

Assessing Efficacy of the Microbial Interventions in Heavy Metal Decontamination of the Environment and Food Production Systems

Fatemeh Fateminasab^{1*}, Mehdi Koushki^{2,3}, Faranak Jafarian⁴, Vahid Mansouri⁵, Alireza Ahmadzadeh⁶, Nasrin Amiri-Dashatan⁷, Masoumeh Farahani^{8*}

1. Department of Physical Chemistry, Faculty of Chemistry, University of Mazandaran, Babolsar, Iran

2. Cancer Gene Therapy Research Center, Zanjan University of Medical Sciences, Zanjan, Iran

3. Department of Clinical Biochemistry, School of Medicine, Zanjan University of Medical Sciences, Zanjan, Iran

4. Department of Chemistry, University of Isfahan, Isfahan, Iran

5. Proteomics Research Center, System Biology Institute, Faculty of Paramedical Sciences, Shahid Beheshti University of Medical Sciences, Tehran, Iran

6. Department of Laboratory Sciences, Faculty of Paramedical Sciences, Shahid Beheshti University of Medical Sciences, Tehran, Iran

7. Zanjan Metabolic Diseases Research Center, Health and Metabolic Diseases Research Institute, Zanjan University of Medical Sciences, Zanjan, Iran

8. Proteomics Research Center, System Biology Institute, Shahid Beheshti University of Medical Sciences, Tehran, Iran

Abstract

Background and Objective: Heavy metals such as arsenic (As), cadmium (Cd), chromium (Cr), mercury (Hg), Copper (Cu), Nickel (Ni), and lead (Pb) pose serious risks to ecosystems and human health, particularly affecting vulnerable groups such as children. These toxic heavy metals can accumulate in food matrices, leading to long-term health effects. People can be exposed to these pollutants through contaminated food, polluted water, inhalation, and direct skin contact. This review focused on the environmental pollution caused by industrialization, specifically heavy metal contamination. Moreover, it assessed bioremediation as a potential solution, which involved using microorganisms and plants to break down and detoxify these hazardous pollutants.

Results and Conclusion: This study investigated various bioremediation techniques, including the use of probiotics for decontamination. These methods aimed to restore contaminated sites and develop sustainable approaches to remove heavy metals from food products. The study highlighted the effectiveness of microbial interventions in addressing the harmful effects of heavy metals and toxins in the environment and food systems. These bioremediation strategies could lessen the risks associated with heavy metal contamination.

Conflict of interest: The authors declare no conflict of interest.

Article Information

Article history:

- Received 7 Nov 2024
 - Revised 16 Dec 2024
 - Accepted 23 Dec 2024

Keywords:

- Bioremediation
- Heavy metal decontamination (HMD)
- Probiotics
- Biotransformation
- Bioadsorption

Corresponding author:

Fatemeh Fateminasab,

Department of Physical Chemistry, Faculty of Chemistry, University of Mazandaran, Babolsar, Iran

E-mail: ftmfatemi61@gmail.com

Masoumeh Farahani

Proteomics Research Center, System Biology Institute, Shahid Beheshti University of Medical Sciences, Tehran, Iran

E-mail: mfarahani@sbmu.ac.ir

How to cite this article

Fateminasab F, Koushki M, Jafarian F, Mansouri V, Ahmadzadeh A, Amiri-Dashatan N, Farahani M. Assessment of milk-based high protein products as ingredients of low-fat ice creams. *Appl Food Biotechnol*. 2024; 11 (2): e8. <http://dx.doi.org/10.22037/afb.v11i1.46832>

1. Introduction

The environment encompasses all natural components, including soil, water, and essential air for sustaining life on the planet. However, rapid industrialization over the past century has led to increased pollution levels and significant environmental challenges. Pollutants occur in various forms such as organic materials, plastics, and inorganic

substances, including heavy metals (HM) and radioactive wastes [1]. People can be exposed to HMs in four major ways eating contaminated foods, breathing polluted air, drinking dirty water, and touching contaminated surfaces in farms, factories, homes, and industrial areas [2]. Metals can be stored in food matrices and at low concentrations

can lead to long-term health problems, especially in children. The spread HMs are arsenic (As), cadmium (Cd), chromium (Cr-VI), mercury (Hg), copper, (Cu), nickel (Ni), and lead (Pb), where they are broadly known as “most problematic HMs” and “toxic heavy metals” (THM) [3]. The HMs such as Pb and Hg can accumulate in the food chain, posing threats to wildlife, plants, and humans. Long-term consequences of pollution extend beyond environmental damages; they destroy habitats, decrease biodiversity, and disrupt ecosystems. Furthermore, pollution includes health risks, contributing to respiratory ailments and cardiovascular diseases. It is critical to tackle these pollution challenges to protect the environment and public health [4]. The HMs are dangerous to food chains and can cause long-term health problems in people. These metals and other pollutants do not break down easily; hence, they persist in the environment consistently. To tackle these harmful substances, the use of biological methods is needed. Researchers study how microbes interact with HMs to create safe and sustainable cleanup methods such as bioremediation [5].

Bioremediation is a process that uses living organisms, mainly microorganisms and plants, to clean up environmental pollutants. The goal is to break down harmful substances in waste and make them less toxic or harmless [6]. This helps restore contaminated sites to their original condition. Bioremediation can decrease the effects of various pollutants, including pesticides, industrial solvents, HMs, and other chemical compounds [7]. The field covers basic research such as studying how organisms break down substances and practical uses such as assessing pollution and predicting how it behaves in the environment. Methods such as probiotics effectively clean toxins and HMs from foods [8,9]. These methods can remove harmful elements such as As, Hg, Pb, and Cd and pesticides. Bioremediation techniques can be used to clean water, soil, lagoons, waste streams, and sludge. Using natural and specially designed microorganisms with appropriate engineering, correct conditions for effective bioremediation can be created [10,11]. Transferring research findings from the laboratory to industrial uses is usually slow and the outcomes can vary significantly from those seen under controlled laboratory conditions. Hence, only a few industrial methods for HM bioremediation have successfully been adopted. This challenge has shifted future studies on technology transfer toward assessing potentials for scaling these processes and verifying the effectiveness of the linked systems. To successfully implement bioremediation at a larger scale, it is critical to investigate biochemical and physical factors such as compositions of the media and growth conditions [12]. As the global population grows and living standards improve, demands for agricultural production are expected to double by 2050. However,

industrial growth in developing nations has resulted in significant contamination of farmland with HMs. Key HMs, including Cd, As, Cu, Hg, Pb, and Cr, are identified as major contributors to soil pollution in China, increasing international awareness of soil degradation through initiatives such as "World Soil Day" and the "International Year of Soils" in 2015. In 2017, the UN Environment Assembly called World Health Organization (WHO) and Food and Agriculture Organization (FAO) to report on global soil pollution and assess risks by 2021. China's strategic plan established in 2016 has aimed to rehabilitate 700,000 hectares of polluted agricultural lands by 2020, targeting to restore and certify 95% of the nation's contaminated lands as safe for agricultural use by 2030 [13]. This report aims to highlight the urgent need to address increasing levels of pollution caused by industrialization and assess their significant effects on environmental health, the food industry, and public safety. Additionally, this study aimed to investigate the potential of bioremediation as an innovative solution for using microorganisms to effectively clean up hazardous pollutants; thereby, helping in restoring the contaminated eco-systems.

2. Results and Discussion

2.1. Toxic heavy metals

The presence of HMs such as Cd, Cr, Pb, Hg, As, Cu, and Ni in wastewater poses significant risks to human health and aquatic life. Developing countries are particularly affected by HM contamination, which increases environmental, health, and economic concerns. Exposure to these metals can damage the central nervous system, decrease energy levels, and hurt vital organs. Long-term exposure can cause degenerative processes similar to neurological disorders such as Alzheimer's and Parkinson's diseases [14].

Cd, a rare metal extensively used in various industries, includes significant health hazards, including damage to vital organs and the development of conditions such as Itai-Itai disease. Mining and refining activities, air pollution, and the use of sewage sludge are the primary contributors to water and soil contaminations with Cd. Exposure to Cd primarily occurs through the consumption of contaminated foods and water, inhalation, and tobacco smoke. The metal can bioaccumulate in plants and animals and has been associated with various forms of cancers and osteoporosis. Even at low exposure levels, typical in the general non-smoking populations, Cd can result in renal tubular dysfunction and bone toxicity. Recent studies have suggested correlations between increased Cd exposure and hormone-linked cancers such as breast cancer, as well as effects on neurodevelopment. Plants absorb Cd through

their root systems, while grain and vegetable products serve as the primary diet sources. Special attention should be paid to vulnerable groups, including infants, vegetarians, smokers, and fertile women with low-iron status facilitating gastrointestinal absorption of Cd and individuals with preexisting renal dysfunction. Moreover, Cd is highly toxic to humans can cause reproductive system failure and brain and kidney damage, and is linked to cancers. It can enter the food chain and accumulate in organisms. The study aimed to use natural microorganisms to completely remove Cd from the environment [14, 15].

Cr, showing various oxidation states from -2 to +6, is used in industrial processes such as metal refining, chrome-plating, and stainless-steel production. This results in the release of Cr(VI) into the atmosphere, leading to potential exposure through polluted air or contaminated drinking water. The International Agency for Research on Cancer categorizes Cr(III) & (VI) as Group 1 carcinogens, highlighting their significant health hazards. Cr(III) occurs naturally in rocks and soil and can enter human diets through plant intakes. Toxic effects of Cr are due to dermal and respiratory exposures. Furthermore, Cr(VI) is an extremely sensitized agent that causes skin allergies [16,17].

Pb, a toxic metal, is commonly detected in soil due to human activities and natural sources. Its presence in soil poses a significant risk to human health, especially through food consumption, with cereals and vegetables are the primary sources of exposure. Despite regulatory efforts in developed nations to control and prohibit the use of Pb in gasoline and certain materials since the 1970s, concerns about Pb exposure from foods are still reported. Extensively, Pb is used in various industries, including batteries, paints, automobile fuels, semiconductors, and electroplating. Prolonged exposure to Pb can lead to serious health problems such as nephropathy, abdominal pain, weakness, and male infertility. It is present in dust, soil, old paints, and leaded gasoline, affecting behaviors, cognitive performance, growth, and overall health. Historical and continued uses of Pb have resulted in its presence in the food chain. Urban agriculture in developing nations, critical for food security, may contribute to higher Pb levels in leafy vegetables due to land shortage and previous waste disposal. While adults primarily encounter Pb exposure through foods, infants are majorly exposed through drinking water, soil ingestion, and dust. Pb in drinking water often originates from water pipes or Pb solders in taps. Additionally, certain shellfish, chocolate products, sweet potatoes, canned fruits, and hot sauces imported from Mexico may contain increased Pb concentrations. Exposure to Pb has been associated with a variety of adverse effects on the cardiovascular system in adults. The effect associated with the lowest Pb exposure includes increases in systolic blood pressure. Polymor-

phisms in aminolevulinic dehyd-ratase gene may play a role in mediating these effects. Relatively low exposure to lead has been associated with functional renal deficits such as decreases in glomerular filtration rate, increased serum creatinine levels, and decreased creatinine clearance [15,18].

Technically, Zn belongs to Group II–B in the periodic table. It is relatively abundant in the earth crust. Furthermore, Zn is a bluish-white lustrous metal, very malleable and moderately reactive that combines with oxygen and other non-metals. It only includes one common oxidation state (+2) and is widely used in corrosion-resistant steel coatings, brass alloys, painting pigments, wood preservatives, dry-cell batteries, cosmetics, and pharmaceuticals. The industry uses a large quantity of Zn to produce die-casting, which contributes to emissions to the atmosphere water, and soil. The principal source of Zn contamination in the environment involves industrial wastes, metal plating, and acid drainage. Sewage and animal wastes constitute a source of Zn in the soil. Additionally, Zn is in contrast to the other two HMs discussed previously; it is an essential trace element for animals, plants, and bacteria necessary for life. It plays an important role in the catalytic activity of proteins. Shortage can cause hair loss, skin lesions, and diarrhea in humans, while in plants it can cause chlorosis, impaired growth, and malformation of leaves and stems. Excess exposures to Zn can lead to loss of weight, impaired immune system, and blockage of essential reactions in the cell [14].

Hg, the only liquid metal, is one of the most THMs in three distinct forms elemental, inorganic, and organic, each with various toxicity levels. Moreover, Hg includes significant industrial uses due to its ability to form amalgams with other metals (e.g. in gold extraction or dental amalgams). The inorganic forms can present health risks to individuals through occupational exposure, while methyl Hg, the most prevalent organic form, can be harmful when ingested through the diet. Furthermore, Hg is released into the environment through natural human activities such as coal combustion and industrial processes. The acceptable levels of Hg in drinking water and soil are 0.002 mg.l⁻¹ and 0.010-0.3 mg.kg⁻¹, respectively. Hg is extensively used in various industries such as electronics, dentistry, wood processing, and pharmaceuticals, emphasizing the importance of responsible use and disposal to minimize its environmental effects and safeguard human health. These compounds include diverse effects on the lungs, kidneys, nerves, skin, eyes, and digestive and immune systems. Hg can cause the immune system to attack the body. Severe hopelessness, extreme fatigue, insomnia, hair loss, vision impairment, memory loss, restlessness, tremors, sudden anger outbursts, brain injuries, and lung and kidney

damage are possible consequences of certain contaminations [19, 20].

As is a dangerous toxin detected in groundwater and an industrial pollutant. The permissible limit of As in primary drinking water and soils is 0.05 mg.l^{-1} and 150 mg.kg^{-1} , respectively. This toxic metal can affect humans through drinking water, inhalation of polluted air, and intake of contaminated foods. Long-term exposure to As can cause cardiovascular and blood diseases, neurotoxicity and nephrotoxicity, dermatitis, and various types of cancers. More than 200 million people worldwide are exposed to its chronic effects. Treatment methods for arsenicosis include chelation therapy, phytopreparations, antioxidants, and appropriately selected diets. Exogenous antioxidants such as Zn and Sn are convenient for As detoxification. In addition, it is noteworthy that the toxic effects of As adversely affect vital cellular functions such as oxidative phosphorylation and ATP synthesis [19–21].

Cu is essential for enzymes and electron transport but can be harmful at higher concentrations. The acceptable limits for Cu in primary and secondary drinking waters and soils are 1.3 mg.l^{-1} , 1.0 mg.l^{-1} , and 2100 mg.kg^{-1} , respectively. Exceeding these limits can lead to adverse health effects. Cu is released into the environment from various sources and can exist in various forms in water. Microorganisms have developed mechanisms to maintain Cu balance, including sequestration, absorption, and efflux. Genes linked to resistance to Cu may be detected on plasmids and chromosomes [19, 22].

Ni, a strong, shiny white metal in the form of Ni^{2+} cations, is commonly detected in a state and used in various uses such as stainless-steel production, catalysis, and coin production. Ni is naturally present in small quantities in soils and essential for the metabolic activities of plants and many bacteria. However, some Ni and Pb compounds can be poisonous to health problems, including cancers, respiratory problems, and heart diseases. Continuous exposure to allergens through inhalation can result in various severe health problems such as allergic skin conditions, respiratory cancers, and negative effects on fertility and hair. These allergens have been identified as immunotoxic, neurotoxic, and genotoxic agents, presenting a significant threat to overall health. The allowed quantity of Ni in soil ranges from $5\text{--}500 \text{ mg.kg}^{-1}$. Additionally, Ni can enter surface water through wastewater drains. While animals need Ni in small quantities, exceeded quantities can be toxic. Ni is essential for certain bacterial enzymes, but excessive Ni can be poisonous by binding to proteins and nucleic acids, often inhibiting enzyme activity as well as DNA replication, transcription and translation [19,20,22]. Table 1 summarizes THM characteristics.

Table 1. Toxic heavy metals, their sources of contamination and potential risks

Toxic Heavy metals	Source of contamination and risk
Cd	Sources include mining, air pollution and sewage sludge. Exposure can lead to kidney damage, cancer and hormonal issues, predominantly via food and water.
Cr	In industrial processes, Cr (VI) is a known carcinogen. Risks include exposure through the air and contaminated water, skin allergies and respiratory effects.
Pb	Common in soil and food due to human activity. Associated with nephropathy, cognitive issues and cardiovascular effects, especially impacting vulnerable populations
Zn	An abundant metal used in various applications like steel coatings and pigments, with a singular common oxidation state of (+2).
Hg	Hg, found in elemental, inorganic and organic forms, includes health risks from environmental release, especially from coal combustion, requiring strict regulations due to its toxicity.
As	Arsenic is a toxic substance found in water and soil that can lead to serious health risks, (i.e. cardiovascular diseases and neurotoxicity). Treatments (i.e. chelation therapy and antioxidants) like Zn and Se may help decrease its harmful effects on cellular functions.
Cu	Cu is vital for enzymatic functions and electron transport but can become toxic in water and soil above specified limits, with microbial resistance strategies involving genes located on plasmids and chromosomes.
Ni	Ni is a crucial metal for plants and bacteria, beneficial in small amounts but potentially toxic at higher levels, leading to health risks and environmental contamination.

2.2. Roles of biotechnology in bioremediation

Bioremediation refers to the removal of environmental pollutants from air, water, soil and flue gasses in natural or artificial settings [3]. Thus, bioremediation, a state-of-the-art and environmentally sustainable technology, uses organic microorganisms to remove pollutions. Hence, biotechnology is a method of using scientific engineering of microorganisms to improve the efficiency of organisms to serve humans and remediate environmental toxic substances [23]. A significantly developed environmentally biotech-nological technology is necessary to remove the contam-inated materials and reestablish the natural resources. Nowadays, recent advancements in the emerging novel methods of biotechnology support the bioremediation process for the protection of the natural environment through recycling waste materials. Later, use of the most advanced technology to boost the bioremediation process is discussed. One of the biotechnology approaches includes use of genetic engineering. For example, it is possible to create an

organism or genetically engineered microbes (GEM) that produce all the necessary enzymes or use all the degradation pathways for the bioremediation processes [24]. Thus, use of engineered microorganisms is more cost-effective than that use of alternative methods is. Usually, GEMs are created by introducing stronger proteins into bacteria through biotechnology or genetic engineering to enhance a desired trait. Biodegradation of oil spills, halobenzoates naphthalenes, toluenes, trichloroethylene, octanes and xylenes has been carried out via GEMs such as bacteria, fungi and algae [25]. Deterioration of polychlorinated biphenyls (PCB) is controlled by groups of genes that were observed in the genetic materials of two various organisms. Use of genetic engineering for achieving recombination between *Pseudomonas pseudoalcaligenes* KF707 and *Burkholderia cepacia* LB400 *bph* genes may increase the degradation rate of PCBs and stimulate remediation of toluene and benzene [25]. Another use of biotechnology is the blending between metallothionein (MT) isolated from rats, IgA protease protein isolated from *Neisseria gonorrhoeae* and *lpp-ompA* fusion vehicle to create bacterial cell walls with metal ion-binding polypeptides [26]. Another branch of biotechnology concerns the use of transgenic plants in bioremediation processes by introducing genes of interest from various sources (other plants, microorganisms, or animals) to improve the plant ability to remove toxic pollutants [27]. Thus, this translocation process enhances the phyto-remediation capacity of plants. Biotechnologically induced microorganisms are stronger than naturally occurring ones and may degrade contaminants faster because they can rapidly accommodate new pollutants they encounter or co-metabolize.

2.3. Cleaning up of the heavy metal contamination

HMs are naturally occurring elements that can enter the human food supply through industrial and agricultural activities, posing health risks due to their accumulation in living organisms. These metals are persistent pollutants that need regulation in water and food sources. The industrial wastewater release, containing HMs, is dangerous and traditional remediation methods are often ineffective and costly. While developed countries have regulations, several developing nations lack adequate frameworks to address the issue. Innovative solutions such as bioremediation with microorganisms are urgently needed to combat HM pollutions in water and soil [28, 29]. Specific microbial species help in environmentally sustainable cleanup and enhance human health. Probiotics such as lactic acid bacteria (LAB), *Bifidobacteria* and *Saccharomyces boulardii* detoxify HMs through attachment, precipitation and complex formation. Gram-positive bacteria, particularly *Bacillus*, are effective in this

process, while Gram-negative bacteria are less effective. In addition, LAB can bioadsorb HMs and convert toxic elements into safer forms such as transforming methylated Hg. Studies show that *Lactobacilli* can convert Cr into less harmful forms, binding to HMs at the cell wall, regardless of their viability [28]. Probiotics, particularly strains such as *Lactobacillus* and *Bifidobacterium*, are effective in protecting foods from HMs and offer health benefits such as treating diseases, improving metabolism, and enhancing immune function. They can decrease HM toxicity by binding and adsorbing metals affected by pH levels with strains such as *L. rhamnosus* showing protective effects against HM poisoning, especially in vulnerable populations. Additionally, probiotics may improve cognitive function and lessen oxidative stress in animal models. These bacteria present a promising cost-effective strategy for detoxifying HMs in foods and individuals [29, 30].

In a review, Goyal et al. (2019) investigated microbial-assisted remediation of HMs as a cost-effective approach, highlighting *Bacillus* genus for its significant biochemical capabilities in the bioremediation of Cd^{2+} and Ni^{2+} . *Bacillus* achieves this through processes such as biosorption and bioaccumulation. Additionally, it has demonstrated potential to decrease toxicity of these metals in eukaryotic cells and mice, similar to the effects observed with probiotic genera such as *Lactobacillus* and *Bifidobacterium* [31]. Hadiani et al. (2018) showed that *S. cerevisiae* removed 88.9% of Hg^{2+} ions from water at pH 5.45 and an initial concentration of 79.8 $\mu\text{g/l}$, demonstrating its potential for low Hg treatments. A 2019 study detected optimal conditions for As bioremediation at pH 5.0, achieving peak bioabsorption efficiencies of 66.2% for As(III) and 15.8% for As(V) with a concentration of 95.0 $\mu\text{g/l}$ and inoculum size of 32.5×10^7 CFU. Massoud et al. (2019) reported 70% Pb removal from milk and similar results were detected for Cd in 2020, indicating *S. cerevisiae* effectiveness against various HMs [29, 32]. A study by Ameen et al. (2020) showed that *L. plantarum*, a metal-resistant LAB from Alexandria's Mediterranean Seacoast, Egypt, effectively removed Ni^{2+} and Cr^{2+} . Optimal Cr removal occurred at 100 ppm Cr^{2+} with a 3% inoculum, while Cd and Pb uptake were highest at pH 2.0 and 22 °C within 1 h. Its biosorption behavior followed the Langmuir isotherm model, making *L. plantarum* a promising solution for treating HM-contaminated wastewater [33]. In 2022, Afsharian et al. studied *L. acidophilus* ATCC 4356 ability to remove water contaminants in microgravity. They detected that heat pretreatment improved As absorption, while sodium hydroxide treatment was more effective for Cd and Pb without affecting Hg removal. The study highlighted that metal complexes with *L. acidophilus* were released under normal gravity and overall simulated microgravity enhanced the

strain's HM bioreduction [34]. Traditional methods can be costly and ineffective, increasing the interest in eco-friendly options. Recent studies by Wahid et al. (2023) highlighted the effectiveness of probiotic bacteria, particularly *Pediococcus pentosaceus*, in metal removals and pathogen decreases. Two yogurt strains, *L. acidophilus*, and *L. plantarum*, were assessed for survival in acidic environments. The two survived simulated gastric conditions, with *L. acidophilus* showing antibiotic resistance except to gentamicin and co-amoxiclav. *L. plantarum* included a higher Pb removal rate of 42.70% for HMs than *L. acidophilus* of 35.50%. Cd removal rates were 11.50% for *L. plantarum* and 3.50% for *L. acidophilus*, indicating the strains' bioremediation potentials [35]. Mushtaq et al. (2023) investigated the probiotic characteristics of LAB capable of biosorbent Pb, a toxic pollutant. Eight strains from carnivores' feces and human breast milk achieved a 70% Pb biosorption rate and were still viable under simulated gastrointestinal conditions. Significantly, *Levilactobacillus brevis* was analyzed, revealing optimal biosorption conditions at pH 6 after 60 m with a cell density of 1 g/l [36]. Salavatifar and Khosravi (2024) studied how microgravity affected HM biosorption by *S. cerevisiae*. They detected that microgravity increased biosorption rates for Hg (97%) and Pb (72.5%) but not for Cd or As. Metal-yeast complexes were still stable in gastrointestinal conditions with Pb binding decreasing initially in gastric conditions but recovering in the intestinal environment. The kinetics followed a pseudo-second-order model and all metals fitted the Langmuir isotherm. These results suggest that microgravity could enhance biosorption efficiency, benefiting detoxification in the food industry and astronaut health [37].

2.4. Microbial-based removal techniques (bioremediation)

Currently, the quantity of toxins in the environment (air, water, and soil) is increasing, and traditional methods of controlling these pollutants are ineffective. Thus, improvements in modern remediation techniques can be an opportunity to reform bioremediation and waste removal from the environment [25]. Relatively, microbial techniques and methods evolved for achieving successful bioremediation with engineered microorganisms. For example, recombination in *E. coli* is introduced by insertion or deletion to improve the bioremediation characteristics of the microorganism [38]. Bioremediation of wastes using recombinant microbes is expensive but effectively removes all the wastes from the environment. Compared to other physical and chemical approaches, the use of microbial metabolism capabilities to deteriorate or eliminate environmental toxins is an economically secure option. These manipulated microorganisms are more

effective than natural strains due to their higher degradation capacity and ability to promptly adapt to various pollutants such as substrates or cometabolites [39]. As previously stated, numerous techniques are available to treat this microbial contamination from water, soil, and other environments. For example, microbes decreasing HMs and improving soil fertility and plant development have made them a preferred source for bioremediation. However, climate statuses can be effective in the degradation of HMs by the microbes. Higher humidity maintains anaerobic conditions and slows the rate of decomposition. In cold statuses, microbial decomposition of HMs is slow, as metabolic activities are inhibited as the microbial transport pathways are frozen by sub-zero water [40]. While, in hot climates, the rate of HM solubility increases, which increases their availability and the rate of microbial biodegradation [41]. However, the power of microbial biodegradation is calculated by the metal or pollutant chemical structure, concentration, bioavailability, toxicity, and stability [42]. Later, microbial-based pollutant removal techniques are discussed. Recombinant micro-organisms and genetically modified microbes have been used as an effective technique for the breakdown of pollution. Recombinant *E. coli* is one of the model organisms used in bioremediation. *E. coli* is known as a “working horse” of molecular biology for its rapid growth rate in defined chemical environments and the diverse tools available for its genetic modifications [43]. Technically, *E. coli* includes favorite cloning genes and can introduce DNA molecules into cells. Due to the functions of *E. coli* for rapid growth and high-level protein expression, the micro-organism leads to protein production [38]. Several studies have shown that enteric *E. coli* develops phenol and p-cresol when grown on natural media (peptone and casein media) [44]. Further studies emphasized the ability of *E. coli* to break down and use a diverse range of aromatic acids such as phenylacetic acid (PA), hydroxyphenylacetic acid (HPA), and phenyl propionic acid (PP) [39]. Genetically modified *E. coli* is used as a highly effective agent in bioremediation processes. The introduction of a gene into bacteria results in the conversion of the bacteria into a distinct strain that can effectively remove hydrocarbon pollutants from the surrounding environment. This system is capable of removing Ni from the aqueous system, reducing Cr(IV) to Cr(III) as an important reaction in the bioremediation of hazardous Cr species in aerobic environmental statuses [45]. These highlights showed that *E. coli* is useful for the degradation of HMs. The persistent presence of HM contamination in the ecosystem has become a significant global concern, posing risks to environmental integrity and human health due to their tendency to bioaccumulate and resistance to biodegradation. Numerous microbes

belonging to various taxonomic categories, including bacteria, fungi, and algae, have been documented to enzymatically transform metal ions into less harmful forms or to remove them from the environment in an environmentally sustainable way. Therefore, microbial species include important roles in the detoxication of HMs and toxins in food through bioremediation. Microbial species are used for bioremediation of water, soil, and air from HMs [46].

Water is essential for the sustenance of life on the planet and it is vital to eliminate any form of contaminations from this precious resource. Demands for water have surged significantly because of industrialization, primarily due to its essential role in industrial production processes [25]. Thus, microbial techniques are needed to remove HMs from polluted water and contaminated soil. Biofilm-mediated bioremediation presents a compelling strategy for the removal of environmental pollutants due to its significant adaptability, substantial biomass and superior ability to absorb, immobilize and degrade contaminants. Biofilms are aggregates of single or mixed microbial cells that adhere to a living cell or are inert to a surface in an aqueous environment [47]. Microorganisms that form biofilms demonstrate significant resilience when subjected to severe environmental stressors. They are capable of competing effectively for nutrients, show enhanced tolerance to pollutants in comparison to free-floating planktonic cells, and create a protective habitat for other cells. Biofilm communities possess the ability to adsorb and metabolize organic pollutants and HMs, facilitated by a precisely regulated gene expression pattern that is affected by quorum sensing [47]. Contrary to organic pollutants, HM remediation is distinctive as biological processes cannot eliminate these contaminants from the environment. Naturally, HMs are detected in the environment as minor constituents of geochemical cycles, suggesting that microbial communities may interact with and use these metals. When HMs are introduced as pollutants, their concentrations frequently exceed natural levels. There is a possibility of the occurrence of mixed contaminations [48]. However, several studies have demonstrated the ability of the biofilms to repopulate after subsequent desorption cycles with the removal of Cu, Zn, and Cd in successive sorption–desorption cycles [49]. In packed-bed bioreactors designed for the treatment of Hg-contaminated wastewater, mixed culture biofilms demonstrated greater capacity for Hg retention and higher diversity when exposed to fluctuating Hg concentrations, in contrast to monoculture biofilms [50]. Findings indicated that biofilms with greater diversity showed enhanced efficiency in the bioremediation of metals, highlighting their significance in the advancement and use of biofilm-based solutions. A moving bed sand filter,

engineered for the treatment of industrial wastewater with increased levels of HMs, facilitated the development of biofilms composed of metal-resistant bacteria [51]. It has been reported that biofilms not only function as biosorption materials but also decrease the pH sufficiently to promote bioprecipitation of certain HMs [51]. A separate investigation used a mixed-species biofilm composed of sulfate-reducing bacteria, lessening the oxidation-decrease potentials to facilitate the precipitation of metal sulfides, including Cu, Zn, Ni and Fe, as well as the simultaneous precipitation of As. Treatment achieved the removal of 98% of Zn, Cu, and Ni, as well as 82 and 78% of Fe, respectively [52]. The total absorptive capacity of the biofilms was inhibited by the resistance of certain bacteria within the community such as *Stenotrophomonas* spp., which demonstrated resistance to Cr(VI) [53].

Soil pollution due to HMs is a global threat to human health and food production safety. Except for uncommon geogenic origins, HM pollutions are inadvertently introduced to soils through anthropogenic activities such as mining, smelting, warfare and military training, electronic industries, fossil fuels, waste disposal, agrochemical uses and irrigation [46]. The presence of HMs in polluted soils disrupts the natural ecosystem services and poses risks to human health through the food chain. Thus, accumulation of HMs in the soil causes ecosystem malfunction, water degradation and food contamination [46]. Numerous *in-situ* and *ex-situ* remediation methods have been established to manage, remediate and rehabilitate soils contaminated with HMs. These techniques include surface capping, soil flushing, electrokinetic extraction, solidification, vitrification, and phytoremediation [46]. These methods can be categorized into five distinct types of physical, chemical, electrical, thermal and biological remediation. Alternatively, they may be divided into three major groups of containment-based approaches (e.g. capping and encapsulation), transformation-based strategies (including stabilization and immobilization) and transport-based techniques (such as extraction and removal) [54]. These techniques vary significantly in effectiveness and costs in field practices. The HMs in soil are present in various forms, including dissolved ions such as Cu^{2+} , Cd^{2+} , CrO_4^{2-} , $\text{Cr}_2\text{O}_7^{2-}$ and MoO_4^{2-} , as well as organic complexes where metals such as Cu^{2+} , Pb^{2+} and Hg^{2+} are bound to dissolve organic matter within the soil solution. Additionally, there are exchangeable ions, including Cu^{2+} , Zn^{2+} , Cd^{2+} , Ni^{2+} and Pb^{2+} , which are adsorbed onto solid soil particles. Furthermore, HM can be detected as (co)precipitates within the soil matrix, represented by compounds such as $\text{Cd}_3(\text{PO}_4)_2$, ZnS , PbCO_3 and HgSO_4 [55].

In-situ remediation eliminates the need for excavating and transporting contaminated soil to off-site treatment facilities. Hence, soil disturbance is minimized, the risk of

exposure to contaminants for workers and the surrounding community decreases and the overall treatment costs may considerably decrease. While, the *ex-situ* remediation techniques entail the excavation of contaminated soil from its original site, followed by treatment at the same location or a various facility [46]. Technology for *in-situ* extraction and migration of potentially toxic elements in soil encompasses the removal of pollutants from the soil using physical, chemical, biological, or a combination of these methods, aimed at diminishing the risk of soil contamination. This approach differs from *in-situ* immobilization remediation as it actively decreases the concentration of harmful pollutants in the soil, necessitating a subsequent appropriate treatment for the extracted materials. Recent uses of *in-situ* extraction for As-contaminated soils have included techniques such as phytoextraction, microbial extraction, and electrokinetic migration [56]. Common *ex-situ* soil remediation technologies include *ex-situ* land farming, *ex-situ* bio piles, *ex-situ* windrow, soil washing, *ex-situ* composting, *ex-situ* ion exchange, *ex-situ* solidification/stabilization, pyrolysis, thermal desorption, ultrasonic technology, and microwave technology. Due to the complexity of contaminated soils and pollutants, more than one remediation technology is usually needed to lessen the total concentration or available content of the target pollutant to an acceptable level [57]. Another technique for bioremediation includes encapsulation. The encapsulation process can be divided into three significant stages. The initial stage involves the creation of an encapsulating solution that contains at least one active ingredient, which may be an encapsulating material or a carrier. In the subsequent stage, microorganisms or materials intended for encapsulation are brought into contact with the encapsulating solution. The final stage, which may occur concurrently with the second, involves the formation of capsules through the use of the encapsulation method [58]. Applicability of these individual techniques in a specific soil remediation project is set primarily by the contamination site geography, contamination characteristics, remediation goal, cost-effectiveness, financial budget, implementation readiness, time needs, and public acceptability.

2.5. Bioremediation of heavy metals in the food industry

Rapid industrialization significantly affects water, food, feeds, and weather quality. Industries such as chemicals, food processing, and metallurgy industries release large quantities of waste, including toxic substances, into the environment. Additionally, agricultural pesticides, chemical fertilizers, and emissions from transportation contribute to harmful pollutions, which threaten food safety [59]. The HM pollution includes significant threats to food safety. Research has shown HM accumulates in various

environmental sources such as water, rice, vegetables, and fish. Accumulation of these metals in human organs and tissues can lead to several health problems, including kidney damage, cardiovascular problems, and neurological disorders [59, 60]. Various methods have been suggested to solve the problem of HM pollution in the environment. Bioremediation has emerged as a promising solution for addressing HM pollution by using living organisms to decrease environmental metal concentrations. This method has received significant attention due to its effectiveness. Organisms such as plants, fungi, and microorganisms of yeasts, bacteria, algae, and cyanobacteria are frequently used in HM bioremediation. Microorganisms are particularly favored because they are easy to use and adapt well to various environments [61].

2.5.1. Roles of microorganisms in bioremediation

One of the major benefits of using microorganisms to remove toxic elements includes their safety in human aspects. An example of such microorganisms is *S. cerevisiae*, commonly known as bakery yeast, which is extensively used in the food industry. Advantages that have led to its popularity in the food industry include its safety for human use, large-scale production as a byproduct of the fermentation industry, and low costs of the growth media [29].

2.5.2. Use of catalase enzyme in bioremediation

Catalase is an enzyme addressed for its function in decomposing hydrogen peroxide into water and oxygen. This enzyme primarily controls the metabolism of hydrogen peroxide. Catalase is a widely occurring enzyme detected in almost all living organisms. It boasts one of the highest turnover rates within the enzymes, capable of breaking down over a million molecules of hydrogen peroxide per molecule of the enzyme. Catalase plays a critical role in several biotechnological uses, including bioremediation. Catalase has been identified as one of the most abundant and readily accessible enzymes of microbial origin, making it a valuable indicator in bioremediation processes, particularly for the remediation of crude oil-contaminated soil, as its activity is highly affected by hydrocarbon pollution. Additionally, catalase facilitates the breakdown of hydrogen peroxide into water and oxygen, providing essential oxygen during the aerobic bioremediation of wastes; thus, serving as a vital source of oxygen for aerobic microorganisms. Its use extends to the removal of hydrogen peroxide from bleaching industry effluents, enabling the reuse of water in subsequent dyeing processes. This demonstrates its significant role in the bioremediation of wastewater from textile industries. In the food industry, catalase is used in cheese production, removal of glucose from egg whites for bakery uses, as an

antioxidant enzyme system with glucose oxidase, in food packaging, and for assessing milk quality [62].

2.5.3. Remediation processes using geotextiles

In recent years, crude oil and its byproducts have significantly affected environmental degradation with contaminations from activities such as exploration, transportation, and accidents. Soil contamination from petroleum products harms soil, groundwater, and air quality. Various soil cleanup methods, including washing, oxidation, microwave heating, and bioremediation, have been used. Absorbent geotextiles have been interested in water purification due to their high oil absorption, low chemical content, energy efficiency, and ease of use. Natural fibers such as kenaf, plant fibers, milkweed floss, wool, and cotton have been used to separate oil from seawater [63].

2.6. Mechanisms of bioremediation

Numerous bacterial strains have developed a variety of distinct mechanisms to adapt, interact, acclimate and thrive in mineral-rich environments, particularly those containing HMs. These mechanisms include the uptake of HMs onto the cell surface through biosorption, intracellular sequestration via accumulation, extracellular sequestration as insoluble compounds through precipitation and production of metabolites that solubilize and chelate metal compounds, leading to leaching (Figure 1) [64].

2.6.1. Bioadsorption/biosorption

Biosorption or bioadsorption refers to non-specific active or passive physicochemical interactions between inorganic and organic metals, minerals and cellular materials [65]. The biosorption mechanism includes key processes such as surface adsorption, physisorption, chemisorption, ion exchange and surface complexation. In surface adsorption, there is an electrical attraction between negatively charged ligands on the cell wall and positively charged metal ions in the media, often resulting in an exchange reaction. Physical adsorption relies majorly on Van der Waals forces, while chemical adsorption involves attraction between the adsorbents and adsorbates. Working together or independently, these mechanisms lead to metal adsorption on the microbial cell surface. The HM binding occurs in two stages of interactions between reactive groups on the bacterial surface and metal ions, followed by metal deposition [66]. Studies on spectroscopic and chemical modifications have revealed that cellular radicals, including hydroxyl, carboxyl, sulfate, sulfhydryl (thiol), thioether, phosphate, phosphonate, phosphodiester, amino, imine, amide, imidazole and carbonyl (ketone), show a

significant ability to bind metals. Most functional groups that bind metals are detected on the bacterial cell wall. Ionization of these groups provides a negative charge to the bacterial surface, enabling the attachment of cationic metals [67].

Living or unliving biological materials, including microorganisms, are used to remove or immobilize HMs and toxins from contaminated environments, including soil and water, in a process known as biosorption. Detoxifying environments that have been polluted by industrial activities, agricultural runoff and other sources of contamination can be the benefits of biosorption [68]. Bacteria, fungi and algae can bind HMs and toxins through various mechanisms, including ion exchange, physical adsorption and complexation. Functional groups of microbial surfaces such as carboxyl, hydroxyl and amino groups can interact with metal ions [69]. Detoxifying soils contaminated with HMs by biosorption can improve safety of crops grown in these areas. Elimination of HMs accumulated in food products can be used by biosorption as well [69].

2.6.1.1. Physical adsorption/physisorption

Adsorption occurs due to non-specific, quick, and reversible attraction forces such as Van der Waals forces. Alternatively, it can occur through electrostatic adsorption, resulting from Coulombic attraction between charged solute particles and bacterial cell surface [70].

2.6.1.2. Ion exchange

In the ion exchange mechanism, metal cations attach to vacant sites that were formerly occupied by other cations. Divalent metal ions are adsorbed through an exchange with polysaccharide counter ions detected on the bacterial cell wall and outer membrane. This process is affected by several factors such as the types and number of sites on the cell surface and their ionization patterns, which are ultimately governed by the pH and pKa values of the respective groups. Protonated amine groups are positively charged and become neutral upon deprotonation. Addition of protons neutralizes phosphate, carboxyl and sulfate groups. In their deprotonated state, these become negatively charged [71].

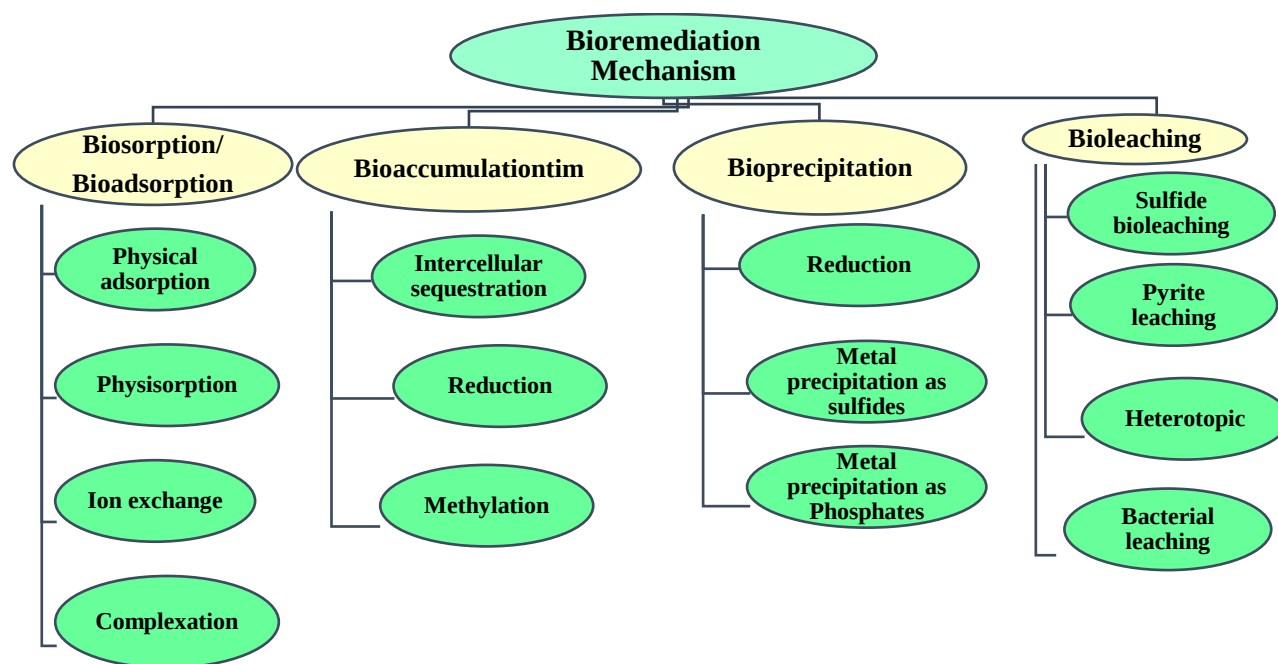


Figure 1. Techniques used by bacteria to efficiently remove HMs from liquid environments.

2.7. Complexation

Metal remediation can occur through the formation of complexes at the bacterial cell periphery, where reactive radicals on the cell wall interact with metal ions in solutions. Amino, carboxyl, hydroxy, thiol, phosphate and hydroxyl-carboxyl groups coordinate with HM ions to form complexes. These complexes, often referred to as coordination compounds or chelates, involve metal cations bonded to ligands. Complexation processes have been addressed for various metals such as Mg, Ca, Cd, Cu, Zn and Hg in certain bacterial species. Environmental factors such as temperature, pH, and composition of wastewater with bacterial strain types affect biosorption. The use of dead bacterial cells is increasingly favored as they are less susceptible to metal toxicity and do not need nutrients, decreasing operational costs. Biomass from fermentation industries can be used for biosorption and metal loading on non-living biomasses occurs rapidly. Bioadsorption, a fast simple process, can use live or dead bacterial cells or exopolymers to remove HMs from aqueous solutions. The process is efficient, metals are adsorbed quickly and biomasses can be reused [72, 73].

2.7.1. Bioaccumulation

Bioaccumulation refers to the accumulation of metals within bacterial cells through the uptake of non-metabolic metals using the same carrier pathways as essential metals. This process involves the binding of metal ions to reactive radicals on the bacterial cell wall and their internal regions via energy-independent mechanisms. Then, metals diffuse

into the cytoplasm through energy-dependent or independent processes. Transport pathways for essential ions such as sodium, potassium, and magnesium are used for the transport of HMs across microbial membranes for intracellular accumulation. Cation transport systems bind with HM ions that share similar ionic radius and charge with essential metal ions [73].

Microorganisms can uptake toxic metals within their cellular structures in the bioaccumulation process. Through bioaccumulation, they can detoxify environments by sequestering harmful substances. Bacterial mechanisms of action include conversion of HMs to less harmful states, absorption and bioaccumulation of HMs, and extracellular precipitation by the production of exopolysaccharides or other compounds that bind HMs [74]. Rhizosphere microbes can assist in breaking down organic pollutants or converting HMs into forms that are easier for plants to uptake or detoxify by phytoremediation synergy [75]. Microbes help ensure that crops growing, having lower levels of harmful substances by cleaning up contaminated soils using bioaccumulation division of bioremediation. Figure 2 classifies roles of microorganisms in detoxification.

2.7.1.1. Intracellular transport

Normally, HMs enter bacterial cells through channels, secondary carrier proteins and primary active transporters

on the cell membrane. Channels are α -helical proteins that facilitate passive diffusion of metals based on the concentration gradients. These proteins, parts of the major intrinsic proteins superfamily, help transport As and Hg in various bacterial species such as *E. coli*, *Corynebacterium*, *Streptomyces coelicolor*, *Serratia* and *Pseudomonas* [76, 77].

2.8. Intracellular fate of bioaccumulated heavy metals

Growing bacterial cells can continuously eliminate metals through internal detoxification processes. These processes include biotransformation and reduction of metals via enzymes, methylation, sequestration through metal-organic complex formation and production of metal chelators such as metallothioneins. These mechanisms help bacteria defend against metal toxicity [78].

2.8.1. Bioprecipitation

Bacteria remove metals from solution through precipitation, a defense mechanism independent of cellular metabolism. This occurs due to chemical interactions between the bacterial surface and metal ions with precipitation happening via reduction, sulfide formation or phosphate formation, depending on the species and environment.

2.8.1.1. Metal precipitation as phosphates

In this precipitation method, the enzyme phosphatase releases inorganic phosphate (Pi) from cellular organic phosphates such as glycerol-2-phosphate. Then, Pi precipitates metals or radionuclides as phosphates on the bacterial cell surface. For example, immobilized cells of *Citrobacter* spp. precipitated Cu, Cd, Pb and U from glycerol-2-phosphate enriched solutions. The phosphatase enzyme catalyzed the cleavage of glycerol-2-phosphate, releasing hydrogen phosphates that precipitate metals extracellularly as insoluble metal phosphates [65].

2.8.1.2. Reduction

Many bacterial strains can decrease hazardous selenite and selenate to elemental selenium, which precipitates as a red deposit. *Desulfomicrobium norvegicum* biofilm precipitates selenium with sulfur [79], while *Alteromonas* (now *Shewanella*) putrefaciens reduces U(VI) to U(IV) carbonate [80]. *Shewanella oneidensis* MR-1 and *Geobacter* species can reduce Hg(II) to Hg(0) [81].

2.8.1.3. Metal precipitation as sulfides

Sulfate-reducing bacteria are anaerobic organisms that use sulfate as a terminal electron acceptor, reducing it to sulfide. This sulfide combines with metals in the cell and

the environment to form insoluble metal sulfides, protecting the bacteria from metal toxicity. These bacteria create reducing conditions that can reduce metals such as U(VI) and Cr (VI) [82]. Enzymatic sulfide formation has been observed in *Salmonella typhimurium* and *Klebsiella planticola*, where metal-sulfide precipitation occurs due to sulfide production from thiosulfate [83].

Rapid industrialization and events such as uncontrolled agrochemicals lead to high soil HM concentrations. Non-bridgeable HM persistent in nature causes harmful effects on human health and disrupts the environment and agricultural food products. Natural organisms such as microbes are useful tools for detoxifying HMs and toxins in food through bioremediation involving various biological methods [48] as follows.

2.9. Biotransformation [(oxidation-reduction (redox reaction))]

Microorganisms can transform THMs and organic pollutants into less toxic forms through oxidation-reduction reactions. This process facilitates the conversion of harmful substances into further benign compounds, enhancing detoxification [84]. However, factors such as temperature, pH, nutrient availability, and the presence of co-contaminants can affect microbial activity and efficacy. Moreover, certain HMs can be toxic to the microbes, potentially limiting their effectiveness [85]. Biotransformation through redox reactions is a vital microbiological process. Detoxification of HMs and toxins makes biotransformation an essential tool in bioremediation to ensure food safety and environmental health.

2.10. Biomineralization

Microorganisms can facilitate precipitation of HMs as mineral forms, effectively immobilizing them and reducing their bioavailability and toxicity in contaminated environments, including soils and aquatic systems, known as biomineralization [86]. Biomineralization can help detoxify contaminants in agricultural soils; thereby, decreasing the presence of harmful metals in crops in the context of food production. This process is critical for maintaining food safety and protecting human health. Identifying and engineering specific microbial strains that show high efficiency in HM detoxification as well as understanding mechanisms underlying biomineralization are essential research interests [86].

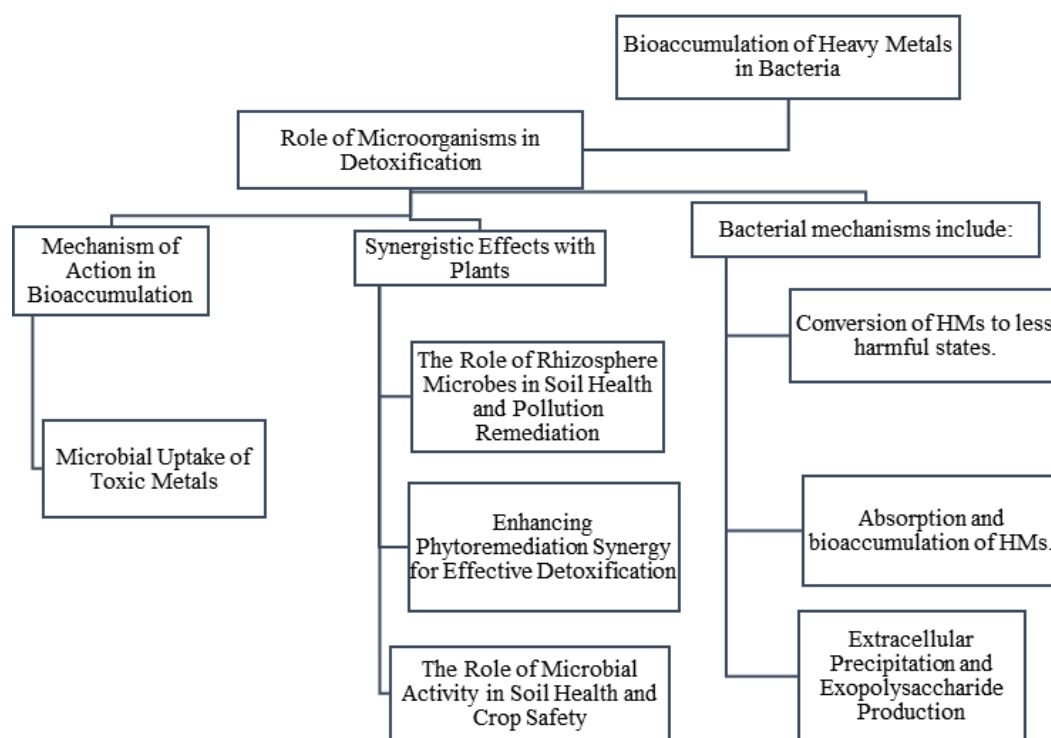


Figure 2. Roles of microorganisms in detoxification

2.11. Bioprecipitation

The primary mechanism of bioprecipitation involves the transformation of soluble metal ions into insoluble precipitates through microbial metabolic activities by metabolic byproducts (e.g. sulfides or phosphates) that react with HMs [87], leading to their removal from solutions. This process can clean contaminated water and soil systems. Bioprecipitation can help detoxify metals through the intervention of specific microbial strains for food products contaminated with HMs such as Cd, Pb, and Hg. Soil and water treatments are used to decrease metal contamination before crops are grown or harvested by bioprecipitation use. This enhances the safety of the food produced [88].

2.12. Bioleaching

Extraction of HMs from minerals or contaminated materials by microbes is known as bioleaching, which facilitates the release of metals into solution through microbial activity, making it easier to remove HMs from contaminated sites [85]. Bioleaching methods can potentially be used to detoxify HMs and other toxins in food products. Harmful substances degrading or transforming them into less toxic forms by microbes can enhance food safety. Bioleaching as a broader strategy for bioremediation may involve phytoremediation (using plants) or other microbiological techniques to improve detoxification efficacy.

2.12.1. Sulfide bioleaching

Sulfide-producing microorganisms such as *Acidithiobacillus* and *Leptospirillum* can solubilize HMs from complex minerals using sulfide bioleaching [89]. It is particularly effective for extracting metals such as Cu and Zn while minimizing environmental effects. The HMs and toxins can enter the food chain through contaminated soil, water, and food processing practices. The use of sulfide bioleaching and associated microbial techniques can help lessen these risks [89].

2.12.2. Pyrite leaching

Certain microorganisms can oxidize pyrite (FeS_2) to solubilize metals during the mineral recovery processes [90]. This method is often used in mining to recover valuable metals while managing metal contamination of soil appropriate for food safety. Oxidation of pyrite in the presence of water and oxygen leads to sulfuric acid production and can release iron and other associated HMs (e.g. Pb, As, and Cd) that may be bound to the pyrite matrix. Bacteria and archaea (e.g., *Acidithiobacillus* spp.) can oxidize pyrite to facilitate the leaching process. Acceleration of the pyrite breaking down using the released iron and sulfur for their metabolic processes, creating an environment that enhances metal solubility and bioavailability [91]. In the context of food safety and agriculture, pyrite leaching with the assistance of microbes

detoxifies soils contaminated with HMs to improve the safety and quality of agricultural products.

2.13. Heterotrophic bacterial leaching

Heterotrophic bacteria can leach metals from contaminated substrates using organic matter, potentially helping in the detoxification of metal-rich wastes or soils and other environmental toxins such as those present in foods [92]. Heterotrophic bacteria rely on other organic compounds for nutrition. They metabolize organic matter and can degrade various pollutants such as HMs, hydrocarbons, pesticides, and other harmful substances. Mechanisms of action include bioaccumulation; in which, bacteria can absorb HMs through their cell walls. These metals accumulate within the cells and can later be harvested or removed. Biotransformation includes the conversion of toxic forms of HMs into less harmful states; they may reduce soluble metal ions to insoluble forms, rendering them less bioavailable [85]. Extracellular precipitation is a way; by which, bacteria can produce exopolysaccharides that bind to HMs, causing them to precipitate and settle out of solutions [93]. In food production and processing, heterotrophic bacterial leaching can be used to remediate crops contaminated by HMs and toxins, decreasing the risks associated with consuming contaminated foods. This process may involve agricultural soils or water used in irrigation; thereby, ensuring a safer food supply. Identifying specific strains of heterotrophic bacteria that show high efficacy in removing HMs and other toxins. Assistance in genetic engineering and synthetic biology can enhance the capabilities of these micro-organisms [94].

2.14. Biosurfactant production

Biosynthesis of surfactant-like substances by micro-organisms such as bacteria and fungi refers to biosurfactant production. Biosurfactants can decrease surface tension and facilitate solubilization, emulsification, and dispersion of hydrophobic compounds, including HMs and organic pollutants due to amphiphilic characteristics [95]. Biosurfactants can play several important roles associated with the detoxification of HMs and toxic substances in foods. Solubility of HMs such as Pb, Cd, Hg, and organic toxins (e.g. pesticides and harmful industrial byproducts) by biosurfactants in water as solubilization makes them further accessible to microorganisms for uptake and transformation. Other characteristics of biosurfactants are microbial growth promotion, bioavailability enhancement of pollutants, stabilization of pollutant-microbe interface, and environmental remediation. Certain bacterial species of *Pseudo-monas*, *Rhodococcus*, *Bacillus*, and *Serratia* are significant producers of biosurfactants. Yeasts such as

Candida spp. and filamentous fungi such as *Aspergillus* spp. can also produce these compounds [96]. Biosurfactants can potentially be used in the food industry by detoxification and food preservation.

2.15. Biomethylation

Microorganisms can convert inorganic metals into less toxic volatile forms through biomethylation, which facilitates the removal of HMs from ecosystems. Bacteria and fungi include enzymes that can facilitate the transfer of a methyl group ($-CH_3$) to HMs (e.g. Hg, As, and Pb) or other organic compounds [97]. Biomethylation is useful in foods to ensure that food products are free from HM decontamination through detoxification and other contaminants. The composition of microbial communities and specific strains or consortia of microbes are selected to promote desired transformations of HMs and enhance bioremediation outcomes.

2.16. Biovolatilization

Transformation of metals into gaseous forms by microbes known as biovolatilization allows for the detoxification and removal of metals from the environment and foods. The HMs such as Hg and As can be converted into volatile organometallic compounds such as methylmercury, which can then be volatilized into the atmosphere by bacteria and fungi [98]. Biovolatilization may be significant when bioavailability of HMs can decrease; thereby, minimizing their uptake by plants and hence their presence in the food supply.

2.17. Microbe-assisted phytoremediation

This approach uses plants and microorganisms (microbes) in combination to clean up contaminated environments, particularly from HMs and toxins. The natural ability of plants to absorb and detoxify pollutants is a sustainable effective bioremediation strategy. Plants uptake HMs and other toxins through their roots and then store them in their tissues or transform them into less harmful substances. This process is known as phytoremediation [99]. Microbes in rhizospheres can transform HMs into further soluble forms, making them further available for uptake by plants. Detoxification by microbes degrades or transforms harmful organic pollutants such as pesticides and industrial chemicals, decreasing their toxicity and symbiotic relationships; in which, plants form mutualistic relationships with beneficial microbes (e.g. mycorrhizal fungi and nitrogen-fixing bacteria) to increase the plant's tolerance and accumulation of HMs [100]. Phytoremediation assisted by bacteria can include agricultural implications and decrease food contamination from HMs and other pollutants.

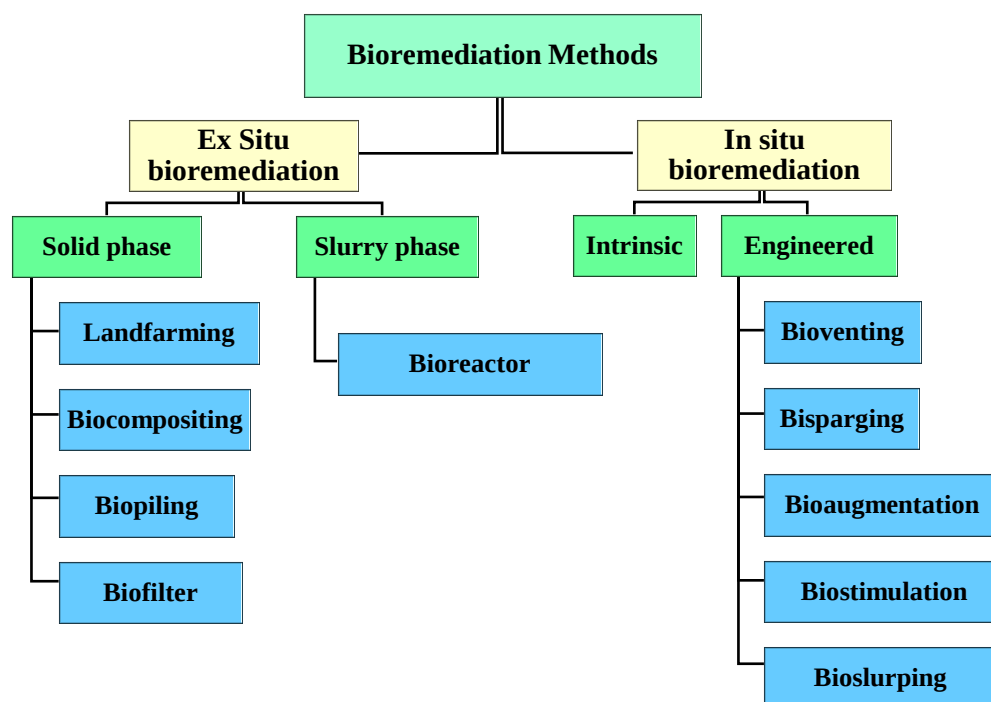


Figure 3. Bioremediation technologies.

2.18. Bioremediation technologies

Bioremediation technologies can broadly be classified as *ex-situ* or *in-situ* technologies (Figure 3).

2.18.1. *Ex-situ* treatments

Ex-situ bioremediation involves relocating pollutants from contaminated sites for treatment. Factors affecting method choice include treatment costs, pollution type and depth, contamination extent, site location and geology. Techniques include piling, bioreactors, landfarming and windrows. Advantages include effective biodegradation, detoxification of pollutants and decrease of treatment time. Limitations include difficulties with chlorinated hydrocarbons and specific soil treatment needs [6, 26, 39]. Biopiles are engineered, aerated composted piles used for treating surface contamination from petroleum hydrocarbons. They represent an advanced version of land farming, helping manage contaminant losses through leach-ing and volatilization. Biopiles substitute an environment for indigenous aerobic and anaerobic microorganisms and introducing effective microbes can enhance pollutant remediation efficiency [101].

A bioreactor accelerates bioremediation of the soil and water pollutants by creating a controlled three-phase system (solid, liquid and gas), enhancing biodegradation, compared to *in-situ* methods. Contaminated soil often needs pre-treatment such as washing before mixing with water and additives in the bioreactor. The process involves agitation to promote contacts with microorganisms and

optimizes conditions for pollutant degradation. After treatment, water is separated from solids, which may need additional disposal or treatment if pollutants persist [3].

Landfarming is an efficient method for treating contaminated soil by spreading and cultivating it to enhance microbial activity, particularly for the upper 10-35 cm of the surface soil. It maintains a neutral pH with agricultural lime and is effective for *ex-situ* and *in-situ* bioremediations of contaminants such as aliphatic hydrocarbons, polycyclic aromatic hydrocarbons and PCBs. This cost-effective approach needs minimal equipment and maintenance [102].

Windrow bioremediation restores contaminated soil by regularly turning materials to enhance hydrocarbon degrading bacterial activity. This method improves aeration, moisture and nutrient distribution, leading to faster bioremediation through assimilation and mineralization. Studies show windrow methods generally outperform pile systems in removing hydrocarbons but may be less effective in soils with toxic volatiles and can produce methane emissions from anaerobic zones if aeration is inadequate [6, 102].

2.18.2. *In-situ* treatment

Natural attenuation and bioremediation are methods to treat polluted environments; in which, microorganisms contribute to pollutant degradation. Natural attenuation is a cost-saving method to treat polluted environments [103]. Natural attenuation is based on natural processes to clean up and attenuate pollutions. It encompasses processes that

lead to decreases of the mass, toxicity, mobility or volume of the contaminants without human intervention, where naturally occurring environmental processes break down and decrease the concentration of contaminants in the environment via microorganisms [104]. Natural attenuation is the most interesting process because the contaminants can be transformed into less harmful products. This method contains the addition of electron acceptors, electron donors, or nutrients to stimulate naturally occurring microbial populations (biostimulation or introduction of nutrients and chemicals to stimulate indigenous microorganisms) or can introduce specific microorganisms that aimed at enhancing biodegradation of the target compounds (bioaugmentation or inoculation with exogenous microorganisms) [105].

Biostimulation or stimulated aerobic biodegradation is the process of eliminating factors that limit the biodegradation of contaminants [106]. It involves modification of the environment to stimulate existing bacteria capable of bioremediation. This was first defined by Perfumo as the addition of nutrients, oxygen or other electron donors and acceptors to the coordinated site to increase population or activity of naturally occurring microorganisms for bioremediation. The key benefit of biostimulation includes that bioremediation is carried out by the natural microorganisms, which are well adapted to the subsurface environment and spatially spread in the subsurface [107]. Bioaugmentation is a method bioremoval of HM contaminated sites using specific or genetically engineered bacteria that are proficient in fighting against HM contaminants [108]. Addition of microbial biomasses to contaminated areas can significantly improve their biodegradation performance. In addition to save time and costs, this method can be adapted to the green environment [109].

Bioventing is an *in-situ* technology that includes stimulating indigenous microorganisms through the addition of gas to destroy contaminants; it uses low airflow rates to provide adequate oxygen to maintain the microbial activity [110]. Therefore, it decreases release of volatile contaminants into the air. Benefits of bioventing vary. First, it offers an environmental friendly solution, minimizing needs of excavation and disposal of the contaminated soil. Second, it is often more cost-effective than that the traditional methods are, needing less labors and specialized equipment [111].

Bioslurping is a novel technology that combines two remediation methods of bioventing and vacuum-enhanced free-product recovery. Bioslurping, known as dual-phase extraction, is an *in-situ* technique that uses vacuum-enhanced dewatering technologies to remediate contaminated sites [112]. Bioslurping use elements of, bioventing and free-product recovery to address two separate contaminant media. Bioslurping can enhance free-

product recovery and is a cost-efficient technology. Depending on the site conditions, operation and maintenance time of bioslurping can vary from a few months to years [113].

Biosparging is an *in-situ* remediation technology that injects air or gases into the contaminated area to stimulate aerobic biological activities for the encouragement of aerobic biodegradation. This recovery method is used to eliminate residual contamination in the site and target chemical compounds that can be degraded under aerobic conditions [114]. Two primary factors may limit the effectiveness of biosparging, including (1) permeability of the contaminated site and (2) biodegradability of the contaminants [115].

Biofiltration is a pollution control system using bioreactors containing living materials to capture and biologically destroy contaminants. This includes pollutant removal via physical separation, adsorption on the filter media and biodegradation and biotransformation by microbes, forming biofilms on the filter media [116]. Biofiltration-based studies have shown significant results in the removal of volatile organic compounds and HMs [117]. A significant advantage of biofiltration techniques is that the contaminants are converted into biodegradable wastes without deriving secondary pollutants within a specific time [118].

Chemical and physical waste cleanup methods are used for the contamination removals; however, these approaches are costly and include harmful environmental effects. Therefore, increases in use of bioremediation have been recorded, leading to development of genetically engineered microbes. Genetic engineering refers to the direct manipulation of DNA to alter characteristics of an organism in a particular way. These designed engineered microorganisms appeared more effective than normal strains and include superior debasement adaptability as well as capacity to rapidly adapt to various contaminants. Use of engineered microorganisms is safer and more cost-effective, compared to other methods [119]. Bioremediation in combination with nanotechnology has been investigated as further effective for the removal of environmental contamination. This combined method can include a broader range of potential uses with decreased costs and lowest negative effects on the environment. Degradation of contaminants using nanoparticle catalysts is a common use of nanotechnology in this field [120].

2.19. Factors limiting bioremediation technologies

Bioremediation has several benefits, compared to conventional methods e.g. landfilling or incineration [121]. However, there are limitations to bioremediation; chemicals e.g. HMs, radionuclides & chlorinated compounds aren't susceptible to biodegradation. Moreover, microbial

systems may produce toxic metabolites from the contaminants (Table 2) [122].

Table 2. Advantages and disadvantages of the bioremediation methods.

Advantages	Disadvantages
It is a natural process	Limited to only biodegradable compound
Use for complete destruction of a wide variety of contaminants	The product of biodegradation may be more toxic than primary
Can be carried out on-site without disrupting normal activities	Biological processes are often highly specific
Eliminate the need to transport the waste off-site	Require suitable environmental, growth conditions
Eliminate the potential threat to human health	Take longer time

3. Conclusion

Various methods are reported to remove contamination, one of which is bioremediation. Use of microorganisms to diminish or decrease concentration of dangerous wastes is called bioremediation. This word refers to a group of methods that use biological systems such as indigenous or genetically modified microbes to restore or clean-up contaminated environments. A majority of indigenous bacteria are capable of successfully restoring the environment by oxidizing, immobilizing and/or converting pollutants into carbon dioxide and water. Such a biological action system includes various uses such as cleanup of the contaminated material (e.g. foods and water). Bioremediation is an easy, cost and timesaving method to treat polluted environments, compared to the conventional methods such as landfilling or incineration. This method is a commonly accepted substitute for cleaning up the environment as it particularly promises to reach clean-up objectives at an economical rate with milder chances of the contaminant spread to other media.

Further studies: Enhancing regulatory frameworks and increasing public awareness about HM exposure is critical for the prevention. Investigation of the innovative technologies for monitoring and removing HMs from wastewater can significantly decrease associated risks. Collaborative efforts within the governments, industries and communities are vital for creating cleaner environments and protecting future generations from contaminations. Focusing on advanced technologies and public education is a key to minimizing health risks.

4. Acknowledgements

This study was supported by Shahid Beheshti University of Medical Sciences (grant no. 43012694).

5. Conflict of Interest

The authors report no conflict of interest.

6. Author contributions

All authors participated in project administration and writing of the primary draft of the manuscript, providing critical revision and editing. All authors approved the final version of the manuscript.

7. Ethical Code:

This project is approved via
IR.SBMU.RETECH.REC.1403.517 ethical code.

References

1. Zaynab M, Al-Yahyai R, Ameen A, Sharif Y, Ali L, Fatima M, Khan KA, Li S. Health and environ-mental effects of heavy metals. *J King Saud Univ Sci*. 2022. 34(1): 101653.
<https://doi.org/10.1016/j.jksus.2021.101653>
2. Budi HS, Catalan Opulencia MJ, Afra A, Abdelbasset WK, Abdullaev D, Majdi A, Taherian M, Ekrami HA, Mohammadi MJ. Source, toxicity and carcinogenic health risk assessment of heavy metals. *Rev Environ Health*. 2024. 39(1): 77-90.
<https://doi.org/10.1515/reveh-2022-0096>
3. Rahman Z, Singh VP. Bioremediation of toxic heavy metals (THMs) contaminated sites: concepts, applica-tions and challenges. *Environ Sci Pollut Res Int*. 2020. 27(22): 27563-27581.
<https://doi.org/10.1007/s11356-020-08903-0>
4. Mushtaq M, Arshad N, Rehman A, Javed GA, Munir A, Hameed M, Javed S. *Levilactobacillus brevis* MZ3840-11 and *Levilactobacillus brevis* MW362779 can miti-gate lead induced hepato-renal damage by regulating visceral dispersion and fecal excretion. *World J Microbiol Biotechnol*. 2024. 40(2): 74.
<https://doi.org/10.1007/s11274-023-03818-7>
5. Kondakindi VR, Pabbati R, Erukulla P, Maddela NR, Prasad R. Bioremediation of heavy metals-contaminated sites by microbial extracellular polymeric substances- A critical view. *Environ Chem Ecotoxicol*. 2024. 6:408-421.
<https://doi.org/10.1016/j.enceco.2024.05.002>
6. Azubuike CC, Chikere CB, Okpokwasili GC. Biorem-ediation techniques–classification based on site of appli-cation: principles, advantages, limitations and prospects. *World J Microbiol Biotechnol*. 2016. 32:1-18.
<https://doi.org/10.1016/B978-0-443-21911-5.00003-9>
7. Panigrahi S, Velraj P, Rao T.S. Functional microbial diversity in contaminated environment and application in bioremediation, in *Microbial diversity in the genomic era*. 2019. Elsevier. 359-385.
<https://doi.org/10.1016/B978-0-12-814849-5.00021-6>
8. Mirmahdi R.S, Zoghi A, Mohammadi F, Khosravi-Darani K, Jazaieri S, Mohammadi R, Rehman Y. Biode-contamination

- of milk and dairy products by probiotics: Boon for bane. Ital. J. Food Sci. 2021. 33(SP1): 78-91.
<https://doi.org/10.15586/ijfs.v33iSP2.2053>
9. Sarlak Z, Khosravi-Darani K, Rouhi M, Garavand F, Mohammadi R. Sobhiyeh MR. Bioremediation of organophosphorus pesticides in contaminated foodstuffs using probiotics. Food Control. 2021. 126:108006.
<https://doi.org/10.2174/1389557519666190318102201>
10. Massoud R, Khosravi-Darani K, Sharifan A, Asadi G, Zoghi A. Lead and cadmium biosorption from milk by *Lactobacillus acidophilus* ATCC 4356. Food Sci. Nutr. 2020. 8(10): 5284-91.
<https://doi.org/10.1016/j.foodcont.2021.108006>
11. Attarianshandiz M. Enhancing immunity against carcinogens through probiotics: A literature review. J Food Sci Nutr The. 2023. 9(1): 013-23.
<https://doi.org/10.17352/jfsnt.000043>
12. Fernández PM, Viñarta SC, Bernal AR, Cruz EL, Figueroa LI. Bioremediation strategies for chromium removal: current research, scale-up approach and future perspectives. Chemosphere. 2018. 208:139-148.
<https://doi.org/10.1016/j.chemosphere.2018.05.166>
13. Shakti P, Pandey AK. Agricultural soil contamination due to industrial discharges: challenges for public health protection and food security. In Bioremediation of Emerging Contaminants from Soils, 2024. Elsevier. 21-42.
<https://doi.org/10.1016/B978-0-443-13993-2.00002-5>
14. Dan S, Sharma A. Microbial Bioremediation of Heavy Metals: Emerging Trends and Recent Advances. Res J Biotechnol. 2020. 15: 164-178.
15. Fowler B.A, Alexander J, Oskarsson A. Toxic metals in food, in Handbook on the Toxicology of Metals. 2015. Elsevier. 123-140.
<https://doi.org/10.1016/B978-0-444-59453-2.00006-8>
16. Iyer M, Anand U, Thiruvengataswamy S, Babu HW, Narayanasamy A, Prajapati VK, Tiwari CK, Gopalakrishnan AV, Bontempi E, Sonne C, Barceló D. A review of chromium (Cr) epigenetic toxicity and health hazards. Sci Total Environ. 2023. 882: 163483.
<https://doi.org/10.1016/j.scitotenv.2023.163483>
17. DesMarias T.L, Costa M. Mechanisms of chromium-induced toxicity. Curr Opin Toxicol. 2019. 14:1-7.
<https://doi.org/10.1016/j.cotox.2019.05.003>
18. Kumar A, Kumar A, MMS CP, Chaturvedi AK, Shabnam AA, Subrahmanyam G, Mondal R, Gupta DK, Malyan SK, Kumar SS, Khan S. Lead toxicity: health hazards, influence on food chain and sustainable remediation approaches. Int J Environ Res Public Health. 2020. 17(7): 2179.
<https://doi.org/10.3390/ijerph17072179>
19. Senthil Kumar P, Gunasundari E. Bioremediation of Heavy Metals. In: Varjani S, Agarwal A, Gnansounou E, Gurunathan B. Bioremediation: Applications for Environmental Protection and Management. Energy, Environment and Sustainability. Singapore, 2018: 165-195.
https://doi.org/10.1007/978-981-10-7485-1_9
20. Dixit R, Wasiullah X, Malaviya D, Pandiyan K. Singh UB, Sahu A, Shukla R, Singh BP, Rai JP, Sharma PK, Lade H. Bioremediation of heavy metals from soil and aquatic environment: an overview of principles and criteria of fundamental processes. Sustainability. 2015. 7(2): 2189-2212.
<https://doi.org/10.3390/su7022189>
21. Bjørklund G, Rahaman MS, Shanida M, Lysiuk R, Oliynyk P, Lenchuk L, Chirumbolo S, Chasapis CT. Peana M, Natural dietary compounds in the treatment of arsenic toxicity. Molecules. 2022. 27(15): 4871.
<https://doi.org/10.3390/molecules27154871>
22. Jobby R, Desai N. Bioremediation of heavy metals. Biodegradation and bioremediation. Environ Eng Sci. 2017. 8: 201-220.
<https://doi.org/10.1080/15569543.2023.2283768>
23. Mohanta TK, Mohanta YK, Mohanta N. Role of biotechnology in bioremediation, in Biotechnology: Concepts, Methodologies, Tools and Applications. 2019. IGI Global. 1-34.
<https://doi.org/10.4018/978-1-5225-8903-7.ch001>
24. Pant G, Garlapati D, Agrawal U, Prasuna RG. Mathi-man T, Pugazhendhi A. Biological approaches practised using genetically engineered microbes for a sustainable environment: a review. J Hazard Mater. 2021. 405: 124631.
<https://doi.org/10.1016/j.jhazmat.2020.124631>
25. Sharma S, Pathania S, Bhagta S, Kaushal N, Bhardwaj S, Bhatia RK, Walia A. Microbial remediation of polluted environment by using recombinant *E. coli*: a review. Biotechnol Environ. 2024. 1(1): 8.
<https://doi.org/10.1186/s44314-024-00008-z>
26. Abo-Alkasem M.I, Hassan N.m.H, Abo Elsouid M.M. Microbial bioremediation as a tool for the removal of heavy metals. Bull Natl Res Cent. 2023. 47(1): 31.
<https://doi.org/10.1186/s42269-023-01006-z>
27. Hakeem K, Bhat R, Qadri H. Bioremediation and Biotechnology. Cham, 2020.
<https://doi.org/10.1007/978-3-030-35691-0>
28. Ansari F, Lee CC, Rashidimehr A, Eskandari S, Ashaolu TJ, Mirzakhani E, Pourjafar H, Jafari SM. The role of probiotics in improving food safety; detoxification of heavy metals and chemicals. Toxin Rev. 2024. 43(1): 63-91.
<https://doi.org/10.1016/j.ejbt.2018.11.003>
29. Massoud R, Hadiani MR, Hamzehlou P, Khosravi-Darani K. Bioremediation of heavy metals in food industry: Application of *Saccharomyces cerevisiae*. Electron J Biotechnol. 2019. 37:56-60.
<https://doi.org/10.1016/j.ejbt.2018.11.003>
30. Homayouni Rad A, Pourjafar H, Mirzakhani E. A comprehensive review of the application of probiotics and postbiotics in oral health. Front Cell Infect Microbiol. 2023. 13:1120995.
<https://doi.org/10.3389/fcimb.2023.1120995>
31. Goyal P, Belapurkar P, Kar A. A review on in vitro and in vivo bioremediation potential of environmental and probiotic species of *Bacillus* and other probiotic micro-organisms for

- two heavy metals, cadmium and nickel. Biosci. Biotechnol. Res. Asia. 2019. 16(1): 01-13.
<http://dx.doi.org/10.13005/bbra/2714>
32. Massoud R, Sharifan A, Khosravi-Darani K, Asadi G. Cadmium bioremoval by *Saccharomyces cerevisiae* in milk. J Med Microbiol Infect Dis. 2020. 8(1): 29-33.
<https://doi.org/10.29252/JoMMID.8.1.29>
33. Ameen F, Hamdan A, El-Naggar M. Assessment of the heavy metal bioremediation efficiency of the novel marine lactic acid bacterium, *Lactobacillus plantarum* MF042018. Sci Rep. 2020.10:314.
<https://doi.org/10.1038/s41598-019-57210-3>
34. Afsharian Z, Salavatifar M, Khosravi-Darani K. Impact of simulated microgravity on bioremoval of heavy-metals by *Lactobacillus acidophilus* ATCC 4356 from water. Heliyon. 2022. 8(12): e12307.
<https://doi.org/10.1016/j.heliyon.2022.e12307>
35. Wahid M, Awais MU, Talat R, Mehmood A, Haq I, Al Farraj DA, Mohammed YH, Banach A. Antibiotic susceptibility and bioremediation potential of probiotic bacteria against lead and cadmium isolated from yogurt. Pak J Pharm Sci. 2023. 36(3): 969-972.
<https://doi.org/10.36721/PJPS.2023.36.3.SP.969-972.1>
36. Mushtaq M, Arshad N, Hameed M, Munir A, Javed GA, Rehman A. Lead biosorption efficiency of *Levilacto-bacillus brevis* MZ384011 and *Levilacto-bacillus brevis* MW362779: A response surface based approach. Saudi J Biol Sci. 2023. 30(2): 103547.
<https://doi.org/10.1016/j.sjbs.2022.103547>
37. Salavatifar M, Khosravi-Darani K. Investigation of the simulated microgravity impact on heavy metal biosorption by *Saccharomyces cerevisiae*. Food Sci Nutr. 2024. 12(5): 3642-3652.
<https://doi.org/10.1002/fsn3.4034>
38. Ali S, Bukhari D.A, Rehman A. Call for biotechnological approach to degrade plastic in the era of COVID-19 pandemic. Saudi J Biol Sci. 2023. 30(3): 103583.
<https://doi.org/10.1016/j.sjbs.2023.103583>
39. Bala S, Garg D, Thirumalesh BV, Sharma M, Sridhar K., Inbaraj BS, Tripathi M. Recent strategies for bioremediation of emerging pollutants: a review for a green and sustainable environment. Toxics, 2022. 10(8): 484.
<https://doi.org/10.3390/toxics10080484>
40. Sharma P, Singh SP, Parakh SK, Tong YW. Health hazards of hexavalent chromium (Cr (VI)) and its microbial reduction. Bioeng. 2022. 13(3): 4923-4938.
<https://doi.org/10.1080/21655979.2022.2037273>
41. Mahmoud GAE. Microbial Scavenging of Heavy Metals Using Bioremediation Strategies. In: Kumar V, Prasad R, Kumar M. Rhizobiont in Bioremediation of Hazardous Waste. 2021. Singapore. 265-289.
https://doi.org/10.1007/978-981-16-0602-1_12
42. Ambaye TG, Vaccari M, Franzetti A, Prasad S, Formicola F, Rosatelli A, Hassani A, Aminabhavi TM, Rtimi S. Microbial electrochemical bioremediation of petroleum hydrocarbons (PHCs) pollution: Recent advances and outlook. Chem Eng J. 2023. 452:139372.
<https://doi.org/10.1016/j.cej.2022.139372>
43. Adamczyk P.A, Reed J.L. Escherichia coli as a model organism for systems metabolic engineering. Curr Opin Syst Biol. 2017. 6:80-88.
<https://doi.org/10.1016/j.coisb.2017.11.001>
44. Bălă GP, Răjnoveanu RM, Tudorache E, Motișan R, Oancea C. Air pollution exposure -the (in) visible risk factor for respiratory diseases. Environ Sci Pollut Res. 2021. 28(16): 19615-19628.
<https://doi.org/10.1007/s11356-021-13208-x>
45. Mohamed MS, El-Arabi NI, El-Hussein A, El-Maaty SA, Abdelhadi AA. Reduction of chromium-VI by chromium-resistant Escherichia coli FACU: a prospective bacterium for bioremediation. Folia Microbiol. 2020. 65:687-696.
<https://doi.org/10.1007/s12223-020-00771-y>
46. Liu L, Li W, Song W, Guo M. Remediation techniques for heavy metal-contaminated soils: Principles and applicability. Sci Total Environ. 2018. 633:206-219.
<https://doi.org/10.1016/j.scitotenv.2018.03.161>
47. Mishra S, Huang Y, Li J, Wu X, Zhou Z, Lei Q, Bhatt S, Chen S. Biofilm-mediated bioremediation is a powerful tool for the removal of environmental pollutants. Chemosphere. 2022. 294:133609.
<https://doi.org/10.1016/j.chemosphere.2022.133609>
48. Verma S, Kuila A. Bioremediation of heavy metals by microbial process. Environ Technol Innov. 2019. 14: 100369.
<https://doi.org/10.1016/j.eti.2019.100369>
49. Ruhail R, Kataria R. Synthetic biology approaches for bioremediation of metals. In: Bioremediation of Toxic Metal - (loid)s. 2022. CRC Press. 292-306.
<https://doi.org/10.1201/9781003229940-19>
50. Mahto KU, Kumari S, Das S. Unraveling the complex regulatory networks in biofilm formation in bacteria and relevance of biofilms in environmental remediation. Crit Rev Biochem Mol Biol. 2022. 57(3): 305-32.
<https://doi.org/10.1080/10409238.2021.2015747>
51. Bai H, Liu D, Zheng W, Ma L, Yang S, Cao J, Lu X, Wang H, Mehta N. Microbially-induced calcium carbonate precipitation by a halophilic ureolytic bacterium and its potential for remediation of heavy metal-contaminated saline environments. Int Biodeter Biodegr. 2021. 165:105311.
<https://doi.org/10.1016/j.ibiod.2021.105311>
52. Chen J, Zhang G, Ma C, Li D. Antimony removal from wastewater by sulfate-reducing bacteria in a bench-scale upflow anaerobic packed-bed reactor. Acta Geochimica. 2020. 39:203-215.
<https://doi.org/10.1007/s11631-019-00382-6>
53. An Q, Deng SM, Zhao B, Li Z, Xu J, Song JI. Simultaneous denitrification and hexavalent chromium removal by a newly isolated *Stenotrophomonas maltophilia* strain W26 under aerobic conditions. Environ Chem. 2021. 18(1): 20-30.
<https://doi.org/10.1071/EN20097>

54. Zhang H, Yuan X, Xiong T, Wang H, Jiang L. Bioremediation of co-contaminated soil with heavy metals and pesticides: Influence factors, mechanisms and evaluation methods. *Chem Eng J*. 2020. 398: 125657.
<https://doi.org/10.1016/j.cej.2020.125657>
55. Kim R.Y, Yoon JK, Kim TS, Yang JE, Owens G, Kim KR. Bioavailability of heavy metals in soils: definitions and practical implementation-a critical review. *Environ Geochem Health*. 2015. 37:1041-1061.
<https://doi.org/10.1007/s10653-015-9695-y>
56. Liao X, Li Y, Miranda-Avilés R, Zha X, Anguiano JH, Sánchez CD, Puy-Alquiza MJ, González VP, Garzon LF. In situ remediation and ex situ treatment practices of arsenic-contaminated soil: An overview on recent advances. *J Hazard Mater Adv*. 2022. 8:100157.
<https://doi.org/10.1016/j.hazadv.2022.100157>
57. Koul B, Taak P. Biotechnological strategies for effective remediation of polluted soils. 2018. Singapore.
<https://doi.org/10.1007/978-981-13-2420-8>
58. Valdivia-Rivera S, Ayora-Talavera T, Lizardi-Jiménez MA, García Cruz U. Encapsulation of microorganisms for bioremediation: techniques and carriers. *Rev Environ Sci Biotechnol*. 2021. 20(3): 815-838.
<https://doi.org/10.1007/s11157-021-09577-x>
59. Sardar K, Ali S, Hameed S, Afzal S, Fatima S, Shakoor MB, Bharwana SA, Tauqeer HM. Heavy metals contamination and what are the impacts on living organisms. *Greener J Environ Manage*. 2013. 2(4): 172-179.
<https://doi.org/10.15580/GJEMPS.2013.4.060413652>
60. Owolabi J, Hekeu M. Heavy metal resistance and antibiotic susceptibility pattern of bacteria isolated from selected polluted soils in Lagos and Ota, Nigeria. *Int J Appl Sci*. 2014. 4(6): 6-12.
61. Halder S. Bioremediation of heavy metals through fresh water microalgae: a review. *Sch Acad J Biosci*. 2014, 2(11): 825-830.
<https://doi.org/10.36347/sajb.2014.v02i11.016>
62. Kaushal J, Mehandia S, Singh G, Raina A, Arya SK. Catalase enzyme: Application in bioremediation and food industry. *Biocatal Agric Biotechnol*. 2018. 16:192-199.
<https://doi.org/10.1016/j.bcab.2018.07.035>
63. Rezaei A, Rowshanzamir M, Hejazi SM, Banitalebi-Dehkordi M. Application of superabsorbent geotextiles to decontaminate and improve crude oil-contaminated soil. *Transp Geotech*. 2023. 38:100910.
<https://doi.org/10.1016/j.trgeo.2022.100910>
64. Sreedevi P, Suresh K, Jiang G. Bacterial bioremediation of heavy metals in wastewater: a review of processes and applications. *J Water Process Eng*. 2022. 48: 102884.
<https://doi.org/10.1016/j.jwpe.2022.102884>
65. Qin H, Hu T, Zhai Y, Lu N, Aliyeva J. The improved methods of heavy metals removal by biosorbents: A review *Environ Pollut*. 2020. 258:113777.
<https://doi.org/10.1016/j.envpol.2019.113777>
66. Priya AK, Gnanasekaran L, Dutta K, Rajendran S, Balakrishnan D, Soto-Moscoso M. Biosorption of heavy metals by microorganisms: Evaluation of different underlying mechanisms. *Chemosphere*. 2022. 307: p.135957.
<https://doi.org/10.1016/j.chemosphere.2022.135957>
67. Singh S, Kumar V, Datta S, Dhanjal DS, Sharma K, Samuel J, Singh J. Current advancement and future prospect of biosorbents for bioremediation. *Sci Total Environ*. 2020. 709: 135895.
<https://doi.org/10.1016/j.scitotenv.2019.135895>
68. Ismail I, Moustafa T. Biosorption of heavy metals. *Heavy metals: Sources, toxicity and remediation techniques*, 2016. Nova Science Publishers, 131-174.
<https://doi.org/10.2166/wst.2013.718>
69. Javanbakht V, Alavi S.A, Zilouei H. Mechanisms of heavy metal removal using microorganisms as biosorbent. *Water Sci. Technol*. 2014. 69(9): 1775-1787.
<https://doi.org/10.1016/j.btre.2016.12.006>
70. Yılmaz Ş, Ecer Ü, Şahan T. An optimization study for bio-removal of lead from aqueous environments by alkali modified *Polyporus Squamosus*. *MANAS J Eng*. 2021. 9: 1-9.
<https://doi.org/10.51354/mjen.804338>
71. Nascimento JM, Otaviano JJ, Sousa HS, Oliveira JD. Biological Method of Heavy Metal Management: Biosorption and Bioaccumulation. *Heavy Metals in the Environment: Management Strategies for Global Pollution*. 2023. ACS Publications, 315-60.
<https://doi.org/10.1021/bk-2023-1456.ch016>
72. Al-Ansari MM, Benabdelkamel H, AlMalki RH, Rahman AM, Alnahmi E, Masood A, Ilavenil S, Choi KC. Effective removal of heavy metals from industrial effluent wastewater by a multi metal and drug resistant *Pseudomonas aeruginosa* strain RA-14 using integrated sequencing batch reactor. *Environ Res*. 2021. 199: 111240.
<https://doi.org/10.1016/j.envres.2021.111240>
73. Jeyakumar P, Debnath C, Vijayaraghavan R, Muthuraj M. Trends in bioremediation of heavy metal contaminations. *Environ Eng Res*. 2023. 28(4): 220631.
<https://doi.org/10.4491/eer.2021.631>
74. Gupta P, Diwan B. Bacterial exopolysaccharide mediated heavy metal removal: a review on biosynthesis, mechanism and remediation strategies. *Biotechnol Rep*. 2017. 13: 58-71.
<https://doi.org/10.1016/j.btre.2016.12.006>
75. Eze K.C, Obasi NP, Inyang OA, Ewa SC. Danger of Contaminants in Foods through Phytoremediation, in *Phytoremediation in Food Safety*. 2024. CRC Press. 83-98.
<https://doi.org/10.1201/9781032683751>
76. Diep P, Mahadevan P, Yakunin A.F. Heavy metal removal by bioaccumulation using genetically engineer-ed microorganisms. *Front Bioeng Biotechnol*. 2018. 6: 157.
<https://doi.org/10.3389/fbioe.2018.00157>
77. Ghosh S, Sarkar B, Khumphon J, Thongmee S. Genetically Modified Microbe Mediated Metal Bioaccumulation: A Sustainable Effluent Treatment Strategy. In *Industrial*

- Wastewater Reuse: Applications, Prospects and Challenges. 2023. Singapore: Springer Nature Singapore. 215-229.
- https://doi.org/10.1007/978-981-99-2489-9_11
78. Tayang A, Songachan LS. Microbial bioremediation of heavy metals. *Curr Sci*. 2021. 120(6): 00113891.
- <https://doi.org/10.18520/cs/v120/i6/1013-1025>
79. Xiong J, Wang H, Yao J, He Q, Ma J, Yang J, Liu C, Chen Y, Huangfu X, Liu H. A critical review on sulfur reduction of aqueous selenite: Mechanisms and applications. *J Hazard Mater*. 2022. 422: 126852.
- <https://doi.org/10.1016/j.jhazmat.2021.126852>
80. Kuippers G, Morris K, Townsend LT, Bots P, Kvashnina K, Bryan ND, Lloyd JR. Biomineralization of uranium-phosphates fueled by microbial degradation of isosaccharinic acid (ISA). *Environmental Science & Technology*. 2021. 55(8): 4597-606.
- <https://doi.org/10.1021/acs.est.0c03594>
81. Zhang X, Guo Y, Liu G, Liu Y, Shi J, Hu L, Zhao L, Li Y, Yin Y, Cai Y, Jiang G. Superoxide mediated extracellular mercury reduction by aerobic marine bacterium *Alteromonas* Sp. KD01. *Environ Sci Technol*. 2023. 57(49): 20595-604.
- <https://doi.org/10.1021/acs.est.3c04777>
82. Janot N, Dunham-Cheatham SM, Lezama Pacheco JS, Cerrato JM, Alessi DS, Noël V, Lee E, Pham DQ, Suvorova E, Bernier-Latmani R, Williams KH. Reducing Conditions Influence U (IV) Accumulation in Sediments during In Situ Bioremediation. *ACS Earth Space Chem*. 2024. 8(2): 148-58.
- <https://doi.org/10.1021/acsearthspacechem.3c00271>
83. Zhang S, Song M, Zhang J, Wang H. Cysteine and thiosulfate promoted cadmium immobilization in strain G303 by the formation of extracellular CdS. *Sci Total Environ*. 2024. 923: 171457.
- <https://doi.org/10.1016/j.scitotenv.2024.171457>
84. Young SD. Chemistry of heavy metals and metalloids in soils. Heavy metals in soils: Trace metals and metalloids in soils and their bioavailability. 2013. Dordrecht: 51-95.
- https://doi.org/10.1007/978-94-007-4470-7_3
85. Dong Y, Zan J, Lin H. Bioleaching of heavy metals from metal tailings utilizing bacteria and fungi: Mechanisms, strengthen measures and development prospect. *J Environ Manage*. 2023. 344: 118511.
- <https://doi.org/10.1016/j.jenvman.2023.118511>
86. Kumari D, Qian XY, Pan X, Achal V, Li Q, Gadd GM. Microbially-induced carbonate precipitation for immobilization of toxic metals. *Adv Appl Microbiol*. 2016. 94:79-108.
- <https://doi.org/10.1016/bs.aambs.2015.12.002>
87. Lin H, Zhou M, Li B, Dong Y. Mechanisms, application advances and future perspectives of microbial-induced heavy metal precipitation: a review. *Int Biodeter Biodegr*. 2023. 178: 105544.
- <https://doi.org/10.1016/j.ibiod.2022.105544>
88. Hou D, O'Connor D, Igalavithana AD, Alessi DS, Luo J, Tsang DS, Sparks DL, Yamauchi Y, Rinklebe J, Ok YS. Metal contamination and bioremediation of agricultural soils for food safety and sustainability. *Nat Rev Earth Environ*. 2020. 1(7): 366-381.
- <https://doi.org/10.1038/s43017-020-0061-y>
89. Sarkodie E.K, Juang L, Li K, Yang J, Guo Z, Shi J, Deng Y, Liu H, Jiang H, Liang Y, Yin H. A review on the bioleaching of toxic metal (loid)s from contaminated soil: Insight into the mechanism of action and the role of influencing factors. *Front Microbiol*. 2022. 13:1049277.
- <https://doi.org/10.3389/fmicb.2022.1049277>
90. Pineda Y.S, Devries SL, Steiner NC, Block-Cora KA. Bioleaching of gold in mine tailings by *Alcaligenes faecalis*. *Minerals*. 2023. 13(3): p. 410.
- <https://doi.org/10.3390/min13030410>
91. Spietz RL, Payne D, Szilagyi R, Boyd ES. Reductive biomining of pyrite by methanogens. *Trends Microbiol*. 2022. 30(11): 1072-1083.
- <https://doi.org/10.1016/j.tim.2022.05.005>
92. Newsome L, Falagán C. The microbiology of metal mine waste: Bioremediation applications and implications for planetary health. *Geo Health*. 2021. 5(10): e20-20GH000380.
- <https://doi.org/10.1029/2020GH000380>
93. Yin KQ, Wang MLV, Chen L. Microorganism remediation strategies towards heavy metals. *Chem Eng J*. 2019. 360: 1553-1563.
- <https://doi.org/10.1016/j.cej.2018.10.226>
94. Zhang W, Zhang H, Xu R, Qin H, Liu H, Zhao K. Heavy metal bioremediation using microbially induced carbonate precipitation: Key factors and enhancement strategies. *Front Microbiol*. 2023. 14: 1116970.
- <https://doi.org/10.3389/fmicb.2023.1116970>
95. Cameotra S.S, Makkar R.S. Biosurfactant-enhanced bioremediation of hydrophobic pollutants. *Pure App Chem*. 2010. 82(1): 97-116.
- <https://doi.org/10.1351/PAC-CON-09-02-10>
96. Hussein H.A, Khan K.M, Abdullah M.A. Mass production and factors affecting biosurfactant productivity using bioreactors in Green Sustainable Process for Chemical and Environmental Engineering and Science, 2021. Elsevier. 379-398.
- <https://doi.org/10.1016/B978-0-12-823380-1.00015-0>
97. Akhtar M.S, Chali B, Azam T. Bioremediation of arsenic and lead by plants and microbes from contaminated soil. *J Plant Res*. 2013. 1(3): 68-73.
- <https://doi.org/10.12691/plant-1-3-4>
98. Srivastava S, Agrawal S, Mondal M.K. Biological based methods for the removal of volatile organic compounds and heavy metals. In: *An Innovative Role of Biofiltration in Wastewater Treatment Plants (WWTPs)*. 2022. Elsevier. 331-346.
- <https://doi.org/10.1016/B978-0-12-823946-9.00022-X>
99. Oladoye P.O, Olowe O.M, Asemoloye M.D. Phyto-remediation technology and food security impacts of heavy metal contaminated soils: A review of literature. *Chemosphere*. 2022. 288:132555.
- <https://doi.org/10.1016/j.chemosphere.2021.132555>

100. Bhantana P, Rana MS, Sun XC, Moussa MG, Saleem MH, Syaifudin M, Shah A, Poudel A, Pun AB, Bhat MA, Mandal DL. Arbuscular mycorrhizal fungi and its major role in plant growth, zinc nutrition, phosphorous regulation and phytoremediation. *Symbiosis*. 2021. 84: 19-37.
<https://doi.org/10.1007/s13199-021-00756-6>
101. Mani D, Kumar C. Biotechnological advances in bioremediation of heavy metals contaminated eco-systems: an overview with special reference to phyto-remediation. *Int J Sci Environ Technol*. 2014. 11: 843-872.
<https://doi.org/10.1007/s13762-013-0299-8>
102. Tyagi B, Kumar N. Bioremediation: Principles and applications in environmental management. In *Bioremediation for Environmental Sustainability*. 2021. Elsevier. 3-28.
103. Chaturvedi A, Saraswat P, Gupta A, Prasad M, Ranjan R. Detoxification of Sewage Sludge by Natural Attenuation and Application as a Fertilizer in Sustainable Management and Utilization of Sewage Sludge. 2022. Springer, Cham. 263-80.
https://doi.org/10.1007/978-3-030-85226-9_13
104. Thornton SF, Spence MJ, Bottrell SH, Spence KH. Natural attenuation of dissolved petroleum fuel constituents in a fractured Chalk aquifer: contaminant mass balance with probabilistic analysis. *Q J Eng Geol Hydrogeol*. 2024. 57(2): qjgh2023-116.
<https://doi.org/10.1144/qjgh2023-116>
105. Tian L, Guan W, Ji Y, He X, Chen W, Alvarez PJ, Zhang T. Microbial methylation potential of mercury sulfide particles dictated by surface structure. *Nat. Geo-sci*. 2021. 14(6): 409-416.
<https://doi.org/10.1038/s41561-021-00735-y>
106. Abdulsalam S, Omale A.B. Comparison of biostimulation and bioaugmentation techniques for the remediation of used motor oil contaminated soil. *Braz Arch Biol Technol*. 2009. 52(3): 747-754.
<https://doi.org/10.1590/S1516-89132009000300027>
107. Juárez-Maldonado A, Tortella G, Rubilar O, Fincheira P, Benavides-Mendoza A. Biostimulation and toxicity: The magnitude of the impact of nanomaterials in microorganisms and plants. *J Adv Res*. 2021. 31: 113-126.
<https://doi.org/10.1016/j.jare.2020.12.011>
108. Ahmad I, Abdullah N, Koji I, Yuzir A, Mohamad SE, Show PL, Cheah WY, Khoo KS. The role of restaurant wastewater for producing bioenergy towards a circular bioeconomy: A review on composition, environmental impacts and sustainable integrated management. *Environ Res*. 2022. 214 (Pt 2): 113854.
<https://doi.org/10.1016/j.envres.2022.113854>
109. Muter O. Current Trends in Bioaugmentation Tools for Bioremediation: A Critical Review of Advances and Knowledge Gaps. *Microorganisms*. 2023. 11(3): 710.
<https://doi.org/10.3390/microorganisms11030710>
110. Khan A, Zytner R. Degradation Rates for Petroleum Hydrocarbons Undergoing Bioventing at the Meso-Scale. *Bioremediation J*. 2013. 17(3): 159-172.
<https://doi.org/10.1080/10889868.2013.807772>
111. Mosco M, Zytner R. Large Scale Bioventing Degradation Rates of Petroleum Hydrocarbons and Determination of Scale-up Factors. *Bioremediation J*. 2017. 21(3-4): 149-62.
<https://doi.org/10.1080/10889868.2017.1312265>
112. Song P, Xu D, Yue J, Ma Y, Dong S, Feng J. Recent advances in soil remediation technology for heavy metal contaminated sites: A critical review. *Sci Total Environ*. 2022. 838:156417.
<https://doi.org/10.1016/j.scitotenv.2022.156417>
113. Macaulay B, Rees D. Bioremediation of oil spills: A review of challenges for research advancement. *J Environ Sci Stud*. 2014. 8: p. 9-37.
114. Hsia KF, Chen CC, Ou JH, Lo KH, Sheu YT, Kao CM. Treatment of petroleum hydrocarbon-polluted ground-water with innovative in situ sulfate-releasing biobarrier. *J Clean Prod*. 2021. 295:126424.
<https://doi.org/10.1016/j.jclepro.2021.126424>
115. Fragkou E, Antoniou E, Daliakopoulos I, Manios T, Theodorakopoulou M, Kalogerakis N. In situ aerobic bioremediation of sediments polluted with petroleum hydrocarbons: a critical review. *J Mar Sci Eng*. 2021. 14(9): 1003.
<https://doi.org/10.3390/jmse9091003>
116. Sinha P, Mukherji S. Biofiltration Process for Treatment of Water and Wastewater. *Trans Ind Nat Acad Eng*. 2022. 7(4): 069-91.
<https://doi.org/10.1007/s41403-022-00360-0>
117. Taherzadeh MJ. Bioengineering to tackle environmental challenges, climate changes and resource recovery. *Bioeng*. 2019. 10(1): 698-699.
<https://doi.org/10.1080/21655979.2019.1705065>
118. Pachaiappan R, Cornejo-Ponce L, Rajendran K, Manavalan K, Femilaa Rajan V, Awad F. A review on biofiltration techniques: recent advancements in the removal of volatile organic compounds and heavy metals in the treatment of polluted water. *Bioeng*. 2022. 13(4): 8432-8477.
<https://doi.org/10.1080/21655979.2022.2050538>
119. Rafeeq H, Afsheen N, Rafique S, Arshad A, Intisar M, Hussain A, Bilal M, Iqbal HM. Genetically engineered microorganisms for environmental remediation. *Chemosphere*. 2023. 310:136751.
<https://doi.org/10.1016/j.chemosphere.2022.136751>
120. Singh Y, Saxena MK. Insights into the recent advances in nano-bioremediation of pesticides from the contaminated soil. *Front Microbiol*. 2022. 13: 982611.
<https://doi.org/10.3389/fmicb.2022.982611>
121. Mishra M., Singh SK, Kumar A. Environmental factors affecting the bioremediation potential of microbes. In *Microbe Mediated Remediation of Environmental Contaminants*, Woodhead publishing series in Food Science, Technology and Nutrition. 2021. 47-58.
<https://doi.org/10.1016/B978-0-12-821199-1.00005-5>
122. Dzionek A, Wojcieszynska D, Guzik U. Natural carriers in bioremediation: A review. *Electron J Biotechnol*. 2016. 23:28-36.
<https://doi.org/10.1016/j.ejbt.2016.07.003>

بررسی اثربخشی مداخلات میکروبی در آلودگی‌زدایی فلزات سنگین در محیط زیست و سیستم‌های تولید مواد غذایی

فاطمه فاطمی نسب^{۱*}، مهدی کوشکی^{۱،۲}، فرانک جعفریان^۳، وحید منصوری^۴، علیرضا احمدزاده^۵، نسرین امیری داش‌آتان^۶، معصومه فراهانی^{۸*}

۱. گروه شیمی فیزیک، دانشکده شیمی، دانشگاه مازندران، بابل‌سر، ایران.
۲. مرکز تحقیقات ژن درمانی سرطان، دانشگاه علوم پزشکی زنجان، زنجان، ایران
۳. گروه بیوشیمی بالینی، دانشکده پزشکی، دانشگاه علوم پزشکی زنجان، زنجان، ایران
۴. گروه شیمی، دانشگاه اصفهان، اصفهان، ایران
۵. مرکز تحقیقات پروتئومیکس، پژوهشکده سیستم بیولوژی، دانشکده پیراپزشکی، دانشگاه علوم پزشکی شهید بهشتی، تهران، ایران
۶. گروه علوم آزمایشگاهی، دانشکده پیراپزشکی، دانشگاه علوم پزشکی شهید بهشتی، تهران، ایران
۷. مرکز تحقیقات بیماری‌های متابولیک زنجان، پژوهشکده سلامت و بیماری‌های متابولیک، دانشگاه علوم پزشکی زنجان، زنجان، ایران
۸. مرکز تحقیقات پروتئومیکس، پژوهشکده سیستم بیولوژی، دانشگاه علوم پزشکی شهید بهشتی، تهران، ایران

چکیده

سابقه و هدف: فلزات سنگین، مانند آرسنیک (As)، کادمیوم (Cd)، کروم (Cr)، جیوه (Hg)، مس (Cu)، نیکل (Ni) و سرب (Pb)، خطرات جدی برای اکوسیستم‌ها و سلامت انسان به ویژه برای گروه‌های آسیب‌پذیر مانند کودکان به همراه دارند. این فلزات سنگین سمی می‌توانند در زنجیره‌های غذایی تجمع یابند و منجر به عوارض طولانی‌مدت بر سلامت شوند. افراد می‌توانند از طریق غذاهای آلوده، آب‌های آلوده، استنشاق و تماس مستقیم با پوست در معرض این آلاینده‌ها قرار گیرند. این مقاله مروری، به آلودگی زیست‌محیطی ناشی از صنعتی‌شدن تمرکز داشته و به‌طور خاص به آلودگی ناشی از فلزات سنگین می‌پردازد. این تحقیق به بررسی زیست‌پالایی، به‌عنوان یک راه‌حل بالقوه می‌پردازد که شامل استفاده از میکروارگانیسم‌ها و گیاهان برای تجزیه و سم‌زدایی این آلاینده‌های خطرناک است.

مواد و روش‌ها: ترکیبات گوناگون پروتئینی برپایه شیر، شامل کنسانتره پروتئین شیر، کازئین رنت (مایه پنیر)، کازئین اسیدی، کازئینات سدیم، کازئینات کلسیم و کنسانتره میسل کازئین، از نظر میزان پروتئین و خاکستر، پروفایل اسید آمینه و ویژگی‌های فراسودمند مانند ظرفیت اتصال آب و ویسکوزیته‌سازی مورد تجزیه و تحلیل قرار گرفتند. این ارزیابی جامع به منظور تعیین توانایی آن‌ها در بازتولید بافت خامه‌ای بستنی‌های سنتی انجام شد.

یافته‌ها و نتیجه‌گیری: در این تحقیق روش‌های مختلف زیست‌پالایی مورد بررسی قرار می‌گیرد؛ که از جمله‌ی آن، استفاده از پروبیوتیک‌ها برای آلودگی‌زدایی می‌باشد. این روش‌ها با هدف بازسازی مکان‌های آلوده و توسعه رویکردهای پایدار برای حذف فلزات سنگین از محصولات غذایی طراحی شده‌اند. این مطالعه بر اثربخشی مداخلات میکروبی در مقابله با اثرات مضر فلزات سنگین و سموم در محیط زیست و سامانه‌های غذایی تأکید می‌کند. این استراتژی‌های زیست‌پالایی می‌توانند خطرات مرتبط با آلودگی فلزات سنگین را کاهش دهند.

تعارض منافع: نویسندگان اعلام می‌کنند که هیچ نوع تعارض منافی مرتبط با انتشار این مقاله ندارند.

تاریخچه مقاله

دریافت ۷ نوامبر ۲۰۲۴

دوری ۱۶ دسامبر ۲۰۲۴

پذیرش ۲۳ دسامبر ۲۰۲۴

واژگان کلیدی

زیست پالایی
آلودگی‌زدایی فلزات سنگین
پروبیوتیک
مدل زیستی
جذب زیستی

نویسنده مسئول

فاطمه فاطمی نسب

گروه شیمی فیزیک، دانشکده شیمی،
دانشگاه مازندران، بابل‌سر، ایران.

پست الکترونیک:

ftmfatemi61@gmail.com

معصومه فراهانی

مرکز تحقیقات پروتئومیکس،
پژوهشکده سیستم بیولوژی، دانشگاه
علوم پزشکی شهید بهشتی، تهران،
ایران

پست الکترونیک:

mfarahani@sbmu.ac.ir