced by heavy metals exposure through drinking water in Fars Province, Iran. *Scientific Reports*, *13*(1), 19080. https://doi.org/10.1038/s41598-023-46262-1
103. Rajan, S., Nandimandalam, J. R. (2024). Environmental health risk assessment and source apportion of heavy metals using chemometrics and pollution indices in the upper Yamuna river basin, India. *Chemosphere*, *346*, 140570. https://doi.org/https://doi.org/10.1016/j.chemosphere.2023.140570
104. Ramrakhiani, L., Ghosh, S., Majumdar, S. (2016). Surface modification of naturally available biomass for enhancement of heavy metal removal efficiency, upscaling prospects, and management aspects of spent biosorbents: A review. *Applied Biochemistry and Biotechnology*, *180*(1), 41–78. https://doi.org/10.1007/s12010-016-2083-y
105. Rekha, R. (2023). Trace metals in the aquatic environment and its effect on aquatic life and human body. *International Journal of Science and Research (IJSR)*, *12*(11), 789–795. https://doi.org/10.21275/SR231111141341
106. Rerknimitr, P., Kantikosum, K., Chottawornsak, N., Tangkijngamvong, N., Kerr, S. J., Prueksapanich, P., Sithisarankul, P., Kumtornrut, C., Asawanonda, P., Sutheparuk, S., Panchaprateep, R. (2019). Chronic occupational exposure to lead leads to significant mucocutaneous changes in lead factory workers. *Journal of the European Academy of Dermatology and Venereology*, *33*(10), 1993–2000. https://doi.org/10.1111/jdv.15678
107. Rezaee, A., Ahmady-Asbchin, S. (2023). Removal of toxic metal Cd (II) by Serratia Bozhouensis CdIW2 using in moving bed biofilm reactor (MBBR). In *Social Science Research Network* (Vol. 344, p. 118361). https://doi.org/10.2139/ssrn.4395647
108. Rocco, D. H. E., Freire, B. M., Oliveira, T. J., Alves, P. L. M., de Oliveira Júnior, J. M., Batista, B. L., Grotto, D., Jozala, A. F. (2024). Bacillus subtilis as an effective tool for bioremediation of lead, copper and cadmium in water. *Discover Applied Sciences*, *6*(8). https://doi.org/10.1007/s42452-024-06101-y
109. Rout, T., Nanda, B., Agrawala, S., Kar, D. (2024). Green solutions for heavy metal cleanup in water through phytoremediation. In *Sustainable Management of Environmental Pollutants through Phytoremediation* 284–304. CRC Press. https://doi.org/10.1201/9781003442295-15
110. Roy, B., Bhunia, B., Bandyopadhyay, T. K., Khan, S. A., Nandi, N. B., Nath, P. C. (2024). Water pollution by heavy metals and their impact on human health. In *Handbook of Water Pollution* (pp. 333–352). Wiley. https://doi.org/10.1002/9781119904991.ch10
111. Sah, P. M., Naik, H. S., Raut, R. W. (2024). Remediation strategies based on nanotechnology for the removal of heavy metal contaminants from wastewater. In *Innovative and Hybrid Technologies for Wastewater Treatment and Recycling* 283–305. CRC Press. https://doi.org/10.1201/9781003454199-13
112. Sebayang, N. U. W., Hidayat, B., Jamilah, Sari, S. P. (2023). Characteristics of Marine Organic Waste Compost Using Brunauer-Emmet-Teller, Fourier Transform Infrared, and Scanning Electron Microscope-Energy Dispersive X-Ray. *IOP Conference Series: Earth and Environmental Science*, *1287*(1), 012032. https://doi.org/10.1088/1755-1315/1287/1/012032
113. Seragadam, P., Rai, A., Ghanta, K. C., Srinivas, B., Lahiri, S. K., Dutta, S. (2021). Bioremediation of hexavalent chromium from wastewater using bacteria-a green technology. *Biodegradation*, *32*(4), 449–466. https://doi.org/10.1007/s10532-021-09947-w
114. Sevak, P. I., Pushkar, B. K., Kapadne, P. N. (2021). Lead pollution and bacterial bioremediation: a review. *Environmental Chemistry Letters*, *19*(6), 4463–4488. https://doi.org/10.1007/s10311-021-01296-7
115. Shi, F., Jiang, D., Ji, J., Yan, J., Chen, H. (2022). Effects of alkali on water soluble hexavalent chromium in ordinary portland cement. *International Journal of Environmental Research and Public Health*, *19*(8). https://doi.org/10.3390/ijerph19084811
116. Singh, D., Chauhan, U., Maurya, S., Gupta, G. (2024). Exploring the potential of grasses in the phytoremediation of various xenobiotic compounds. In *Sustainable Management of Environmental Pollutants through Phytoremediation* 120–134. CRC Press. https://doi.org/10.1201/9781003442295-6
117. Singh, V., Ahmed, G., Vedika, S., Kumar, P., Chaturvedi, S. K., Rai, S. N., Vamanu, E., Kumar, A. (2024). Toxic heavy metal ions contamination in water and their sustainable reduction by eco-friendly methods: isotherms, thermodynamics and kinetics study. *Scientific Reports*, *14*(1), 7595. https://doi.org/10.1038/s41598-024-58061-3
118. Singh, V., Mishra, V. (2021). Microbial removal of Cr (VI) by a new bacterial strain isolated from the site contaminated with coal mine effluents. *Journal of Environmental Chemical Engineering*, *9*(5), 106279. https://doi.org/10.1016/j.jece.2021.106279
119. Sitarska, M., Traczewska, T., Hołtra, A., Zamorska-Wojdyła, D., Filarowska, W., Hanus-Lorenz, B.

(2023). Removal of mercury from water by phytoremediation process with *Salvinia natans*(L.) All. *Environmental Science and Pollution Research*, *30*(36), 85494–85507. https://doi.org/10.1007/s11356-023-27533-w

120. Srivastava, I., Pal, A., Sahu, S., Singh, K. R. (2023). A study of the suitability of microbial cells for the biosorption and bioaccumulation of heavy metal removal. *International Journal of Current Science Research and Review*, *6*(5). https://doi.org/10.47191/ijcsrr/V6-i5-29
121. Stadnik, J., Giusti, E. D., Borges, A. R. (2023). Investigation of the zero-charge point of orange biomass for further use as a metal biosorbent. In *A Look at Development*. Seven Editora. https://doi.org/10.56238/alookdevelopv1-103
122. Tandel, D. J., Panchal, H. N., Desai, S. (2024). Types of heavy metals found in the environment and their toxicological properties. In *Heavy Metal Contamination in the Environment* 58–70. CRC Press. https://doi.org/10.1201/9781032685793-5
123. Tarekegn, M. M., Hiruy, A. M., Dekebo, A. H. (2021). Nano zero valent iron (nZVI) particles for the removal of heavy metals (Cd 2+, Cu 2+ and Pb 2+) from aqueous solutions. *RSC Advances*, *11*(30), 18539–18551. https://doi.org/10.1039/D1RA01427G
124. Tri, C. L., Tung, V. H., Hong, N. T., Tuan, L., Nguyen, D. D., Nguyen, X. C., La, D. D., Le, D. K. (2024). *Optimization of hexavalent chromium removal from aqueous solutions using Eichhornia crassipes-derived adsorbents through a response surface methodology*. Research Square. https://doi.org/10.21203/rs.3.rs-4593512/v1
125. Turan, K., Kalfa, O. M. (2022). Removal of lead from aqueous solution using electrospun nanofibers: preparation, characterization, adsorption isotherm, and kinetic study. *Analytical Methods*, *14*(35), 3382–3396. https://doi.org/10.1039/D2AY00691J
126. Ushurhe, O., Famous, O., Gunn, E. O., Ladebi, S.-O. M. (2024). Lead, zinc and iron pollutants load assessment in selected rivers in southern nigeria: implications for domestic uses. *Journal of Water Resource and Protection*, *16*(1), 58–82.
127. Vishan, I., Saha, B., Sivaprakasam, S., Kalamdhad, A. (2019). Evaluation of Cd(II) biosorption in aqueous solution by using lyophilized biomass of novel bacterial strain Bacillus badius AK: Biosorption kinetics, thermodynamics and mechanism. *Environmental Technology & Innovation*, *14*, 100323. https://doi.org/10.1016/j.eti.2019.100323
128. Visvanathan, P., Kirubakaran, D., Selvam, K., Manimegalai, P., Rajkumar, M., Vasantharaj, K. (2024). Recent strategies for natural bioremediation of emerging pollutants: development of a green and sustainable environment. In *Bioremediation of Emerging Contaminants in Water* 1–19. https://doi.org/10.1021/bk-2024-1476.ch001
129. Wang, Y., Yang, Y., Shi, J., An, W., Lyu, T., Zhang, P. (2024). Processes and mechanisms in remediation of aqueous chromium contamination by sulfidated nano-scale zerovalent iron (S-nZVI): Experimental and computational investigations. *Journal of Hazardous Materials*, *469*, 134031. https://doi.org/10.1016/j.jhazmat.2024.134031
130. Wang, Z., Li, Z., Gao, C., Jiang, Z., Huang, S., Li, X., Yang, H. (2025). *Bacillus subtilis* as an excellent microbial treatment agent for environmental pollution: A review. *Biotechnology Journal*, *20*(4). https://doi.org/10.1002/biot.70026
131. World Health Organization (WHO). (2022). *Guidelines for Drinking Water Quality*.
132. Xu, X., Guo, Q., Yang, C., Hu, Z., Chen, Q., Hu, J. (2022). Highly effective removal of Hg (II) solution using corn bract@MoS2 as a new biomass adsorbent. *RSC Advances*, *12*(49), 31792–31800. https://doi.org/10.1039/D2RA05638K
133. Yang, Q., Han, B., Li, S., Wang, X., Wu, P., Liu, Y., Li, J., Han, B., Deng, N., Zhang, Z. (2022). The link between deacetylation and hepatotoxicity induced by exposure to hexavalent chromium. *Journal of Advanced Research*, *35*(600), 129–140. https://doi.org/10.1016/j.jare.2021.04.002
134. Zahir, M. H., Irshad, K., Rahman, M. M., Shaikh, M. N., Rahman, M. M. (2021). Efficient capture of heavy metal ions and arsenic with a CaY–carbonate layered double-hydroxide nanosheet. *acs omega*, *6*(35), 22909–22921. https://doi.org/10.1021/acsomega.1c03294
135. Zhang, X., Hua, J., Zhu, Y., Ding, X., Zhang, Q., Zhang, T., Yang, D., Qiu, F. (2024). Birnessite-type MnO 2 modified sustainable biomass fiber toward adsorption removal heavy metal ion from actual river aquatic environment. *Langmuir*, *40*(16), 8738–8750. https://doi.org/10.1021/acs.langmuir.4c00723
136. Zirpe, M., Thakur, J. (2023). Magnetically recoverable CMC/Fe_3O_4 nanocomposite for efficient removal of Hg(II) and Cd(II) ions from the aqueous solution. *Separation Science and Technology*, *58*(15–16), 2692–2703. https://doi.org/10.1080/01496395.2023.2225733