frontiers | Frontiers in Water

TYPE Systematic Review
PUBLISHED 06 February 2026
DOI 10.3389/frwa.2026.1749800

OPEN ACCESS

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RECEIVED 19 November 2025
REVISED 27 December 2025
ACCEPTED 12 January 2026
PUBLISHED 06 February 2026

CITATION
Sati S, Sharma PK, Naithani P, Jha PK, Panwar V, Behera NR, Karmakar R, Prashant and Mittal A (2026) Bioremediation of heavy metals in contaminated water: conventional vs. advanced methods.
Front. Water 8:1749800.
doi: 10.3389/frwa.2026.1749800

Bioremediation of heavy metals in contaminated water: conventional vs. advanced methods

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Heavy metal (HM) contamination by cadmium (Cd), chromium (Cr), arsenic (As), zinc (Zn), lead (Pb), mercury (Hg), and other toxic elements in the environment poses substantial threat to public health and different ecosystems. Originating from diverse anthropogenic and natural sources, these elements can induce several ecological disturbances and multi-organ toxicity in humans and wildlife. Conventional biological and physicochemical methods for the removal of HMs, though effective in some contexts, often have limitations such as being energy intensive, costly, and generation of secondary waste. As a result, there is growing interest in exploring cleaner, efficient, and more sustainable approaches like bioremediation. Bioremediation is progressively acknowledged as one of the cost effective and sustainable strategy for pollution abatement by employing plants, bacteria, and other microorganisms capable of eliminating, transforming, or immobilizing HMs. This work aims to provide an overview of the conventional and advanced methods for the remediation of HMs, weighing up their benefits and limitations. Various methods for detection of HMs are also reviewed highlighting suitability, sensitivity, cost, portability, and field applicability. Further, we have discussed about the synergistic advantages of combining biological and physicochemical methods over standalone approaches, highlighting the need of hybrid methods like integration of artificial intelligence (AI) and nanotechnology in bioremediation. Overall, this review highlights bioremediation as a pivotal strategy for achieving cleaner ecosystems and sustainability, while underscoring the need for further research to optimize bioremediation technologies for broader real-world environmental management applications.

KEYWORDS

artificial intelligence, bioremediation, heavy metal contamination, nanotechnology, toxicity

1 Introduction

HM contamination in water systems is one of the major environmental issues in the world caused due to various human and natural phenomenon including mining, industrial activities, agricultural runoff, and improper waste management (Saravanan et al., 2024; Xu et al., 2024). Various pollutants like Cd, Cr, As, Zn, Pb, Hg pose significant threat to the various ecosystems present on earth (Balali-Mood et al., 2021). Being detrimental even at small concentrations, these can persist in the environment for very long durations and can cause ill effects on aquatic ecosystems, human health, and biodiversity that are majorly based on water for survival (Hama Aziz et al., 2023). Conventional physiochemical methods like ion exchange, chemical precipitation, and membrane filtration are generally preferred options but they often exhibit various disadvantages such as high operational cost, secondary pollutants generation, and their inability to address the contaminants at low levels (Zinicovscaia, 2016; Ahmed et al., 2022). Bioremediation has emerged as one of the environmentally sustainable techniques that detoxifies or eliminates the HMs from polluted water bodies by utilization of plants, biological agents, and by harnessing the metabolic capabilities of bacteria or microbes like in microbial fuel cells (Raju and Scalvenzi, 2017; Kuppan et al., 2024; Ayub et al., 2025). Recent advancements in environmental science, bioengineering, and molecular biology has significantly boosted the efficacy and usefulness of bioremediation techniques.

Despite these enormous achievements, challenges such as HMs toxicity to bioremediating agents, environmental variability, and appropriateness of lab findings to the real word applications remains unresolved. Existing studies over HMs needs to be refined more precisely to achieve great results and eliminate HM toxicity. HMs contamination in aquatic systems is a major environmental issue caused due to human as well as natural sources (Lea-Smith et al., 2025; Karnwal et al., 2024). HMs like Cd, Cr, As, Zn, Pb, Hg are environmentally persistent, non-biodegradable, and severely hazardous even at trace concentrations. They put forward a critical threat to global ecosystems, human health, and water safety. HMs need to be carefully monitored at source and managed to prevent the contamination of water systems as these can enter our food chain and bioaccumulate in organisms causing detrimental effects (Angon et al., 2024; Mitra et al., 2022). Additionally, secondary pollution can be generated when the HMs undergo either physical or chemical changes in our environment, fostering growth of other much harmful pollutants (Haghighizadeh et al., 2024; Tchounwou et al., 2012).

Powerful strategies and advanced methods like ion exchange, adsorption. and phytoremediation are capable of completely removing or stabilizing the contaminants before any alterations in the environment (Nti et al., 2023; Satyam and Patra, 2024; Aryal, 2024). Furthermore, implementing strict regulations and oversight systems can help minimize the release of such toxic chemicals that adds to secondary contamination (Onyeaka et al., 2024). HMs pose significant health hazards including neurological disorders, respiratory diseases, and cardiovascular diseases when exposed to it (Balali-Mood et al., 2021). Understanding these health issues is very significant for the public health policies and interventions, ultimately promoting global health equity (Gelaye, 2024). In particular, low- and middle-income countries experience more cases of HMs contamination in the environment due to poorly managed waste disposal practices, loosely enforced industrial regulations, and the over-exploitation of resources. Economically, phytoremediation methods and other locally generated material like agricultural residue can prove to be cost effective and sustainable solutions to tackle and reduce the HMs contamination, promoting global health (Dagdag et al., 2023; Ali et al., 2024; Oladimeji et al., 2024; Ahmed et al., 2025).

HMs contamination can severely impact the natural resources like soil, water, and biodiversity in a negative way. Contaminated soil can reduce agricultural production by affecting soil fertility and put forward critical issues like food security (Briffa et al., 2020; Haghighizadeh et al., 2024). Conservation of natural resources needs a prospective approach that incorporates pollution prevention, restoration, and sustainable resources management to ensure the long-term prospectus of ecosystems. Ensuring the compliance with regulatory standards such as that set by World Health Organization (WHO) is very crucial for reducing the HMs contamination and encouragement of environmental care. Bioremediation proves to be an economical and environmentally sustainable strategy that aligns with global sustainable goals and health justice (Jhariya et al., 2022; Dange et al., 2024; Bala et al., 2022).

2 Bioremediation as a sustainable solution

Bioremediation is a green technology that involves the use of living things like bacteria, fungi, and plants to break down or neutralize pollutants such as HMs, pesticides, and hydrocarbons in soil and water. This biological method is the most useful of the traditional ones such as chemical treatments or incineration, that are in general expensive and produce secondary pollution. Bioremediation is based on the microbial mechanisms of bioaccumulation, biosorption, enzymatic degradation, and redox reactions, through which toxic pollutants are converted into less harmful or inert forms (Ayilara and Babalola, 2023). The technique incorporated are either *in-situ*, e.g., bioventing, bio-sparging, and bioaugmentation or *ex-situ* like land farming, biopiles, composting, and bioreactors, thus being capable of adapting to local conditions and the nature of contaminants (Adams et al., 2020; Mahanayak, 2024). Figure 1 presents various types and agents of bioremediation (Angon et al., 2024; Karnwal et al., 2024; Ayub et al., 2025; Lea-Smith et al., 2025).

Latest developments feature genetically engineered microorganisms that can degrade contaminants much faster, and nanotechnology that makes enzymes more stable, thus the process can be both rapid and cheap. Besides, the microbe-assisted phytoremediation which is a symbiotic exploitation of microbes and plants, to absorb, stabilize or transform contaminants, while at the same time, revitalizing soil and increasing its diversity, has become very popular. The method is particularly effective against HMs pollution and more than 300 plant species have been identified with the potential to be used as metal sinks. Bioremediation is well compatible with the principles of the circular economy and the United Nations Sustainable Development Goals as it contributes to the provision of clean water, healthy soil, and climate action. Nevertheless, its performance and feasibility depend on factors such as soil permeability, contaminant depth, and biodegradability. Even so, steps taken in research and technology promise that bioremediation will be able to play a bigger role in environmental cleanup and pollution control, thus it will become a very important instrument in the face of the ever-increasing global contamination problems (Sales da Silva et al., 2020; Lone et al., 2008; Visvanathan et al., 2024; Xiang et al., 2022; Yusuf et al., 2023).

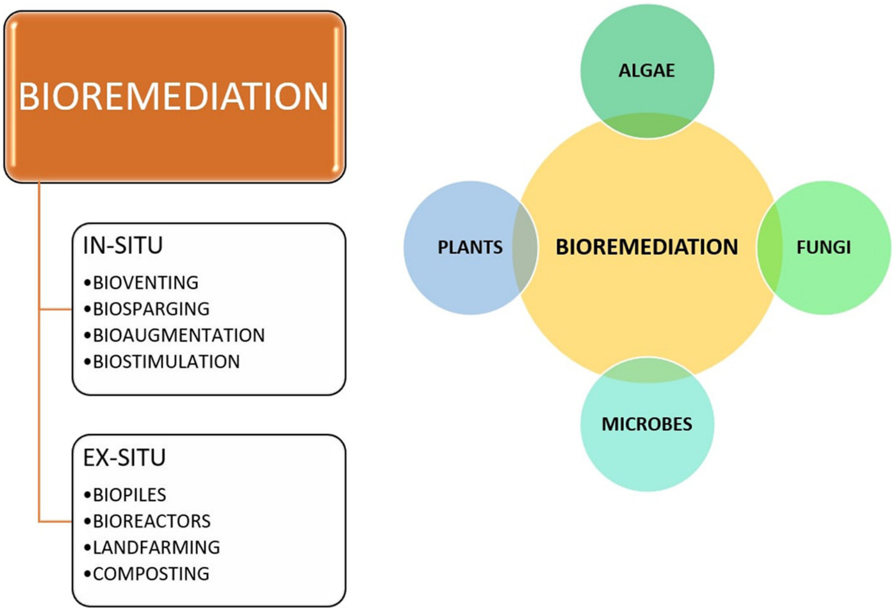

FIGURE 1
Types and agents of bioremediation.

3 Prevalent HMs in water pollution

3.1 Arsenic

As is a prominent semi-metallic toxic compound categorized as a HM that presents substantial ecological and health hazards. Regarded as a worldwide health risk factor, As occurs naturally in the earth's crust in numerous forms including oxides, sulfides, and salts of iron, sodium, calcium, and copper from where it leaches into drinking water (Jaishankar et al., 2014; Abdul et al., 2015; Balali-Mood et al., 2021). Ranked as the 20th most prevalent element in the Earth's crust, it contaminates water by natural deposits, industrial activities, pesticides, and improper disposal (Maiti et al., 2019; Jaishankar et al., 2014). As acts as a protoplasmic toxin that targets sulfhydryl groups in cells, disrupting cellular respiration, enzyme activitjaishankary, and mitotic processes. Predominantly absorbed in the small intestine, it can also enter via inhalation, ingestion, and dermal contact. As is converted into monomethylarsonic acid (MMA) and dimethylarsinic acid (DMA), with MMA being the primary urinary excretion form (Patel et al., 2023; Siddique et al., 2020). As may cause acute and chronic toxicity by inhibiting sulfhydryl-dependent enzymes which disrupts pyruvate dehydrogenase and the Krebs cycle, reducing Adenosine Triphosphate (ATP) production, and damaging capillary endothelium, leading to vascular permeability, vasodilation, and circulatory collapse (Shen et al., 2013; Jaishankar et al., 2014; Balali-Mood et al., 2021).

3.2 Lead

Lead, a bright silver toxic element in nature is one of the causes of serious pollution and health problems all over the world. Depending on the environmental conditions, Pb starts to get dull and forms a complex mixture of compounds when exposed to the air (Madkour, 2020). Pb being a highly toxic element with no biological role disrupts plant physiology by inducing reactive oxygen species (ROS), damaging lipid membrane, chlorophyll, and inhibiting photosynthesis. Studies indicate that in tea plants, Pb slows down the plant's growth, reduces the biomass and its quality. In terms of source, Pb can encompass through industrial operations, diet, tobacco use, water, and residential origins (Gupta et al., 2024; Trentin et al., 2025; Wu et al., 2011). Pb can also leach into the soil and water bodies through various industrial plants resulting in human and animal exposure through food and drinking water (Ali et al., 2022; Generalova et al., 2025). Pb is mostly absorbed via the respiratory and digestive systems and can cause neurological, pulmonary, urinary, and cardiovascular diseases due to immunological regulation, oxidative stress, and inflammatory processes. The global threshold for Pb poisoning is 10 μg/dl in blood (Balali-Mood et al., 2021; Siddiqi et al., 2023). Environmental Pb exposure continues to pose a public health risk, even at minimal concentrations and yet it is employed in more than 900 diverse sectors like mining, smelting, and battery manufacturing (Siddiqi et al., 2023).

3.3 Cadmium

Cadmium is a toxic non-biodegradable trace element from natural and human-induced sources that contaminates soil and groundwater. With a half-life of 20 years, Cd is among the most hazardous HMs and mobile elements in the environment, substituting calcium in minerals because of its analogous ionic radius, same charge, and chemical properties. The WHO suggest a recommendation value of 3 μg/L in terms of drinking water quality but higher concentrations of Cd may disrupt essential bodily functions, leading to acute or chronic illnesses (Khan et al., 2022; Kubier et al., 2019). Upon absorption by humans, Cd accumulates within the body during a lifetime (Jaishankar et al., 2014). Cd occurs naturally in soil and minerals such as sulfides, sulfates, carbonates, chlorides, and hydroxides. Similarly, Cd is also present in water and can enter the human diet via vegetables. Elevated Cd levels may stem from industrial operations, consumption of contaminated food, and tobacco use (Kubier et al., 2019; Balali-Mood et al., 2021). The presence of hexavalent Cd has been classified as a group I occupational carcinogen by the International Agency for Research on Cancer (IARC) (Balali-Mood et al., 2021; Khoshakhlagh et al., 2024). Occupational Cd exposure may also stem from sources like in the alloy, battery, glass manufacturing, and electroplating sectors. This is why Cd levels in the atmosphere are regularly monitored in certain nations due of their utmost importance (Lombaert et al., 2023; Mehrifar et al., 2025).

3.4 Mercury

Mercury is a naturally occurring, lustrous silver-white, odorless liquid metal present in air, water, and soil. It exists as metallic elements, inorganic salts and organic molecules with varying toxicity and bioavailability (Sattar et al., 2025). Since elemental Hg exists as a liquid at ambient temperature it can be vaporized, whereas organic Hg compounds exhibit more toxicity than their inorganic counterparts due to higher bioavailability (Park and Zheng, 2012; Wu et al., 2024). Mercury is mostly utilized in electrical equipment, industry, and scientific devices (Jang et al., 2005; Park and Zheng, 2012; Shukla, 2025). Once Hg is heated, it can change into a colorless and odorless gas which is very toxic and bio-accumulative, eventually impacting the marine ecosystem adversely (Jaishankar et al., 2014). Sources of Hg pollution includes agriculture, municipal wastewater effluents, mining, incineration, and industrial wastewater discharges (Veeraswamy et al., 2023). Being highly toxic and pervasive contaminant, Hg poses risks to human health and ecosystem integrity. Besides, anthropogenic Hg emissions exceed natural geogenic sources, creating reservoirs that drives global dispersion. Ultimately, Hg accumulates in persistent soil reservoirs and deep oceanic waters and sediments (Brocza et al., 2024; Driscoll et al., 2013).

3.5 Chromium

Chromium, a naturally occurring HM in the earth's crust and saltwater, ranks seventh in abundances and is released by oil, coal, and petroleum combustion (Jaishankar et al., 2014; Balali-Mood et al., 2021). Cr occurs as ores in natural deposits and includes other elements, such as ferric chromite ($FeCr_2O_4$), crocoite ($PbCrO_4$), and chrome ochre (Cr_2O_3) (Ihsanullah et al., 2016). Expected to be the sixth most abundant transition metal, makes it very dangerous in potable water, with trivalent Cr (Cr(III)) and hexavalent Cr (Cr(VI)) being the most stable forms. Among the two, Cr (III) is relatively less harmful than Cr (VI) and is a necessary component for human physiology (Ayele and Godeto, 2021; Balali-Mood et al., 2021). Conversely, Cr(VI) is very toxic and present in industrial effluents, resulting in severe diarrhea, vomiting, lung congestion, and damage to the liver and kidneys (Yan et al., 2023; Yatera et al., 2018). Cr is utilized in the textile industry, electroplating, leather tanning, metal finishing, and chromate production (Jaishankar et al., 2014; Ihsanullah et al., 2016). Highlighting the toxicity, a meta-analysis of 973,697 workers revealed that 11,564 developed cancer as a result of exposure to Cr in food and water or through skin contact with Cr-laden items (Balali-Mood et al., 2021).

3.6 Zinc

Zinc, the 23rd most prevalent element in the Earth's crust is an essential metal, vital for numerous biochemical processes and physiological activities. Zn acts as a cofactor for major proteins and is a key factor in the control of immunomodulatory activities such as the regulation of enzymes, proteins, DNA and DNA binding proteins, the immune system, and cell metabolism (Hussain et al., 2022; Kiouri et al., 2023). Excessive anthropogenic Zn can be toxic and cause vomiting, diarrhea, abdominal pain, nausea, and cramps (Hussain et al., 2022; Schoofs et al., 2024). Industrial sources of Zn contamination include galvanization, production of brass, bronze, Zn-based alloys, metal-coating, paint, dyes, and pigments, whereas soil contamination arises from smelting activities and mining (Hussain et al., 2022; Van et al., 2024). Zn concentrations in wastewater vary from under 1 ppm to over 48,000 ppm according to many studies (Rahman et al., 2021). Zn toxicity may also result from excessive supplements, contaminated environments, or natural exposure, with its bioavailability mainly coming from vegetables, beef, and dairy. Additionally, environmental Zn arises from soil and water via weathering and industrial discharges, with major inputs from mining, combustion, and steel production (Hussain et al., 2022; Khalef et al., 2022; Parmar and Thakur, 2013).

4 Source of HMs in water bodies

HMs contamination in the water bodies stems from a combination of natural and anthropogenic sources, each contributing significantly to the degradation of the environment and public health risks. Various naturally occurring process like volcanic eruptions, forest fire, weathering of rocks like granite, shale, basalt releases trace metals like As, Pb, Hg, and various other metals into the water bodies. These metals, often present as sulfates, oxides, and silicates leach into the rivers, lakes, and aquifers through water rock interaction. Rocks weather through physical, chemical, and biological processes that break their mineral structures and enable the release of metals by leaching agents such as water, acids, and organic compounds. On top of that, human activities have been the major contributors to the contamination of water bodies, thus, increasing the magnitude of HMs pollution. The process of industrialization, urbanization, and agricultural development has also resulted in the release and discharge of untreated wastewater into the aquatic systems (Hama Aziz et al., 2023; Singh et al., 2022; Fulke et al., 2024; Zhang et al., 2023).

Specific contributors of the anthropogenic activities include the coal mining, leather industry and chemical manufacturing, which bring about the release of various toxic metals like nickel (Ni), Pb, Hg through a number of processes like smelting, oil combustion, and pyrometallurgy. Domestic sewage often laden with detergent, plastic waste, nutrients, and bacterial contaminants exemplify the severeness of eutrophication which lower the levels of dissolved oxygen and, therefore, endanger the aquatic ecosystems. Adding to the toxicity, the agricultural run-offs add to the pollution by introducing HMs like Cd(II), Pb(II), Cr(VI), As(III), Hg(II), Ni(II), Cu(II), and Zn(II) into the water bodies through the means of fertilizers, pesticides, and irrigation activities. These metals are extremely harmful to both humans and animals as they can affect the liver, kidney, and nervous system even at very low exposure levels (Singh et al., 2022; Fulke et al., 2024; Zhang et al., 2023).

Moreover, leachates laden with metals due to the unsanitary landfills and open dumping sites are polluting the surface and groundwater. Municipal solid waste, normally a combination of residential, healthcare, and industrial refuse lacks proper segregation and management, intensifying the environmental health hazards and public health problems to a great extent. Also, plants that take up metals from the polluted soil can also pass them on in the food chain, which is an illustration of the risks. The persistence and bioaccumulation of these toxic metals in the aquatic ecosystems not only leads to the loss of marine diversity but also cause the water quality to worsen and public health to deteriorate. Table 1 presents the toxic HMs, their sources, exposure, health effects, and regulatory limits. Understanding these diverse sources and pathways is crucial for developing the mitigation strategies and technologies that will help to protect both the ecological integrity and the wellbeing of our environment (Pichhode and Nikhil, 2016; Huang et al., 2024; Singh V. et al., 2024; Ayub et al., 2025).

5 Conventional methods and their limitations

Traditional methods for removal of HMs from contaminated water bodies, like chemical precipitation, ion exchange, membrane filtration, and adsorption have been globally utilized. However, these methods are effective to an extent but faces significant challenges in terms of cost, efficiency, and environmental impact, especially when dealing with low concentrations of HMs or complex mixtures. Various research and technological advancements have been on the continuous loop to develop more sustainable and effective methods for HMs removal from contaminated water (Ahmed et al., 2022; Zinicovscaia, 2016).

5.1 Chemical precipitation

Chemical precipitation is one of the widely used traditional methods applied in the process of water treatment for the removal of HMs from the wastewaters. Being simple makes it the best method for removal of suspended solids, oils, metals, etc. from wastewater (Gahrouei et al., 2024; United States Environmental Protection Agency Office of Water Washington, 2000). The process of chemical precipitation includes the reactions of reagents known as precipitants with the HMs, forming compounds that is insoluble. This solid precipitate then can be filtered out by various methods. Another process involved in this method is the removal of ionic constituents where the pH of a solution is adjusted to a point that helps in reaching the maximum lowest point of its solubility. With increase in pH, dissolved metal ions convert into metal hydroxide. Along with the ion implantations and high temperature it leads to formation of precipitates and is then followed by solid separation operations like filtration and coagulation (Ayach et al., 2024; Zueva, 2018). This method proves to be very effective in removal of HMs with removal efficiencies reaching to 99.99% in carbonate, hydroxide and sulfide precipitation processes at pH ranging from 2–12, but it produces significant amount of sludge containing toxic elements. During the precipitation method, the use of sulfide containing reagents is done and this can cause release of hydrogen sulfide gas that is very toxic and can impact the wellbeing of humans and the environment (Pohl, 2020; Gahrouei et al., 2024).

5.2 Ultrafiltration

Ultrafiltration (UF) is one of the best proven technologies for the removal of HMs from wastewater in different industrial processes and water treatment processes. This method of HMs recovery includes the utilization of a semi permeable membrane with different pore sizes to allow selective small particles or molecules to pass through and retain large ones (Barakat and Schmidt, 2010; Aziz et al., 2024). Ultrafiltration technique is operational at certain low operating pressure known as transmembrane operating pressure that aids in the passing of small molecules through the membrane (Qasem et al., 2021). Water soluble polymer is another essential component of this method that binds itself to the cations in order to increase the molecular weight and size of the molecules. This allows for easy filtration of heavy molecules and recovers the HMs. However, the choice of water-soluble polymer is of utmost importance as the concept of molecular weight and the ability to complex HMs ions is based on this component only.

The UF technique has proven to be very useful along with the incorporation of the water-soluble polymer. This is evident from the study by Alfalahy and Al-Jubouri (2022) where they investigated the efficiency of zeolite incorporated polyethersulfone (PES) membranes for the removal of Pb(II) ions from aqueous solutions. The performance was evaluated under varying operational parameters, including pH (2–7), initial lead concentration (50–200 ppm), feed temperature (25 °C, 36 °C, and 46 °C), and a constant transmembrane pressure (TMP) of 1.6 bar. The optimum removal efficiency of 97% was achieved at pH 6, a temperature of 25 °C, TMP of 1.6 bar, and an initial lead concentration of 50 ppm. Other studies related to the development of UF membranes for the HMs removal also achieved removal efficiencies of 94.8% with Extracellular polymer substances-enhanced UF (EPS-UF), 94% with Polyelectrolyte-enhanced UF followed by dithionite-based chemical reduction, 90%—96% with a mixed matrix membrane of UF impregnated with Graphene oxide, 99% with Polyethersulfone/hydrous manganese dioxide UF mixed matrix membrane, 99.7% with Polysulfone

TABLE 1 Toxic HMs: sources, exposure, health effects, and regulatory limits (Kapahi and Sachdeva, 2019; Pande et al., 2022; Singh et al., 2022; Suja et al., 2024).

Metal	Environmental occurrence & major sources	Anthropogenic uses	Exposure routes	Health effects	Toxicity mechanisms	Max. limit (mg/L)
Arsenic (As)	Soil erosion, volcanic activity, smelting, mining, pesticides	Wood preservatives, metal refining, pharmaceuticals	Ingestion, dermal contact, inhalation	Carcinogenic, skin lesions, vascular disease, diabetes	Biomethylation to MMA; As(III) inactivates enzymes; As(V) mimics phosphate	0.01
Cadmium (Cd)	Sedimentary rocks, mining, fertilizers, welding	Batteries, pigments, plastics, pesticides	Ingestion, inhalation, occupational exposure	Renal injury, bone resorption, cancer, Itai–Itai disease, hypertension	DNA damage; metallothionein complex formation leading to nephrotoxicity	0.005
Chromium (Cr)	Soil and water Cr(II)–Cr(VI)), tanning, dyes, metallurgy	Chrome plating, wood preservation, welding	Ingestion, inhalation, dermal contact	Liver damage, respiratory cancer, gastrointestinal disorders, dermatitis	Cr(VI) causes DNA strand breaks and chromosomal aberrations	0.01
Lead (Pb)	Earth's crust, mining, coal combustion	Batteries, pigments, solder, paints	Ingestion, inhalation of leaded dust	Anemia, CNS damage, reproductive toxicity, mental retardation in children	Mimics calcium; disrupts DNA synthesis and repair; affects tumor suppressor proteins	0.015
Mercury (Hg)	Water, soil, air; mining, paints, batteries	Dentistry, electrical switches, paper industry	Ingestion, inhalation, dermal contact	Neurotoxicity, nephrotoxicity, dermatitis, muscle, and nervous system damage	Covalent bonding with proteins; antioxidant depletion	0.002
Copper (Cu)	Mining, polishing, plating, paints	Electronics, pigments, plumbing	Ingestion, dermal contact	Diarrhea, neurotoxicity, Wilson's disease, insomnia	Disrupts redox balance and enzyme function	1.30
Zinc (Zn)	Mining, brass manufacturing, plumbing	Galvanization, refineries, alloys	Ingestion, inhalation	Metal-fume fever, neurological signs, increased thirst, depression	Interferes with copper metabolism and enzyme activity	5.00
Nickel (Ni)	Soil, mining, electroplating	Paints, alloys, ceramics	Inhalation, dermal contact	Lung cancer, chronic bronchitis, reduced lung function	Binds DNA and proteins; induces oxidative stress	0.01

amine-functionalized nanocomposite membrane. But it also has few drawbacks including inefficient UF membranes and time consuming as higher volumes will take longer time to process and might cause clogged filters after a long use (Barakat and Schmidt, 2010; Shoshaa et al., 2023; Alfalahy and Al-Jubouri, 2022).

5.3 Phytoremediation

Phytoremediation is a plant based green strategy or technique that utilizes the plants to extract, remove or remediate the contaminated water bodies, soil or other media. Several Plants have the ability to uptake the HMs from water or soil and accumulate them in their tissues to prevent from leaching or sometimes they degrade the pollutant. However, due to different mechanisms of ion uptake, each species of plants has varied ability to accumulate HMs based on their genetics, morphology, or anatomical characters (Kafle et al., 2022; Lone et al., 2008). Plants absorb ionic compound like HMs with their root systems from the soil or contaminated water even at very low concentrations. Due to presence of good root systems, plants set up rhizosphere ecosystem and accumulate the HMs and regulate the absorption rate of HMs, thereby, recovering the contaminated soil and regaining the soil fertility (Yan et al., 2020). Phytoremediation incorporates the use different mechanisms depending on the contaminants present, environmental conditions, and the plant species. These includes (1) Phyto stabilization, (2) Phytoextraction, (3) Phytovolatization, (4) Phyto filtration, (5) Immobilization (Ghosh and Singh, 2005; Nedjimi, 2021).

Table 2 presents various types of mechanisms in phytoremediation. Phytoremediation offers a range of compelling advantages that make it an attractive strategy for environmental cleanup. Since it is an autotrophic process that is powered by sunlight, it is naturally very cheap, only requiring a little maintenance and low installation costs. Being environmentally friendly, it guarantees less release of pollutants to the surrounding ecosystems, thus being a sustainable alternative to the other traditional methods of remediation. Phytoremediation is also very suitable for large scale bioremediation and the biomass can be disposed of easily. Besides that, it is very important for the metal ions to be immobilized, hence phytoremediation prevents the metal ions from being eroded and reduce the possibility of contaminants leaking into the water bodies or soil that are close by. On top of that, by providing the soil with organic matter, phytoremediation helps to make soil more fertile and is a way of renewing land for the future (Yan et al., 2020; Nedjimi, 2021; Kafle et al., 2022).

TABLE 2 Mechanisms of phytoremediation (Ghosh and Singh, 2005; Islam et al., 2024; Kafle et al., 2022).

Techniques	Mechanism	Pollutants removed	Plant species	Action on pollutants
Phytostabilization	Complexation	As	*Eupatorium cannabinum*	Retained *in situ*
Phytoextraction	Hyper accumulation	Pb	*Brassica juncea*	Removed
Phytovolatilization	Volatilization by leaves	Organochlorines	*Phragmites australis*	Removed
Phytofiltration	Rhizosphere accumulation	Iron, Cr	*Eichhornia crassipes*	Absorbed in the roots
Phytodegradation	Degradation in plants	DDT	*Elodea canadensis*	Attenuated *in situ*

One of the studies by Balamoorthy et al. (2022) demonstrated the efficiency of phytoremediation for the removal of HMs in wastewater. The study was performed in a laboratory with pH adjusted to 6, temperature at 25° ± 5 °C and the relative humidity at 35. Synthetic wastewater containing the HMs like Cd (0.25 mg/L), Pb (0.5 mg/L), and Cu (2 mg/L) was treated for 16 days using *Mimosa pudica*. Lab results showed reduction in concentrations to 0.02 mg/L Cd, 0.21 mg/L Pb, and 0.4 mg/L Cu, indicating accumulation efficiencies of 92%, 58%, and 80%, respectively (Balamoorthy et al., 2022).

5.4 Microbial biosorption and bioaccumulation

Microbial biosorption is an efficient method employed for the removal of HMs and xenobiotic compounds from contaminated soil and water. It generally relies on the passive, metabolically independent interaction between microbial biomass and pollutants, mainly through the processes like ion exchange, complexation, and physical adsorption. Living biomass has continuously depicted greater biosorption capacity than the non-living biomass due to its active metabolization and interaction with functional groups like amine, carboxyl, phosphonate, and hydroxyl present in the cell walls of microbes (Priya et al., 2022; Tripathi et al., 2023). Gram-positive bacteria that have thicker peptidoglycan layers are especially sorptive (Rohde, 2019; Yao et al., 2025). Besides, bacteria, fungi, algae, and yeasts, all can be used as biosorbents. The efficiency of their biosorption depends on the environmental conditions, sorbing materials, and the type of metal ions (Priya et al., 2022; Tripathi et al., 2023). Biosorption is carried out at temperatures between 20 and 35 °C for being the optimal range and for this reason, it is recommended for toxic metals such as Cd, Cr, Pb, Hg, and As (Pham et al., 2022; Priya et al., 2022).

Evidence from the study by El-Naggar et al. (2020), confirms that microbial biosorption using *Pseudomonas alcaliphila* strain NEWG-2 for the bio-removal of Cr^{6+} can achieve a great removal efficiency of 96.6% of the total 200 mg/L Cr^{6+} under optimized conditions and by using yeast extract 5.6 g/L, glucose 4.9 g/L, with pH 7 for 48 h (El-Naggar et al., 2020; Pham et al., 2022). Another study reported the efficient removal of Uranium (VI) by 50% from contaminated water with the employing of *Acidithiobacillus ferrooxidans* strain 8,455 in *ex-situ* conditions (Romero-González et al., 2016).

To distinguish between bioaccumulation and biosorption, the latter one involves physicochemical adsorption of contaminants on microbial surfaces without metabolic transformation. While both are used for the removal of metal cations from the solutions. The use of immobilized microbial consortia provides more efficiency and can be used for certain pollutants without the need for transport and disposal, which is costly. This technology, however, still faces problems such as the survival of microbial cultures and scalability before it can be commercialized widely. Still, biosorption complies with the principles of green chemistry and is in line with regulatory standards, hence it can be considered as a positive alternative to wastewater treatment (Cao et al., 2022; Chojnacka, 2010; Derco and Vrana, 2018; Najim et al., 2024; Qattan, 2025).

5.5 Algal-based remediation

Algae-based methods for HMs removal from water are a green, and cheap biotechnological way to solve the problem of water pollution. This approach harmoniously combines biological and physicochemical reactions of microalgae with pollutants. Some HMs like molybdenum, cobalt, copper, Zn, Ni, manganese, iron, and boron are essential micronutrients that support metabolism of microalgae, while others metals like Hg, Cd, Pb, As, and aluminum are toxic and delay the growth of microalgae. Among all bio-remediators, microalgae are the most powerful which is mainly due to their extremely high tolerance capacity, large surface area, very rapid growth, and ability to perform with both living and dead biomass (Chugh et al., 2022; El-Sheekh et al., 2025). The clean-up process is mainly comprised of two stages—biosorption and bioaccumulation. The biosorption stage is a very fast one and it is extracellular and passive. Biosorption is the process by which HMs are adsorbed on the algal cell surface. Sometimes it may involve metabolism while most of the time it is a non-metabolic process. It is highly dependent on the cell wall functional groups like hydroxyl, carboxyl, sulfate, and amino groups which bind metal ions via different metallurgical mechanisms including electrostatic attraction, complexation, chelation, ion exchange, and surface precipitation. In addition, both live and dead algal biomass are able to perform biosorption. Thus, it is considered an energy-saving process for the elimination of pollutants.

Several species such as *Chlorella vulgaris, Scenedesmus sp., and Nostoc sp.* have demonstrated that they can be highly effective in removing HMs and organic pollutants from wastewater (Chugh et al., 2022; Chen et al., 2023; Machado et al., 2024). The bioaccumulation stage is an energy-demanding active intracellular one in which the metals are carried via cell membranes and eventually get stored in cytoplasmic or organelle compartments. Thus, it leads to the capture and detoxification of HMs by stabilizing intracellular complexes or converting them into less toxic forms (Chen et al., 2023). On top of that, algae apply few strategies such as gene regulation, chelation, antioxidation, and compartmentalization, which help to overcome metal toxicity and ensure the vital cellular functions are protected (Chugh et al., 2022).

Moreover, immobilization methods have been used to upgrade the efficacy of remediation by making algal biomass more stable and reusable (El-Sheekh et al., 2025). Besides that, the EPS released by algae create a negatively charged shield that grabs the metal ions and thereby, further diminishing the toxic interactions (Liu et al., 2025). The biopolymers in the algal matrices—consisting of polysaccharides, proteins, lipids, and nucleic acids serve as strong metal-binding ligands and open the door to the formation of flocs that facilitate pollutant separation (Pal and Paul, 2008). Many studies conducted have shown that microalgae like *Chlorella minutissima* removed 62% Zn, 84% manganese, 74% Cd, and 84% copper. *Cladophora sp*. removed 99% copper and 85% Zn and are highly efficient in the removal of As from drinking water as well (Hasnain et al., 2023). Due to their eco-friendly properties, which include CO_2 capture, nutrient recycling, and tolerance to industrial effluents, microalgae-based technologies such as high-rate algal ponds (HRAPs) can achieve removal efficiencies of over 90% for certain pollutants. As a result, phycoremediation via algae represents a green, efficient, and renewable way of reclaiming water quality, which at the same time, is beneficial for the environment and leads to economic sustainability (Delrue et al., 2016; Calijuri et al., 2025).

5.6 Constructed wetlands systems (CWs)

CWs treatment systems are biologically engineered ecosystems which emulate the natural processes of wetlands for the removal of pollutants such as HMs from wastewater. While traditional wastewater treatment systems are energy-intensive, CWs use energy that is renewable and naturally available such as solar radiation, wind, and precipitation. Though these systems occupy a lot of space, they are energy-efficient and therefore, can provide long hydraulic retention times, up to 14 days, which increases their performance in stabilizing variable inflows and pollutant loads (Hassan et al., 2021; Knox et al., 2021). CWs operate through the interaction of components such as the wetland vegetation, soils, and the diverse microbial communities, thus forming a strong biogeochemical filter that is capable of the removal of pollutants through various mechanisms like physical settling, sedimentation, adsorption, chemical precipitation, and biological uptake processes (Biswal and Balasubramanian, 2022).

As far as HMs removal is concerned, these systems can be a viable solution to those that are energy and cost-intensive such as chemical precipitation, ion exchange, and reverse osmosis (Knox et al., 2021; Yu et al., 2022). This has resulted in the high removal rates of aggregate organics (91%) and HMs (Cd: 32%, Cr: 86%, Cu: 92%, Fe: 83%, Ni: 91%, Pb: 43%, and Zn: 96%) in modified CWs that contain biochar, zeolite, and granular activated carbon (GAC). Additionally, the hydraulic retention time (HRT) has been significantly reduced (Abdel-Fattah et al., 2015; Ofiera et al., 2025). In many of the CW systems, these unique properties have been realized by the optimization of system design, substrate selection, and the integration of plants. A study by Singh and Chakraborty (2023) found that CWs have the potential to treat acid mine drainage (AMD). In particular, metal removal efficiencies achieved by the system were Fe (100%), Al (87%), Zn (98%), Ni (98%), Cr (99%) (Singh and Chakraborty, 2023). In one of the other studies conducted by Saeed et al. (2021), two hybrids subsurface flow CW systems were developed, with each one of them comprising a vertical flow (VF) unit followed by a horizontal flow (HF) unit. These systems were filled with either organic media (coco peat) or construction materials (brick and sand) and planted with *Phragmites australis* or *Chrysopogon zizanioides* (Vetiver). The total removal efficiencies achieved for Zn, Cr, Ni, and Pb in the hybrid systems were between 20%−97%, 95%−99%, 55%−73%, and 69%−83%, respectively (Saeed et al., 2021).

The statistical data presented here clearly show that plants not only facilitated the capture of metals via phytoremediation but also controlled pH and thus made it possible for microbial metal transformation processes to take place. These results emphasize the ecological and technological aspects of using vegetated wetlands for HMs pollution abatement. Moreover, the economic practicability of these systems makes them a great option for the developing areas which are characterized by inadequate wastewater treatment infrastructure and where there is an increasing demand for freshwater due to population growth and climate variability. Apart from water purification, CWs also generate some other secondary benefits such as the creation of habitats, groundwater recharge, and public environmental education. Therefore, CWs done with proper design and monitoring are an environmentally sustainable, cheap, and scalable method of HMs bioremediation, which is in harmony with current resource-saving and water reuse goals (Stefanakis, 2019; Sharma et al., 2022; Agaton and Guila, 2023). Figure 2 depicts various mechanism of HMs removal in CWs (Malyan et al., 2021; Yu et al., 2021; Zhang et al., 2024).

While CWs have proven to be efficient in HMs removal from contaminated water, they demonstrate seasonal variability which negatively affects the treatment efficiency. This is mainly due to the factors like temperature fluctuations, plant phenology, and hydrological shifts (Dykes et al., 2025). Low temperature and vegetation dormancy in the autumn and winter season reduces the microbial activities and uptake of nutrient which results in poor nitrogen and phosphorus retention (Zhai et al., 2016). Variable influent discharge, fluctuating hydrological condition further affects the pollutant removal efficiency. Various temperature dependent process like nitrification, denitrification, and plant assimilation also gets hindered and shows climate seasonality, leading to inconsistent treatment outcomes. These fluctuations emphasize the necessity for regular monitoring and adaptive management to address the uncertainties and optimize the systems for year-round performance (Dykes et al., 2025; Mesquita et al., 2017).

Dykes et al. (2025) conducted a study over 1 year to examine the effects of seasonality on the integrated CWs. He found out notable seasonal fluctuations in the concentrations removal rates (CRR) and Mass Removal Rates (MRR) for all nutrients. Nitrate CRRs ranged from −39.1% to +51.64%, corresponding to decreases of up to 14.57 mg/L and increases of 26.71 mg/L

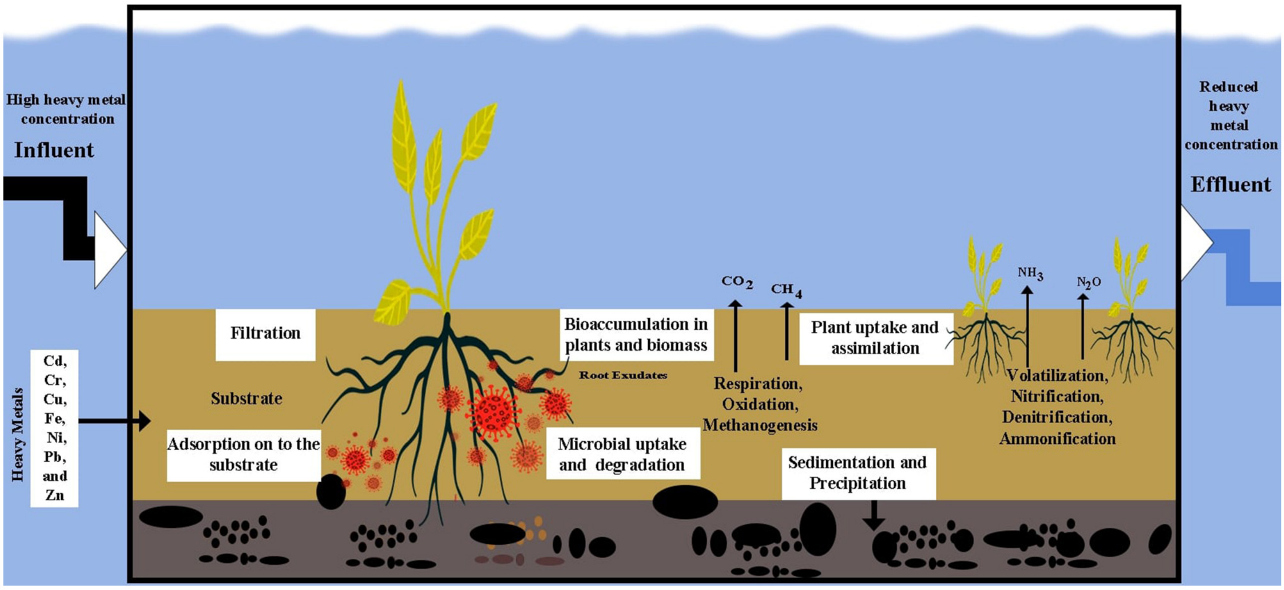

FIGURE 2
Various mechanisms of HMs removal in CWs.

in effluent concentrations, while MMRs varied between −77.13% and +84.25%, indicating changes from −38.93 kg/day to +26.69 kg/day. For phosphate, CRRs ranged from −22.79% to +2.57%, and MMRs ranged from −71% to +93.22%, corresponding to −0.57 kg/day to +0.26 kilograms per day. Additionally, the Nitrogen removal declined in late autumn and winter due to low temperature and low vegetation activity. Overall, the winter and high flow periods posed increased nutrient risks to the receiving waters during the storm and high wastewater treatment plants discharge events (Dykes et al., 2025). In another study by Chen and Shiau (2025), higher alpha diversity in CWs during the winter season and in subsurface soils was observed and was referred to be the result of elevated summer water temperature heating the surface soils, which could inhibit the microbial communities (Chen and Shiau, 2025). As reported by Zhai et al. (2016), the artificially aerated CWs when applied on a full-scale hybrid CW for 1 year achieved good efficiency in the pollutant removal including the 65% total nitrogen and total phosphorus approximately. However, the nutrient removal was lower in the winter season, most likely due to the reduced microbial activity and plant uptake temperature (Zhai et al., 2016).

6 Recent advanced methods of bioremediation

6.1 Molecular and genetically engineered microbes

Molecular and genetic engineering have significantly improved bioremediation by increasing the efficacy and functionality of microorganisms and plants employed in remediation efforts and has proven to be an effective remedy for the inefficient and slow breakdown of waste and other organic materials. The efficiency of microbes depends upon the fact that whether it has genes that can assist in the absorption of metals and can survive the prevailing environmental conditions where it is employed (Rafeeq et al., 2023). Genetically engineered microorganisms (GEMs) are microorganisms (such as bacteria, fungi, and yeast) that have been modified with the help of genetic engineering. This technology can be used to insert some specific genes in a microorganism or a plant to improve its capacity to absorb, ingest, or alleviate the HMs' effects. GEMs are bacteria wherein a stronger protein has been introduced via biotechnological or genetic engineering means to enhance the desired trait.

The use of engineered microorganisms is safer and economically more sound than the alternative methods (Hanlon and Sewalt, 2021; Rafeeq et al., 2023). The genetically engineered microbes are efficient and capable of breaking down most of the contaminants that normal indigenous microbes cannot degrade (Rebello et al., 2021). Genetically modified bacteria with improved biosorption and bioaccumulation capacities can be created to specifically target HMs like As, Hg, Zn, Cd, Cr (Fatima et al., 2024). Transgenic plants can be developed to enhance tolerance and absorption of HMs, hence improving phytoremediation efficacy. Among the molecular approaches, CRISPR-Cas9 is the most precise technology for gene editing linked to HMs metabolism and thus supporting the production of tailored bioremediation agents. The innovations in molecular and genetic engineering have a major impact on the effectiveness of bioremediation techniques (Farias et al., 2011; Chen et al., 2024).

Molecular and genetically modified microbes also raise concerns about the biosafety and regulatory issues spanning human health, the environment and dual use risk like bioterrorism or bioweapons development (Mahdizade Ari et al., 2024; Zeng et al., 2022). Although, most microbial strains are engineered for the diverse advantages like therapeutics delivery, nitrogen fixation, and industrial bioproduction, genetic modifications might unpredictably affect the host range, virulence, immunogenicity, and metabolic interactions, complicating evidence-based risk assessment (Mahdizade Ari et al., 2024; Rubinstein et al., 2025). Besides, the Horizontal Gene Transfer (HGT) and rapid microbial evolution raise critical concerns about various engineered traits like antibiotic resistance markers or novel metabolic pathways may spread into the natural microbiomes and non-target organisms. Field deployment of the engineered organisms for environmental applications like bioremediation, and agriculture faces uncertainties related to persistence, ecosystem disruption and living pollution. And that too the long-term empirical data for these remains very limited (Lensch et al., 2024; Rubinstein et al., 2025). Regulatory frameworks derived from the Genetically modified organisms (GMO) and contained use frameworks are increasingly challenged by the modularity of synthetic biology, affordable DNA synthesis, and Do It Yourself (DIY) platforms. This necessitates for the adaptive multi-tiered governance that is safe by design safeguard technologies and enhanced biosecurity oversight (Asin-Garcia et al., 2023; Bouchaut and Asveld, 2020; Zeng et al., 2022).

6.2 Integration of nanotechnology

Nano-bioremediation, the use nanotechnology in bioremediation, is one of the most recent developments to a green and almost energy independent removal technology for the abatement of HMs in polluted media. The incorporation of nanotechnology to bioremediation has made it possible to exploit the combined effect of nanotechnology and biological systems. The principal means of the nano-bioremediation are adsorption and reduction where the biogenic nanoparticles bind to the pollutants either by physical or chemical adsorption or through direct sequential reduction pathways. Chemical adsorption facilitated by functional groups on the surface of nanoparticles is usually preferred mostly because of its excellent binding efficiency (Milano et al., 2024; Thangavelu and Veeraragavan, 2022). Figure 3 presents various mechanism of HMs removal with the integration of nanotechnology (Akpomie et al., 2022; Baby et al., 2022; Bakhtiari et al., 2024; de Silva et al., 2025; Karnwal and Malik, 2024; Le et al., 2019; Olawade et al., 2024; Solanki et al., 2024; Thekkudan et al., 2017; Yang et al., 2019).

Nanostructured materials exhibit enhanced reactivity and lower activation energy owing to their high surface area to mass ratio and quantum effects, enabling them to reach and remediate contaminated environments that are inaccessible to bulk materials. Carbon based nanomaterials like graphene oxide, fullerenes, and carbon nanotubes have signified excellent adsorption capacities for metal ions due to their modifiable surface chemistry and extraordinary electronic characteristics (Mandeep and Shukla, 2020). Metal and metal oxide nano adsorbents entailing iron, silver and gold nanoparticles have also depicted high selectivity and efficiency in the removal of HMs like As, Cd, Hg, and Cr (Onotu et al., 2025; Safavi et al., 2025). Demonstrating the capability of nano-technology, iron oxide nanocomposites enclosed in the microporous silica exhibited high As adsorption capacities 47 times higher than the conventional adsorbents, while silver nanoparticles synthesized using the leaf extract *of Ficus benjamina* effectively removed Cd ions (Thangavelu and Veeraragavan, 2022). Biogenic synthesis methods with the integration of fungi (e.g., *Aspergillus niger*), algae (e.g., *Chlorococcum sp*.), and plants (e.g., Aloe vera) have made easy the production of eco-friendly nanoparticle production, lowering chemical usage, and aggregation issues (Sharma and Sharma, 2022).

Further, the functionalization with biomolecules like enzymes increases the environmental compatibility by lowering the surface energy and cellular interactions (Abdel-Mageed, 2025). Moreover, the magnetic nanoparticles coated with activated carbon or silver have already achieved notable removal efficiencies of 36.56% chemical oxygen demand (COD) and 97.4% fluoride ions from wastewater. The integration of microbial fuel cells and nano catalysts also has opened a way for bioelectricity generation alongside the remediation processes. Overall, the incorporation of nano technology in the field of bioremediation offers scalable, cost effective, viable and environmentally excellent approach to mitigate HMs with the potential to revolutionize wastewater treatment and environmental restoration through tailored nanomaterial configuration/design and assisted synthesis (Douvris et al., 2023; Milano et al., 2024).

While the beneficial effects of the nano materials are widely known, several studies have suggested toward the negative effects like nano-particle toxicity and aggregation (Islam, 2025). Nano-particles toxicity arises due to their unique nanoscale properties. Toxicity varies with parameters like charge, size, shape, surface properties, and zeta potential which potentially influence the uptake and persistence in biological cells (Akintola and Yahaya, 2024; Karakoti et al., 2006). While the nanomaterials can easily interact with microbes, plants, and animals by entering various aquatic systems via runoffs and other sources, toxicity through inhalation can also affect animals and humans. Inhalation being the primary exposure route, as even $<50\ \mu g/m^3$ of the carbon nanotubes or fullerenes in air can enter the body. Dermal exposure is one other pathway for nano particle to enter human body through sunscreens and cosmetics made of TiO_2 and ZnO (Akintola and Yahaya, 2024; Karakoti et al., 2006). Once released, these small sized particles can disperse widely, accumulate in sediments, bioaccumulate through food chains, potentially causing oxidative stress in algae and invertebrates (Akintola and Yahaya, 2024; Islam, 2025).

Besides, nano particles can penetrate plant roots and move through xylem where the silver nanoparticles (AgNPs) accumulate in the tissues and entering food chain. While the mobility and toxicity of the nano particles are generally influenced by environmental factors like pH, temperature, and pollutants, they can also be dependent on soil conditions, nutrient availability, and plant species like in case of AgNPs. AgNPs can easily

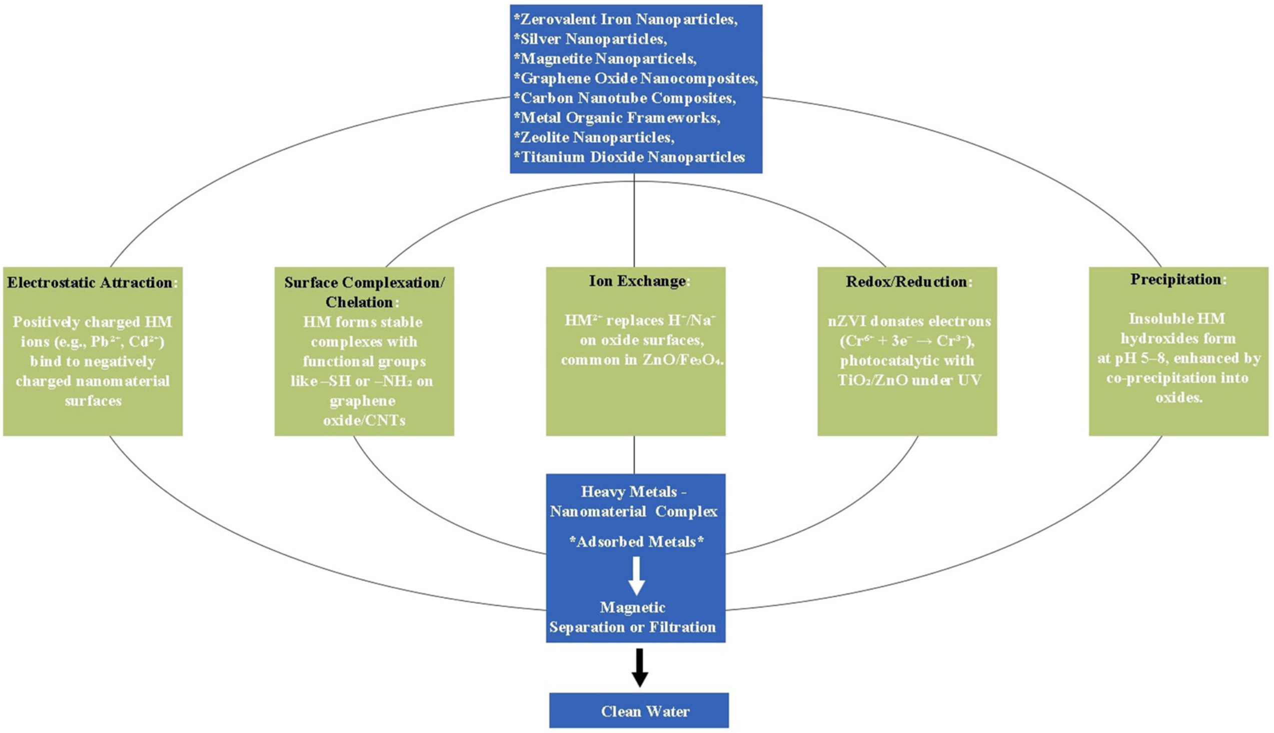

FIGURE 3
Various mechanisms of HMs removal with the integration of nanotechnology.

dissolve and oxidized to Ag^+, which is more toxic than the particulate form, potentially harming biodiversity, soil health, and microbial communities. One another harmful effects of nanoparticle sis the aggregation, where the nano particles cluster together causing alteration in their stability, reactivity, and behavior in diverse environments. Driven by surface charge, ionic strength, pH and multivalent cations, nanoparticle aggregation along with dissolution of metal based engineered nano particles (ENPs) releases ions with distinct mobility and toxicity. Soil constituents like clays and oxides strongly adsorb nanoparticles, influencing the transport and hetero-aggregation. Widely used ZnO, iron oxide, Fe_2O_3 and TiO_2 may help enhance growth of the plants and other processes at low concentrations but may also cause oxidative stress, reduced germination, root changes, microbial disruption, and soil accumulation at higher levels (Ihtisham et al., 2021; Islam, 2025; Singh and Saxena, 2022).

6.3 AI in bioremediation

AI is one of the increasingly recognized transformative tools that is being widely used in the bioremediation of HMs, providing data drive solutions for the monitoring, optimization, and predictive modeling (Blessing and Olateru, 2025). AI systems facilitate environmental data acquisition from the diverse contaminated sites of soil and water, and through the analysis of variables such as microbial activity, pollutant concentration, pH, temperature, and nutrient levels. Thus, bioremediation conditions can be dynamically adjusted to enhance microbial efficiency and pollutant degradation (Akintola, 2024). Predictive modeling is instrumental in forecasting remediation outcomes, enabling the timely interventions that both quicken and ensure the success of the process. Several AI algorithms that include machine learning (ML), neural networks (ANN), genetic algorithms (GA), particle swarm optimization (PSO), and boosted regression trees (BRTs) are utilized to promote the simulation of complex environmental systems and the improvement of treatment strategies by optimization. These models can work diligently with the historical data on pollutant dispersion to efficiently solve the issues of identifying the high-risk zones, and support the targeted interventions. ANN, inspired from the structure of biological neurons, is quite powerful when it comes to handling multivariate non-linear complex problems and therefore widely adopted in water treatment processes modeling.

Several studies have reported that ANN based models significantly improves and enhances the prediction accuracy (R^2) and reduces the common error metrics in comparison with the conventional methods of waste water treatments (Alsulaili and Refaie, 2021; Minh et al., 2024; Sabour and Amiri, 2017). Alsulaili and Refaie (2021) in a study achieved the R^2 values of 0.752 for BOD, 0.612 for COD, and 0.631 for TSS in WWTP effluent, with an influent BOD5 soft sensor reaching $R^2 = 0.754$ for real-time control (Alsulaili and Refaie, 2021). Ibrahim et al. (2024) reported R^2 up to about 0.89 for COD/BOD prediction, outperforming linear models (Sabour and Amiri, 2017; Ibrahim et al., 2024). While Sabour and Amiri (2017) showed ANN superior to RSM in modeling Fenton treatment of landfill leachate (Sabour and Amiri, 2017). Minh et al. (2024) further confirmed ANN performance with

$R^2 = 0.9604$ vs. RSM's 0.9528, along with lower MAE, MSE, and RMSE, and greywater BOD prediction studies reported $R^2 = 0.88$ for ANN models (Minh et al., 2024). Zhao et al. (2020) performed a bibliometric analysis between the period of 1995–2019 to determine the trends in the application of A.I to waste water treatment. Their findings indicated rapid growing acceptance and reliance on the ANN modeling for simulation and prediction of performance of biological waste water treatment plant (Dantas et al., 2023; Zhao et al., 2020).

The use of convolutional neural networks (CNNs), radial basis function (RBF) networks, and self-organizing maps (SOMs) as variants allows complex statistical modeling and real-time control systems to be performed (Bhagat et al., 2020; Blessing and Olateru, 2025; Kumari et al., 2025). Additionally, AI aids in the monitoring strategies and the designing of genetically engineered microbes that are tailored to the specific contaminants and are also equipped with the feedback mechanism for real-time effectiveness assessment (Akintola, 2024). When combined with AI, remote sensing technologies such as hyperspectral and LiDAR imaging become more efficient in carrying out and facilitating land cover mapping, object detection, and change analysis, with being further improved through data fusion and integration. These attributes facilitate the recognition of space and time patterns in pollutant concentrations and supply extensive understanding of environmental dynamics through AI supported pollution monitoring systems (Blessing and Olateru, 2025; Lovynska et al., 2024).

Despite being so useful and powerful, AI driven bioremediation faces challenges related to data quality, availability, training optimization, integrity, and ethical issues like environmental justice as well as equitable access. Nevertheless, future tech like AI, machine learning (ML), and deep learning (DL) pave the way for less expensive alternatives to conventional remediation processes through such means as cutting down human interventions and efforts, sampling requirements, and overall efficiency. The flexible capacity of AI reflects it's more general ecological applications linked to the quality of air, water, and soil, biodiversity monitoring, and resilience planning. As AI continue to evolve, its integration into bioremediation is a radical change to the intelligent, adaptive, and sustainable management of HMs contamination. Thus, it is considered one of the efficient technologies for environmental engineering (Akintola, 2024; Alotaibi and Nassif, 2024; Blessing and Olateru, 2025).

6.4 Biofilm technologies

Biofilm mediated bioremediation put forward a promising, and a sustainable solution to deal with the environmental threat of HMs contamination that endangers almost all living organisms (Jasua et al., 2021). Biofilms are assemblages of microorganisms enveloped in a matrix of self-produced EPS, which contain water, proteins, carbohydrates, and extracellular DNA. This microbial community, which usually comprises bacteria, fungi, algae, and archaea, adheres to the surface and grows in a humid environment if there is enough nutrition. Their generation is a multistep process: irreversible attachment, quorum sensing, development of layered colony, and planktonic cell dispersion (Flemming et al., 2024; Jasu and Ray, 2021; Zhao et al., 2023). Biofilms protect from the various environmental stresses like pH changes, salinity, extreme temperatures, and toxic chemicals. Figure 4 presents various mechanism of HMs removal with the integration of biofilm technologies (Arora and Khosla, 2021; Mohapatra et al., 2020; Priyadarshanee and Das, 2021; Syed et al., 2022). Variable gene expression in biofilms controlled by nutrient and oxygen gradients allows metabolic specialization and division of labor, which is a part of the pollutant degradation and breakdown process. Chemotaxis, flagellar motility, and quorum sensing also help microbial coordination and movement toward contaminants (van Gestel et al., 2015; Yin et al., 2019). Biofilms are very effective in the sequestration and detoxification of HMs like Pb^{2+}, Cd^{2+}, and Zn^{2+}, with EPS playing a significant role due to the anionic charge and enhanced capacity of binding metals (Mahto et al., 2022). Fungal-bacterial biofilms (FBBs) have depicted significant metal removal potential and reduced penetration into the tissues of plant during the remediation studies of soil. Superior metal uptake and enhanced resistance have been noticed in the strain related to biofilm formation, making them an ideal choice for *in situ* remediation.

Natural attenuation, a passive bioremediation strategy, depends on the indigenous biofilm forming microbes as to transform, immobilize, and detoxify pollutants without engineered intervention. Biofilms also act as a valuable indicator for the monitoring of environment, especially in the aquatic ecosystems (Jambon et al., 2018; Pandit et al., 2020; Henagamage et al., 2022). A change in biomass, species composition, pigment production, photosynthesis, and enzymatic activity can signal the rise or reduction of pollution levels (Rai, 2016; Yadav and Nikam, 2024). Microbial profiling is found to be a very efficient instrument for the determination of ecosystem health during seasonal changes and pollutant loads from metals such as Zn and Cd that affect the diversity of river biofilms. Besides, biofilms are the first biological interface with pollutants in water bodies and react rapidly when in contact with toxicants, thus providing a convenient early warning system. Their easy sampling method, rapid growth, and pollutant adsorption capacity make them even more valuable in environmental assessment. To sum up, the biofilm-based remediation system harnesses microbial adaptability, metabolic diversity, and ecological resilience, thereby providing an environmentally-friendly solution to the problem of HMs pollution while at the same time, functioning as a tool for environmental monitoring (Mitra and Mukhopadhyay, 2016; Griffero et al., 2024; Iqbal et al., 2025; Kollati et al., 2025).

6.5 Internet of things (IoT) in bioremediation

The management and monitoring of water and soil HMs contamination have been exponentially improved through the integration of Internet of Things (IoT) technology into the bioremediation system. IoT devices equipped with low-cost sensors can detect the levels of HMs in the water that is used for irrigation, which is an essential aspect of precision agriculture. The Interconnected sensors to IoT networks share data in real-time to

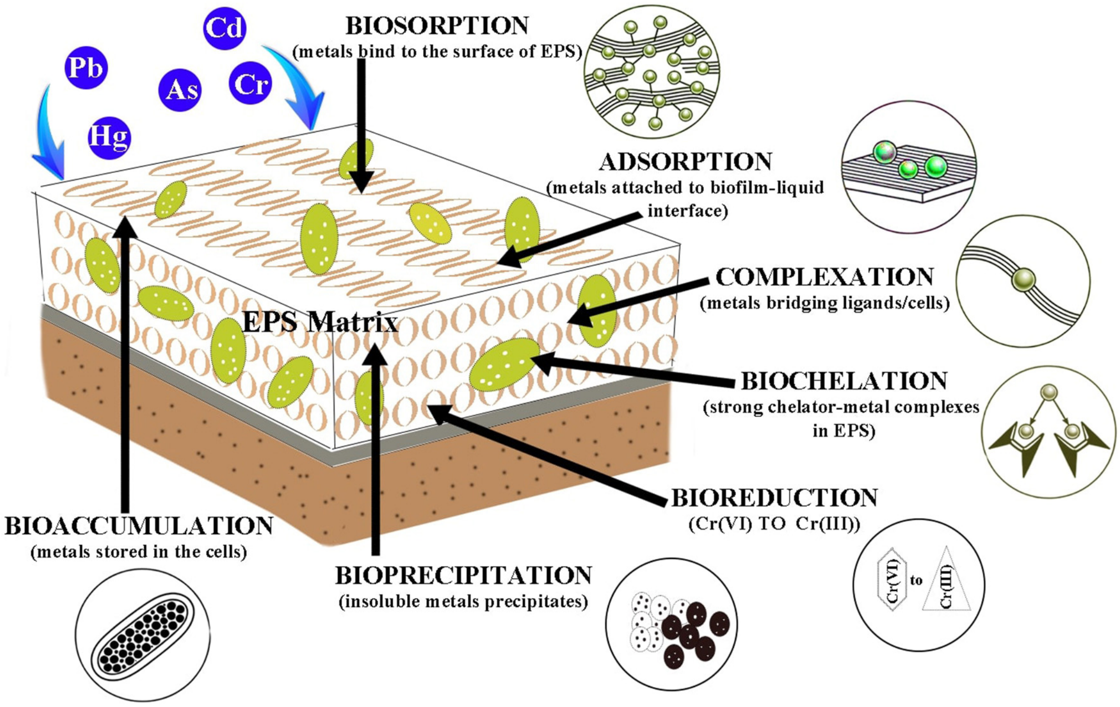

FIGURE 4
Various mechanisms of HMs removal with the integration of biofilm technologies.

the platforms that can be updated immediately, thus making it possible to have instant insights and early warning to curb crop and soil damage. By integrating sophisticated components such as those based on NodeMcu8266 architecture, continuous monitoring and alarm mechanisms can be realized, thus allowing timely intervention (Anil Kumar and Mahabhaleshwara, 2024; Kumar et al., 2024; Kuppan et al., 2024). In the case of bioremediation and waste management, IoT-enabled sensors keep track of environmental variables like pH, temperature, and pollutant levels, thus ensuring and facilitating the automated control of nutrient supply to microbial communities and the optimization of the pollutant degradation process (Kuppan et al., 2024; Ngwenya et al., 2025).

Furthermore, systems of this nature can also help in the monitoring, and controlling of the bioremediation activities at many different remote locations, thus the need for human intervention is reduced and efficiency of operations is concurrently improved. IoT devices and networks have proved to be of great importance in the urban wastewater treatment as a result these are being embedded across the sewage treatment nodes and equipments, allowing for remote online control of pipe valves and real time management of treatment processes. The usage of such systems in the wastewater treatment leads to positive effects such as faster crisis response, standardized operations and increased energy and economic efficiency. The system's framework is oriented toward operations that are continuous for up to 24 h, with sensor deployment strategies designed to maintain integrity and prevent disturbances. Furthermore, smart soil remediation equipment utilizes IoT to collect samples and evaluate the status of the soil, which also involves the recognition of HMs and transmission of data for timely action and applications of remediation agents (Dhanaraju et al., 2022; Pamula et al., 2022; Mowla et al., 2023; Dada et al., 2024).

6.6 Hybrid systems

Advanced hybrid systems utilized in the bioremediation of HMs in water is a novel technology that combines both biological and physicochemical methods to enhance the removal of HMs and microplastics. These hybrid systems synergistically combine microbial bioremediation with ultra-modern technologies such as nanotechnology, electrochemical methods, and membrane bioreactors, thereby diminishing the drawbacks of traditional bioremediation like slow kinetics and incomplete detoxification (Yadav et al., 2023; Khan et al., 2025; Vuković Domanovac et al., 2025). For instance, electrochemical treatment along with microbial bioreactors (MBRs) has shown enhanced performance by coupling biodegradation with physical retention and electrochemical transformation of HMs and other pollutants. Thus, resulting in the achievement of higher efficiency and longer operational lifespans than that of microbial methods alone. The enhanced efficiency of the integrated system of electro-membrane bioreactors (eMBRs) is evidenced from data collected by Ensano et al. (2016). For the municipal and industrial wastewaters, eMBRs achieved 85%–98% COD removal compared to 72%–95% for conventional MBRs. While the phosphorus removal ranged from 94%–99% compared with 59%–65% in conventional stems, demonstrating superior organic and nutrient removal. Besides, sludge retention times (SRTs) up to about 268 days and 81%–82%

reductions in specific cake resistance and fouling index at 12A/m^2 current densities demonstrated superior long-term stability and reduced fouling (Ensano et al., 2016).

In these hybrid electrochemical MBR systems, pollutant breakdown is brought to the maximum level while membrane fouling, which is a common disadvantage in pure biological systems, is avoided (Ensano et al., 2016; Vasanthapalaniappan et al., 2020). Furthermore, the use of nanomaterials such as nanoscale zero-valent iron (nZVI) particles in conjunction with bioremediation brings about the enhancement of HMs adsorption and their reduction to less toxic forms. These nanoparticles are the most effective reductants and adsorbents as they can immobilize metals, whereas the microorganisms consume organic co-contaminants, thus forming a single remediation platform with greater sustainability (Verma et al., 2025; Wang et al., 2025). The recent emphasis on plant-microbe interactions mediated by plant growth promoting rhizobacteria (PGPR) is one of the main reasons for the advances in this field and it implies that plants together with metal-resistant microbes can significantly increase phytoextraction of HMs from water and soil. This hybrid phytoremediation technique utilizes microbial bioaugmentation and phytostimulation to get the remediation process faster and complete (Karnwal et al., 2024; Khoso et al., 2024). Besides that, hybrid systems that use biosorbents obtained from agricultural waste and lignocellulosic biomass not only attract metal ions but also offer numerous functional groups for metal binding, thereby lowering metal bioavailability in water (Lindholm-Lehto, 2019; Kainth et al., 2024). Table 3 presents the comparative analysis of various new technologies for the bioremediation of HMs. The integration of these biological components with nanotechnology, electrokinetic processes, and membrane filtration forms a multi-pronged, adaptable approach for HMs bioremediation. Hybrid bioremediation systems are, in essence, environmentally friendly, scalable, and economically feasible measures to reduce HMs pollution in water (Firincă et al., 2025).

6.6.1 Advantages of combining biological and physicochemical methods (Hybrid Systems) over standalone approaches

Hybrid stems combing the biological and physicochemical approaches offers synergistic advantages that surpass the limitations of standalone methods in the field of bioremediation of HMs. Combining methods such as chemical precipitation, ultrafiltration, and biosorption with biological processes like phytoremediation, bioaccumulation, algal-based remediation, and CWs boost the removal efficiency and optimize the operational stability (Das and Mishra, 2025; Bang Truong et al., 2024; Sharma and Sharma, 2020). Physicochemical methods provide the rapid initial reduction of HMs concentrations, ultimately leading to improved bioavailability, better biological uptake, and transformation. Meanwhile the biotechnological method like molecularly engineered microbes and biofilm-based technologies allows selective metal sequestration, biotransformation, and detoxification at low costs (Gahrouei et al., 2024; Hashim et al., 2025).

The coupling of advanced technologies like nanotechnology, AI, IoT further improves the strength and performance of the system by allowing real time monitoring, adaptive control, predictive modeling, and decision making. Nano materials can functionalize biosorbents and membranes to improve the efficiency of adsorption and regeneration potential, while AI driven optimization helps monitoring, reporting, and controlling complex bioprocesses. Standalone approaches including biological approaches are inherently sustainable, yet they suffer from slower kinetics, limited tolerance, and lower efficiency in heterogenous environments (Lowe et al., 2022; Alprol et al., 2024; Maurya et al., 2024; Siddique et al., 2025). Conversely, physicochemical approaches deliver robust and rapid removal of HMs but are often constrained by the high operational costs, risk of secondary pollution, and limited selectivity. Thus, this is where the hybrid systems are utilized for overcoming the limitations of standalone approaches. The hybrid methods, strategically integrate the different domains and capitalize on the complementary strengths of each standalone methods, creating remediation platforms that are both efficient and adaptable with applications over diverse contamination scenarios. Moreover, these hybrid systems are more resilient in real world conditions where the pollutant load and diverse parameters like pH, temperature may vary unpredictably (Goswami et al., 2022; Hamdi et al., 2025; Karnwal et al., 2024; Khoso et al., 2024).

6.6.2 Future of hybrid approaches and digital technologies for HMs bioremediation

Development and utilization of integrated and hybrid systems, uniting the strengths of diverse biological, physicochemical, and cutting-edge digital technologies have paved the way for innovative approaches to the bioremediation of HMs. The convergence of biological remediation with A.I., IoT, and nanotechnology not just enhances the process monitoring, performance optimization, and on-site decision making but also ensures sustainability and adaptability in addressing the various challenges related to the remediation of contaminated sites. Predictive models driven by A.I. combined with real time IoT sensor networks allows dynamic monitoring and control of microbial and various necessary parameters of the system. This integrated system aids in the maximization of removal of HMs while minimizing the operational costs, failure, and uncertainties. Meanwhile, hybrid systems combining the microbial, electrochemical, and nano material-based remediation strategies achieve synergistic effects by coupling various mechanisms of metal removal like adsorption, reduction, and detoxification of different methods and technologies. Such interconnected framework represents a key transformation toward autonomous, efficient, sustainable and data responsive remediation platforms, offering a scalable, intelligent, and environmentally adaptive approach for the management of HMs (Lowe et al., 2022; Siddique et al., 2025; Lahari et al., 2025).

7 Methods used for detection of HMs

7.1 Atomic absorption spectroscopy (AAS)

AAS is a highly sensitive technique that finds its application most commonly in detecting minute traces of HMs in solutions or wastewater (Elkhatat, 2023). The method involves atomizing a sample, which may be done in a flame or graphite furnace,

TABLE 3 Comparative analysis of various new technologies for the bioremediation of HMs.

Technology/ Methods	Target metals	Efficiency range	Advantages	Disadvantages	Technology readiness	References
Molecular and genetically engineered microbes	Cd(II), Ni(II), Hg(II), Hg(II), As(III), Zn(II), Cd(II), Hg(II), Pb(II), As(III), Hg(II)	90%—98% removal efficiency in case of *E. coli* (Jm109) And 212– 250 mg L^{-1} for *E. coli* (MT2 and MT3)	Enhanced specificity, multi-step transformation, complex biochemical conversion, controlled implementation, and high removal efficiency	May disrupt native microbes, degradation of traits in high temperature and pH, high development cost, special management of metal-laden biomass needed	Promising but not yet ready for full-scale application	Srivastava, 2021; Ghosh et al., 2023; Iravani and Varma, 2022
Integration of nanotechnology	Pb(II), V.(III), Cesium, Hg(II), Ni(II), Hg, Fluoride, As, Ni, Chromium (VI)	Mercury removal efficiency of 96% in AuNP–Al_2O_3 adsorbent	High surface area, fast kinetics, magnetic recovery, tunable, versatile	Toxicity, agglomeration, high cost, unclear regulation, recovery issues	Greatest efficacy in laboratory and pilot-scale applications	Singh G. et al., 2024; Scheverin et al., 2024; Akintola and Yahaya, 2024; Julius et al., 2025; Thangavelu and Veeraragavan, 2022
Integration of AI	Cd, Pb, Cr	95% HMs removal efficiency	Real-time optimization, predictive maintenance, pattern detection, automation, cost savings	Data needs, model opacity, high setup cost, cybersecurity, skill demand	Full-scale municipal deployment and field-scale remediation	Lowe et al., 2022; Alprol et al., 2024; Maurya et al., 2024; Siddique et al., 2025
Biofilm technologies	Cd, Cu, Ni, Zn, Pb, Cr	Removal efficiency of 30% to 98% depending on the concentrations of HMs.	Self-organizing, long-term stable, low cost, multi-mechanism, resilient	Slow start, mass transfer limits, variable performance, biofouling, low control	Laboratory scale systems	Volarić et al., 2021; Manju et al., 2023; Asri et al., 2018; Azizi et al., 2016; Rene et al., 2016
Integration of Internet of Things (IoT)	Cd^{2+}, Pb^{2+}, Cu^{2+}, and Hg^{2+}	Detection limits of 0.99 μM, 0.62 μM, 1.38 μM, and 0.72 μM	Real-time data, remote access, sensor fusion, predictive analytics, scalable	Sensor accuracy, connectivity, data security, high initial cost, maintenance, device compatibility	Field scale at industrial WWTPs	Lowe et al., 2022; Essamlali et al., 2024; Chavhan et al., 2025; Lahari et al., 2025

followed by measuring the absorption of light by the free atoms. Each metal has its unique wavelength at which it absorbs light, and the absorption is proportional to the metal concentration. The technique yields precise quantitative data and can detect metals such as Pb, Cd, copper, and As at a level as low as parts per billion or even parts per trillion. Samples are usually prepped through digestion to obtain atomic forms of metals. AAS is a method of choice because of its selectivity, sensitivity, relatively low cost, and the availability of standardized protocols. It especially finds application in routine monitoring of industrial and municipal wastewater in the environment (Slavin, 1994; Hina et al., 2023; Abdelmonem et al., 2025). Since AAS could detect only a single element at a time and could not establish simultaneous methods, these limitations paved the way for multi-element techniques such as Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES), which could detect several elements at a time and has several other benefits (Ferreira et al., 2018).

7.2 Inductively coupled plasma optical emission spectrometry (ICP-OES)

ICP-OES can detect several HMs at the same time by using a plasma source that excites atoms and they emit light at the characteristic wavelengths. The intensity of the emitted light is directly related to the amount of the metal. ICP-OES provides fast multi-element detection from trace levels to high concentrations, has high sensitivity and wide dynamic range. It is also very effective in handling complex wastewater matrices. The procedure involves the use of very advanced instruments, and operators must be highly skilled, thus making it expensive when compared to AAS. However, the capability of the instrument to perform a large number of metals determinations in one run shortens the total time of the analysis significantly. The technique is largely used by laboratories that monitor wastewater from metal industries (Dressler et al., 1998; Hou and Jones, 2000; Khan et al., 2021; Douvris et al., 2023).

7.3 Electrochemical methods

To address the need of portable and cost-effective monitoring outside the lab, electrochemical methods emerged as practical alternatives of ICP-OES (Motshakeri et al., 2025). Electrochemical methods for HMs detection, such as anodic stripping voltammetry (ASV), make use of electrochemical cells wherein metals are pre-concentrated on electrodes and, upon the application of voltage, are stripped off. The electrical current thus generated is in direct proportion to the concentration of the metal (Ariño et al., 2022;

Zhao et al., 2022). Such sensors offer rapid detection with high sensitivity of trace HMs like Pb, Hg, and Cd (Helim et al., 2024).

Most of the standard analytical methods like atomic absorption spectroscopy, atomic fluorescence spectroscopy, and x-ray fluorescence sensors needs complex equipment, expert personnel, and lengthy procedures. To overcome these issues, electrochemical sensors offer superior advantages via rapid, accurate, simple, and less costly analysis for real time multi parametric detection of HMs. Notable examples include dumbbell-like Au/Fe_3O_4 nanoparticles on screen-printed carbon electrodes (SPCE) for arsenic limit of detection (LOD 0.0215 ppb, sensitivity 9.43 μA/ppb), $Fe_3O_4/Bi_2O_3/C_3N_4$-modified glassy carbon electrode (GCE) for cadmium (LOD $<3 \times 10^{-9}$ mol/L, range 0.01–3 μmol/L), DNA-based sensors with ethyl green/multi-walled carbon nanotubes (MWCNTs) (Cd LOD 2 nM, sensitivity 5 nA/nM), and comb-shaped Parafilm electrodes for Pb, Cu, Hg at 0.05 mg/L with signal enhancement ratio 1.42 during Anodic Stripping Voltammetry (ASV) (Madadelahi et al., 2025; Sulthana et al., 2024).

Additionally, the electrochemical sensors allow sensitive quantifications of a diverse range of HMs, with the detection limits generally spanning from nanomolar to sub ppb levels. Lead is detected by ASV at a copper electrode with (LOD) of 21 nM, while cadmium reaches 3.8 nM using Square Wave Voltammetry (SWV)/Differential Pulse Voltammetry (DPV) at a CNT–polyaniline-modified glassy carbon electrode. Mercury, arsenic, and copper are monitored by Cyclic Voltammetry (CV)/DPV with graphene or conducting-polymer composites, achieving LODs of 0.8 μM, 0.12 μM and about 1.2×10^{-6} M, respectively. Cr, Ni, and cobalt show μg/L limits (0.8, 2.5 and 2.4 μg/L), whereas manganese, Zn and iron are detected around 4.2, 1 μg/L and 0.05 mg/L. Advanced platforms, including Bi-film, ion-imprinted and nanocomposite electrodes, push LODs to 2.1×10^{-9} mol/L for Sn, 0.03 ppb for thallium (Tl) and 0.43 μg/L for uranium (U), highlighting the ultra-trace capabilities of modern electrochemical sensing techniques (Madadelahi et al., 2025; Sulthana et al., 2024; Tian et al., 2025).

Electrochemical methods are also portable and can be used for on-site testing, thus making them a suitable option for on-field wastewater monitoring. Nevertheless, they need calibration, clean electrodes, and can be affected by the interference of other substances. Despite the drawbacks, electrochemical methods provide a low-cost, real-time detection alternative which complements traditional lab-based techniques (Umapathi et al., 2022; Shabib et al., 2025). To overcome the limitations of lower sensitivity and limits of detection as in electrochemical methods of detection, biosensors can be used, which offers high sensitivity, selectivity, rapid, and accurate real time monitoring (Bansod et al., 2017; Hara and Singh, 2021; Wu et al., 2023).

7.4 Biosensors

Biosensors use biological recognition elements such as enzymes, antibodies, or microorganisms that selectively interact with HMs in wastewater and thus release an electrical or optical signal which can be used for detection (Fdez-Sanromán et al., 2025; Velusamy et al., 2022). They ensure fast, specific, and potentially real-time monitoring without the need for a complicated sample preparation step (Nath, 2024; Nnachi et al., 2022). Biosensors can specifically be designed for certain metals and are becoming increasingly popular as *in situ* environmental assessment tools. However, their sensitivity might be lower than that of instrumental techniques; also, they often require frequent calibration, and must be handled carefully in order to maintain the biological activity. Besides, they can be limited by stability and lifespan issues. The fact that these devices are easy to use and respond quickly makes them a valuable tool serving the functions of preliminary screening and continuous monitoring (Ding et al., 2015; Odobašić et al., 2019; Huang et al., 2023).

Since the core and most critical characteristics of biosensors are high sensitivity, short response time, specificity, and relatively less costly, they are best utilized for detection of toxic substances like pollutants, pesticides, and HMs. Biosensors may be tailored for the real time and continuous monitoring of certain pollutants in order to regulate and support the management of the water safety and quality. Biosensors can complement bioremediation of HMs and other pollutants by achieving on site and real time environmental data. Besides, biosensors can also be integrated into pollutant monitoring systems and employed as a predictive tool for assessing the chemical pollution in the environment (Huang et al., 2023; Odobašić et al., 2019).

Microbial fuel cell (MFCs) based configurations, employing carbon fiber or graphite felt electrodes in double or single chamber setups, achieved detection limits of 0.5–10 mg L^{-1} for Cu, As, Cr, Hg in municipal and industrial wastewater with response times as fast as 5–18 min, complementing the *in-situ* adjustments during microbial biosorption or bioaccumulation. Whole-cell bacterial biosensors in sol-gel matrices detected Cd, Cu, Zn at 1.42×10^{-4}–3.16×10^{-4} mg L^{-1} in soil within 4–7 h, while DNAzyme and magnetoelastic systems offer ultrasensitive limits (e.g., 0.23–0.33 μM for Pb, 1×10^{-6} nM for Hg) in water samples, often in minutes. Additionally, whole cell biosensors, engineered with metal responsible promoters like arsR for arsenic, cadC for cadmium, and merR for mercury, detect ions such as Cd^{2+}, Pb^{2+}, and Hg^{2+} at ppb levels within minutes to hours, providing rapid feedback that traditional lab methods like ICP-MS cannot match. These portable cost-effective tools like MFCs, Surface-Enhanced Raman Spectroscopy (SERS) or conductometric biosensors ensures bioavailability assessment, prevent rebound pollution and optimize the strategies for bioremediation (Bereza-Malcolm et al., 2014; Huang et al., 2023).

7.5 Membrane filtration techniques

Membrane technologies extend beyond detection by offering rapid removal, making them valuable in integrated monitoring–remediation systems. They complement biosensors and electrochemical methods by providing a physical barrier to the contaminants (Selivanovitch et al., 2024; Urtiaga, 2021; Kapepula and Luis, 2024). Membrane filtration technologies like nanofiltration and reverse osmosis are primarily aimed at HMs removal from wastewater (Castro and Abejón, 2024).

Their main function is treatment, yet they can also be used as indirect supportive means for metal quantification by providing concentration in permeate and retentate streams. Such membranes are semipermeable and act as physical barriers that allow the separation of metal ions based on their size and charge. These methods provide removal efficiencies that are very high for a widely varied set of metals such as As, Cd, and Pb (Mukherjee, 2019; Azmi et al., 2025). While not being a direct detection tool, metal detection and approximate quantification can be obtained from system performance monitoring (Cavaliere et al., 2025; Phattaranawik et al., 2008). Membrane fouling, high operational costs, and the need for pre-treatment are the problems it faces. These approaches harmonize with detection in a way that they reduce metal loads and are thus necessary for wastewater management. Each of these methods brings different benefits and drawbacks with respect to their sensitivity, costs, complexity, and the context of application, thereby allowing for the most suitable method to be selected depending on the characteristics of the wastewater and the monitoring needs (Dawam et al., 2025; Ezugbe and Rathilal, 2020).

7.6 Suitability of HMs detection methods

Detection methos for HMs vary widely in terms of suitability for various developing regions. In these regions, constrained infrastructure, high cost, and very limited technical expertise hinders the effective bioremediation monitoring. Laboratory based detection techniques like Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) and AAS delivers high sensitivity with accuracy for multi-elemental analysis even at very low concentrations, making them one of the best detection tools for precise quantification. However, due to expensive large equipments, maintenance, expenses for inert gases and consumables plus stable electricity, clean laboratory environments, and need of highly skilled experts, resources are not generally available in remote or under-resourced regions of developing countries. These multiple barriers make these methods inherently limited to centralized labs, necessitating sample transport to over poor road networks which risks delay and contamination (Eskina et al., 2020; Filippidou and Chatzandroulis, 2023; Hu et al., 2023; Mukherjee et al., 2021). They do offer a more accessible alternative for pretreatment and industrial reuse with high sensitivity and low-cost setups plus the advantage of scalability and less space requirements. While highly portable for sampling or filtration, they do rely on the lab analysis for heavy metal quantification, complicating the logistic with inadequate transport and storage facilities in some developing regions (Aziz et al., 2024; Azmi et al., 2025; Filippidou and Chatzandroulis, 2023; Haider et al., 2024).

Table 4 presents a comparative overview highlighting sensitivity, cost, portability, and field applicability of different HMs' detection techniques for better understanding of these technologies. Other detection tools and techniques including the biosensors and electrochemical methods like anode stripping voltammetry are exceptionally well suited and provide high sensitivity with low-cost option for disposable/hand held units, high portability due to compact battery powered IoT ready designs and capability for *in-situ* or on-site real-time monitoring. These allows local technician with minimal training to perform rapid assessment at sites without being depended on advanced infrastructure (Eskina et al., 2020; Hara and Singh, 2021; Hu et al., 2023).

8 Challenges and limitations

Bioremediation of HMs is limited by challenges and problems, most of which raise concerns about its efficiency and viability in practice. The major problem, essentially, is the bioavailability of HMs to the microorganisms which is often influenced by the changes in soil pH, organic matter content, metal speciation, temperature, moisture, and oxygen level (Igiri et al., 2018; Karnwal et al., 2024). Metals that are tightly bound to soil particles or those that exist in insoluble forms are less available for microbial uptake, thus, the effectiveness of bioremediation is lowered. At the same time, the survival and activity of microbial agents may be negatively affected if the environmental conditions are extreme. Moreover, the specificity of microorganisms for pollutant degradation limits bioremediation as well. Also the microorganisms need good conditions such as oxygen and nutrients in order to grow and this may affect the natural soil microbial communities (Igiri et al., 2018; Kour et al., 2022; Karnwal et al., 2024). Bioremediation is usually slow and it takes more time than other remediation methods like excavation or incineration in most cases (Maheshwari et al., 2014; Naseem et al., 2023). Besides that, sites with high metal concentrations and the presence of toxic pollutants can have a negative impact on microbial activity and thus, bioremediation will be less efficient. The porosity and nature of soil, such as the low permeability of clay, can also become factors that limit microbial access and oxygen circulation (Abo-Alkasem et al., 2023; Das et al., 2025).

One more important problem is the possibility of generating toxic byproducts or secondary contaminants during bioremediation, which are as toxic or even more toxic than the original pollutants (Bala et al., 2022). Also, the differences in microbial strains, their genetic variations, and their adaptability are factors that affect bioremediation efficiency (Arora et al., 2024). Transferring techniques from a controlled laboratory setting to the field is still difficult because of the heterogeneity of the site, complexity of management, and cost-effectiveness issues. To sum up, bioremediation of HMs could be a green and cheap solution to detoxifying metal pollutants, but it is challenged by the slow degradation of contaminants, its sensitivity to environment, limited bioavailability of metals, emergence of toxic byproducts, and difficulty in scaling up. Enhanced microbial formulations and genetic engineering may pave the way for future breakthroughs beyond these limitations (Koolivand et al., 2024; Mahanayak, 2024).

9 Policy frameworks and community-based remediation

Policy frameworks for dealing with HMs and community-based remediation demand measures that involve regulation,

TABLE 4 Comparative overview highlighting sensitivity, cost, portability, and field applicability of different HMs' detection techniques.

Techniques/ methods	Typical sensitivity	Cost	Portability	Field applicability	References
Membrane filtration techniques	High	Low-cost setup, but High cost in large scale industrial setups	Requires less space and can be scaled up or down accordingly	Good for pretreatment/industrial reuse	Aziz et al., 2024; Azmi et al., 2025; Haider et al., 2024
Biosensors	High sensitivity	low-cost	High portability due to small size	*In-situ* detections	Hara and Singh, 2021; Hu et al., 2023
Electrochemical methods	High sensitivity	low-cost technique	High (handheld, IoT-ready)	On-site real-time monitoring	Filippidou and Chatzandroulis, 2023; Tian et al., 2025
Inductively coupled plasma optical emission spectrometry	High sensitivity	Expensive	large and expensive equipment	Limited to labs; not suitable for field deployment	Filippidou and Chatzandroulis, 2023; Hu et al., 2023
Atomic absorption spectroscopy	High sensitivity	Expensive	large and expensive equipment	Limited to labs; not suitable for field deployment	Eskina et al., 2020; Hara and Singh, 2021

science, and the participation of the local people. Good policies lay down the standards for the allowed concentrations of HMs in the air, water, and soil and, at the same time, encourage the implementation of cleaner production technologies and waste management systems (Gelaye, 2024). Besides, governments must upgrade monitoring, put into practice compliance, and give industries the energy to choose safer alternatives in their activities. Public health and risk assessment should be the main guide for policy-political decisions. Community-based remediation is a good supplement to these frameworks as it gives the power to local communities to identify the sources of contamination, choose phytoremediation or bioremediation methods, and monitor the recovery process. Involving citizens in learning and data gathering raises transparency and accountability (Chen and Ding, 2023; Meena et al., 2024; Parrott, 2017). Cooperation between government departments, NGOs, and universities not only facilitates the transfer of knowledge but also enhances the skills of the local people. If backed by an inclusive policy and technical resources, community work can be a recyclable energy for the revival of the environment as well as for the prevention of HMs pollution in the future (Chen and Ding, 2023; Dagdag et al., 2023).

10 Conclusion and future perspective

Bioremediation has emerged as a leading sustainable strategy for HMs removal in polluted water, providing an environmentally friendly and financially feasible option in place of traditional physicochemical methods. Chemicals precipitation, ion exchange, reverse osmosis, and electrochemical treatments are among the traditional remediation techniques that, although efficient, are often criticized for their high operational costs, need for energy, and secondary pollution production. On the other hand, biological processes such as biosorption, bioaccumulation, and phytoremediation eliminate most of the above disadvantages and offer lower prices, less sludge generation, and eco-friendly characteristics. Still, biological technologies of the past suffer from the slow pace of remediation, little specificity for metals, and their efficiency being affected by environmental factors (Agoun and Avci, 2025; Ali and Farhan, 2025; Oziegbe et al., 2025).

Today, a plethora of innovations continues to elevate bioremediation far beyond the conventional level, it is now effectively harnessed through molecular biology techniques, genetic engineering, and nanobiotechnology for the HMs removal in microbes and algae. Additionally, in the presence of suitable biological agents, nanomaterials have significantly improved the bioavailability and adsorption rates to deliver higher yields for the remediation process. But with the molecular, genetically engineered microbes and integration of nanotechnology comes various limitations like disruption of native microbes, degradation of traits in high temperature, high development cost, and toxicity (Srivastava, 2021; Ghosh et al., 2023; Singh G. et al., 2024; Scheverin et al., 2024; Akintola and Yahaya, 2024; Iravani and Varma, 2022; Julius et al., 2025; Thangavelu and Veeraragavan, 2022).

Also, algal-based bioremediation is gaining wider acceptance as a viable alternative. It has been claimed that microalgae such as trimmed *Scenedesmus abundans* could be able to remove up to 98 percent of certain types of microplastic particles that come together with HMs pollution, hence showing the dual benefit of such pollutant's abatement (Abbas et al., 2025; Ali and Farhan, 2025; Parmar and Patel, 2025). To sum up, despite the limitations of traditional methods of bioremediation that have paved the way for dealing with the issue of HMs in water, the advent of biotechnological tools is opening new horizons for revolutionary changes. Such transformations can come only through the interplay of biology, nanotechnology, and data science which unfolds the potential for less impactful, gradually changing on the situation, and highly efficient cleanup systems. Looking ahead, the future research and technology should shift toward using omics approaches, AI, and machine learning for perfecting bioremediation applications by forecasting microbial reactions under various environmental scenarios. Besides, the use of synthesized biology for reconfiguring cellular metabolic pathways for higher selectivity of metal absorption and conversion may become a reality in the future. Moreover, among the expected benefits arising from the adoption of IoT technology are the instantaneous checks carried out critically and reliably between multiple capabilities present on the bioremediation platform together with process operationalization and sustainability evaluations thus, facilitating the easy scaling up of the clean technology's deployment (Ali and Farhan, 2025).

Emerging research should focus more in the genetically engineered microbes that can be tailored for selective metal uptake ad detoxification. These engineered microbes could be coupled with biosensing modules or sensors so as to get real-time feedback, enabling adaptive bioremediation without delay. From a broader sustainability view, future research should emphasize more on the closed loop bioremediation frameworks where recovered metals are valorized for reuse in industrial cycles, aligning with the principles of circular economy. Policy support, life-cycle assessments, and risk evaluation protocols for genetically modified and nano-enabled bioremediators will also be critical for safe adoption. Policy support, life-cycle assessments, and risk evaluation protocols for genetically modified and nano-enabled bioremediators will also be critical for safe adoption. The perpetual need for interdisciplinary collaboration, policy incentives, and verbal support to the cause by the general public will act as the fuel to go through to reduce the weight of present challenges and allow one to see the prospect of a safe water management practice as well as environmental conservation on the global scale. Overall, the convergence of biology, material science, and digital technologies will help transform HMs bioremediation form a low efficiency treatment strategy to an intelligent and effective, adaptive resource recovering process, introducing a new generation of smart and sustainable remediation systems.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

Author contributions

SS: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. PS: Conceptualization, Data curation, Investigation, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. PN: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Validation. PJ: Methodology, Conceptualization, Writing – original draft, Writing – review & editing. VP: Methodology, Conceptualization, Writing – original draft, Writing – review & editing. NB: Data curation, Formal analysis, Writing – original draft, Writing – review & editing. RK: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. P: Conceptualization, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. AM: Conceptualization, Writing – original draft, Writing – review & editing.

Funding

The author(s) declared that financial support was not received for this work and/or its publication.

Acknowledgments

Authors wish to thank Graphic Era (Deemed to be University) for the guidance and infrastructural support. This manuscript was prepared with the assistance of Mendeley for reference management, Grammarly for language improvement and grammar correction. All content has been reviewed and approved by the authors.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was used in the creation of this manuscript. Mendeley was used for reference management and Grammarly was used for Proofread.

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References

Abbas, S., Zulfiqar, S., Arshad, M., Khalid, N., Hussain, A., and Ahmed, I. (2025). Molecular characterization of heavy metal-tolerant bacteria and their potential for bioremediation and plant growth promotion. *Front. Microbiol.* 16:1644466. doi: 10.3389/fmicb.2025.1644466

Abdel-Fattah, T. M., Mahmoud, M. E., Ahmed, S. B., Huff, M. D., Lee, J. W., and Kumar, S. (2015). Biochar from woody biomass for removing metal contaminants and carbon sequestration. *J. Indus. Eng. Chem.* 22, 103–109. doi: 10.1016/j.jiec.2014.06.030

Abdel-Mageed, H. M. (2025). Frontiers in nanoparticles redefining enzyme immobilization: a review addressing challenges, innovations, and unlocking sustainable future potentials. *Micro Nano Syst. Lett.* 13:7. doi: 10.1186/s40486-025-00228-2

Abdelmonem, B. H., Kamal, L. T., Elbaz, R. M., Khalifa, M. R., and Abdelnaser, A. (2025). From contamination to detection: the growing threat of heavy metals. *Heliyon* 11:e41713. doi: 10.1016/j.heliyon.2025.e41713

Abdul, K. S., Jayasinghe, S. S., Chandana, E. P., Jayasumana, C., and De Silva, P. M. (2015). Arsenic and human health effects: a review. *Environ. Toxicol. Pharmacol.* 40, 828–846. doi: 10.1016/j.etap.2015.09.016

Abo-Alkasem, M. I., Hassan, N. H., and Abo Elsoud, M. M. (2023). Microbial bioremediation as a tool for the removal of heavy metals. *Bull. Natl. Res Centre* 47:31. doi: 10.1186/s42269-023-01006-z

Adams, G. O., Fufeyin, P. T., Okoro, S. E., and Ehinomen, I. (2020). Bioremediation, biostimulation and bioaugmention: a review. *Int. J. Environ. Bioremed. Biodegrad.* 3, 28–39. doi: 10.12691/ijebb-3-1-5

Agaton, C. B., and Guila, P. M. C. (2023). Ecosystem services valuation of constructed wetland as a nature-based solution to wastewater treatment. *Earth* 4, 78–92. doi: 10.3390/earth4010006

Agoun, N. A., and Avci, F. G. (2025). Phycoremediation: a path towards heavy metal bioremediation from wastewater. *J. Chem. Technol. Biotechnol.* 100, 13–23. doi: 10.1002/jctb.7745

Ahmed, M., Mavukkandy, M. O., Giwa, A., Hasan, S. W., Elektorowicz, M., Katsou, E., et al. (2022). Recent developments in hazardous pollutants removal from wastewater and water reuse within a circular economy. *npj Clean Water* 5, 1–25. doi: 10.1038/s41545-022-00154-5

Ahmed, M. N., Afroze, C. A., and Jahan, R. (2025). Phytoremediation: sustainable solutions for heavy metal pollution and bioenergy in Bangladesh. *Sci. World J.* 2025:5510989. doi: 10.1155/tswj/5510989

Akintola, A. A. (2024). AI-driven monitoring systems for bioremediation: real-time data analysis and predictive modelling. *World J. Adv. Res. Rev.* 24, 788–803. doi: 10.30574/wjarr.2024.24.1.3099

Akintola, A. A., and Yahaya, S. (2024). Nanotechnology in bioremediation: synergistic approaches for targeted contaminant removal. *Int. J. Res. Publ. Rev. J.* 5, 843–855. doi: 10.55248/gengpi.5.1024.2725

Akpomie, K. G., Conradie, J., Adegoke, K. A., Oyedotun, K. O., Ighalo, J. O., Amaku, J. F., et al. (2022). Adsorption mechanism and modeling of radionuclides and heavy metals onto ZnO nanoparticles: a review. *Appl. Water Sci.* 13:20. doi: 10.1007/s13201-022-01827-9

Alfalahy, H. N., and Al-Jubouri, S. M. (2022). Preparation and application of polyethersulfone ultrafiltration membrane incorporating NaX zeolite for lead ions removal from aqueous solutions. *Desalination and Water Treat.* 248, 149–162. doi: 10.5004/dwt.2022.28072

Ali, A. S., Bayih, A. A., and Gari, S. R. (2022). Meta-analysis of public health risks of lead accumulation in wastewater, irrigated soil, and crops nexus. *Front. Public Health* 10:977721. doi: 10.3389/fpubh.2022.977721

Ali, H. A., and Farhan, M. B. (2025). Bioremediation techniques for water and soil pollution: review. *Nat. Eng. Sci.* 10, 89–109. doi: 10.28978/nesciences.1633049

Ali, S. T., Shahadha, R. W., Abdulkareem, W. S., and Abbas, M. N. (2024). Available low cost agro-waste as an efficient medium to eliminate heavy metal contamination using sustainable approach achieving zero residue level. *J. Ecol. Eng.* 25, 160–175. doi: 10.12911/22998993/191945

Alotaibi, E., and Nassif, N. (2024). Artificial intelligence in environmental monitoring: in-depth analysis. *Discov. Artif. Intell.* 4:84. doi: 10.1007/s44163-024-00198-1

Alprol, A. E., Ashour, M., Mansour, A. T., and Ibrahim, M. E. E. D. (2024). Artificial intelligence technologies revolutionizing wastewater treatment: current trends and future prospective. *Water* 16:314. doi: 10.3390/w16020314

Alsulaili, A., and Refaie, A. (2021). Artificial neural network modeling approach for the prediction of five-day biological oxygen demand and wastewater treatment plant performance. *Water Supply* 21, 1861–1877. doi: 10.2166/ws.2020.199

Angon, P. B., Islam, M. S., Kc, S., Das, A., Anjum, N., Poudel, A., et al. (2024). Sources, effects and present perspectives of heavy metals contamination: Soil, plants and human food chain. *Heliyon* 10:e28357. doi: 10.1016/j.heliyon.2024.e28357

Anil Kumar, M., and Mahabhaleshwara, G. (2024). Precision farming through IOT: monitoring heavy metals in water. *Int. J. Eng. Appl. Sci. Technol.* 9, 207–211. doi: 10.33564/IJEAST.2024.v09i01.034

Ariño, C., Pérez-Ràfols, C., Banks, C. E., Crapnell, R. D., Bobrowski, A., Królicka, A., et al. (2022). Electrochemical stripping analysis. *Nat. Rev. Methods Prim.* 2:62. doi: 10.1038/s43586-022-00143-5

Arora, J., Srivastav, R., Kumari, A., Ranjan, A., Rajput, V. D., Shende, S., et al. (2024). Microbial adaptation in different extreme environmental conditions and its usefulness in differently polluted soil. *Extremophiles Sustain. Agric. Soil Health Improv.* 47–62. doi: 10.1007/978-3-031-70203-7_3

Arora, V., and Khosla, B. (2021). "Conventional and contemporary techniques for removal of heavy metals from soil," in *Biodegradation Technology of Organic and Inorganic Pollutants* (London: IntechOpen).

Aryal, M. (2024). Phytoremediation strategies for mitigating environmental toxicants. *Heliyon* 10:*e*38683. doi: 10.1016/j.heliyon.2024.e38683

Asin-Garcia, E., Robaey, Z., Kampers, L. F. C., and Martins Dos Santos, V. A. P. (2023). Exploring the impact of tensions in stakeholder norms on designing for value change: the case of biosafety in industrial biotechnology. *Sci. Eng. Ethics* 29:9. doi: 10.1007/s11948-023-00432-6

Asri, M., Elabed, S., Koraichi, S. I., and Ghachtouli, N. E. (2018). "Biofilm-based systems for industrial wastewater treatment," in *Handbook of Environmental Materials Management,* ed. C. Hussain (Cham: Springer), 1–21. doi: 10.1007/978-3-319-58538-3_137-1

Ayach, J., El Malti, W., Duma, L., Lalevée, J., Al Ajami, M., Hamad, H., et al. (2024). Comparing conventional and advanced approaches for heavy metal removal in wastewater treatment: an in-depth review emphasizing filter-based strategies. *Polymers* 16:1959. doi: 10.3390/polym16141959

Ayele, A., and Godeto, Y. G. (2021). Bioremediation of chromium by microorganisms and its mechanisms related to functional groups. *J. Chem.* 2021:7694157. doi: 10.1155/2021/7694157

Ayilara, M. S., and Babalola, O. O. (2023). Bioremediation of environmental wastes: the role of microorganisms. *Front. Agron.* 5:1183691. doi: 10.3389/fagro.2023.1183691

Ayub, A., Wani, A. K., Malik, S. M., Ayub, M., Chopra, C., Singh, R., et al. (2025). Harnessing microbes and plants for bioremediation of heavy metal contaminants: current paradigms and future perspectives. *Environ. Chall.* 20:101220. doi: 10.1016/j.envc.2025.101220

Aziz, S., Mazhar, A. R., Ubaid, A., Shah, S. M. H., Riaz, Y., Talha, T., et al. (2024). A comprehensive review of membrane-based water filtration techniques. *Appl. Water Sci.* 14:169. doi: 10.1007/s13201-024-02226-y

Azizi, S., Kamika, I., and Tekere, M. (2016). Evaluation of heavy metal removal from wastewater in a modified packed bed biofilm reactor. *PLoS ONE* 11:*e*0155462. doi: 10.1371/journal.pone.0155462

Azmi, L. S., Jabit, N., Ismail, S., Ishak, K. E. H. K., and Abdullah, T. K. (2025). Membrane filtration technologies for sustainable industrial wastewater treatment: a review of heavy metal removal. *Desalination Water Treat.* 323:101321. doi: 10.1016/j.dwt.2025.101321

Baby, R., Hussein, M. Z., Abdullah, A. H., and Zainal, Z. (2022). Nanomaterials for the treatment of heavy metal contaminated water. *Polymers* 14:583. doi: 10.3390/polym14030583

Bakhtiari, S., Salari, M., Shahrashoub, M., Zeidabadinejad, A., Sharma, G., and Sillanpää, M. (2024). A comprehensive review on green and eco-friendly nano-adsorbents for the removal of heavy metal ions: synthesis, adsorption mechanisms, and applications. *Curr. Pollut. Rep.* 10, 1–39. doi: 10.1007/s40726-023-00290-7

Bala, S., Garg, D., Thirumalesh, B. V., Sharma, M., Sridhar, K., Inbaraj, B. S., et al. (2022). Recent strategies for bioremediation of emerging pollutants: a review for a green and sustainable environment. *Toxics* 10:484. doi: 10.3390/toxics10080484

Balali-Mood, M., Naseri, K., Tahergorabi, Z., Khazdair, M. R., and Sadeghi, M. (2021). Toxic mechanisms of five heavy metals: mercury, lead, chromium, cadmium, and arsenic. *Front. Pharmacol.* 12:643972. doi: 10.3389/fphar.2021.643972

Balamoorthy, D., Velusamy, P., Rath, B., R, P. T., and Kabeto, J. (2022). Removal of heavy metals from wastewater by using phytoremediation technology. *J. Civil Eng. Sci. Technol.* 13, 23–32. doi: 10.33736/jcest.4473.2022

Bang Truong, H., Nguyen, T. H. T., Ba Tran, Q., Son Lam, V., Thao Nguyen Nguyen, T., and Cuong Nguyen, X. (2024). Algae-constructed wetland integrated system for wastewater treatment: a review. *Bioresour. Technol.* 406:131003. doi: 10.1016/j.biortech.2024.131003

Bansod, B., Kumar, T., Thakur, R., Rana, S., and Singh, I. (2017). A review on various electrochemical techniques for heavy metal ions detection with different sensing platforms. *Biosens. Bioelectron.* 94, 443–455. doi: 10.1016/j.bios.2017.03.031

Barakat, M. A., and Schmidt, E. (2010). Polymer-enhanced ultrafiltration process for heavy metals removal from industrial wastewater. *Desalination* 256, 90–93. doi: 10.1016/j.desal.2010.02.008

Bereza-Malcolm, L. T., Mann, G., and Franks, A. E. (2014). Environmental Sensing of heavy metals through whole cell microbial biosensors: a synthetic biology approach. *ACS Synth. Biol.* 4, 535–546. doi: 10.1021/sb500286r

Bhagat, S. K., Tung, T. M., and Yaseen, Z. M. (2020). Development of artificial intelligence for modeling wastewater heavy metal removal: state of the art, application assessment and possible future research. *J. Clean. Prod.* 250:119473. doi: 10.1016/j.jclepro.2019.119473

Biswal, B. K., and Balasubramanian, R. (2022). Constructed wetlands for reclamation and reuse of wastewater and urban stormwater: a review. *Front. Environ. Sci.* 10:836289. doi: 10.3389/fenvs.2022.836289

Blessing, A. A., and Olateru, K. (2025). AI-driven optimization of bioremediation strategies for river pollution: a comprehensive review and future directions. *Front. Microbiol.* 16:1504254. doi: 10.3389/fmicb.2025.1504254

Bouchaut, B., and Asveld, L. (2020). Safe-by-design: stakeholders' perceptions and expectations of how to deal with uncertain risks of emerging biotechnologies in the Netherlands. *Risk Anal.* 40, 1632–1644. doi: 10.1111/risa.13501

Briffa, J., Sinagra, E., and Blundell, R. (2020). Heavy metal pollution in the environment and their toxicological effects on humans. *Heliyon* 6:e04691. doi: 10.1016/j.heliyon.2020.e04691

Brocza, F. M., Rafaj, P., Sander, R., Wagner, F., and Jones, J. M. (2024). Global scenarios of anthropogenic mercury emissions. *Atmos. Chem. Phys.* 24, 7385–7404. doi: 10.5194/acp-24-7385-2024

Calijuri, M. L., Do Couto, E. A., Assemany, P. P., Ribeiro, V. J., Lorentz, J. F., Castro, J. S., et al. (2025). Microalgae-based wastewater treatment and biomass valorization: insights, challenges, and opportunities from 15 years of research. *ACS Omega* 10, 49273–49299. doi: 10.1021/acsomega.5c04364

Cao, Z., Yan, W., Ding, M., and Yuan, Y. (2022). Construction of microbial consortia for microbial degradation of complex compounds. *Front. Bioeng. Biotechnol.* 10:1051233. doi: 10.3389/fbioe.2022.1051233

Castro, K., and Abejón, R. (2024). Removal of heavy metals from wastewaters and other aqueous streams by pressure-driven membrane technologies: an outlook on reverse osmosis, nanofiltration, ultrafiltration and microfiltration potential from a bibliometric analysis. *Membranes* 14:180. doi: 10.3390/membranes14080180

Cavaliere, G., Tari, L., Siconolfi, F., Rehman, H., Kuzhir, P., Maffucci, A., et al. (2025). A novel ML-powered nanomembrane sensor for smart monitoring of pollutants in industrial wastewater. *Sensors* 25:5390. doi: 10.3390/s25175390

Chavhan, N., Bhattad, R., Khot, S., Patil, S., Pawar, A., Pawar, T., et al. (2025). APAH: an autonomous IoT driven real-time monitoring system for Industrial wastewater. *Digit. Chem. Eng.* 14:100217. doi: 10.1016/j.dche.2025.100217

Chen, F., Chen, L., Yan, Z., Xu, J., Feng, L., He, N., et al. (2024). Recent advances of CRISPR-based genome editing for enhancing staple crops. *Front. Plant Sci.* 15:1478398. doi: 10.3389/fpls.2024.1478398

Chen, S., and Ding, Y. (2023). Tackling heavy metal pollution: evaluating governance models and frameworks. *Sustainability* 15:15863. doi: 10.3390/su152215863

Chen, T. K., and Shiau, Y. J. (2025). Effects of soil properties and seasonal variations on microbial communities in constructed wetlands. *Microb. Ecol.* 88:64. doi: 10.1007/s00248-025-02564-7

Chen, Z., Yap, P. S., Osman, A. I., Rooney, D. W., and Oh, W. D. (2023). Remediation of heavy metals in polluted water by immobilized algae: current applications and future perspectives. *Sustainability* 15:5128. doi: 10.3390/su15065128

Chojnacka, K. (2010). Biosorption and bioaccumulation – the prospects for practical applications. *Environ. Int.* 36, 299–307. doi: 10.1016/j.envint.2009.12.001

Chugh, M., Kumar, L., Bharadvaja, N., and Shah, M. P. (2022). Algal bioremediation of heavy metals: an insight into removal mechanisms, recovery of by-products, challenges, and future opportunities. *Energy Nexus* 7:100129. doi: 10.1016/j.nexus.2022.100129

Dada, M. A., Majemite, M. T., Obaigbena, A., Daraojimba, O. H., Oliha, J. S., and Nwokediegwu, Z. Q. S. (2024). Review of smart water management: IoT and AI in water and wastewater treatment. *World J. Adv. Res. Rev.* 21, 1373–1382. doi: 10.30574/wjarr.2024.21.1.0171

Dagdag, O., Quadri, T. W., Akpan, E. D., Ebenso, E. E., Haldhar, R., Kim, S. C., et al. (2023). An overview of heavy metal pollution and control. *ACS Symp. Ser.* 1456, 3–24. doi: 10.1021/bk-2023-1456.ch001

Dange, S., Arumugam, K., and Saraswathi Vijayaraghavalu, S. (2024). Geochemical insights into heavy metal contamination and health hazards in palar river basin: a pathway to sustainable solutions. *Ecol. Indic.* 166:112568. doi: 10.1016/j.ecolind.2024.112568

Dantas, M. S., Christofaro, C., and Oliveira, S. C. (2023). Artificial neural networks for performance prediction of full-scale wastewater treatment plants: a systematic review. *Water Sci. Technol.* 88, 1447–1470. doi: 10.2166/wst.2023.276

Das, A., and Mishra, S. (2025). Reimagining biofiltration for sustainable industrial wastewater treatment. *Discov. Sustain.* 6:826. doi: 10.1007/s43621-025-01784-8

Das, K., Masud, M. A. A., Sarker, A., Arafa, R. A., and Patel, M. (2025). Unveiling the sustainable and biological remediation of heavy metals contaminations in soils and water ecosystems through potential microbes—a review. *Sustainability* 17:7357. doi: 10.3390/su17167357

Dawam, M., Gobara, M., Oraby, H., Zorainy, M. Y., and Nabil, I. M. (2025). Advances in membrane technologies for heavy metal removal from polluted water: a comprehensive review. *Water Air Soil Pollut.* 236:461. doi: 10.1007/s11270-025-08035-6

de Silva, M., Cao, G., and Tam, K. C. (2025). Nanomaterials for the removal and detection of heavy metals: a review. *Environ. Sci. Nano* 12, 2154–2176. doi: 10.1039/D4EN01041H

Delrue, F., Álvarez-Díaz, P. D., Fleury, G., Sassi, J. F., and Fon-Sing, S. (2016). The environmental biorefinery: using microalgae to remediate wastewater, a win-win paradigm. *Energies* 9:132. doi: 10.3390/en9030132

Derco, J., and Vrana, B. (2018). "Introductory chapter: biosorption," in *Biosorption,* eds. J. Derco and B. Vrana (London: InTech).

Dhanaraju, M., Ramalingam, K., Chenniappan, P., Pazhanivelan, S., and Kaliaperumal, R. (2022). Smart farming: internet of things (IoT)-based sustainable agriculture. *Agriculture* 12:1745. doi: 10.3390/agriculture12101745

Ding, X., Srinivasan, B., and Tung, S. (2015). Development and applications of portable biosensors. *SLAS Technol.* 20, 365–389. doi: 10.1177/22110682155 81349

Douvris, C., Vaughan, T., Bussan, D., Bartzas, G., and Thomas, R. (2023). How ICP-OES changed the face of trace element analysis: review of the global application landscape. *Sci. Total Environ.* 905:167242. doi: 10.1016/j.scitotenv.2023.167242

Dressler, V. L., Pozebon, D., and Curtius, A. J. (1998). Determination of heavy metals by inductively coupled plasma mass spectrometry after on-line separation and preconcentration. *Spectrochim. Acta Part B At. Spectrosc.* 53, 1527–1539. doi: 10.1016/S0584-8547(98)00180-3

Driscoll, C. T., Mason, R. P., Chan, H. M., Jacob, D. J., and Pirrone, N. (2013). Mercury as a global pollutant: sources, pathways, and effects. *Environ. Sci. Technol.* 47, 4967–4983. doi: 10.1021/es305071v

Dykes, C., Pearson, J., Bending, G., and Abolfathi, S. (2025). Impact of seasonal climate variability on constructed wetland treatment efficiency. *J. Water Process Eng.* 72:107350. doi: 10.1016/j.jwpe.2025.107350

Elkhatat, A. (2023) "Advances in techniques for copper analysis in aqueous systems," in *Copper Overview - From Historical Aspects to Applications*. doi: 10.5772/INTECHOPEN.1003793

El-Naggar, N. E., El-Khateeb, A. Y., Ghoniem, A. A., El-Hersh, M. S., and Saber, W. I. A. (2020). Innovative low-cost biosorption process of Cr6+ by Pseudomonas alcaliphila NEWG-2. *Sci. Rep.* 10:14043. doi: 10.1038/s41598-020-70473-5

El-Sheekh, M. M., El-Kassas, H. Y., and Ali, S. S. (2025). Microalgae-based bioremediation of refractory pollutants: an approach towards environmental sustainability. *Microb. Cell Fact.* 24:19. doi: 10.1186/s12934-024-02638-0

Ensano, B. M. B., Borea, L., Naddeo, V., Belgiorno, V., Luna, M. D. G. d., and Ballesteros, F. C. (2016). Combination of electrochemical processes with membrane bioreactors for wastewater treatment and fouling control: a review. *Front. Environ. Sci.* 4:210811. doi: 10.3389/fenvs.2016.00057

Eskina, V. V., Baranovskaya, V. B., Karpov, Y. A., and Filatova, D. G. (2020). High-resolution continuum source atomic absorption spectrometry: a review of current applications. *Russ. Chem. Bull.* 69, 1–16. doi: 10.1007/s11172-020-2718-6

Essamlali, I., Nhaila, H., and el Khaili, M. (2024). Advances in machine learning and IoT for water quality monitoring: a comprehensive review. *Heliyon* 10:e27920. doi: 10.1016/j.heliyon.2024.e27920

Ezugbe, E. O., and Rathilal, S. (2020). Membrane technologies in wastewater treatment: a review. *Membranes* 10:89. doi: 10.3390/membranes10050089

Farias, P. C. de M., Soares Chaves, A. L., and Lencina, C. L. (2011). "Transgenic plants for enhanced phytoremediation – physiological studies," in *Genetic Transformation*, eds. M. Alvarez (London: IntechOpen).

Fatima, Z., Azam, A., Iqbal, M. Z., Badar, R., and Muhammad, G. (2024). A comprehensive review on effective removal of toxic heavy metals from water using genetically modified microorganisms. *Desalination Water Treat.* 319:100553. doi: 10.1016/j.dwt.2024.100553

Fdez-Sanromán, A., Bernárdez-Rodas, N., Rosales, E., Pazos, M., González-Romero, E., and Sanromán, M. Á. (2025). Biosensor technologies for water quality: detection of emerging contaminants and pathogens. *Biosensors* 15:189. doi: 10.3390/bios15030189

Ferreira, S. L., Souza, A. S., Brandao, G. C., Ferreira, H. S., dos Santos, W. N., Pimentel, M. F., et al. (2018). Atomic absorption spectrometry – A multi element technique. *TrAC Trends Anal. Chem.* 100, 1–6. doi: 10.1016/j.trac.2017.12.012

Filippidou, M. K., and Chatzandroulis, S. (2023). Microfluidic devices for heavy metal ions detection: a review. *Micromachines* 14:1520. doi: 10.3390/mi14081520

Firincă, C., Zamfir, L. G., Constantin, M., Răut, I., Jecu, M. L., Doni, M., et al. (2025). Innovative approaches and evolving strategies in heavy metal bioremediation: current limitations and future opportunities. *J. Xenobiot.* 15:63. doi: 10.3390/jox15030063

Flemming, H. C., van Hullebusch, E. D., Little, B. J., Neu, T. R., Nielsen, P. H., Seviour, T., et al. (2024). Microbial extracellular polymeric substances in the environment, technology and medicine. *Nat. Rev. Microbiol.* 23, 87–105. doi: 10.1038/s41579-024-01098-y

Fulke, A. B., Ratanpal, S., and Sonker, S. (2024). Understanding heavy metal toxicity: implications on human health, marine ecosystems and bioremediation strategies. *Mar. Pollut. Bull.* 206:116707. doi: 10.1016/j.marpolbul.2024.116707

Gahrouei, A. E., Rezapour, A., Pirooz, M., and Pourebrahimi, S. (2024). From classic to cutting-edge solutions: a comprehensive review of materials and methods for heavy metal removal from water environments. *Desalination Water Treat.* 319:100446. doi: 10.1016/j.dwt.2024.100446

Gelaye, Y. (2024). Public health and economic burden of heavy metals in Ethiopia: review. *Heliyon* 10:e39022. doi: 10.1016/j.heliyon.2024.e39022

Generalova, A., Davidova, S., and Satchanska, G. (2025). The mechanisms of lead toxicity in living organisms. *J. Xenobiot.* 15:146. doi: 10.3390/jox15050146

Ghosh, D., Chaudhary, S., and Dhara, S. (2023). "Prospects and potentials of microbial applications on heavy-metal removal from wastewater," in *Metal Organic Frameworks for Wastewater Contaminant Removal,* eds. A. Lal Srivastav, L. Rani, J. Kaushal, and T. Duc Pham (Hoboken, NJ: John Wiley & Sons), 177–201.

Ghosh, M., and Singh, S. P. (2005). A review on phytoremediation of heavy metals and utilization of its by-products. *Appl. Ecol. Environ. Res.* 3:474. doi: 10.15666/aeer/0301_001018

Goswami, R. K., Agrawal, K., Shah, M. P., and Verma, P. (2022). Bioremediation of heavy metals from wastewater: a current perspective on microalgae-based future. *Lett. Appl. Microbiol.* 75, 701–717. doi: 10.1111/lam.13564

Griffero, L., Pereira-Flores, E., Lescano, C., Rodríguez-Gallego, L., Pérez-Parada, A., and Alonso, C. (2024). Microbial communities indicate fine differences in pollution levels by emerging contaminants. *Ecol. Indic.* 169:112875. doi: 10.1016/j.ecolind.2024.112875

Gupta, M., Dwivedi, V., Kumar, S., Patel, A., Niazi, P., and Yadav, V. K. (2024). Lead toxicity in plants: mechanistic insights into toxicity, physiological responses of plants and mitigation strategies. *Plant Signal. Behav.* 19:2365576. doi: 10.1080/15592324.2024.2365576

Haghighizadeh, A., Rajabi, O., Nezarat, A., Hajyani, Z., Haghmohammadi, M., Hedayatikhah, S., et al. (2024). Comprehensive analysis of heavy metal soil contamination in mining environments: impacts, monitoring techniques, and remediation strategies. *Arab. J. Chem.* 17:105777. doi: 10.1016/j.arabjc.2024.105777

Haider, A., Rafique, A., Akram, A., Iqbal, S., Abbas, S., Yousaf, S., et al. (2024). *A review on nano filtration system - JournalsPub*. Available online at: https://journalspub.com/publication/ijec/article=9508/ (Accessed December 24, 2025).

Hama Aziz, K. H., Mustafa, F. S., Omer, K. M., Hama, S., Hamarawf, R. F., and Rahman, K. O. (2023). Heavy metal pollution in the aquatic environment: efficient and low-cost removal approaches to eliminate their toxicity: a review. *RSC Adv.* 13, 17595–17610. doi: 10.1039/D3RA00723E

Hamdi, F. M., Ganbat, N., Altaee, A., Samal, A. K., Ibrar, I., Zhou, J. L., et al. (2025). Hybrid and enhanced electrokinetic system for soil remediation from heavy metals and organic matter. *J. Environ. Sci.* 147, 424–450. doi: 10.1016/j.jes.2023.11.005

Hanlon, P., and Sewalt, V. (2021). GEMs: genetically engineered microorganisms and the regulatory oversight of their uses in modern food production. *Crit. Rev. Food Sci. Nutr.* 61, 959–970. doi: 10.1080/10408398.2020.1749026

Hara, T. O., and Singh, B. (2021). Electrochemical biosensors for detection of pesticides and heavy metal toxicants in water: recent trends and progress. *ACS ES&T Water* 1, 462–478. doi: 10.1021/acsestwater.0c00125

Hashim, M., Tabassum, B., Khan, T., Khan, M., Hasan, A., and Khan, N. (2025). "Microbial innovations for a greener future: biotechnological approaches to metal pollution detoxification," in *Sustainable Green Technologies. Sustainable Economy and Ecotechnology*, ed. Kiran (Cham: Springer), 249–274.

Hasnain, M., Zainab, R., Ali, F., Abideen, Z., Yong, J. W. H., El-Keblawy, A., et al. (2023). Utilization of microalgal-bacterial energy nexus improves CO2 sequestration and remediation of wastewater pollutants for beneficial environmental services. *Ecotoxicol. Environ. Saf.* 267:115646. doi: 10.1016/j.ecoenv.2023.115646

Hassan, I., Chowdhury, S. R., Prihartato, P. K., and Razzak, S. A. (2021). Wastewater treatment using constructed wetland: current trends and future potential. *Processes* 9:1917. doi: 10.3390/pr9111917

Helim, R., Zazoua, A., and Korri-Youssoufi, H. (2024). Sustainable biopolymer-based electrochemical sensors for trace heavy metal determination in water: a comprehensive review. *Chemosensors* 12:267. doi: 10.3390/chemosensors12120267

Henagamage, A. P., Peries, C. M., and Seneviratne, G. (2022). Fungal-bacterial biofilm mediated heavy metal rhizo-remediation. *World J. Microbiol. Biotechnol.* 38:85. doi: 10.1007/s11274-022-03267-8

Hina, B., Rizwani, G., Naseeb, U., Huma, A., and Hyder, Z. (2023). Application of atomic absorption spectroscopy to determine mineral and heavy metal distribution level of medicinal plants. *J. Anal. Tech. Res.* 5, 26–32. doi: 10.26502/jatr.38

Hou, X., and Jones, B. T. (2000). "Inductively coupled plasma/optical emission spectrometry," in *Encyclopedia of Analytical Chemistry* (Chichester: Wiley).

Hu, T., Lai, Q., Fan, W., Zhang, Y., and Liu, Z. (2023). Advances in portable heavy metal ion sensors. *Sensors* 23:4125. doi: 10.3390/s23084125

Huang, C. W., Lin, C., Nguyen, M. K., Hussain, A., Bui, X. T., and Ngo, H. H. (2023). A review of biosensor for environmental monitoring: principle, application, and corresponding achievement of sustainable development goals. *Bioengineered* 14, 58–80. doi: 10.1080/21655979.2022.2095089

Huang, Z., Liu, G., Zhang, Y., Yuan, Y., Xi, B., and Tan, W. (2024). Assessing the impacts and contamination potentials of landfill leachate on adjacent groundwater systems. *Sci. Total Environ.* 930:172664. doi: 10.1016/j.scitotenv.2024.172664

Hussain, S., Khan, M., Sheikh, T. M. M., Mumtaz, M. Z., Chohan, T. A., Shamim, S., et al. (2022). Zinc essentiality, toxicity, and its bacterial bioremediation: a comprehensive insight. *Front. Microbiol.* 13:900740. doi: 10.3389/fmicb.2022.900740

Ibrahim, M., Haider, A., Lim, J. W., Mainali, B., Aslam, M., Kumar, M., et al. (2024). Artificial neural network modeling for the prediction, estimation, and treatment of diverse wastewaters: a comprehensive review and future perspective. *Chemosphere* 362:142860. doi: 10.1016/j.chemosphere.2024.142860

Igiri, B. E., Okoduwa, S. I. R., Idoko, G. O., Akabuogu, E. P., Adeyi, A. O., and Ejiogu, I. K. (2018). Toxicity and bioremediation of heavy metals contaminated ecosystem from tannery wastewater: a review. *J. Toxicol.* 2018:2568038. doi: 10.1155/2018/2568038

Ihsanullah, n., Abbas, A., Al-Amer, A. M., Laoui, T., Al-Marri, M. J., Nasser, M. S., et al. (2016). Heavy metal removal from aqueous solution by advanced carbon nanotubes: critical review of adsorption applications. *Sep. Purif. Technol.* 157, 141–161. doi: 10.1016/j.seppur.2015.11.039

Ihtisham, M., Noori, A., Yadav, S., Sarraf, M., Kumari, P., Brestic, M., et al. (2021). Silver Nanoparticle's toxicological effects and phytoremediation. *Nanomaterials* 11:2164. doi: 10.3390/nano11092164

Iqbal, S., Begum, F., Nguchu, B. A., Claver, U. P., and Shaw, P. (2025). The invisible architects: microbial communities and their transformative role in soil health and global climate changes. *Environ. Microb.* 20:36. doi: 10.1186/s40793-025-00694-6

Iravani, S., and Varma, R. S. (2022). Genetically engineered organisms: possibilities and challenges of heavy metal removal and nanoparticle synthesis. *Clean Technol.* 4, 502–511. doi: 10.3390/cleantechnol4020030

Islam, M. M., Saxena, N., and Sharma, D. (2024). Phytoremediation as a green and sustainable prospective method for heavy metal contamination: a review. *RSC Sustain.* 2, 1269–1288. doi: 10.1039/D3SU00440F

Islam, S. (2025). Toxicity and transport of nanoparticles in agriculture: effects of size, coating, and aging. *Front. Nanotechnol.* 7:1622228. doi: 10.3389/fnano.2025.1622228

Jaishankar, M., Tseten, T., Anbalagan, N., Mathew, B. B., and Beeregowda, K. N. (2014). Toxicity, mechanism and health effects of some heavy metals. *Interdiscip. Toxicol.* 7, 60–72. doi: 10.2478/intox-2014-0009

Jambon, I., Thijs, S., Weyens, N., and Vangronsveld, J. (2018). Harnessing plant-bacteria-fungi interactions to improve plant growth and degradation of organic pollutants. *J. Plant Interact.* 13, 119–130. doi: 10.1080/17429145.2018.1441450

Jang, M., Hong, S. M., and Park, J. K. (2005). Characterization and recovery of mercury from spent fluorescent lamps. *Waste Manag.* 25, 5–14. doi: 10.1016/j.wasman.2004.09.008

Jasu, A., and Ray, R. R. (2021). Biofilm mediated strategies to mitigate heavy metal pollution: a critical review in metal bioremediation. *Biocatal. Agric. Biotechnol.* 37:102183. doi: 10.1016/j.bcab.2021.102183

Jasua, A., Ray, R. R., Lahiri, D., and Nag, M. (2021). "Biofilm-associated metal bioremediation," in *Biotechnology for Sustainable Environment,* eds. S. J. Joshi, A. Deshmukh, and H. Sarma (Singapore: Springer), 201–221.

Jhariya, M. K., Banerjee, A., and Meena, R. S. (2022). Importance of natural resources conservation: moving toward the sustainable world. *Nat. Resourc. Conserv. Adv. Sustain.* 2022, 3–27. doi: 10.1016/B978-0-12-822976-7.00027-2

Julius, S. O., Ariremako, J. I., Oluwaseun, O. M., Okikiola, M. I., Agboola, P. O., Ali, A. S., et al. (2025). Advancing bioremediation through engineered nanoparticles and microbial interactions. *IJRSI* 12, 1538–1552. doi: 10.51244/IJRSI.2025.1210000137

Kafle, A., Timilsina, A., Gautam, A., Adhikari, K., Bhattarai, A., and Aryal, N. (2022). Phytoremediation: mechanisms, plant selection and enhancement by natural and synthetic agents. *Environ. Adv.* 8:100203. doi: 10.1016/j.envadv.2022.100203

Kainth, S., Sharma, P., and Pandey, O. P. (2024). Green sorbents from agricultural wastes: a review of sustainable adsorption materials. *Appl. Surf. Sci. Adv.* 19:100562. doi: 10.1016/j.apsadv.2023.100562

Kapahi, M., and Sachdeva, S. (2019). Bioremediation options for heavy metal pollution. *J. Health Pollut.* 9:191203. doi: 10.5696/2156-9614-9.24.191203

Kapepula, V. L., and Luis, P. (2024). Removal of heavy metals from wastewater using reverse osmosis. *Front. Chem. Eng.* 6:1334816. doi: 10.3389/fceng.2024.1334816

Karakoti, A. S., Hench, L. L., and Seal, S. (2006). The potential toxicity of nanomaterials—the role of surfaces. *JOM* 58, 77–82. doi: 10.1007/s11837-006-0147-0

Karnwal, A., and Malik, T. (2024). Nano-revolution in heavy metal removal: engineered nanomaterials for cleaner water. *Front. Environ. Sci.* 12:1393694. doi: 10.3389/fenvs.2024.1393694

Karnwal, A., Martolia, S., Dohroo, A., Al-Tawaha, A. R. M. S., and Malik, T. (2024). Exploring bioremediation strategies for heavy metals and POPs pollution: the role of microbes, plants, and nanotechnology. *Front. Environ. Sci.* 12:1397850. doi: 10.3389/fenvs.2024.1397850

Khalef, R. N., Hassan, A. I., and Saleh, H. M. (2022). "Heavy metal's environmental impact," in *Environmental Impact and Remediation of Heavy Metals* (London: IntechOpen).

Khan, S., Kalsoom, U., Kashif, M., Gul, M., Hussain, S. A., Azizi, S., et al. (2025). Smart and sustainable microplastic removal: hybrid systems, bio-inspired technologies, real-time sensing, and policy integration. *Water Air Soil Pollut.* 236:900. doi: 10.1007/s11270-025-08468-z

Khan, S. R., Sharma, B., Chawla, P. A., and Bhatia, R. (2021). Inductively coupled plasma optical emission spectrometry (ICP-OES): a powerful analytical technique for elemental analysis. *Food Anal. Methods* 15, 666–688. doi: 10.1007/s12161-021-02148-4

Khan, Z., Elahi, A., Bukhari, D. A., and Rehman, A. (2022). Cadmium sources, toxicity, resistance and removal by microorganisms-a potential strategy for cadmium eradication. *J. Saudi Chem. Soc.* 26:101569. doi: 10.1016/j.jscs.2022.101569

Khoshakhlagh, A. H., Ghobakhloo, S., and Gruszecka-Kosowska, A. (2024). Inhalational exposure to heavy metals: carcinogenic and non-carcinogenic risk assessment. *J. Hazard. Mater. Adv.* 16:100485. doi: 10.1016/j.hazadv.2024.100485

Khoso, M. A., Wagan, S., Alam, I., Hussain, A., Ali, Q., Saha, S., et al. (2024). Impact of plant growth-promoting rhizobacteria (PGPR) on plant nutrition and root characteristics: current perspective. *Plant Stress* 11:100341. doi: 10.1016/j.stress.2023.100341

Kiouri, D. P., Tsoupra, E., Peana, M., Perlepes, S. P., Stefanidou, M. E., and Chasapis, C. T. (2023). Multifunctional role of zinc in human health: an update. *EXCLI J.* 22, 809–827. doi: 10.17179/excli2023-6335

Knox, A. S., Paller, M. H., Seaman, J. C., Mayer, J., and Nicholson, C. (2021). Removal, distribution and retention of metals in a constructed wetland over 20 years. *Sci. Total Environ.* 796:149062. doi: 10.1016/j.scitotenv.2021.149062

Kollati, R. V., Mazumdar, B., Keshav, A., and Sharma, A. (2025). "An overview of role of microbial biofilms in environment pollution remediation," in *Development in Waste Water Treatment Research and Processes: Applied Technologies for Clean up of Environmental Contaminants* (Oxford: Academic Press), 427–450.

Koolivand, A., Coulon, F., Ball, A. S., Khudur, L. S., Ismail, N., ParsiMehr, M., et al. (2024). Challenges with bioaugmentation and field-scale application of bioremediation processes for petroleum-contaminated sites: a review. *Indian J. Microbiol.* doi: 10.1007/s12088-024-01408-1

Kour, D., Khan, S. S., Kour, H., Kaur, T., Devi, R., Yadav, A. N., et al. (2022). Microbe-mediated bioremediation: current research and future challenges. *J. Appl. Biol. Biotechnol.* 10, 6–24. doi: 10.7324/JABB.2022.10s202

Kubier, A., Wilkin, R. T., and Pichler, T. (2019). Cadmium in soils and groundwater: a review. *Appl. Geochem.* 108:104388. doi: 10.1016/j.apgeochem.2019.104388

Kumar, V., Sharma, K. V., Kedam, N., Patel, A., Kate, T. R., and Rathnayake, U. (2024). A comprehensive review on smart and sustainable agriculture using IoT technologies. *Smart Agric. Technol.* 8:100487. doi: 10.1016/j.atech.2024.100487

Kumari, B., Seedat, N., Moothi, K., and Roopchund, R. (2025). Artificial intelligence-assisted modelling of heavy metal adsorption using cellulose-based and bio-waste adsorbents: a focus on ANN and ANFIS architectures. *Results Eng.* 28:107147. doi: 10.1016/j.rineng.2025.107147

Kuppan, N., Padman, M., Mahadeva, M., Srinivasan, S., and Devarajan, R. (2024). A comprehensive review of sustainable bioremediation techniques: eco friendly solutions for waste and pollution management. *Waste Manag. Bull.* 2, 154–171. doi: 10.1016/j.wmb.2024.07.005

Lahari, S. A., Kumawat, N., Amreen, K., Ponnalagu, R. N., and Goel, S. (2025). IoT integrated and deep learning assisted electrochemical sensor for multiplexed heavy metal sensing in water samples. *npj Clean Water* 8:10. doi: 10.1038/s41545-025-00441-x

Le, A. T., Pung, S. Y., Sreekantan, S., Matsuda, A., and Huynh, D. P. (2019). Mechanisms of removal of heavy metal ions by ZnO particles. *Heliyon* 5:e01440. doi: 10.1016/j.heliyon.2019.e01440

Lea-Smith, D. J., Hassard, F., Coulon, F., Partridge, N., Horsfall, L., Parker, K. D. J., et al. (2025). Engineering biology applications for environmental solutions: potential and challenges. *Nat. Commun.* 16, 1–12. doi: 10.1038/s41467-025-58492-0

Lensch, A., Lindfors, H. A., Duwenig, E., Fleischmann, T., Hjort, C., Kärenlampi, S. O., et al. (2024). Safety aspects of microorganisms deliberately released into the environment. *EFB Bioecon. J.* 4:100061. doi: 10.1016/j.bioeco.2023.100061

Lindholm-Lehto, P. (2019). *Biosorption of heavy metals by lignocellulosic biomass and chemical analysis: BioResources*. Available online at: https://bioresources.cnr.ncsu.edu/resources/biosorption-of-heavy-metals-by-lignocellulosic-biomass-and-chemical-analysis/ (Accessed November 14, 2025).

Liu, F., Han, X., Ge, H., Wang, Z., Zhao, X., and Zhang, Y. (2025). Extracellular polymeric substances protect *Chlorella* sp. against the cadmium stress. *Ecologies* 6:65. doi: 10.3390/ecologies6040065

Lombaert, N., Gilles, M., and Verougstraete, V. (2023). Cadmium monitoring at the workplace: effectiveness of a combination of air- and biomonitoring. *Toxics* 11:354. doi: 10.3390/toxics11040354

Lone, M. I., He, Z. L., Stoffella, P. J., and Yang, X. E. (2008). Phytoremediation of heavy metal polluted soils and water: progresses and perspectives. *J. Zhejiang Univ. Sci. B* 9, 210–220. doi: 10.1631/jzus.B0710633

Lovynska, V., Bayat, B., Bol, R., Moradi, S., Rahmati, M., Raj, R., et al. (2024). Monitoring heavy metals and metalloids in soils and vegetation by remote sensing: a review. *Remote Sens.* 16:3221. doi: 10.3390/rs16173221

Lowe, M., Qin, R., and Mao, X. (2022). A review on machine learning, artificial intelligence, and smart technology in water treatment and monitoring. *Water* 14:1384. doi: 10.3390/w14091384

Machado, A. A., Valiaparampil, J. G., and Lavanya, M. (2024). Unlocking the potential of algae for heavy metal remediation. *Water Air Soil Pollut.* 235:629. doi: 10.1007/s11270-024-07436-3

Madadelahi, M., Romero-Soto, F. O., Kumar, R., Tlaxcala, U. B., and Madou, M. J. (2025). Electrochemical sensors: types, applications, and the novel impacts of vibration and fluid flow for microfluidic integration. *Biosens. Bioelectron.* 272:117099. doi: 10.1016/j.bios.2024.117099

Madkour, L. H. (2020). "Heavy metals and free radical-induced cell death mechanisms," in *Reactive Oxygen Species (ROS), Nanoparticles, and Endoplasmic Reticulum (ER) Stress-Induced Cell Death Mechanisms* (Oxford: Academic Press), 131–157.

Mahanayak, B. (2024). Environmental restoration through bioremediation: methods, advantages, and challenges. *Int. J. Res. Publ. Rev. J.* 5, 6661–6664. doi: 10.55248/gengpi.5.0624.1637

Mahdizade Ari, M., Dadgar, L., Elahi, Z., Ghanavati, R., and Taheri, B. (2024). Genetically engineered microorganisms and their impact on human health. *Int. J. Clin. Pract.* 2024:6638269. doi: 10.1155/2024/6638269

Maheshwari, R., Singh, U., Singh, P., Singh, N., Lal Jat, B., and Rani, B. (2014). To decontaminate wastewater employing bioremediation technologies. *J. Adv. Sci. Res.* 5, 7–15.

Mahto, K. U., Vandana, n., Priyadarshanee, M., Samantaray, D. P., and Das, S. (2022). Bacterial biofilm and extracellular polymeric substances in the treatment of environmental pollutants: beyond the protective role in survivability. *J. Clean. Prod.* 379:134759. doi: 10.1016/j.jclepro.2022.134759

Maiti, A., Mishra, S., and Chaudhary, M. (2019). "Nanoscale materials for arsenic removal from water," in *Nanoscale Materials in Water Purification* (Amsterdam: Elsevier), 707–733.

Malyan, S. K., Yadav, S., Sonkar, V., Goyal, V. C., Singh, O., and Singh, R. (2021). Mechanistic understanding of the pollutant removal and transformation processes in the constructed wetland system. *Water Environ. Res.* 93, 1882–1909. doi: 10.1002/wer.1599

Mandeep and Shukla, P. (2020). Microbial nanotechnology for bioremediation of industrial wastewater. *Front. Microbiol.* 11:590631. doi: 10.3389/fmicb.2020.590631

Manju, n., Verma, R. K., Bohra, Y., Gautam, A. K., Sushma, n., Avasthi, S., et al. (2023). "Role of microbial biofilms in bioremediation: current perspectives," in *Microbial Inoculants: Recent Progress and Applications* (Cambridge: Academic Press), 253–276.

Maurya, B. M., Yadav, N., T, A., J, S., A, S., V, P., et al. (2024). Artificial intelligence and machine learning algorithms in the detection of heavy metals in water and wastewater: methodological and ethical challenges. *Chemosphere* 353:141474. doi: 10.1016/j.chemosphere.2024.141474

Meena, P. M., Aggarwal, R. K., Meena, R., and Rathore, M. S. (2024). "Soil contamination, risk assessment, and remediation," in *The Future of Risk Management* (London: IntechOpen).

Mehrifar, Y., Pirami, H., and Farhang Dehghan, S. (2025). Occupational exposure to cadmium and its compounds: a review on health effects and monitoring techniques. *J. Occup. Health Epidemiol.* 14, 133–149. doi: 10.61882/johe.14.2.133

Mesquita, M. C., Albuquerque, A., Amaral, L., and Nogueira, R. (2017). Seasonal variation of nutrient removal in a full-scale horizontal constructed wetland. *Energy Procedia* 136, 225–232. doi: 10.1016/j.egypro.2017.10.246

Milano, F., Giotta, L., and Lambreva, M. D. (2024). Perspectives on nanomaterial-empowered bioremediation of heavy metals by photosynthetic microorganisms. *Plant Physiol. Biochem.* 216:109090. doi: 10.1016/j.plaphy.2024.109090

Minh, T. N., Thanh Truyen, N., and Hong Loan, D. T. (2024). Artificial neural networks for modeling pollutant removal in wastewater treatment: a review. *Galore Int. J. Appl. Sci. Human.* 8, 88–98. doi: 10.52403/gijash.20240211

Mitra, A., and Mukhopadhyay, S. (2016). Biofilm mediated decontamination of pollutants from the environment. *AIMS Bioeng.* 3, 44–59. doi: 10.3934/bioeng.2016.1.44

Mitra, S., Chakraborty, A. J., Tareq, A. M., Emran, T. B., Nainu, F., Khusro, A., et al. (2022). Impact of heavy metals on the environment and human health: novel therapeutic insights to counter the toxicity. *J. King Saud Univ. Sci.* 34:101865. doi: 10.1016/j.jksus.2022.101865

Mohapatra, R. K., Behera, S. S., Patra, J. K., Thatoi, H., and Parhi, P. K. (2020). "Potential application of bacterial biofilm for bioremediation of toxic heavy metals and dye-contaminated environments," in *New and Future Developments in Microbial Biotechnology and Bioengineering: Microbial Biofilms Current Research and Future Trends in Microbial Biofilms* (Amsterdam: Elsevier), 267–281.

Motshakeri, M., Angoro, B., Phillips, A. R. J., Svirskis, D., Kilmartin, P. A., and Sharma, M. (2025). Advancements in mercury-free electrochemical sensors for iron detection: a decade of progress in electrode materials and modifications. *Sensors* 25:1474. doi: 10.3390/s25051474

Mowla, M. N., Mowla, N., Shah, A. F. M. S., Rabie, K. M., and Shongwe, T. (2023). "Internet of things and wireless sensor networks for smart agriculture applications: a survey," in *IEEE Access* (New York, NY: IEEE), 145813–145852.

Mukherjee, S. (2019). "Isolation and purification of industrial enzymes: advances in enzyme technology," in *Advances in Enzyme Technology, 1st Edn*. (Amsterdam: Elsevier), 41–70.

Mukherjee, S., Bhattacharyya, S., Ghosh, K., Pal, S., Halder, A., Naseri, M., et al. (2021). Sensory development for heavy metal detection: a review on translation from conventional analysis to field-portable sensor. *Trends Food Sci. Technol.* 109, 674–689. doi: 10.1016/j.tifs.2021.01.062

Najim, A. A., al-Doori, I., Radeef, A. Y., and Jabbar, Z. H. (2024). Immobilization: the promising technique to protect and increase the efficiency of microorganisms to remove contaminants. *J. Chem. Technol. Biotechnol.* 99, 1707–1733. doi: 10.1002/jctb.7638

Naseem, M., Syab, S., Akhtar, S., Ikram, M., Batool, M., Saeed, Z., et al. (2023). Ex-situ and in-situ bioremediation strategies and their limitations for solid waste management: a mini-review. *J. Qual. Assur. Agric. Sci.* 3, 28–31. doi: 10.38211/jqaas.2023.3.39

Nath, S. (2024). Advancements in food quality monitoring: integrating biosensors for precision detection. *Sustain. Food Technol.* 2, 976–992. doi: 10.1039/D4FB00094C

Nedjimi, B. (2021). Phytoremediation: a sustainable environmental technology for heavy metals decontamination. *SN Appl. Sci.* 3, 1–19. doi: 10.1007/s42452-021-04301-4

Ngwenya, B., Paepae, T., and Bokoro, P. N. (2025). Monitoring ambient water quality using machine learning and IoT: a review and recommendations for advancing SDG indicator 6.3.2. *J. Water Process Eng.* 73:107664. doi: 10.1016/j.jwpe.2025.107664

Nnachi, R. C., Sui, N., Ke, B., Luo, Z., Bhalla, N., He, D., et al. (2022). Biosensors for rapid detection of bacterial pathogens in water, food and environment. *Environ. Int.* 166:107357. doi: 10.1016/j.envint.2022.107357

Nti, E. K., Cobbina, S. J., Attafuah, E. E., Senanu, L. D., Amenyeku, G., Gyan, M. A., et al. (2023). Water pollution control and revitalization using advanced technologies: uncovering artificial intelligence options towards environmental health protection, sustainability and water security. *Heliyon* 9:*e*18170. doi: 10.1016/j.heliyon.2023.e18170

Odobašić, A., Šestan, I., and Begić, S. (2019). "Biosensors for determination of heavy metals in waters," in *Biosensors for Environmental Monitoring* (London: IntechOpen).

Ofiera, L. M., Wintgens, T., and Kazner, C. (2025). Adsorbent modified constructed wetlands for advanced removal of bulk organics and heavy metals from municipal wastewater effluent. *Environ. Sci. Water Res. Technol.* 11, 2248–2264. doi: 10.1039/D4EW00870G

Oladimeji, T. E., Oyedemi, M., Emetere, M. E., Agboola, O., Adeoye, J. B., and Odunlami, O. A. (2024). Review on the impact of heavy metals from industrial wastewater effluent and removal technologies. *Heliyon* 10:*e*40370. doi: 10.1016/j.heliyon.2024.e40370

Olawade, D. B., Wada, O. Z., Egbewole, B. I., Fapohunda, O., Ige, A. O., Usman, S. O., et al. (2024). Metal and metal oxide nanomaterials for heavy metal remediation: novel approaches for selective, regenerative, and scalable water treatment. *Front. Nanotechnol.* 6:1466721. doi: 10.3389/fnano.2024.1466721

Onotu, O. P., Samuel, H. S., Undie, D. A., Akinpelu, O. O., Ibekwe, F. A., and Etim, E. E. (2025). Nanoparticles for targeted removal of emerging contaminants in wastewater: mechanisms and sustainable practices. *Discov. Nano* 20:191. doi: 10.1186/s11671-025-04341-4

Onyeaka, H., Miri, T., Nwaiwu, O., Ghosh, S., Obileke, K. C., Odeyemi, O. A., et al. (2024). Preventing chemical contaminants in food: challenges and prospects for safe and sustainable food production. *Food Control* 155:110040. doi: 10.1016/j.foodcont.2023.110040

Oziegbe, O., Oziegbe, E. J., and Ojo-Omoniyi, O. (2025). Bioremediation of heavy metals in aquatic environment: a review. *Clean. Chem. Eng.* 11:100193. doi: 10.1016/j.clce.2025.100193

Pal, A., and Paul, A. K. (2008). Microbial extracellular polymeric substances: central elements in heavy metal bioremediation. *Indian J. Microbiol.* 48, 49–64. doi: 10.1007/s12088-008-0006-5

Pamula, A. S. P., Ravilla, A., and Madiraju, S. V. H. (2022). Applications of the internet of things (IoT) in real-time monitoring of contaminants in the air, water, and soil. *Eng. Proc.* 27:26. doi: 10.3390/ecsa-9-13335

Pande, V., Pandey, S. C., Sati, D., Bhatt, P., and Samant, M. (2022). Microbial interventions in bioremediation of heavy metal contaminants in agroecosystem. *Front. Microbiol.* 13:824084. doi: 10.3389/fmicb.2022.824084

Pandit, A., Adholeya, A., Cahill, D., Brau, L., and Kochar, M. (2020). Microbial biofilms in nature: unlocking their potential for agricultural applications. *J. Appl. Microbiol.* 129, 199–211. doi: 10.1111/jam.14609

Park, J. D., and Zheng, W. (2012). Human exposure and health effects of inorganic and elemental mercury. *J. Prev. Med. Public Health* 45, 344–352. doi: 10.3961/jpmph.2012.45.6.344

Parmar, K. S., and Patel, K. M. (2025). Biosorption and bioremediation of heavy metal ions from wastewater using algae: a comprehensive review. *World J. Microbiol. Biotechnol.* 41:262. doi: 10.1007/s11274-025-04424-5

Parmar, M., and Thakur, L. S. (2013). *Heavy metal Cu, Ni and Zn: Toxicity, health hazards and their removal techniques by low cost adsorbents: a short overview.* Available online at: https://www.researchgate.net/publication/271281628_Heavy_metal_Cu_Ni_and_Zn_Toxicity_health_hazards_and_their_removal_techniques_by_low_cost_adsorbents_A_short_overview#fullTextFileContent (Accessed November 13, 2025).

Parrott, R. L. (2017). "Health and risk policymaking, the precautionary principle, and policy advocacy," in *Oxford Research Encyclopedia of Communication* (Oxford: Oxford University Press (OUP)).

Patel, K. S., Pandey, P. K., Martín-Ramos, P., Corns, W. T., Varol, S., Bhattacharya, P., et al. (2023). A review on arsenic in the environment: contamination, mobility, sources, and exposure. *RSC Adv.* 13, 8803–8821. doi: 10.1039/D3RA00789H

Pham, V. H. T., Kim, J., Chang, S., and Chung, W. (2022). Bacterial biosorbents, an efficient heavy metals green clean-up strategy: prospects, challenges, and opportunities. *Microorganisms* 10:610. doi: 10.3390/microorganisms10030610

Phattaranawik, J., Fane, A.G., and Wong, F. S. (2008). Novel membrane-based sensor for online membrane integrity monitoring. *J. Membr. Sci.* 323, 113–124. doi: 10.1016/j.memsci.2008.06.008

Pichhode, M., and Nikhil, K. (2016). *Effect of Heavy Metals on Plants: An Overview*. Hyderabad: International Journal of Application or Innovation in Engineering & Management (IJAIEM). doi: 10.13140/RG.2.2.27583.87204

Pohl, A. (2020). Removal of heavy metal ions from water and wastewaters by sulfur-containing precipitation agents. *Water Air Soil Pollut.* 231, 1–17. doi: 10.1007/s11270-020-04863-w

Priya, A. K., Gnanasekaran, L., Dutta, K., Rajendran, S., Balakrishnan, D., and Soto-Moscoso, M. (2022). Biosorption of heavy metals by microorganisms: evaluation of different underlying mechanisms. *Chemosphere* 307:135957. doi: 10.1016/j.chemosphere.2022.135957

Priyadarshanee, M., and Das, S. (2021). Bioremediation potential of biofilm forming multi-metal resistant marine bacterium Pseudomonas chengduensis PPSS-4 isolated from contaminated site of Paradip Port, Odisha. *J. Earth Syst. Sci.* 130:125. doi: 10.1007/s12040-021-01627-w

Qasem, N. A. A., Mohammed, R. H., and Lawal, D. U. (2021). Removal of heavy metal ions from wastewater: a comprehensive and critical review. *npj Clean Water* 4, 1–15. doi: 10.1038/s41545-021-00127-0

Qattan, S. Y. A. (2025). Harnessing bacterial consortia for effective bioremediation: targeted removal of heavy metals, hydrocarbons, and persistent pollutants. *Environ. Sci. Eur.* 37:85. doi: 10.1186/s12302-025-01103-y

Rafeeq, H., Afsheen, N., Rafique, S., Arshad, A., Intisar, M., Hussain, A., et al. (2023). Genetically engineered microorganisms for environmental remediation. *Chemosphere* 310:136751. doi: 10.1016/j.chemosphere.2022.136751

Rahman, D. Z., Vijayaraghavan, J., and Thivya, J. (2021). A comprehensive review on zinc(II) sequestration from wastewater using various natural/modified low-cost agro-waste sorbents. *Biomass Convers. Biorefin.* 13, 5469–5499. doi: 10.1007/s13399-021-01822-1

Rai, P. K. (2016). Impacts of particulate matter pollution on plants: implications for environmental biomonitoring. *Ecotoxicol. Environ. Saf.* 129, 120–136. doi: 10.1016/j.ecoenv.2016.03.012

Raju, M. N., and Scalvenzi, L. (2017). "Petroleum degradation: promising biotechnological tools for bioremediation," in *Recent Insights in Petroleum Science and Engineering* (London: InTech).

Rebello, S., Nathan, V. K., Sindhu, R., Binod, P., Awasthi, M. K., and Pandey, A. (2021). Bioengineered microbes for soil health restoration: present status and future. *Bioengineered* 12, 12839–12853. doi: 10.1080/21655979.2021.2004645

Rene, E. R., Pakshirajan, K., and Lens, P. N. L. (2016). Special issue on biofilm engineering for heavy-metal removal and recovery. *J. Environ. Eng.* 142:C2016001. doi: 10.1061/(ASCE)EE.1943-7870.0001168

Rohde, M. (2019). The gram-positive bacterial cell wall. *Microbiol. Spectr.* 7:10.1128/microbiolspec.gpp3-0044-2018. doi: 10.1128/microbiolspec.GPP3-0044-2018

Romero-González, M., Hufton, J. M., Nwaobi, B. C., and Gilmour, D. J. (2016). Ex-situ bioremediation of U(VI) from contaminated mine water using acidithiobacillus ferrooxidans strains. *Front. Environ. Sci.* 4:187156. doi: 10.3389/fenvs.2016.00039

Rubinstein, C., Levitus, G., Vicien, C., Modena, N. A., Ruzal, S., Vesprini, F., et al. (2025). Genetically modified microorganisms for agricultural use: an opportunity for the advancement of risk assessment criteria in Argentina. *Front. Bioeng. Biotechnol.* 13:1612226. doi: 10.3389/fbioe.2025.1612226

Sabour, M. R., and Amiri, A. (2017). Comparative study of ANN and RSM for simultaneous optimization of multiple targets in Fenton treatment of landfill leachate. *Waste Manag.* 65, 54–62. doi: 10.1016/j.wasman.2017.03.048

Saeed, T., Alam, M. K., Miah, M. J., and Majed, N. (2021). Removal of heavy metals in subsurface flow constructed wetlands: application of effluent recirculation. *Environ. Sustain. Indic.* 12:100146. doi: 10.1016/j.indic.2021.100146

Safavi, S., Raouf, F., and Naghavi, A. (2025). Fe-Mn-alginate: a highly effective adsorbent for arsenic removal. *Environ. Pollut. Bioavailability* 37:2556181. doi: 10.1080/26395940.2025.2556181

Sales da Silva, I. G., Gomes de Almeida, F. C., da Rocca e Silva, N. M. P., Casazza, A. A., Converti, A., and Sarubbo, L. A. (2020). Soil bioremediation:

overview of technologies and trends. *Energies* 13:4664. doi: 10.3390/en13184664

Saravanan, P., Saravanan, V., Rajeshkannan, R., Arnica, G., Rajasimman, M., Baskar, G., et al. (2024). Comprehensive review on toxic heavy metals in the aquatic system: sources, identification, treatment strategies, and health risk assessment. *Environ. Res.* 258:119440. doi: 10.1016/j.envres.2024.119440

Sattar, S., Hussain, R., Aziz, S., Naz, J., Yahya, M., Ali, F., et al. (2025). "Mercury and its chemical balance in the soil environment," in *Beneficial Elements for Remediation of Heavy Metals in Polluted Soil* (Amsterdam: Elsevier), 259–295.

Satyam, S., and Patra, S. (2024). Innovations and challenges in adsorption-based wastewater remediation: a comprehensive review. *Heliyon* 10:*e*29573. doi: 10.1016/j.heliyon.2024.e29573

Scheverin, N., Patiño, A. B., Díaz, M., and Horst, M. F. (2024). "Nanomaterials and water purification: opportunities for improving and protecting water," in *Nanomaterials for Air and Water Purification* (Weinheim: Wiley-VCH), 165–196.

Schoofs, H., Schmit, J., and Rink, L. (2024). Zinc toxicity: understanding the limits. *Molecules* 29:3130. doi: 10.3390/molecules29133130

Selivanovitch, E., Ostwalt, A., Chao, Z., and Daniel, S. (2024). Emerging designs and applications for biomembrane biosensors. *Ann. Rev. Anal. Chem.* 17:339. doi: 10.1146/annurev-anchem-061622-042618

Shabib, A., Maraqa, M. A., Mohammad, A. F., and Awwad, F. (2025). Design, fabrication, and application of electrochemical sensors for microplastic detection: a state-of-the-art review and future perspectives. *Environ. Sci. Eur.* 37:94. doi: 10.1186/s12302-025-01138-1

Sharma, I., and Sharma, I. (2020). "Bioremediation techniques for polluted environment: concept, advantages, limitations, and prospects," in *Trace Metals in the Environment - New Approaches and Recent Advances* (London: InTechOpen).

Sharma, P., Singh, S. P., and Tong, Y. W. (2022). "Phytoremediation employing constructed wetlands,: in *Current Developments in Biotechnology and Bioengineering: Advances in Phytoremediation Technology* (Amsterdam: Elsevier), 93–108.

Sharma, U., and Sharma, J. G. (2022). Nanotechnology for the bioremediation of heavy metals and metalloids. *J. Appl. Biol. Biotechnol.* 10, 34–43. doi: 10.7324/JABB.2022.100504

Shen, S., Li, X. F., Cullen, W. R., Weinfeld, M., and Le, X. C. (2013). Arsenic binding to proteins. *Chem. Rev.* 113, 7769–7792. doi: 10.1021/cr300015c

Shoshaa, R., Ashfaq, M. Y., and Al-Ghouti, M. A. (2023). Recent developments in ultrafiltration membrane technology for the removal of potentially toxic elements, and enhanced antifouling performance: a review. *Environ. Technol. Innov.* 31:103162. doi: 10.1016/j.eti.2023.103162

Shukla, S. (2025). *Uses and effects of mercury: a review article*. Available online at: www.ijcrt.org (Accessed November 13, 2025).

Siddiqi, M. N., Ahmad, K., and Almayuf, O. (2023). Lead and its effect on humans: a mini-review. *Int. J. Innov. Sci. Res. Technol.* 8, 2196–2201. doi: 10.5281/zenodo.8233328

Siddique, K. R., Bose, D., Bhattacharya, R., Rodriguez, R. V., and Ray, A. (2025). Artificial intelligence driven bioinformatics for sustainable bioremediation: integrating computational intelligence with ecological restoration. *Environ. Sci. Adv.* 4, 1987–1997. doi: 10.1039/D5VA00240K

Siddique, T. A., Dutta, N. K., and Choudhury, N. R. (2020). Nanofiltration for arsenic removal: challenges, recent developments, and perspectives. *Nanomaterials* 10:1323. doi: 10.3390/nano10071323

Singh, A., Sharma, A., Verma, R. K., Chopade, R. L., Pandit, P. P., Nagar, V., et al. (2022). "Heavy metal contamination of water and their toxic effect on living organisms," in *The Toxicity of Environmental Pollutants* (London: Intechopen), 1–19.

Singh, G., Yadav, N., Yadav, P., Singh, S. K., and Kumar, A. (2024). Incorporation of nanotechnology in wastewater remediation: Advancement and challenges. *Adv. Chem. Pollut. Environ. Manag. Prot.* 10, 363–382. doi: 10.1016/bs.apmp.2023.08.006

Singh, S., and Chakraborty, S. (2023). Application of alternative organic wetland media for acid mine drainage treatment: insights on reformations of microbial community structure. *J. Environ. Chem. Eng.* 11:111399. doi: 10.1016/j.jece.2023.111399

Singh, V., Ahmed, G., Vedika, S., Kumar, P., Chaturvedi, S. K., Rai, S. N., et al. (2024). Toxic heavy metal ions contamination in water and their sustainable reduction by eco-friendly methods: isotherms, thermodynamics and kinetics study. *Sci. Rep.* 14, 1–13. doi: 10.1038/s41598-024-58061-3

Singh, Y., and Saxena, M. K. (2022). Insights into the recent advances in nano-bioremediation of pesticides from the contaminated soil. *Front. Microbiol.* 13:982611. doi: 10.3389/fmicb.2022.982611

Slavin, W. (1994). "Atomic absorption spectrometry flame AAS," in *Techniques and Instrumentation in Analytical Chemistry* (Amsterdam: Elsevier), 87–90.

Solanki, S., Sinha, S., Tyagi, S., and Singh, R. (2024). Nanomaterials for efficient removal of heavy metals. *Adv. Chem. Pollut. Environ. Manag. Prot.* 10, 117–136. doi: 10.1016/bs.apmp.2023.08.008

Srivastava, N. (2021). "Remediation of heavy metals through genetically engineered microorganism," in *Environmental Pollution and Remediation. Environmental and Microbial Biotechnology,* ed. R. Prasad (Singapore: Springer), 315–366.

Stefanakis, A. I. (2019). The role of constructed wetlands as green infrastructure for sustainable urban water management. *Sustainability* 11:6981. doi: 10.3390/su11246981

Suja, S. K., Almaas, S., Gracy, A. P., Gowsika, P., Jeyapradeepa, K., Sri, G. S., et al. (2024). Contamination of water by heavy metals and treatment methods – a review. *Curr. World Environ.* 19, 4–21. doi: 10.12944/CWE.19.1.2

Sulthana, S. F., Iqbal, U. M., Suseela, S. B., Anbazhagan, R., Chinthaginjala, R., Chitathuru, D., et al. (2024). Electrochemical sensors for heavy metal ion detection in aqueous medium: a systematic review. *ACS Omega* 9, 25493–25512. doi: 10.1021/acsomega.4c00933

Syed, Z., Sogani, M., Rajvanshi, J., and Sonu, K. (2022). Microbial biofilms for environmental bioremediation of heavy metals: a review. *Appl. Biochem. Biotechnol.* 195, 5693–5711. doi: 10.1007/s12010-022-04276-x

Tchounwou, P. B., Yedjou, C. G., Patlolla, A. K., and Sutton, D. J. (2012). Heavy metal toxicity and the environment. *EXS* 101, 133–164. doi: 10.1007/978-3-7643-8340-4_6

Thangavelu, L., and Veeraragavan, G. R. (2022). A survey on nanotechnology-based bioremediation of wastewater. *Bioinorg. Chem. Appl.* 2022:5063177. doi: 10.1155/2022/5063177

Thekkudan, V. N., Vaidyanathan, V. K., Ponnusamy, S. K., Charles, C., Sundar, S., Vishnu, D., et al. (2017). Review on nanoadsorbents: a solution for heavy metal removal from wastewater. *IET Nanobiotechnol.* 11, 213–224. doi: 10.1049/iet-nbt.2015.0114

Tian, Y., Liu, J., Qiao, J., Ge, F., Yang, Y., and Zhang, Q. (2025). Advancements in electrochemical sensing technology for heavy metal ions detection. *Food Chem.* 25:102204. doi: 10.1016/j.fochx.2025.102204

Trentin, R., Nai, I., Schumann, S., Santovito, G., Moschin, E., Custódio, L., et al. (2025). Effect of lead on photosynthetic pigments, antioxidant responses, metabolomics, thalli morphology and cell ultrastructure of Iridaea cordata (*Rhodophyta*) from Antarctica. *Comp. Biochem. Physiol. C Toxicol. Pharmacol.* 287:110063. doi: 10.1016/j.cbpc.2024.110063

Tripathi, M., Singh, P., Singh, R., Bala, S., Pathak, N., Singh, S., et al. (2023). Microbial biosorbent for remediation of dyes and heavy metals pollution: a green strategy for sustainable environment. *Front. Microbiol.* 14:1168954. doi: 10.3389/fmicb.2023.11689 54

Umapathi, R., Ghoreishian, S. M., Sonwal, S., Rani, G. M., and Huh, Y. S. (2022). Portable electrochemical sensing methodologies for on-site detection of pesticide residues in fruits and vegetables. *Coord. Chem. Rev.* 453:214305. doi: 10.1016/j.ccr.2021.214305

United States Environmental Protection Agency Office of Water Washington. (2000). *Wastewater Technology Fact Sheet Chemical Precipitation*. Available online at: https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P1001QTR.txt (Accessed November 13, 2025).

Urtiaga, A. (2021). Electrochemical technologies combined with membrane filtration. *Curr. Opin. Electrochem.* 27:100691. doi: 10.1016/j.coelec.2021.100691

van Gestel, J., Vlamakis, H., and Kolter, R. (2015). Division of labor in biofilms: the ecology of cell differentiation. *Microbiol. Spectr.* 3. doi: 10.1128/microbiolspec.MB-0002-2014

Van, H., Hoang, V. H., Nga, L. T. Q., and Nguyen, V. Q. (2024). Effects of Zn pollution on soil: pollution sources, impacts and solutions. *Results Surf. Interf.* 17:100360. doi: 10.1016/j.rsurfi.2024.100360

Vasanthapalaniappan, K., Palani, K., Saravanabhavan, S. S., Jonna, N., Natesan, B., Pounsamy, M., et al. (2020). A study on novel coupled membrane bioreactor with electro oxidation for biofouling reduction. 26. doi: 10.4491/eer.2020.039

Veeraswamy, D., Subramanian, A., Mohan, D., Ettiyagounder, P., Selvaraj, P. S., Ramasamy, S. P., et al. (2023). Exploring the origins and cleanup of mercury contamination: a comprehensive review. *Environ. Sci. Pollut. Res.* 31, 53943–53972. doi: 10.1007/s11356-023-30636-z

Velusamy, K., Periyasamy, S., Kumar, P. S., Rangasamy, G., Nisha Pauline, J. M., Ramaraju, P., et al. (2022). Biosensor for heavy metals detection in wastewater: a review. *Food Chem. Toxicol.* 168:113307. doi: 10.1016/j.fct.2022.113307

Verma, Y., Verma, A., Bhaskaralingam, A., Dhiman, P., Kumar, A., Sharma, G., et al. (2025). Application of zero-valent iron and its derivatives in the removal of toxic metal ions from groundwater. *Water* 17:1524. doi: 10.3390/w17101524

Visvanathan, P., Kirubakaran, D., Selvam, K., Manimegalai, P., Rajkumar, M., and Vasantharaj, K. (2024). Recent strategies for natural bioremediation of emerging pollutants: development of a green and sustainable environment. *ACS Symp. Ser.* 1476, 1–19. doi: 10.1021/bk-2024-1476.ch001

Volarić, A., Svirćev, Z., Tamindžija, D., and Radnovic, D. (2021). Microbial bioremediation of heavy metals, *Hem. Ind.* 75, 103–115. doi: 10.2298/HEMIND200915010V

Vuković Domanovac, M., Volf, M., Runjavec, M. Š., and Terzić, I. (2025). Sustainable and advanced strategies for bioremediation of highly contaminated wastewater. *Processes* 13:2250. doi: 10.3390/pr13072250

Wang, M., Zheng, X., Oba, B. T., Lin, Y., Shen, C., Huang, X., et al. (2025). Innovations in nanomaterials for remediation of heavy metal–polluted soil: advances, mechanistic insights, and future prospects. *Nano Mater. Sci.* doi: 10.1016/j.nanoms.2025.06.008

Wu, B., Ga, L., Wang, Y., and Ai, J. (2023). Recent advances in the application of bionanosensors for the analysis of heavy metals in aquatic environments. *Molecules* 29:34. doi: 10.3390/molecules29010034

Wu, Y., Liang, Q., and Tang, Q. (2011). Effect of Pb on growth, accumulation and quality component of tea plant. *Proc. Eng.* 18, 214–219. doi: 10.1016/j.proeng.2011.11.034

Wu, Y. S., Osman, A. I., Hosny, M., Elgarahy, A. M., Eltaweil, A. S., Rooney, D. W., et al. (2024). The toxicity of mercury and its chemical compounds: molecular mechanisms and environmental and human health implications: a comprehensive review. *ACS Omega* 9, 5100–5126. doi: 10.1021/acsomega.3c07047

Xiang, L., Harindintwali, J. D., Wang, F., Redmile-Gordon, M., Chang, S. X., Fu, Y., et al. (2022). Integrating biochar, bacteria, and plants for sustainable remediation of soils contaminated with organic pollutants. *Environ. Sci. Technol.* 56, 16546–16566. doi: 10.1021/acs.est.2c02976

Xu, W., Jin, Y., and Zeng, G. (2024). Introduction of heavy metals contamination in the water and soil: a review on source, toxicity and remediation methods. *Green Chem. Lett. Rev.* 17:2404235. doi: 10.1080/17518253.2024.2404235

Yadav, N., Jyoti, Thakur, I. S., Srivastava, S. (2023). "Omics approach in bioremediation of heavy metals (HMs) in industrial wastewater," in *Genomics to Bioremediation: Principles, Applications, and Perspectives,* eds. V. Kumar, M. Bilal, L. F. Romanholo Ferreira, and H. M. N. Iqbal (Hoboken, NJ: Wiley Semiconductors), 343–361.

Yadav, R., and Nikam, J. (2024). Biomonitoring the impact of air pollution on plants by air pollution tolerance index in Amli industrial estate. *Int. J. Ecol. Environ. Sci.* 6, 22–27.

Yan, A., Wang, Y., Tan, S. N., Mohd Yusof, M. L., Ghosh, S., and Chen, Z. (2020). Phytoremediation: a promising approach for revegetation of heavy metal-polluted land. *Front. Plant Sci.* 11:513099. doi: 10.3389/fpls.2020.00359

Yan, G., Xue, K., Qi, Y., Fan, Y., Tian, X., Liu, Y., et al. (2023). Toxicity mechanisms and remediation strategies for chromium exposure in the environment. *Front. Environ. Sci.* 11:1131204. doi: 10.3389/fenvs.2023.1131204

Yang, J., Hou, B., Wang, J., Tian, B., Bi, J., Wang, N., et al. (2019). Nanomaterials for the removal of heavy metals from wastewater. *Nanomaterials* 9:424. doi: 10.3390/nano9030424

Yao, X., Yi, Z., Xu, M., and Han, Y. (2025). A review on the extraction, structural characterization, function, and applications of peptidoglycan. *Macromol. Rapid Commun.* 46:e2400654. doi: 10.1002/marc.202400654

Yatera, K., Morimoto, Y., Ueno, S., Noguchi, S., Kawaguchi, T., Tanaka, F., et al. (2018). Cancer risks of hexavalent chromium in the respiratory tract. *J. UOEH* 40, 157–172. doi: 10.7888/juoeh.40.157

Yin, W., Wang, Y., Liu, L., and He, J. (2019). Biofilms: the microbial 'protective clothing' in extreme environments. *Int. J. Mol. Sci.* 20:3423. doi: 10.3390/ijms20143423

Yu, G., Li, P., Wang, G., Wang, J., Zhang, Y., Wang, S., et al. (2021). A review on the removal of heavy metals and metalloids by constructed wetlands: bibliometric, removal pathways, and key factors. *World J. Microbiol. Biotechnol.* 37157. doi: 10.1007/s11274-021-03123-1

Yu, G., Wang, G., Chi, T., Du, C., Wang, J., Li, P., et al. (2022). Enhanced removal of heavy metals and metalloids by constructed wetlands: a review of approaches and mechanisms. *Sci. Total Environ.* 821:153516. doi: 10.1016/j.scitotenv.2022.153516

Yusuf, S. D., Omojorla, V., Umar, I., and Loko, A. Z. (2023). Implementation of a 220v Ac overload and high voltage monitor alert system with auto shut down. *IJEMT* 8, 32–40. doi: 10.56201/ijssmr.v8.no1.2022.pg32.40

Zeng, X., Jiang, H., Yang, G., Ou, Y., Lu, S., Jiang, J., et al. (2022). Regulation and management of the biosecurity for synthetic biology. *Synth. Syst. Biotechnol.* 7, 784–790. doi: 10.1016/j.synbio.2022.03.005

Zhai, J., Xiao, J., Rahaman, M. H., John, Y., and Xiao, J. (2016). Seasonal variation of nutrient removal in a full-scale artificial aerated hybrid constructed wetland. *Water* 8:551. doi: 10.3390/w8120551

Zhang, P., Yang, M., Lan, J., Huang, Y., Zhang, J., Huang, S., et al. (2023). Water quality degradation due to heavy metal contamination: health impacts and eco-friendly approaches for heavy metal remediation. *Toxics* 11:828. doi: 10.3390/toxics11100828

Zhang, Z., Zhao, Y., Wei, T., Bai, X., Chen, Z., Lei, X., et al. (2024). Constructed wetlands for metallic wastewater treatment: an updated global profile. *J. Water Process Eng.* 65:105852. doi: 10.1016/j.jwpe.2024.105852

Zhao, A., Sun, J., and Liu, Y. (2023). Understanding bacterial biofilms: from definition to treatment strategies. *Front. Cell. Infect. Microbiol.* 13:1137947. doi: 10.3389/fcimb.2023.1137947

Zhao, G., Tran, T. T., Modha, S., Sedki, M., Myung, N. V., Jassby, D., et al. (2022). Multiplexed anodic stripping voltammetry detection of heavy metals in water using nanocomposites modified screen-printed electrodes integrated with a 3D-printed flow cell. *Front. Chem.* 10:815805. doi: 10.3389/fchem.2022.815805

Zhao, L., Dai, T., Qiao, Z., Sun, P., Hao, J., and Yang, Y. (2020). Application of artificial intelligence to wastewater treatment: a bibliometric analysis and systematic review of technology, economy, management, and wastewater reuse. *Process Saf. Environ. Protection* 133, 169–182. doi: 10.1016/j.psep.2019.11.014

Zinicovscaia, I. (2016). "Conventional methods of wastewater treatment," in *Cyanobacteria for Bioremediation of Wastewaters*, eds. I. Zinicovscaia and L. Cepoi (Cham: Springer), 17–25.

Zueva, S. B. (2018). "Current legislation and methods of treatment of wastewater coming from waste electrical and electronic equipment processing," in *Waste Electrical and Electronic Equipment Recycling: Aqueous Recovery Methods* (Amsterdam: Elsevier), 213–240.