Journal of Water Process Engineering 48 (2022) 102884

Contents lists available at ScienceDirect

Journal of Water Process Engineering

journal homepage: www.elsevier.com/locate/jwpe

Bacterial bioremediation of heavy metals in wastewater: A review of processes and applications

P.R. Sreedevi [a,*], K. Suresh [a,*], Guangming Jiang [b]

[a] Surface and Environmental Control Plasma Laboratory, Department of Physics, Bharathiar University, Coimbatore 641046, Tamil Nadu, India
[b] School of Civil, Mining and Environmental Engineering, University of Wollongong, Australia

ARTICLE INFO

Keywords:
Bacterial remediation
Bioadsorption
Bioaccumulation
Bioprecipitation
Bioleaching

ABSTRACT

Heavy metals, a treasure of nature, turns to be toxic at high concentrations in water. Among several methods adopted to alleviate heavy metal pollution, bioremediation is considered to be a sustainable, cost-effective technology. Bioremediation largely relies on bacteria, apart from other microbes and plants. The inherent and adaptive mechanisms evolved in bacteria to defend the metal toxicity include bioadsorption/biosorption, bioaccumulation, bioprecipitation and bioleaching. Heavy metal resistant bacterial strains are easy to culture and maintain, and even dead cell biomass display high heavy metal remediation potential in solution. All the heavy metal remediation mechanisms exhibited by bacteria in water is comprehensively reviewed with recent research outputs and in-situ and ex-situ techniques. The cellular mechanisms of heavy metal remediation are discussed, considering efficient bacterial strains, physiochemical parameters, nutrient supplementation and design of novel microbial techniques. Research at omics level would effectuate further manipulation of the cellular process and increase its efficiency. Bacterial heavy metal remediation technique provides double benefit of metal recovery and water purification, along with reuse prospects for both water and metal resources. Technological intervention could meet the challenges of process acceleration, resist biofouling, compete with native wild bacterial species in wastewater, design for commercialization. Industrial translation of the technology is the pivotal avenue to be tackled. Ultimately, understanding of bacterial heavy metal remediation process is essential for the implementation of this promising technology to safeguard the environmental health.

1. Introduction

Heavy metals are elements with specific density of more than 5 g cm^{-3} [1] and some of which are quintessential at low concentrations for the normal physiological functions of living organisms [2]. Specific amounts of Calcium (Ca), Sodium (Na), Magnesium (Mg), Potassium (K), Copper (Cu), Iron (Fe), Zinc (Zn), and Chromium (Cr) are required for the survival of organisms, while their high concentrations cause toxicity [3]. Several metals like Cadmium (Cd), Mercury (Hg), Nickel (Ni), Arsenic (As) and Lead (Pb) are toxic at any quantity causing deleterious effect on the wellbeing and survival of living organisms [4]. And it causes ecological, nutritional, genetic and evolutionary impacts. Heavy metals reach the environment by natural and anthropogenic activities [5]. As the heavy metals are non-degrading and bio accumulating with well-delineated toxic effects; government agencies, has imposed rules and legislations to limit the use and discharge of toxic metals to environment. World Health Organization [6] has defined the permissible heavy metal concentration in safe drinking water. Whereas Food and Agriculture Organization has stipulated the maximum permissible limit of toxic heavy metals in irrigation water [7].

To comply with the regulations and standards, many strategies and techniques have been investigated and implemented to alleviate heavy metals from water. The generally employed techniques are coagulation, ion exchange, membrane filtration, chemical precipitation, adsorption, electrochemical treatment, flocculation and bioremediation [8]. Bioremediation is gaining tremendous attention since a few decades due to its less or no requirement of chemicals, cost-effectiveness, absence of solid sludge by-products and eco-friendly operating techniques [9].

Bioremediation can be defined as the process that utilizes and depends on biological mechanisms to transform/degrade/detoxify

Abbreviations: ATP, Adenosine triphosphate; ABC, ATP binding cassette transporter; FTIR, Fourier transform infrared spectroscopy; GTP, Guanosine triphosphate; LPS, Lipopolysacharide; NADH, Nicotinamide adenine dinucleotide hydride.

* Corresponding authors.
E-mail addresses: sreedevi.rathan@gmail.com (P.R. Sreedevi), ksureshphy@buc.edu.in (K. Suresh).

https://doi.org/10.1016/j.jwpe.2022.102884
Received 8 February 2022; Received in revised form 17 May 2022; Accepted 18 May 2022
Available online 26 May 2022

pollutants to innoxious state, and ultimately mineralize to carbon dioxide, nitrogen, and water etc., using live or dead biomass [10]. Plants, fungi, bacteria, algae, and cyanobacteria are widely researched and employed for heavy metal bioremediation. Microorganisms are most suitable for the purpose as they are easier to handle, culture and implement. In recent years, microorganisms especially bacteria reckoned recognition with their ability to adsorb, solubilize and precipitate heavy metals by bioadsorption (biosorption), bioaccumulation, bioleaching and bioprecipitation. Omni presence, abundance, diversity, small size and unique capacity to grow and propagate under controlled and uncontrolled conditions with environmental resilience make bacteria the best candidate for bioremediation [11].

Bacterial bioremediation of heavy metals in solution mostly occur by means of adsorption on bacterial cell surface. It is the first line defence of bacteria to resist metal toxicity. Wherein, negatively charged carboxyl, amino, phosphoryl, and sulfo groups on bacterial cell wall acts as potential ion exchange sites and metal sinks. Thus, adsorption occurs on cell wall by redox process, ion-exchange, complexation, electrostatic attraction, and precipitation. Bioadsorption or biosorption is an inactive process, where heavy metals are adsorbed on to the cell surface devoid of energy expenditure (metabolism independent) until equilibrium is achieved. While bioaccumulation is predominantly metabolism dependent or active uptake of heavy metals by living biomass/cells [10]. Bacteria bind heavy metal ions by means of exopolymers/polysaccharides to their cell surface, further circumscribe or internalise these metal species into the cell for various metabolic functions, besides chelate the metals by producing several metabolic ligands [12]. Bioleaching is the bio-recovery of metals by releasing/excreting ligands, like organic acids, cyanide, thiosulphate and phenol derivatives. These ligands interact/react with metals in its vicinity, bind and form mostly soluble complexes directly or indirectly. Bioprecipitation of metals is a metal sequestering process exhibited by metabolically active cells, where metabolites produced react with metals present in water and form metal precipitates. Microorganisms, particularly anaerobic bacteria, convert the metals present or dissolved in aqueous solution into solid precipitates via sulphate, carbonate, phosphate or hydroxide precipitation [13].

1.1. Significance of the study

To explore and understand the underlying mechanisms by which bacteria remediate heavy metals is vital for the development of feasible technologies and treatment strategies using bacteria, for heavy metal removal from polluted environments. Better knowledge on cellular process leading to hazardous heavy metal removal is quintessential for

- The selection of appropriate syntrophic bacterial strains for effective elimination and extraction of heavy metals from wastewater.
- Suitably modulate or enhance the remediation process by controlled supplementation of necessary nutrients (nitrogen/carbon sources), or electron acceptors (O_2, Fe, and S), thereby conditioning the cellular metabolism.
- Adjust physiochemical working parameters like, pH, temperature, media composition, etc., to achieve maximum remediation.
- Choose compatible bacterial species or strains with specific metabolic features, distinct competencies, and synergistic potentialities to design and develop microbial consortia/biofilm to detoxify heavy metals by bioaugmentation.
- Proper and productive construction of microbial fuel cells, which elide heavy metals with greater redox potential than the existing anode and deposit it at cathode chamber, facilitating metal recovery.
- Determine and incorporate the precise bacterial candidates in novel techniques like constructed wetlands [14], particularly floating treatment wetland and combined ecological floating beds. The efficiency of the process is inevitably related to the microbial community attached to the floating mats and rhizomes.
- Expand the knowledge spheres to omics (genomics, transcriptomics, proteomics, and metabolomics) and suitably manipulate the process by gene editing and engineering for enhanced expression of heavy metal transporter proteins, sequestering proteins and enzymes of relevant metabolic pathways [15].
- Capacitate fruitful interventions in microbial nanotechnology, especially bacterial synthesis of metal nanoparticles [16].

Therefore, the present review delineates the remediation mechanisms and its underneath cellular processes exhibited by bacteria, that aid in the removal of heavy metals in aqueous media. Relevant reports of previous researchers are discussed. Additionally, very recent research findings are briefly summarised and tabulated. Diagrammatic representations are provided to support the descriptions.

The keywords used for data retrieval from scientific sources (*Scopus, Web of Science, PubMed)* were - bioremediation of heavy metals using bacteria, biosorption, bioadsorption, bioaccumulation, bioprecipitation and bioleaching. The publications that deal with heavy metal remediation from aqueous medium using bacteria were included for the study. Other microbial (fungi, algae and nanomaterials) remediation procedures were excluded. Even bacterial remediation in solid substrates like soil was also not considered. Publications from the year 2000 to 2022 were scrutinized and the bacterial remediation mechanism elucidated in each research paper were probed and discerned. As most of the literature available were confined to bioadsorption and bioaccumulation, and both seldom differentiated, emphasis was given to discrete and delineate each mechanism precisely. The papers published from 2018 to 2022 on bioremediation of heavy metals from water with specified bacterial strains and mechanism were compiled and tabulated. The practical applications of bacteria mediated heavy metal bioremediation is provided, mentioning the bacterial species involved and its removal efficiency.

2. Mechanism of bioremediation

Several bacterial strains have evolved diverse, discrete mechanisms to adapt, interact, acclimate and thrive in environment rich in minerals, especially heavy metals. These include uptake of heavy metals on to the cell surface by biosorption, intracellular sequestration by accumulation, extracellular sequestration as insoluble compounds by precipitation, and production of metabolites that solubilize and chelate metal compounds that leads to leaching. The different mechanisms and its several modes, exhibited by bacteria to remove and annihilate heavy metals is depicted in Fig. 1 and discussed in following section.

2.1. Bioadsorption/biosorption

Biosorption/bio adsorption is the non-directed active or passive physiochemical interaction between inorganic and organic metal/minerals with cellular substances [17,18]. The major processes involved in biosorption mechanism are surface adsorption, physisorption, chemisorption, ion exchange, and surface complexation. Surface adsorption involves electrical attraction between negatively charged ligands present on cell wall and the positively charged metal ions in medium and is often an “exchange” reaction [19]. Physical adsorption majorly comprises Van der Waals forces, whereas in “chemical” or “activated” adsorption, attraction occurs between the adsorbent and adsorbate. An assemblage of all these mechanisms, either functioning together or independently, leads to the overall metal adsorption on microbial cell surface [20]. Heavy metal binding, possibly a two-stage task, comprises interaction between reactive groups on bacterial cell surface and the metal ions, followed by deposition of metal [19].

Spectroscopic and chemical modification studies have depicted that, the cellular radicals like-hydroxyl, carboxyl, sulfate, sulfhydryl (thiol), thioether, phosphate, phosphonate, phosphodiester, amino, imine, amide, imidazole, and carbonyl (ketone) possess high metal binding potential [21]. Table 1 elucidates the chemical structure, occurrence

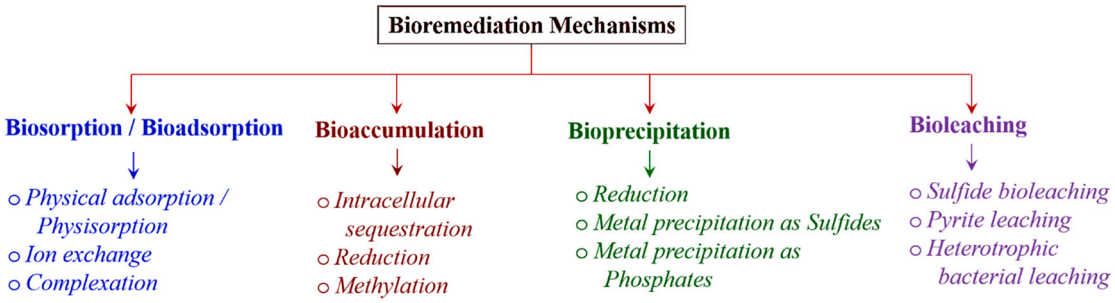


Fig. 1. Different mechanisms involved in heavy metal remediation by bacteria in liquid medium.

and position of these active radicals in bacterial cell structure. Most of these groups are present on bacterial cell wall. Ionization of these functional groups turns the bacterial cell surface negatively charged, viable for cationic metal attachment [20].

Cell walls of bacteria are primarily formed of peptidoglycans, which constitute linear chains of sugar; the disaccharide *N*-acetylglucosamine-β1-4-*N*-acetylmuramic acid interconnected with peptide chains. The peptide chains are tetramers composed of L-alanine, D-glutamic acid, D-amino pimelic acid or L-lysine and another L-alanine. Apart from that, a glycopolymer teichoic acid is embedded in gram positive bacterial cell walls increasing its gross negative charge. Cell walls of gram-negative bacteria are not profusely cross-linked and composed of thinner peptidoglycan layer than gram-positive bacteria. Gram-negative bacteria harness an outer membrane formed of lipopolysaccharides (LPS), lipoproteins and phospholipids. Gram-positive bacterial cell wall contains glycoproteins on its outer side, dispensing more accessible binding sites than LPS and phospholipids [19].

2.1.1. Physical adsorption/physisorption

It is the phenomenon of transferring ions from one phase to another namely, liquid phase to solid phase, involving: (i) bulk transfer to peripheral layer; (ii) inward diffusion or massive transmission through pores and/or random motion of atoms by solid diffusion; and (iii) adhesion or adsorption to the exterior surface of bacterial cells. Physical adsorption, is due to non-specific, rapid and reversible attraction forces like Van der Waals forces. Or, it occurs by electrostatic adsorption on account of coulombic attractive forces arising between charged solute particles and bacterial cell surface [18]. Ahalya et al. [22] reported that copper biosorption on *Zoogloea ramigera* bacterium occurred through electrostatic interaction. Physicochemical interactions between the cellular radicals on the bacterial cell wall and membrane, and the metal species in solute are the prime factors responsible for rapid and reversible metabolism-independent biosorption in dead cell biomasses. FTIR studies by Hasan et al. [23] elucidated that amine, hydroxyl and carboxyl groups existing on the cell surface (dead dried biomass) of *Aeromonas hydrophila* was the fundamental cause of Pb (II) sorption, besides the passage through pores. Anionic groups, –C–O, –COO, –NH, –OH and –C = O present on dead *Streptomyces rimosus* bacterial cell walls exhibited fairly high adsorption towards Pb^{2+} ions [24].

2.1.2. Ion exchange

In ion exchange mechanism, metal cations bind to a vacant site, previously occupied by another cation. Divalent ions of metals are adsorbed by exchange with polysaccharide counter ions present on the cell wall and outer membrane of bacteria [25]. This process relies on several factors like the different kinds and number of sites present on the cell surface and their ionization pattern, which is eventually determined by the pH and pKa value of respective groups. Protonated amine groups are positive in charge; and turns neutral while deprotonated. Addition of protons convert phosphate, carboxyl, and sulfate groups into neutral, and in deprotonated condition turns negatively charged [26]. Nickel biosorption by ion exchange was reported in *Pseudomonas fluorescens* 4F39 [27]. *Pseudomonas pseudoalcaligenes and Micrococcus luteus, adsorbed significant quantities of lead and copper, which further increased with pH from 2 to 6* [28]. Hasan et al. [23] has inferred that Pb (II) ions compete with H^+ at low pH and get adsorbed to *Aeromonas hydrophila* by ion exchange.

2.1.3. Complexation

Remediation of metals could also occur by formation of complexes over cell periphery by the interaction of reactive radicals on cell wall and metal ions in solution. Amino, carboxyl, hydroxy, thiol, phosphate, and hydroxyl-carboxyl groups interact in coordination with heavy metal ions [29]. 'Complex or co-ordination compound' is a poly-atomic molecule with neutral, or negative or positive charge, and it consists of single or numerous central atoms (generally metal cations) bounded and joined to ligands (other negative or neutrally charged atoms or groups). If a ligand is connected through two or more coordinating atoms to central atom, then the complex is termed as 'Chelate' [26]. Magnesium, calcium, cadmium, copper, zinc, and mercury complexation were found to occur in *Pseudomonas syringae*. Complexation is the major biosorption process involved during alkaline pH. Mercury and uranium complexation has been reported at pH above 7 in *Pseudomonas fluorescens* 4F39 by López et al. [28]. Hydroxyl, phosphoryl, carboxyl and amino groups of proteins and polysaccharides on the extracellular matrix of *Shewanella putrefaciens* was found to complex with Cr(VI) [30].

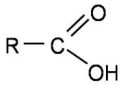
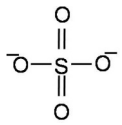
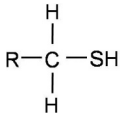
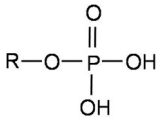
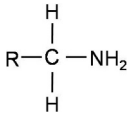
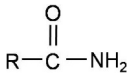
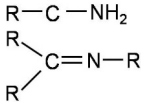
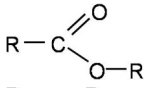
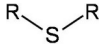
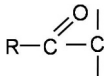
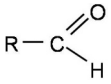
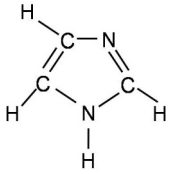
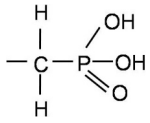
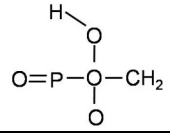
Recent research outcomes on bacterial biosorption of heavy metals are tabulated (Table 2). Environmental factors like temperature, pH and composition of wastewater, concentration and oxidation state of heavy metals, organic and inorganic entities present, colloids and emulsions, may influence biosorption, along with the type of bacterial strain and mechanism of metal removal. Use of dead cells is more propounded, as dead biomass is hardly susceptible to heavy metal toxicity, and nutrients are not required for the growth of bacterial cells [19,31], lowering operational cost. The biomass waste from fermentation industries could be used for the purpose. Metal loading on biomass is very rapid, as the non-living biomass is an efficient ion exchanger. Sterilization is not mandatory, with storage options and pretreatment of bacterial biomass may further improve the biosorptive capacity. Moreover, operating conditions like pH, temperature, time etc. could be controlled with possibility for metal recovery. However, the improvement of biosorption potential by genetic engineering or biological altering of metal valency state is limited in dead biomass [19].

Bioadsorption is a simple and fast process that could utilize alive or dead bacterial cells or exopolymers alone, to retrieve heavy metals from aqueous solution. Though physical and chemical parameters of media and oxidation state of metal ions determine the efficiency of the process, metals are adsorbed within few hours. Rather resorption is easy, and biomass could be reused. This is the most common heavy metal defence mechanism exhibited by mesophilic bacterial strains.

2.2. Bioaccumulation

Bioaccumulation is the influx and accretion of metals within

Table 1
Heavy metal binding radicals present in bacterial cell structure.

Metal binding cellular radicals	Chemical structure	Presence in cellular compounds	Position in cell structure
Carboxyl		Fatty acids, proteins, organic acids	Cell membrane, cell wall, cytosol
Hydroxyl		Alcohols, carbohydrates	Cell membrane, cell wall, cytosol
Sulfate		Aminoacids-cysteine, methionine	Cell membrane, cytosol
Sulfhydryl (Thiol)		Amino acid-cysteine	Cell membrane, cytosol proteins
Phosphate		DNA, RNA, ATP	Cell membrane, cytosol, chromosomes
Amino		Proteins and nucleic acids	Cell membrane, cell wall, cytosol
Amide		Fattyacid-aminoacid bonds	Cell membrane lipids
Imine		Deaminated aminoacids	Cell membrane, cell wall, cytosol
Ester		Lipids	Cell membrane, cytosol
Thioether		Aminoacids	Cell membrane, cell wall, cytosol
Carbonyl (ketone)	Internal 	Polysaccharides, ketones	Cell membrane, cell wall, cytosol
	Terminal 	Polysaccharides, aldehydes	
Imidazole		Aminoacids and nucleic acids	All protein components in cell membrane, cytosol, ribosomes and nucleic acids
Phosphonate		Lipid fractions, phosphonolipids	Exoploysaccharides
Phosphodiester		DNA, RNA	DNA, RNA, ribosomes

bacterial cells by the uptake of non-metabolic metals through the same carrier pathway involved for metabolically essential metals. The mechanism constitutes, binding of metal ions to the reactive radicals at the outer surface of bacterial cell wall, likewise and furthermore to its internal region through energy independent mechanism. Subsequently, metals diffuse into the cell cytoplasm, by means of energy dependent/independent process. The pathway for the transport of metabolically pivotal ions like sodium (Na), potassium (K), magnesium, etc. would be relied for the transport of heavy metals through microbial cell membranes for intracellular accumulation. The cation transport systems will bind with heavy metal ions of identical ionic radius and charge as of essential metal ions [29].

2.2.1. *Intracellular transport*

Heavy metals are imported to the bacterial cell by means of channels, secondary carrier proteins and primary active transporters present on

Table 2
Recent research reports on bacterial adsorption of heavy metals.

Bacterial species	Heavy metals adsorbed	Mode of adsorption	Ref.
Bacillus cereus	Pb	Ion exchange, complexation	[32]
Bacillus cereus	Pb, Ni	Complexation, physisorption	[33]
Oceanobacillus profundus	Pb, Zn	Ion exchange, complexation	[34]
Bacillus thuringiensis, *Pseudomonas stutzeri*, *Micrococcus yunnanensis*	As	Ion exchange, physisorption	[35]
Lactobacillus plantarum	Cd, Pb	Complexation, physisorption	[36]
Pseudomonas aeruginosa, *Bacillus subtilis*, *Azotobacter chroococcum*	Cu, Ni, Pb, Cd, Cr	Ion exchange, physisorption, complexation	[37]
Agrobacterium tumefaciens	Pb, Cd, Ni	Ion exchange	[38]
Sinorhizobium sp	Cr	Ion exchange, physisorption	[39]
Bacillus xiamenensis	Pb	Physisorption, ion exchange	[40]
Pseudomonas stutzeri, *Bacillus subtilis*	Cd	Physisorption, complexation, ion exchange	[41]
Pseudomonas koreensis, *Patonea sp*	Cd, Cr, Pb	Ion exchange, physisorption	[42]
Ochrobactrum sp	Cu	Physisorption, complexation	[43]

bacterial cell membrane. Channels are α-helical proteins that serve for the passive diffusion of heavy metals across the membrane according to concentration gradient. These channel proteins belong to Major intrinsic proteins super family and are found to transport arsenic and mercury in a series of bacterial species like *E. coli*, *Cornebacterium*, *Streptomyces coelicolor*, *Serratia* and *Pseudomonas* [44]. β-barrel proteins and porins present in gram-negative bacteria have also been found to translocate heavy metals. Uniporters, symporters and antiporters are the secondary carrier proteins involved in heavy metal accumulation. Transporter-Opsin-G protein coupled receptor super family and major facilitator super family proteins form the chief carrier proteins behind this function. These proteins rely on proton motive force for metal shifts into the bacterial cell. Likewise, uptake of Ni, Co and As has been reported in *Helicobacter pylori* [45], *Rhodopseudomonas palustris* [46], *Novosphingobium aromaticivorans* and *Staphylococcus aurens* [47]. Primary active transporter proteins are multi domain tertiary proteins embedded in the plasma membrane of bacterial cells, which comprises a transmembrane portion and cytosolic ATPase coupling component. Periplasmic solute binding domain is also sometimes present. P-type ATPase proteins and ABC transporter proteins are the major protein super families that constitute primary active transporters [44]. These transporters transit heavy metals against concentration gradient using energy derived from the hydrolysis of ATP or GTP reserves in cell. *Lactobacillus plantarum* [48], *Thlaspi caerulescens* [49], and *Enterobacter hirae* [50] bioaccumulated Cd into the cell through primary transporters.

Apart from the membrane carrier proteins, interaction of metals with bacterial surface ligands subsequently leads to its slow transport into the cell. Bacteria including cyanobacteria release high-affinity, low-molecular-weight (200–2000 Da), coordination molecules termed as siderophores, that bind iron atoms. The synthesis of siderophores in bacteria is a stimulatory response towards iron scarcity in environment. In addition to iron radicals, siderophores are able to join and bind with other metals also e.g. Thorium (Th), Uranium (U), Ni, Gallium (Ga) and Cu [51]. Bacterial siderophores constitute catecholates (e.g., enterobactin), carboxylates (e.g., rhizobactin), and hydroxamates (e.g., ferrioxamine B) [52]. Bacteria use different siderophore-mediated iron (Fe) transport systems and it varies in gram-positive and negative bacteria. Gram-negative bacteria like *Escherichia strains* possess outer membrane TonB-dependent receptors which recognize Fe(III)–siderophore complexes accessible at the cell surface and bind them thenceforth. Fe(III)–siderophore bound to the TonB-dependent outer membrane receptors, crosses the outer membrane to periplasmic space via high-affinity periplasmic binding protein, which accompanies the Fe(III)–siderophore complex up to cytoplasmic membrane, and is relieved back to periplasmic space to resume its carrier function. Fe(III)–siderophore complexes are shuttled across the cytoplasmic membrane to cytoplasm by ATP-binding cassette (ABC) transport system. Finally, Fe(III) is dissociated from the siderophore complex via reduction of Fe(III) to Fe (II). Subsequently, siderophores are either degraded or recycled, through a shuttle mechanism using specific efflux pump [53] (Fig. 2). Whereas, in gram-positive bacteria like *Bacillus*, no outer membrane receptors are present due to the lack of outer membrane.

Therefore, the Fe(III)-siderophore complexes directly attach to the periplasmic siderophore binding proteins embedded on cytoplasmic membrane. After which, the Fe(III)-siderophore complexes are transported to the cytoplasm as like in gram-negative bacteria, by the ATP-dependent ABC transport system [54].

2.2.2. *Intracellular fate of bioaccumulated heavy metals*

Growing bacterial cells are capable of eliminating metals perpetually by internal detoxification methods. Biotransformation and reduction of metals using enzymes, methylation, sequestration by metal-organic complexion, and production of metal chelators-metallothioneins are the different mechanisms exhibited by bacteria to defend metal toxicity [55].

2.2.2.1. Intracellular sequestration. Intracellular sequestration is the process of formation of composites of metal ions with various cellular cytoplasmic compounds. Upon entry to the cells, heavy metal ions are translocated, attached, or imbedded in cellular organelles, depending on the element concerned and the bacterial strain. Chelation is the process of binding of metals to ligands or compounds. Cytoplasmic metal chelation is mostly aided by metallothineins-peptides rich in cysteine, γ – glutamylcysteine- a glutathione analogue present in haloarchaea, and by polyphosphate-the chelating molecule produced in most halophilic bacteria and archaea species. Iron-storage protein ferritin, copper and zinc-storing metallothioneins are the common metal sequestering proteins found in bacterial cells [56]. Metal stress induces high expression of metallothionein genes and its overproduction in bacteria, resulting in augmented metal binding and sequestration [57].

This metal accumulation potential of specific bacterial strains has been manipulated mainly for effluent treatment. *Rhizobium leguminosarum* with the aid of glutathione, manifested considerable quantity of intracellular cadmium ion sequestration [58]. Jroundi et al. [59], reported intracellular accumulation of lead in polyphosphate grains within the cells of *Bacillus* species isolated from Mediterranean sea. Cyanobacteria, *Anabaena cylindrica* and *Plectonema boryanum*, accumulated cadmium and aluminium in polyphosphate bodies [19].

2.2.2.2. Reduction of heavy metal ions. Bacteria make use of metals and metalloids as electron donors or acceptors for energy generation. Bacterial cells can transform the oxidation state of metal ions, thus reducing its toxicity. Oxidized metals act as terminal electron acceptors in bacteria during anaerobic respiration. Many anaerobic and facultative anaerobic bacterial species use oxidized metallic elements like Fe(III), Mn(IV) or Cr(VI) as terminal electron acceptors [60]. Reduction of selenium and arsenic coupled to organic substrates, lactic acid, acetic acid and aromatics is observed in certain bacterial species. Oxyanions of selenium and arsenic are also used as terminal electron acceptors during anaerobic respiration by bacterial strains, that provide energy for metabolism and growth [61].

Enzymatic reduction results in the generation of less toxic forms of mercury and chromium. Mercury detoxification is accomplished in

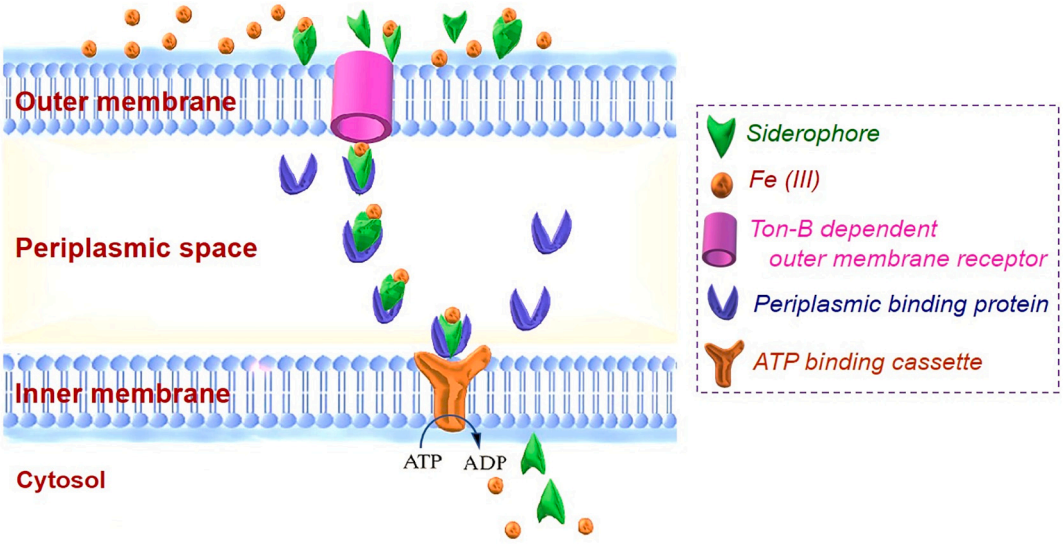


Fig. 2. Intracellular transport of ferric [Fe(III)] ions by siderophores in bacteria.

bacterial strains by organomercurial lyase (MerB) and mercuric reductase (MerA) enzymes. Enzymatic chromate reduction that involves copper-dependent reductase was observed in haloalkaliphilic *Amphibacillus* sp. [62]. Membrane-associated NADH-dependent chromate reductases catalysed chromate reduction is prevalent in halophilic *Halomonas* strains [63]. NADH-dependent nitrate reductase catalyses ionic silver (Ag^{+}) reduction to inactive metallic colloidal silver nanoparticles in *Bacillus licheniformis* [64]. Arsenate reduction in prokaryotes is carried out by soluble arsenate reductases (ArsC) [65]. Several bacterial strains of *Bacillus*, *Pseudomonas putida* and *Pedomicrobium* reduces manganese- Mn (III and IV) to Mn (II) and further oxidize it to be used as terminal electron acceptor in electron transport chain [66].

2.2.2.3. Methylation of metals. Certain bacterial strains are proficient in methylating various metal, metalloid and organometallic compounds to methyl derivatives, which is often volatile and evaporates [19]. Methylation is one of the fundamental biochemical pathways of bacterial cell. Intracellular metal and metalloid methylation occur by any of the three pathways namely involving-S-adenosylmethionine, methylcobalamin and *N*-methyltetrahydrofolate. Sulphate or iron reducing

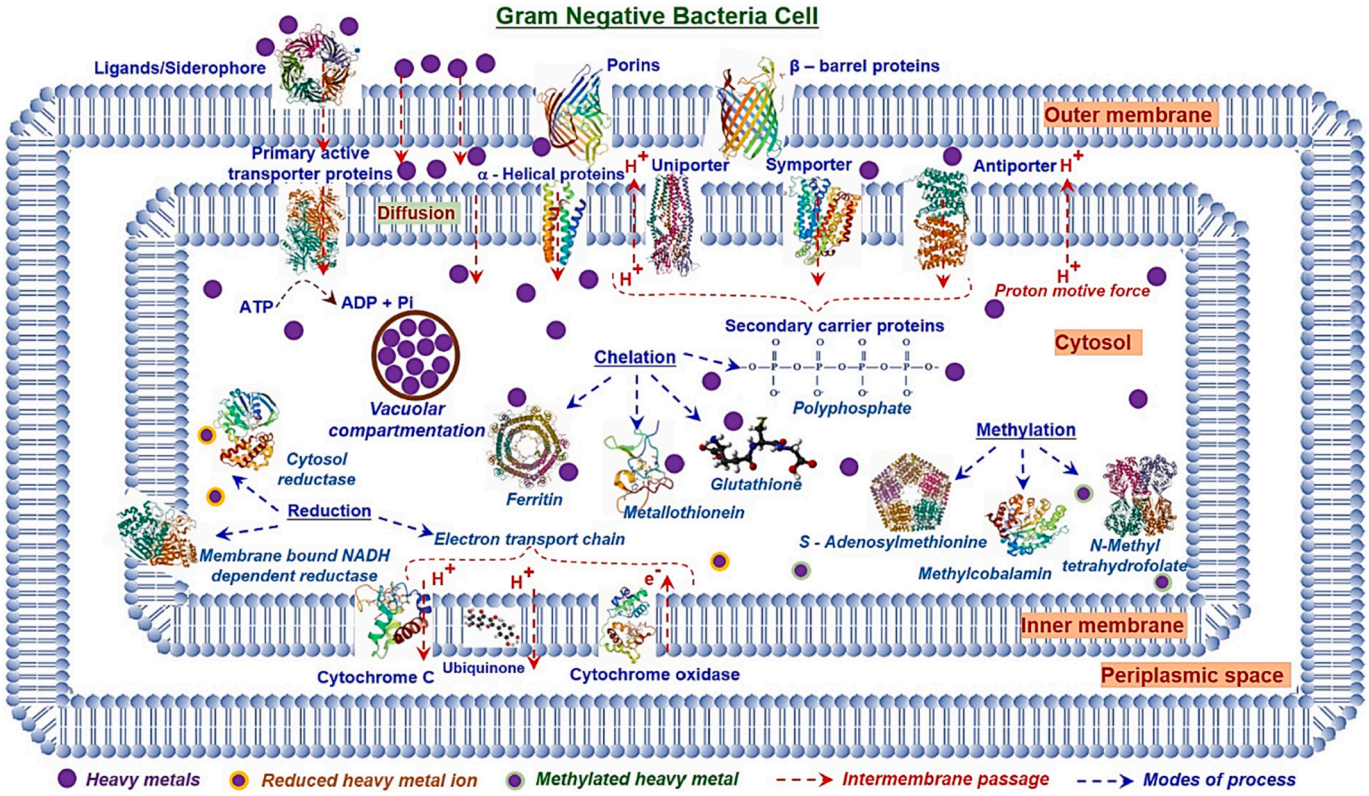


Fig. 3. Illustration of intracellular passage of heavy metals by different channels and its bioaccumulation within bacterial cell through various mechanisms (i) Vacuolar storage, (ii) Sequestration by ferritin, metallothionein, glutathione and polyphosphate molecules, (iii) Reduction by receiving electrons from Electron transport chain or by enzymatic action, and (iv) Methylation. (*Protein structures according to PDB format)*.

bacteria utilize methylcobalamin to methylate mercury (Hg). Whereas, methylation of Arsenic (As) occurs via S-adenosylmethionine [67]. Metal compounds, when methylated turns to be explosive mostly; for instance, *Escherichia sp*, *Bacillus sp*, *Pseudomonas sp,* and *Clostridium sp* biomethylate Hg (II) to gaseous methyl mercury. Bio methylation of As to gaseous arsines; selenium (Se) to volatile dimethyl selenide, and lead (Pb) to decomposable dimethyl lead has been observed in solutions stagnant on polluted top soil containing bacteria [55]. Each methylation pathway is distinct, and the pathways involved vary among bacterial species and oxidation state of metals in aqueous solution [67]. Schematic representation of intracellular transport of heavy metals and its cellular accumulation process is depicted in Fig. 3.

Table 3 outlines the recent research findings on heavy metal accumulation by bacterial species. Bioaccumulation is a toxicokinetic process influenced by the sensitivity of living cells to heavy metals. It depends on the type of bacteria, concentration and metals involved; and could be inhibited by metabolic inhibitors like low temperatures and nutrient deficiency. Moreover, metal ion uptake is dependent on cell age, pH of metal solution and composition of media, initial metal concentration, contact time, and finally the concentration of bacterial cells in aqueous solution. Kinetics of bioaccumulation of metal ions is biphasic with an initial rapid phase rendering 90% of metal uptake, which last for about 10 to 30 min and a gradual second phase of approximately 4 h [68].

Bioaccumulation is a heavy metal bioextration process with numerous application prospects. The essential metal ions are accumulated rapidly than the non-essential ones, and this process could only be realized with live bacterial cells. Genetic engineering works are more focused in this aspect of bacterial process by redesigning the transporter proteins for enhanced passage of preferred metals. Proteomics and its manipulation of metal sequestering proteins are also underway. Evolving research could brighten up the possibilities of bacterial bioaccumulation in heavy metal extraction and recovery.

2.3. Bioprecipitation

Removal of metals from solution by means of precipitation is often coupled with the defence mechanism of bacteria. Cellular metabolism-independent precipitation is due to the chemical interaction of bacterial cell surface and metal ions [22]. Precipitation occurs by reduction, sulfide formation and as phosphates depending on the bacterial species and environment.

2.3.1. Reduction

Reduction process occurs in bacterial species as mentioned earlier. Numerous bacterial strains catalyse the reduction of hazardous selenite [Se(IV)] and selenate [Se(VI)] ionic forms to elemental selenium, which gets deposited as red precipitate over bacterial colonies. Biofilm of *Desulfomicrobium norvegicum*, was shown to precipitate elemental selenium with sulfur [72]. A strain of *Alteromonas (Shewanella) putrefaciens* that normally reduce Mn(*IV*)and Fe(III), was also found to reduce U(VI), producing black precipitate of U(IV) carbonate [73]. *Shewanella oneidensis* MR-1 and two *Geobacter* species reduced Hg(II) to Hg(0) in the presence of electron acceptors [74]. The bacterial species involved in uranium reduction and the mechanisms involved has been thoroughly reviewed by You et al. [75].

Table 3
Recent research reports on bacterial bioaccumulation of heavy metals.

Bacterial species	Heavy metals bioaccumulated	Mode of accumulation	Ref.
Lactobacillus plantarum	Ni, Cr	Reduction	[36]
Bacillus megaterium	Pb, Ni, Cd	Reduction	[69]
Bacillus sp	Pb	Polyphosphate chelation	[59]
Pseudomonas stutzeri	Cd	Sequestration, chelation	[41]
Bacillus xiamenensis	Pb	Sequestration, chelation	[40]
Pseudomonas taiwanensis	As, Cd	Sequestration, enzymatic reduction	[70]
Cupriavidus necator	Cu, Zn	Chelation, reduction	[71]

2.3.2. Metal precipitation as sulphides

Sulphate-reducing bacteria are heterotrophic, obligate anaerobes which oxidizes organic compounds or hydrogen for energy metabolism using sulphate as terminal electron acceptor. It reduces sulphate to sulfide which further combines with available metals in the cell and environment leading to the formation of metal sulphides (Fig. 4). Metal sulphides except alkali and alkaline-earth metals are insoluble and the resultant precipitation of sulphides protect sulphate-reducing bacteria from metal toxicity, and metals protect the organisms from sulfide toxicity, vice versa [19]. Sulphate-reducing bacteria also generate an extremely reducing condition which could bio-chemically reduce metals like U(VI) and Cr(VI) [76].

Enzymatic sulfide formation with the aid of thiosulfate reductase has been reported in *Salmonella typhimurium.* When thiosulfate reductase gene (*phs*ABC) of *S. typhimurium* cloned and highly expressed in *E. coli,* metal-sulfide precipitation happened due to sulfide production from inorganic thiosulfate compounds [77]. *Klebsiella planticola* Cd-resistant strains cultured in thiosulfate supplemented media precipitated substantial quantities of cadmium sulfide (CdS) [78].

2.3.3. Metal precipitation as phosphates

In this precipitation method, the enzyme phosphatase liberates inorganic phosphate (Pi) from cellular organic phosphate like glycerol-2-phosphate, and Pi in turn precipitates metals/ radionuclides as phosphates on the cell (Fig. 4). Immobilized cells of *Citrobacter sp* precipitated Cu, Cd, Pb, and U from glycerol-2-phosphate enriched solutions. Here, phosphatase catalysed glycerol-2-phosphate cleavage released hydrogen phosphates, which precipitated metals extracellularly as insoluble metal phosphates [17]. A mixture of hydrated zirconia (ZrO_2) and $Zr(HPO_4)_2$, was obtained upon mineralization of zirconium by *Citrobacter* sp. [19].

Precipitation can be either metabolically dependent or independent. In metabolically active precipitation, reaction between the molecular compound(s) produced by the bacterial defence system and target metal (s) in medium results in crystallisation of metals. On the other hand, metabolism-independent precipitation is due to chemical interaction between the dissolved heavy metal ions and the reactive radicals on bacterial cell surface (Fig. 4). Metal crystallisation occurs in media/ wastewater/effluent and on the peripheral region of bacterial cells during bioprecipitation, and is dependent on cell metabolism and metal concentration [22]. Recent reports on bioprecipitation of heavy metals by bacteria is comprehensively presented in Table 4.

Alive and dead bacterial cells do exhibit heavy metal precipitation; but dead biomass is less efficient in the process, as only passive interaction of bacterial surface ions and the metal ions in medium is the sole cause of precipitation in latter. The metal recovery is comparatively easy in case of precipitated metals and is suitable to treat mine effluents and electroplating industry sewage.

2.4. Bioleaching

Bioleaching is the solubilization of metals from its natural parent materials such as ore substrates or its crystals suspended or present in contact with the bacterial medium. It occurs directly as a part of bacterial metabolism or indirectly by bacterial metabolic by products. Bioleaching is more often a bio hydrometallurgical method used to recover metals like gold, copper, zinc, arsenic, antimony, cobalt, uranium, bismuth, nickel, molybdenum, lead and vanadium. Mostly, chemolithotrophic, mesophilic bacteria which require metabolic energy sources like ferrous sulphate, pyrite and sulfur are involved in metal

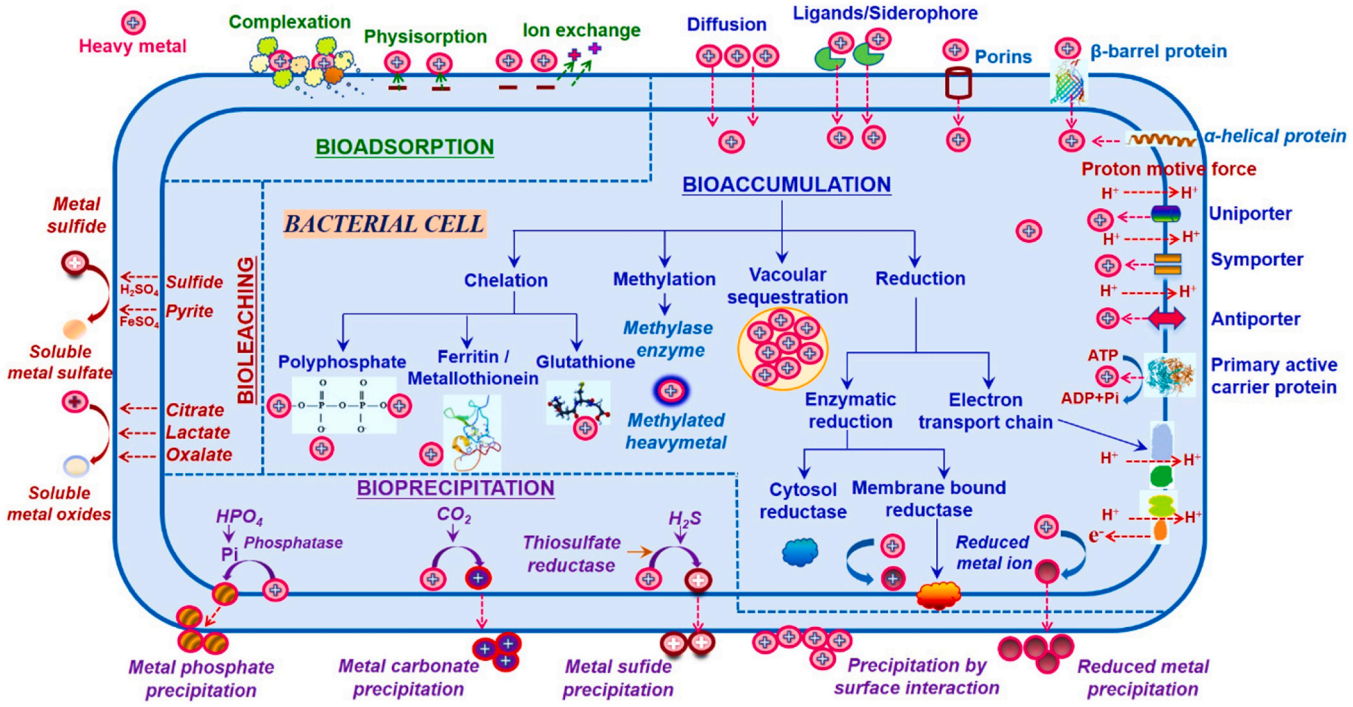


Fig. 4. Schematic representation bioremediation mechanisms exhibited by bacteria. Dotted line compartmentation is provided to differentiate each process separately.

Table 4
Recent research reports on bacterial bioprecipitation of heavy metals.

Bacterial species	Heavy metals bio precipitated	Mode of precipitation	Ref.
Sporosarcina sp	Cu, Zn, Ni, Cd	Enzymatic reduction (Urease)	[79]
Geobacter, Desulfovibrio sp	Fe, Zn, Cu, Mn	Sulphide precipitation, reduction	[80]
Sphingobium sp	Ni	Sulphide precipitation	[81]
Escherichia coli mutant strains	Mn	Passive interaction on cell surface	[82]
Sporosarcina pasteurii, Stenotrophomonas rhizophila, Variovorax boronicumulans	Zn, Pb, Cd	Enzymatic reduction (Urease)	[83]
Stenotrophomonas sp	U	Phosphate precipitation	[84]
Bacillus, Micrococcus	Zn, U, Cu, Cr, Fe	Phosphate precipitation passive interaction on cell surface	[59]
Bacillus atropharus, B.subtilis, B.aryabhattai, B. amyloliquefaciens, Proteus mirabilis	Cd, Ni	Enzymatic reduction (Urease)	[85]
Brochothrix thermosphacta, Vibrio alginolyticus	Al	Passive interaction on cell surface	[86]
Staphylococcus epidermis	Cr, Pb	Enzymatic reduction (Urease)	[87]
Desulfovibrio desulfuricans	Zn	Sulphide precipitation	[88]
Achromobacter xylosoxidans	Pb	Phosphate precipitation	[89]
Bacillus cereus	U	Phosphate precipitation	[90]

leaching. Predominantly iron-oxidizing *Acidithiobacillus ferrooxidans* and sulfur-oxidizing bacteria *Acidithiobacillus thiooxidans* are used in bioleaching. Besides, *Acidophilium, Nirospira, Leptospirilum ferrooxidans, Ferroplasma*, sulfur-oxidizing bacteria-*Acidithiobacillus albertis* and *Acidithiobacillus caldus*, are also used in mine sludge bioleaching. Thermophilic bacteria *Sulfobacillus thermosulfidooxidans* are used for faster bioleaching rate at higher temperatures. Several heterotrophic bacterial species like *Acidophilum, Arthrobactor, Acetobacter, Trichoderma* and *Pseudomonas* are capable of producing organic acids like citric acid, malic acid and oxalic acid. These acid moieties when released to the medium join with metals by supplying both protons and metal complexing anions, thus leading to metal leaching [91].

2.4.1. Sulfide bioleaching

Direct and indirect mechanisms are involved in sulfur based leaching process by bacteria leading to the formation of metal sulfides and its dissolution (Fig. 4). In direct leaching process, bacteria directly contact and react with metal sulfide and oxidize it to soluble metal sulfates like NiS, ZnS, CuS, etc. On the contrary, in indirect bacterial leaching, the sulfur-oxidizing bacteria oxidize reduced sulfur compounds and elemental sulfur to sulfuric acid, thus reducing the pH of the persisting medium consequently augmenting the solubility of metals in solution [91]. Sulfate-reducing bacteria, *Sulfobacillus thermosulfidooxidans, Sulfolobus* sp., *S. acidophilus, Thiobacillus denitrificans*, and *T. thioparus* were successfully applied in the remediation of mine seepage water [92]. Successful removal of Fe, Cu, Zn, As and Ni sulphates from mine drainage using *Desulfovibrio desulfuricans* and *Desulfomicrobium baculatum* strains, has been reported by Sahinkaya et al. [93].

2.4.2. Pyrite leaching

In iron based bioleaching mechanism, reduced sulfur and iron compounds are oxidized through direct or indirect process. Non-iron metal sulphides are oxidized directly by iron-oxidizing bacteria like *Acidithiobacillus ferrooxidans* into soluble metal sulfate (Fig. 4). In direct leaching, bacterial cells adhere selectively to the surface structure of minerals, by chemotactic behavior. On the other hand, in indirect pathway, the bacteria oxidize Fe^{2+} to Fe^{3+}, and the Fe^{3+} in turn react with metals and leaches through chemical reaction. The bacterial cells are not in need of direct contact with minerals during this process. The production of sulfuric acid as a by-product of this mechanism, further

enhances the solubilization process [91]. *Gallionella ferruginea* has been reported to oxidize iron in mine water drainage [94]. Bacteria such as, *Acidithiobacillus thiooxidans, At. ferrooxidans, At. cryptum, Acidiphilium caldus, Acidianus brierleyi, Ochrobactrum anthropic, Citrobacter, Cronobacter, Clostridium, Ferroplasma acidiphilum, Ferribacterium limneticum, Leptospirillum ferrooxidans, L. ferriphilum,* have demonstrated excellent ability in leaching metals from their corresponding ore waste exudates [95]. Latorre et al. [96] has found that L. *ferriphilum* and *At. thiooxidans* leach ores of copper sulfide, and metals like copper and arsenic with better efficiency, by oxidizing iron and thereby reducing inorganic sulfur compounds.

2.4.3. Heterotrophic bacterial leaching

Heterotrophic bacteria, namely *Pseudomonas sp* have the potential to produce acidic metabolites that are capable to extract and solubilize metals from non-sulfidic minerals present in sewage sludge via acidolysis (the formation of organic or inorganic acids), complexation (excretion of complexing agents) and reduction (oxidation and reduction reactions). Currently, heterotrophic bioleaching is mostly applied in metal recovery of gold, silver, titanium, aluminium, nickel, copper, manganese, chromium and uranium from sewage [97]. Heterotrophic bacteria release organic acids, like lactic acid, citric acid, oxalic acid, gluconic acid and phenolic derivatives that have at least two hydrophilic reactive groups capable of dissolving heavy metals by displacing metal ions with hydrogen ions. This process is supplemented by the production of soluble metal chelates and complexes (Fig. 4). Role and interactions of heterotrophic bacterial strains of *Staphylococcus*, *Rhodococcus*, *Pseudomonas aeruginosa* PAO1 and *Cupriavidus metallidurans* with autotrophic bacteria during bioleaching of copper has been delineated by Jeremic et al. [98]. Heterotrophic bacteria, *Bacillus*, NS-1 has been found to increase metal leaching efficiency in electroplating sewage treatment [99].

The solubilised metals could be recovered or removed from solution by using ligands, electro winning, biosorption or solvent extraction. Different factors like temperature, pH, contact time, composition of medium, tolerance towards the metal, biomass concentration, types and quantity of metabolites produced and released by bacterial strains into the medium, affect the bacterial leaching mechanism [100]. Recent research reports on heavy metals leached by bacterial species are tabulated (Table.5).

Bioleaching is a bio-extraction technique to retract metals from its ores. The metals could be biologically dissolved and abstracted. Though the process is gradual, it is eco-friendly, sustainable technique with potential to retrieve precious metals.

Bacteria has turned to be a potent bioremediating agent of heavy metal contaminants from effluents. Bacterial biosorption, accumulation, precipitation and leaching of heavy metals, are inexpensive methods to remediate or stabilize heavy metal pollutants from contaminated water. The boon and bane of each mechanism is enlisted in Table 6. The whole process of bioremediation mechanisms is collectively represented in Fig. 4. Appropriate understanding of cellular mechanism is essential for the accurate selection of strains, for urban and industrial wastewater treatment, which is the most challenging task of degradation and retrieval of heavy metals from e-waste processing by-product exudates. Bacterial heavy metal remediation mechanisms are easy to understand when it refers to a single metal through single pathway or process; but it becomes complicated in the presence of multiple ions, generally encountered in effluents. Standardization of physicochemical parameters that imparts maximum remediation is highly essential for better results. Furthermore, molecular level studies are required to discover the exact and apparent cellular mechanisms exhibited by bacteria to eliminate toxic heavy metals at different conditions and environments. Researchers are exploring novel bacterial species with great heavy metal removal potential and subsequent genetic engineering works are also in

Table 5
Recent research reports on Bacterial bioleaching of heavy metals.

Bacterial species	Heavy metals bioleached	Mode of leaching	Ref.
Pseudomonas putida, P. fluorescens, P. azotoformans	Zn, Mn, Cu, Al	Heterotrophic leaching	[101]
Leptospirillum sp, Acidithiobacillus sp, Acidithiomicrobium sp, Sulfobacillus sp	Ni, Co, Zn, Cu	Sulphide and pyrite leaching	[102]
Acidithiobacillus ferroxidans	Cu, Ni	Sulphide and pyrite leaching	[103]
Acidithiobacillus ferroxidans	Fe, Cu, Pb, Zn	Pyrite and sulphide leaching	[104]
Streptomyces albidoflavus	Al, Cu, Cd, Fe, Ni, Zn, Ag, Pb,	Sulphide leaching	[105]
Acidithiobacillus thiooxidans	Ni, Mo, Al	Sulphide leaching	[106]
Acidithiobacillust thiooxidans	Co, Mn	Sulphide leaching	[107]
Acidithiobacillus ferroxidans	Cu, Ni, Zn, Pb, Cr, Cd	Sulphide and Pyrite leaching	[108]
Sulfobacillus acidophilus, S. thermosulfidooxidans, Acidithiobacillus caldus	Mn, Zn, Ni, Cu, Cr	Sulphide leaching	[109]
Leptospirillum ferriphilum, Sulfobacillus thermosulfidooxidans	Cu	Sulphide and pyrite leaching	[110]
Bacillus sp, Thiobacillus ferroxidans, T. telloxidans	Cd, Cu, Pb	Heterotrophic and Sulphide leaching	[99]

Table 6
Advantages and disadvantages of bacterial heavy metal bioremediation mechanisms.

Mechanism	Advantages	Disadvantages
Bioadsorption	• Both live and dead bacterial biomass perform adsorption • Could be carried out exclusively using bacterial exopolymers • Comparatively simple and fast process • Common heterotrophic and aerobic bacteria could be used for the purpose	• More efficient in alkaline pH • Emulsion and colloids in waste water interfere adsorption process • Oxidation state of metals influence adsorption efficiency
Bioaccumulation	• Accumulation accomplished within 4 to 5 h • It is a bio extraction process without huge sludge production • Genetic engineering could modulate the process and preference of metals to be accumulated	• Only possible with alive bacterial cells • Dependent on concentration gradient of metals on either side of bacterial cell membrane • Optimum physio-chemical parameters and nutrient availability essential for efficient accumulation • Essential metal ions are accumulated faster than non-essential metals • Cells are disrupted for metal recovery, hence cannot be reused
Bioprecipitation	• Both alive and dead cells exhibit precipitation process • Genetic manipulation feasible to enhance the process • Metals could be crystallized in either water or bacterial cell surface • Metals could be easily recovered even by filtration	• Precipitates as sulfides, phosphates carbonates or oxides of metals • Multimetal contamination hinder the process
Bioleaching	• Retrieve metals from its ores • Mostly employed for recovery of precious metals (gold, silver titanium, uranium, etc.,) from mine effluent	• Iron and sulfur bacteria are proficient and efficient for leaching • Gradual process, mostly occurring in low pH

progress. At the same time various bioremediation strategies and protocols has been designed and devised, relying on the inimitable decontamination prospects of bacteria. These techniques have proved application potential in almost all industrial sectors like tannery, textile, electroplating, printing, and municipal sewage, where wastewater treatment is pivotal.

3. Applications of bacterial bioremediation in wastewater treatment

Several bacterial based processes have been developed, implemented and practised for heavy metal remediation in wastewater treatment, which includes both ex-situ and in-situ approaches. The ex-situ techniques crafted and materialized are microbial bioreactors, microbial fuel cell or microbial electrolysis cell and microbial desalination units (Table 7). While, constructed floating wetlands and bioaugmentation are the in-situ bacterial based heavy metal remediation systems (Table 8). Research have evolved from proof-of-concept study, to pilot and full-scale approaches and these remediation protocols and practises have recognized immense application in domestic sewage, landfill leachate, industrial effluent treatment and polluted natural water resource (lakes, ground water, reservoir, etc.) decontamination.

Bioreactors are specially engineered devices that provide optimum conditions to foster the growth and biochemical activity of specific bacterial species for desired remediation purpose. Polluted water samples are fed to the reactor for the removal and retrieval of contaminants. The reactor design and bacterial strain selection depends on the purpose and polluted source, which can be slurry phase, packed bed, fluidised partitioned, suspended carrier, airlift, up-flow anaerobic stage reactor, continuous flow, sequence batch, stirred tank, biofilter based and membrane bioreactors [111–113]. This can be installed at industrial and open leachate sites and its operational procedures and treatment duration varies with the input wastewater parameters and the desired product quality [111].

Microbial fuel cells employ microbes especially bacteria to generate electrons from metabolic reactions. These electrons generated are used for the concomitant reduction/oxidation of heavy metal contaminants, thereby its precipitation at anode chamber; and/or for electron transport to cathode. The electrons reaching cathode combines with the available oxygen; and protons are released and transferred back. A continuous flow of these entities produce energy that could be used for varied purposes [128]. Microbial desalination cell is the integrated process of electrodialysis using microbial fuel cell for the effective treatment of wastewater with simultaneous desalination, electricity generation and metal recovery. Mixed or pure culture of exoelectrogenic bacteria is used for this procedure. *Shewanella putrefaciens*, *Proteobacteria*, *Actinobacteria*, *Pseudomonas*, *Bacillus subtilis* are the major bacterial strains used in microbial desalination cells [132]. Ship spillage was found to be effectively treated using this technique. The ex-situ bacterial bioremediation techniques and its heavy metal removal efficiency are tabulated in Table 7.

Constructed wetland or floating treatment wetland is a novel phyto-microbial technique for the treatment of water bodies to mitigate pollution. These artificial wetlands consist of floating mat, over which vegetative plants are grown and its roots hang in the water column. Bacterial biofilms are attached to these hanging roots and desired endophytic bacteria are also inoculated to the plants [134,135]. These bacterial colonies aid heavy metal adsorption and water

Table 7
Bacterial based ex-situ techniques developed and practiced for heavy metal remediation.

Technology and bacterial species involved	Heavy metals removed with efficiency in percentage (%)	Ref.
Bioreactors		
Desulfovibrio sp	Cu-96.4, Cd-92, Zn-79.8, Fe-71, Pb-61.5, Ni-47.5,	[111]
Desulfovibrio sp	Cu-98.5, Zn-96.3, Fe-95.2, Mn-93.8	[112]
Pseudomonas aeruginosa	Cu-100, Cd-100, Zn-100, Fe-62, Pb-47	[113]
Syntrophobacter, Methanosaeta, Geobacter, Anaerolinea, Longilinea	Cu-99.3, Zn-99.4, Fe-99.9	[114]
Acidothiobacillus ferroxidans	Cu-100, Zn-100, Fe-85, Ni-90, As-95, Co-75, Cr-100	[115]
Kosmotogal, Ruminococcus, Clostridium	Ni-99	[116]
Proteobacteria, Cyanobacteria, Bacteroidetes, Firmicutes, Acidobacteria, Chlorobium, Acinobacteria, Spirochaetes Nitrospirae, Armatimonadetes	Cu-99, Cd-99.7	[117]
Desulfovibrio halophilus	Fe-85.3	[118]
Comamonas, Pseudomonas, Desulfomicrobium, Burkholderia, Halomonas	Hg-88.9	[119]
Ferrovum, Delftia, Acinetobacter, Metallibacterium, Acidibacter, Acidiphilium	Fe-93.7	[120]
Pseudogulbenkiania	Zn-83, Fe-50	[121]
Desulfovibrionaceae	Zn-95, Fe-95, Pb-95, Mn-80	[122]
Microbial fuel (electrolysis) cell		
Desulfovibrio	Cu-98	[123]
Pseudomonas, Geobacter	Cu-87.7, Hg-97.3, Ag-98.5	[124]
Pseudomonas	U-90	[125]
Enterococcus avium	Cu-89.2, Fe-77, Cd-57.5, Pb-97.1, Ni-98.1, Cr-12.4, Tl-91	[126]
Bacillus, Klebsiella, Enterobacter	Cd-88, Pb-90.14, Cr-90.34	[127]
Corynebacterium vitaeruminis	Cr-98.63	[128]
Ochrobactrum, Halomonas, Achromobacter	Cd-87, Ni-92	[129]
Serratia marcescens	Cr-100	[130]
Castellaniella	Cu-99.89, Cd-99.91, Cr-99.59	[131]
Microbial desalination cell		
Acaligenes aquatilis	Cu-91.8, Ni-92.2, Mg-68.5	[132]
Desulfomicrobium, Aquamicrobium, Paracoccus, Stappia, Alcaligenes, Rhodobacterales	Zn, Ca, Mg-99.85(Collective removal)	[133]

Table 8
Bacterial based in-situ techniques developed and practiced for heavy metal remediation.

Technology and bacterial species involved	Heavy metals removed with efficiency in percentage (%)	Ref.
Constructed (floating) wetlands		
Bacillus cereus, Aeromonas salmonicida, Pseudomonas gessardii	Fe-72.5, Pb-40.9, Ni-70.3, Cr-77.7, Mn-83.5	[134]
Acinetobacter junii, Rhodococcus sp, Pseudomonas indoloxydans	Fe-90, Cd-60, Cr-90, Ni-80	[136]
Serratia, Pseudomonas	Cd-99.6, Zn-94.41	[137]
Bacillus endophyticus, Bacillus pumilus, Microbacterium arborescens, Pantonea sp	Fe-89, Cd-72, Cr-97, Ni-88	[138]
Acinetobacter junii, Rhodococcus sp, Pseudomonas indoloxydans	Cu-77.5, Zn-89.7, Fe-81.0, Pb-73.3, Ni-86.9, Mn-70	[139]
Aeromonas salmonicida, Pseudomonas indoloxydans, Bacillus cereus, Pseudomonas gessardii, Rhodococcus sp	Fe-85.7, Pb-91.6, Cr-98.1, Ni-75.3, Mn-85.3	[140]
Pseudomonas aeruginosa, Onchrobactrum sp, Enterobacter	Cr-88	[141]
Bacillus cereus, Paenibacillus alvei, Aeromonas caviae, Paenibacillus taiwanensis, Achromobacter spanius	Cu-95, Pb-93.4	[142]
Proteobacteria, Acidobacteria, Bacteroidetes, Actinobacteria, Firmicutes, Nitrospirae, Spirochaetes, Cyanobacteria	Cu-97.6, Zn-80.1, Cd-74, Ni-69.8, Co-67.1	[143]
Acetoanaerobium, Exiguobacterium	Cu-99	[144]
Bioaugmentation		
Desulfovibrio desulfuricans	Zn-100	[145]
Bacillus, Enterobacter aerogenes, Bacillus pumilus	Cr-96	[146]
Pseudomonas sagittaria	Mn-95	[147]
Aeromonas hydrophila	Cr-93.71	[148]
Klebsiella pneumoniae, Enterobacter cloacae	Cu-81, Zn-77, Fe-39, Cd-19, Cr-51, Pb-50, Ni-73, Mn-53	[149]

decontamination. This procedure is implemented in several regions and sites, and fruitful results were achieved. Bioaugmentation in wastewater decontamination is the addition of selective bacteria (single strain or consortia) to the polluted water bodies. This is done according to the prevailing physiochemical conditions of polluted source, and the heavy metal to be removed. The bacterial strains used and the removal efficiency of in-situ remediation methods is compiled in Table 8.

4. Challenges to meet

Selection of most suitable bacterial strain according to its remediation potential, and process relied is instrumental for the design, development and implementation of bioremediation techniques [150,151]. Genetic engineering has enhanced the efficiency of the technology; but, treatment of huge volumes of wastewater is still a challenge. Though genetic engineering efforts have been practiced for over two decades, its industrial translation faces several impediments [152]. The genetic stability of recombined species is always in speculation, and the incorporation of unnatural amino acids in designed proteins seldom confer unexpected functions, turning the venture risky in distant future [153]. The competency of genetically modified bacteria to thrive in real wastewater effluents and to remediate metals, like that of native wild species is yet to be demonstrated. The capacity of genetically modified species to resist competitive exclusion has to be revealed. Substantial bacterial load of treated water is another challenge to be addressed. Thus, inception to abate the same is a perpetual need to scale up the technology to successfully meet the technoeconomic, environmental risks and assessments. These are the unexplored avenues of research. To advance and promote bacterial based heavy metal remediation techniques, bioprocess level development is recommended. Protocooperation of bacteria with algae has demonstrated better heavy metal remediation in waste water [154]; and more reliable research is essential in this sphere. Research could be routed towards metal recovery as major destination with remediation as the direction to attain the same. A strong understanding of the mechanism inevitably aids to modulate the research in right path. Implementing faster operation procedure and metagenomic manipulation of bacterial remediation process would facilitate to achieve more recognition and popularity to these eco-friendly techniques.

5. Future prospects

Despite several proven research works; bacterial heavy metal remediation technique is mostly confined to laboratory. The major challenge and pitfall of this technology is the lack of large-scale production and commercialization. Development of integrated technologies is imperative to scale up the efficiency and meet the sustainable development goals. Progressive and exploratory research in this regard is essential with in-depth investigations on molecular level remediating mechanisms, modelling of site-specific and adaptive bacterial strains with regeneration capacity. More research works are to be directed towards customising bacterial remediation for bulk quantities of water with faster rate of action, by suitably manipulating the inherent capacity of bacterial strains to remediate heavy metals. Economic feasibility of the bacterial based bioremediation techniques has to be addressed in future research. The multiple benefits of bacterial aided heavy metal remediation have to be popularized, at the same time bacterial kits are to be commercialized; as better availability will obviously promote the prevalence of usage.

6. Conclusions

Bacterium is one of the most versatile microbes with immense bioremediation potential that has to be widely explored and implemented. Bacteria rely on any one of the aforementioned mechanisms or a combination of different mechanisms based on the heavy metals present, prevailing physiochemical factors and the strains involved.

- Bioremediation of heavy metals by bacteria is an eco-friendly, economically feasible and sustainable process and could also act as a treatment process that enhances the efficacy of industrial wastewater treatment.
- Selection and utilization of proper bacterial strains that exhibit tolerance to heavy metals with exceptional remediation properties and adaption skills to the environment are critical for successful bioremediation.
- Research should be further channelled to increase the remediation rate thus to decrease the treatment time concurrently achieving high efficiency. Technical interventions are necessary to elevate the 'bacterial remediation platform' with engineering support. The threats of biofouling and competitive exclusion by the nascent bacteria and microbes in the effluents are to be resolved.
- Procedures to recover metals from bacteria has to be standardised, simplified and effectuated as non-destructive, for the possible reuse of cells.
- Bacterial strains or consortiums proficient to remediate each metal and its different ions are to be well differentiated; at the same time, strains that could act in multi-metal environment have to be recognized and commercialized.

Scientific outputs have to be channelled to industrial sector and have to be publicized, as this technology has proven potential to decontaminate polluted natural water bodies. Expansion and implementation of both ex-situ and in-situ techniques is imperative in different sectors, at the same time, research has to be undertaken to establish its potential in more arenas.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the works reported in this paper.

Acknowledgements

This work was supported by Women Scientist Scheme - A (WOS - A) No. SR/WOS-A/EA-28/2017 (G), Department of Science & Technology, Ministry of Science & Technology, Government of India.

References

[1] L. Järup, Hazards of heavy metal contamination, Br. Med. Bull. 68 (2003) 167–182, https://doi.org/10.1093/bmb/ldg032.
[2] M. Jaishankar, T. Tseten, N. Anbalagn, B.B. Mathew, K.N. Beeregowda, Toxicity mechanisms and health effects of some heavy metals, Interdiscip. Toxicol. 7 (2014) 60–72, https://doi.org/10.2478/intox-2014-0009.
[3] S. Fahad, S. Hussain, S. Saud, S. Hassan, M. Tanveer, M.Z. Ihsan, A.N. Shah, A. Ullah, N.F. Khan, S. Ullah, H. Alharby, W. Nasim, C. Wu, J. Huang, A combined application of biochar and phosphorus alleviates heat-induced adversities on physiological, agronomical and quality attributes of rice, Plant Physiol. Biochem. 103 (2016) 191–198, https://doi.org/10.1016/j.plaphy.2016.03.001.
[4] D.P.J. De Buyck, S.W.H. Van Hulle, A. Dumoulin, D.P.L. Rousseau, Roof runoff contamination: a review on pollutant nature, material leaching and deposition, Rev. Environ. Sci. Biotechnol. 20 (2021) 549–606, https://doi.org/10.1007/s11157-021-09567-z.
[5] B. Wei, L. Yang, A review of heavy metal contaminations in urban soils, urban road dusts and agricultural soils from China, Microchem. J. 94 (2010) 99–107, https://doi.org/10.1016/j.microc.2009.09.014.
[6] World Health Organization, Guidelines for drinking-water quality, 4th edition, incorporating the 1st addendum. https://www.who.int/publications/i/item/9789241549950, 2017.
[7] FAO, Water quality for agriculture - Food and agriculture organization, irrigation and drainage papers. https://www.fao.org/3/t0234e/T0234E06.htm (accessed 17 May 2022).
[8] B.E. Igiri, I.R.O. Stanley, O.I. Grace, P.A. Ebere, O.A. Abraham, K. Ibe, Ejiogu, Toxicity and bioremediation of heavy metals contaminated ecosystem from tannery wastewater: a review, J. Toxicol. 2568038 (2018), https://doi.org/10.1155/2018/2568038.

[9] M. Yadav, R. Gupta, R.K. Sharma, Green and sustainable pathways for wastewater purification, Adv. Water Purif. Tech. (2018) 355–383, https://doi.org/10.1016/B978-0-12-814790-0.00014-4.

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

[11] S. Srivastava, S.B. Agrawal, M.K. Mondal, A review on progress of heavy metal removal using adsorbents of microbial and plant origin, Environ. Sci. Pollut. Res. 22 (2015) 15386–15415, https://doi.org/10.1007/s11356-015-5278-9.

[12] S. Ilyas, M.S. Kim, J.C. Lee, Integration of microbial and chemical processing for a sustainable metallurgy, J. Chem. Technol. Biotechnol. 93 (2018) 320–332, https://doi.org/10.1002/jctb.5402.

[13] D. Kumari, X.Y. Qian, X. Pan, V. Achal, Q. Li, G.M. Gadd, Microbially-induced carbonate precipitation for immobilization of toxic metals, Adv. Appl. Microbiol. 94 (2016) 79–108, https://doi.org/10.1016/bs.aambs.2015.12.002.

[14] Q. Wang, G. Zhou, Y. Qin, R. Wang, H. Li, F. Xu, Y. Du, C. Zhao, H. Zhang, Q. Kong, Sulfate removal performance and co-occurrence patterns of microbial community in constructed wetlands treating saline wastewater, J. Water Process Eng. 43 (2021), 102266, https://doi.org/10.1016/j.jwpe.2021.102266.

[15] L. Liu, M. Bilal, X. Duan, H.M.N. Iqbal, Mitigation of environmental pollution by genetically engineered bacteria-current challenges and future perspectives, Sci. Total Environ. 667 (2019) 444–454, https://doi.org/10.1016/j.scitotenv.2019.02.390.

[16] P. Mandeep, Shukla, microbial nanotechnology for bioremediation of industrial wastewater, Front. Microbiol. 11 (2020) 2411, https://doi.org/10.3389/fmicb.2020.590631.

[17] R. Gupta, P. Ahuja, S. Khan, R.K. Saxena, H. Mohapatra, Microbial biosorbents: meeting challenges of heavy metal pollution in aqueous solutions, Curr. Sci. 78 (2000) 967–973. http://www.jstor.org/stable/24103732.

[18] M.N. Sahmoune, K. Louhab, Kinetic analysis of trivalent chromium biosorption by dead *Streptomyces rimosus* biomass, Arab. J. Sci. Eng. 35 (2010) 69–80.

[19] G.M. Gadd, Accumulation and transformation of metals by microorganisms, in: H. J. Rehm, G. Reed, A. Puhler, P.W. Stadler (Eds.), Biotechnology, A Multi-volume Comprehensive Treatise 10, Wiley-VCH, 2001, pp. 225–264, https://doi.org/10.1002/9783527620937.ch9k.

[20] P.A. Brown, S.A. Gill, S.J. Allen, Metal removal from wastewater using peat, Water Res. 34 (2000) 3907–3916, https://doi.org/10.1016/S0043-1354(00)00152-4.

[21] S. Singh, V. Kumar, D. S. Datta, S. Dhanjal, K. Sharma, J. Samuel, J. Singh, Current advancement and future prospects of biosorbents for bioremediation, Sci. Total Environ. 709 (2020) 135895, https://doi.org/10.1016/j.scitotenv.2019.135895.

[22] N. Ahalya, T.V. Ramachandra, R.D. Kanamadi, Biosorption of heavy metals, Res. J. Chem. Environ. 7 (2003) 71–79. http://wgbis.ces.iisc.ernet.in/energy/water/paper/biosorption_heavymetals/Biosorption.pdf.

[23] S.H. Hasan, P. Srivastava, M. Talat, Biosorption of Pb (II) from water using biomass of Aeromonas hydrophila: central composite design for optimization of process variables, J. Hazard. Mater. 168 (2009) 1155–1162, https://doi.org/10.1016/j.jhazmat.2009.02. 142.

[24] A. Selatnia, A. Boukazoula, N. Kechid, M.Z. Bakhti, A. Chergui, Y. Kerchich, Biosorption of lead (II) from aqueous solution by a bacterial dead *Streptomyces rimosus* biomass, Biochem. Eng. J. 19 (2004) 127–135, https://doi.org/10.1016/j.bej.2003.12.007.

[25] Q. Li, L. Chai, Z. Yang, Q. Wang, Kinetics and thermodynamics of Pb (II) adsorption onto modified spent grain from aqueous solutions, Appl. Surf. Sci. 255 (2009) 4298–4303, https://doi.org/10.1016/j.apsusc.2008.11.024.

[26] G.M. Naja, V. Murphy, B. Volesky, Biosorption, metals, in: M.C. Flickinger (Ed.), Encyclopedia of Industrial Biotechnology: Bioprocess, Bioseparation, and Cell Technology, Wiley, Hoboken, NJ, USA, 2010, pp. 1–29, https://doi.org/10.1002/9780470054581.eib166.

[27] A. López, N. Lázaro, J.M. Priego, A.M. Marqués, Effect of pH on the biosorption of nickel and other heavy metals by *Pseudomonas fluorescens* 4F39, J. Ind. Microbiol. Biotech. 24 (2000) 146–151, https://doi.org/10.1038/sj.jim.2900793.

[28] W.C. Leung, M.F. Wong, H. Chua, W. Lo, P.H.F. Yu, C.K. Leung, Removal and recovery of heavy metals by bacteria isolated from activated sludge treating industrial effluents and municipal wastewater, Water Sci. Technol. 41 (2000) 233–240, https://doi.org/10.2166/wst.2000.0277.

[29] Y. Sag, T. Kutsal, Recent trends in the biosorption of heavy metals: a review, Biotechnol.Bioprocess Eng. 6 (2001) 376–385, https://doi.org/10.1007/BF02932318.

[30] H. An, T. Tian, Z. Wang, R. Jin, J. Zhou, Role of extracellular polymeric substances in the immobilization of hexavalent chromium by *Shewanella putrefaciens* CN32 unsaturated biofilms, Sci. Total Environ. 810 (2022), 151184, https://doi.org/10.1016/j.scitotenv.2021.151184.

[31] C.-J. Tang, X. Chen, F. Feng, Z.-G. Liu, Y.-X. Song, Y.-Y. Wang, X. Tang, Roles of bacterial cell and extracellular polymeric substance on adsorption of Cu(II) in activated sludges: a comparative study, J. Water Process Eng. 41 (2021), 102094, https://doi.org/10.1016/j.jwpe.2021.102094.

[32] B. Sharma, P. Shukla, Lead bioaccumulation mediated by *Bacillus cereus* BPS-9 from an industrial waste contaminated site encoding heavy metal resistant genes and their transporters, J. Hazard. Mater. 401 (2021), 123285, https://doi.org/10.1016/j.jhazmat.2020.123285.

[33] R. Sharma, T. Jasrotia, R. Kumar, R. Kumar, A.U. Fahad, A. Alharth, A. A. Alghamdi, N.A. Zaqri, An insight into the mechanism of symbiotic-bioremoval of heavy metal ions from synthetic and industrial samples using bacterial consortium, Environ. Technol. Innov. 21 (2021), 101302, https://doi.org/10.1016/j.eti.2020.101302.

[34] W. Mwandira, K. Nakashima, S. Kawasaki, A. Arabelo, K. Banda, I. Nyambe, M. Chirwa, M. Ito, T. Sato, T. Igarashi, H. Nakata, S. Nakayama, M. Ishizuka, Biosorption of Pb (II) and Zn (II) from aqueous solution by *Oceanobacillus profundus* isolated from an abandoned mine, Sci. Rep. 10 (2020) 21189, https://doi.org/10.1038/s41598-020-78187-4.

[35] W.A.H. Altowayti, S.A. Haris, H. Almoalemi, S. Shahi, Z. Zakaria, S. Ibrahim, The removal of arsenic species from aqueous solution by indigenous microbes: batch bioadsorption and artificial neural network model, Environ. Technol. Innov. 19 (2020), 100830, https://doi.org/10.1016/j.eti.2020.100830.

[36] F.A. Ameen, A.M. Hamdan, M.Y. El-Naggar, Assessment of the heavy metal bioremediation efficiency of the novel marine lactic acid bacterium, *Lactobacillus plantarum* MF042018, Sci. Rep. 10 (2020) 314, https://doi.org/10.1038/s41598-019-57210-3.

[37] A. Rizvi, B. Ahmed, A. Zaidi, M.S. Khan, Biosorption of heavy metals by dry biomass of metal tolerant bacterial biosorbents: an efficient metal clean-up strategy, Environ. Monit. Assess. 192 (2020) 801, https://doi.org/10.1007/s10661-020-08758-5.

[38] D. Cui, C. Tan, H. Deng, X. Gu, S. Pi, T. Chen, L. Zhou, A. Li, Biosorption mechanism of aqueous Pb^{2+}, Cd^{2+}, and Ni^{2+} ions on extracellular polymeric substances (EPS), Archea 8891543 (2020), https://doi.org/10.1155/2020/8891543.

[39] R. Jobby, P. Jha, A. Gupta, A. Gupte, N. Desai, Biotransformation of chromium by root nodule bacteria *Sinorhizobium sp*. SAR1, Plos One 14 (2019), e0219387, https://doi.org/10.1371/journal.pone.0219387.

[40] R.K. Mohapatra, P.K. Parhi, S. Pandey, B.K. Bindhani, H. Thatoi, C.R. Panda, Active and passive biosorption of Pb(II) using live and dead biomass of marine bacterium *Bacillus xiamenensis* PbRPSD202: kinetics and isotherm studies, J. Environ. Manag. 247 (2019) 121–134, https://doi.org/10.1016/j.jenvman.2019.06.073.

[41] J. Li, Y.R. Liu, L.M. Zhang, J.Z. He, Sorption mechanism and distribution of cadmium by different microbial species, J. Environ. Manag. 237 (2019) 552–559, https://doi.org/10.1016/j.jenvman.2019.02.057.

[42] A.S. Ayangbenro, O.O. Babalola, O.S. Aremu, Bioflocculant production and heavy metal sorption by metal resistant bacterial isolates from gold mining soil, Chemosphere 231 (2019) 113–120. https://doi.org/10.1016/j.Chemosphere.2019.05.092.

[43] H. Peng, W. Xie, D. Li, M. Wu, Y. Zhang, H. Xu, J. Ye, T. Ye, L. Xu, Y. Liang, W. Liu, Copper-resistant mechanism of *Ochrobactrum* MT180101 and its application in membrane bioreactor for treating electroplating wastewater, Ecotoxicol. Environ. Saf. 168 (2019) 17–26, https://doi.org/10.1016/j.ecoenv.2018.10.066.

[44] P. Diep, R. Mahadevan, A.F. Yakunin, Heavy metal removal by bioaccumulation using genetically engineered microorganisms, Front. Bioeng. Biotechnol. 6 (2018) 157, https://doi.org/10.3389/fbioe.2018.00157.

[45] R. Krishnaswamy, D.B. Wilson, Construction and characterization of an *Escherichia coli* strain genetically engineered for Ni(II) bioaccumulation, Appl. Environ. Microbiol. 66 (2000) 5383–5386, https://doi.org/10.1128/AEM.66.12.5383-5386.2000.

[46] R. Gogada, S.S. Singh, S.K. Lunavat, M.M. Pamarthi, A. Rodrigue, B. Vadivelu, P.-B. Phanithi, V. Gopala, S.K. Apte, Engineered *Deinococcus radiodurans* R1 with NiCoT genes for bioremoval of trace cobalt from spent decontamination solutions of nuclear power reactors, Appl. Microbiol. Biotechnol. 99 (2015) 9203–9213, https://doi.org/10.1007/s00253-015-6761-4.

[47] X. Deng, J. He, N. He, Comparative study on Ni^{2+}-affinity transport of nickel/cobalt permeases (NiCoTs) and the potential of recombinant *Escherichia coli* for Ni^{2+} bioaccumulation, Bioresour. Technol. 130 (2013) 69–74, https://doi.org/10.1016/j.biortech.2012.11.133.

[48] H.S. Kang, S. Singh, J.Y. Kim, W. Lee, A. Mulchandani, W. Chen, Bacteria metabolically engineered for enhanced phytochelatin production and cadmium accumulation, Appl. Environ. Microbiol. 73 (2007) 6317–6320, https://doi.org/10.1128/AEM.01237-07.

[49] S. Chang, H. Shu, The construction of an engineered bacterium to remove cadmium from wastewater, Water Sci. Technol. 70 (2013) 2015–2021, https://doi.org/10.2166/wst.2014.448.

[50] N. Zagorski, D.B. Wilson, Characterization and comparison of metal accumulation in two *Escherichia coli* strains expressing either CopA or MntA, heavy metal-transporting bacterial P-type adenosine triphosphatases, Appl. Biochem. Biotechnol. 117 (2004) 33–48, https://doi.org/10.1385/ABAB:117:1:33.

[51] S.M. Glasauer, T.J. Beveridge, E.P. Burford, F.A. Harper, G.M. Gadd, Metals and metalloids, transformation by microorganisms, in: Encyclopedia Soils Environ, 2005, pp. 438–447, https://doi.org/10.1016/B978-0-12-409548-9.05217-9.

[52] E. Ahmed, S.J. Holmström, Siderophores in environmental research: roles and applications, Microb. Biotechnol. 7 (2014) 196–208, https://doi.org/10.1111/1751-7915.12117.

[53] T. Rezanka, A. Palyzová, A. Faltýšková, K. Sigler, Siderophores: amazing metabolites of microorganisms, Stud. Nat. Prod. Chem. 60 (2018) 157–188, https://doi.org/10.1016/B978-0-444-64181-6.00005-X.

[54] T. Fukushima, B.E. Allred, A.K. Sia, R. Nichiporuk, U.N. Andersen, K.N. Raymond, Gram-positive siderophore shuttle with iron-exchange from fe-siderophore to apo-siderophore by *Bacillus cereus* YxeB, Proc. Natl. Acad. Sci. U. S. A. 110 (2013) 13821–13826, https://doi.org/10.1073/pnas.1304235110.

[55] K. Ramasamy, S. Kamaludeen, B. Parwin, Bioremediation of metals: microbial processes and techniques, in: S.N. Singh, R.D. Tripathi (Eds.), Environmental

Bioremediation Technologies, Springer Publication, New York, USA, 2006, pp. 173–187.
[56] S.K. Joshua, L. Oded, Bacterial ATP-driven transporters of transition metals: physiological roles, mechanisms of action, and roles in bacterial virulence, Metallomics 3 (2011) 1098–1108, https://doi.org/10.1039/c1mt00073j.
[57] W. Bae, W. Chen, A. Mulchandani, R.K. Mehra, Enhanced bioaccumulation of heavy metals by bacterial cells displaying synthetic phytochelatins, Biotechnol. Bioeng. 70 (2000) 518–524, https://doi.org/10.1002/1097-0290(20001205)70:5<518:AID-BIT6>3.0.CO;2-5.
[58] A.I.G. Lima, S.C. Corticeiro, E.M.D.P. Figueira, Glutathione-mediated cadmium sequestration in *Rhizobium leguminosarum*, Enzym. Microb. Technol. 39 (2006) 763–769, https://doi.org/10.1016/j.enzmictec.2005.12.009.
[59] F. Jroundi, F. Martinez-Ruiz, M.L. Merroun, M.T. Gonzalez-Muñoz, Exploring bacterial community composition in Mediterranean deep-sea sediments and their role in heavy metal accumulation, Sci. Total Environ. 712 (2020), 135660, https://doi.org/10.1016/j.scitotenv.2019.135660.
[60] B. Thamdrup, Bacterial manganese and iron reduction in aquatic sediments, in: Bernhard Schink (Ed.), Advances in Microbial Ecology 16, Springer, Boston, MA, 2000, pp. 41–84, https://doi.org/10.1007/978-1-4615-4187-52.
[61] Y.V. Nancharaiah, P.N. Lens, Ecology and biotechnology of selenium-respiring bacteria, Microbiol Mol Biol Rev. 79 (2015) 61–80, https://doi.org/10.1128/MMBR.00037-14.
[62] M.E. Mabrouk, M.A. Arayes, S.A. Sabry, Hexavalent chromium reduction by chromate-resistant haloalkaliphilic *Halomonas* sp. M-Cr newly isolated from tannery effluent, Biotechnol. Biotechnol. Equip. 28 (2014) 659–667, https://doi.org/10.1080/13102818.2014.937092.
[63] S. Focardi, M. Pepi, G. Landi, S. Gasperini, R. Marcella, P.D. Biasio, S.E. Focardi, Hexavalent chromium reduction by whole cells and cell free extract of the moderate halophilic bacterial strain *Halomonas* sp. TA-04, Int. Biodeterior. Biodegradation 66 (2012) 63–70, https://doi.org/10.1016/j.ibiod.2011.11.003.
[64] K. Kalimuthu, R. Suresh Babu, D. Venkataraman, M. Bilal, S. Gurunathan, Biosynthesis of silver nanocrystals by *Bacillus licheniformis*, Colloids Surf. B Biointerfaces 65 (2008) 150–153, https://doi.org/10.1016/j.colsurfb.2008.02.018.
[65] D.M. Voica, L. Bartha, H.L. Banciu, A. Oren, Heavy metal resistance in halophilic bacteria and archaea, FEMS Microbiol. Lett. 363 (2016) 146, https://doi.org/10.1093/femsle /fnw146.
[66] S. Mohanty, S. Ghosh, B. Bal, A.P. Das, A review of biotechnology processes applied for manganese recovery from wastes, Rev. Environ. Sci. Biotechnol. 17 (2018) 791–811, https://doi.org/10.1007/s11157-018-9482-1.
[67] R.P. Mason, The methylation of metals and metalloids in aquatic systems, in: Anica Dricu (Ed.), Methylation-From DNA, RNA and Histones to Diseases and Treatment, In Tech Open, 2012, https://doi.org/10.5772/51774.
[68] J. Kadukova, E. Vircikova, Comparison of differences between copper bioaccumulation and biosorption, Environ. Int. 31 (2005) 227–232, https://doi.org/10.1016/j.envint.2004.09.020.
[69] K.L. Njoku, O.R. Akinyede, O.F. Obidi, Microbial remediation of heavy metals contaminated media by *Bacillus megaterium* and *Rhizopus stolonifera*, Sci. Afr. 10 (2020), e00545, https://doi.org/10.1016/j.sciaf.2020.e00545.
[70] P. Satapute, M.K. Paidi, M. Kurjogi, S. Jogaiah, Physiological adaptation and spectral annotation of arsenic and cadmium heavy metal-resistant and susceptible strain *Pseudomonas taiwanensis*, Environ. Pollut. 251 (2019) 555–563, https://doi.org/10.1016/j.envpol. 2019.05.054.
[71] R.P. Vicentin, J.V. Santos, C.R.G. Labory, A.M. Costa, F.M.S. Moreira, E. Alves, Tolerance to and accumulation of cadmium, copper, and zinc by *Cupriavidus necator*, Rev. Bras. Ciênc. Solo 42 (2018), e0170080, https://doi.org/10.1590/18069657rbcs20170080.
[72] S. Hockin, G. Gadd, Linked redox precipitation of sulfur and selenium under anaerobic conditions by sulfate-reducing bacterial biofilms, Appl. Environ. Microbiol. 69 (2004) 7063–7072, https://doi.org/10.1128/AEM.69.12.7063-7072.2003.
[73] J.K. Fredrickson, J.M. Zachara, D. Kennedy, M. Duff, Y. Gorby, S. Li, K. Kenneth, Reduction of U(VI) in goethite (α-FeOOH) suspensions by a dissimilatory metal-reducing bacterium, Geochim. Cosmochim. Acta 64 (2000) 3085–3098, https://doi.org/10.1016/S00167037(00)00397-5.
[74] H.A. Wiatrowski, P.M. Ward, T. Barkay, Novel reduction of mercury (II) by mercury-sensitive dissimilatory metal reducing bacteria, Environ. Sci. Technol. 40 (2006) 6690–6696, https://doi.org/10.1021/es061046g.
[75] W. You, W. Peng, Z. Tian, M. Zheng, Uranium bioremediation with U(VI)-reducing bacteria, Sci. Total Environ. 798 (2021), 149107, https://doi.org/10.1016/j.scitotenv.2021.149107.
[76] J.R. Spear, L.A. Figueroa, B.D. Honeyman, Modelling reduction of uranium U(VI) under variable sulfate concentrations by sulfate-reducing bacteria, Appl. Environ. Microbiol. 66 (2000) 3711–3721, https://doi.org/10.1128/aem.66.9.3711-3721.2000.
[77] S.W. Bang, D.S. Clark, J.D. Keasling, Engineering hydrogen sulfide production and cadmium removal by expression of the thiosulfate reductase gene (phs ABC) from *Salmonella enterica* serovar typhimurium in *Escherichia coli*, Appl. Environ. Microbiol. 66 (2000) 3939–3944, https://doi.org/10.1128/aem.66.9.3939-3944.2000.
[78] P.K. Sharma, D.L. Balkwill, A. Frenkel, M.A. Vairavamurthy, A new *Klebsiella planticola* strain (Cd-1) grows anaerobically at high cadmium concentrations and precipitates cadmium sulfide, Appl. Environ. Microbiol. 66 (2000) 3083–3087, https://doi.org/10.1128/aem.66.7.3083-3087.2000.
[79] S. Qiao, G. Zeng, X. Wang, C. Dai, M. Sheng, Q. Chen, F. Xu, H. Xu, Multiple heavy metals immobilization based on microbially induced carbonate precipitation by ureolytic bacteria and the precipitation patterns exploration, Chemosphere 274 (2021), 129661, https://doi.org/10.1016/j.chemosphere.2021.129661.
[80] E.W. Nogueira, L.A. Gouvêa de Godoi, L.N. Marques Yabuki, M.H.R.Z. Brucha Damianovic, Sulphate and metal removal from acid mine drainage using sugarcane vinasse as electron donor: performance and microbial community of the down-flow structures bed bioreactor, Bioresour. Technol. 330 (2021), 124968, https://doi.org/10.1016/j.biortech.2021.124968.
[81] J. Chen, N. Li, S. Han, Y. Sun, L. Wang, Z. Qu, M. Dai, G. Zhao, Characterization and bioremediation potential of nickel-resistant endophytic bacteria isolated from the wetland plant *Tamarix chinensis*, FEMS Microbiol. Lett. 367 (2020), fnaa098, https://doi.org/10.1093/femsle/fnaa098.
[82] T. Couasnon, D. Alloyeau, B. Menez, F. Guyot, J.M. Ghigo, A. Gelabert, In situ monitoring of exopolymer-dependent Mn mineralization on bacterial surfaces, Sci. Adv. 6 (2020), eaaz3125, https://doi.org/10.1126/sciadv.aaz3125.
[83] N. Jalilvand, A. Akhgar, H.A. Alikhani, H.A. Rahmani, F. Rejali, Removal of heavy metals zinc, lead, and cadmium by biomineralization of urease-producing bacteria isolated from iranian mine calcareous soils, J. Soil Sci. Plant Nutr. 20 (2020) 206–219, https://doi.org/10.1007/s42729-019-00121-z.
[84] S.I. Castro, P. Martínez-Rodríguez, F. Jorundi, P.L. Solari, M. Descostes, M. L. Merroun, High-efficient microbial immobilization of solved U(VI) by the *Stenotrophomonas* strain Br8, Water Res. 183 (2020), 116110, https://doi.org/10.1016/j.watres.2020.116110.
[85] H.J. Khadim, S.H. Ammar, S.E. Ebrahim, Biomineralization based remediation of cadmium and nickel contaminated wastewater by ureolytic bacteria isolated from barn horse soil, Environ. Technol. Innov. 14 (2019), 100315, https://doi.org/10.1016/j.eti.2019.100315.
[86] I.F. Purwanti, S.B. Kurniawan, N.I. Ismail, M.F. Imron, S.R.S. Abdullah, Aluminium removal and recovery from wastewater and soil using isolated indigenous bacteria, J. Environ. Manag. 249 (2019), 109412, https://doi.org/10.1016/j.jenvman.2019.109412.
[87] J. He, X. Chen, Q. Zhang, V. Achal, More effective immobilization of divalent lead than hexavalent chromium through carbonate mineralization by *Staphylococcus epidermidis* HJ2, Int. Biodeterior. Biodegrad. 140 (2019) 67–71, https://doi.org/10.1016/j.ibiod.2019.03.012.
[88] S.K. Hwang, E.H. Jho, Heavy metal and sulfate removal from sulfate-rich synthetic mine drainages using sulfate reducing bacteria, Sci. Total Environ. 635 (2018) 1308–1316, https://doi.org/10.1016/j.scitotenv.2018.04.231.
[89] J. Sharma, K. Shamim, S.K. Dubey, Phosphatase mediated bioprecipitation of lead as pyromorphite by *Achromobacterxylos oxidans*, J. Environ. Manag. 217 (2018) 754–761, https://doi.org/10.1016/j.jenvman.2018.04.027.
[90] J. Zhang, H. Song, Z. Chen, S. Liu, Y. Wei, J. Huang, C. Guo, Z. Dang, Z. Lin, Biomineralization mechanism of U(VI) induced by *Bacillus cereus* 12–2: the role of functional groups and enzymes, Chemosphere 206 (2018) 682–692, https://doi.org/10.1016/j.chemosphere.2018.04.181.
[91] T. Kamizela, M. Worwag, Processing of water treatment sludge by bioleaching, Energies 13 (2020) 6539, https://doi.org/10.3390/en13246539.
[92] H.M. Anawar, Sustainable rehabilitation of mining waste and acid mine drainage using geochemistry, mine type, mineralogy, texture, ore extraction and climate knowledge, J. Environ. Manag. 158 (2015) 111–121, https://doi.org/10.1016/j.jenvman.2015.04.045.
[93] E. Sahinkaya, A. Yurtsever, Y. Toker, H. Elcik, M. Cakmaci, A.H. Kaksonen, Biotreatment of As-containing simulated acid mine drainage using laboratory scale sulfate reducing upflow anaerobic sludge blanket reactor, Minerals Eng. 75 (2015) 133–139, https://doi.org/10.1016/j.mineng.2014.08.012.
[94] K. Hallberg, New perspectives in acid mine drainage microbiology, Hydrometallurgy 104 (2010) 48–453, https://doi.org/10.1016/j.hydromet.2009.12.013.
[95] A. Schippers, A. Breuker, A. Blazejak, K. Bosecker, D. Kock, T. Wright, The biogeochemistry and microbiology of sulfidic mine waste and bioleaching dumps and heaps, and novel Fe (II)-oxidizing bacteria, Hydrometallurgy 104 (2010) 342–350, https://doi.org/10.1016/j.hydromet.2010.01.012.
[96] M. Latorre, M.P. Cortés, D. Travisany, A. Di Genova, M. Budinich, A. Reyes-Jara, C. Hödar, M. González, P. Parada, R.A. Bobadilla-Fazzini, V. Cambiazo, A. Maass, The bioleaching potential of a bacterial consortium, Bioresour. Technol. 218 (2016) 659–666, https://doi.org/10.1016/j.biortech.2016.07.012.
[97] W.X. Ren, P.J. Li, N. He, S.X. Fan, E.V. Verkhozina, Application of heterotrophic microorganisms in metals removal by bioleaching, Chin.J. Ecol. 26 (2007) 1835–1841.
[98] S. Jeremic, V.P. Beškoski, L. Djokic, B. Vasiljevic, M.M. Vrvić, J. Avdalović, G. Gojgić Cvijović, L.S. Beškoski, J. Nikodinovic-Runic, Interactions of the metal tolerant heterotrophic microorganisms and iron oxidizing autotrophic bacteria from sulphidic mine environment during bioleaching experiments, J. Environ. Manag. 172 (2016) 151–161, https://doi.org/10.1016/j.jenvman.2016.02.041.
[99] C. Liu, Q. Ma, X. Zhou, H. Lai, L. Li, Bioleaching of heavy metals from sludge by mixed strains, IOP Conf. Series: Earth Environ. Sci. 208 (2018), 012077, https://doi.org/10.1088/1755-1315/208/1/012077.
[100] F. Vakilchap, S.M. Mousavi, S.A. Shojaosadati, Role of *Aspergillus niger* in recovery enhancement of valuable metals from produced red mud in Bayer process, Bioresour. Technol. 218 (2016) 991–998, https://doi.org/10.1016/j.biortech.2016.07.059.
[101] A.J. Williamson, K. Folens, S. Matthijs, Y.P. Cortez, J. Varia, G.D. Laing, N. Boon, T. Hennebel, Selective metal extraction by biologically produced siderophores during bioleaching from low-grade primary and secondary mineral resources, Miner. Eng. 163 (2021), 106774, https://doi.org/10.1016/j.mineng.2021.106774.

[102] A. Hubau, A.G. Guezennec, C. Joulian, C. Falagán, D. Dew, A. Karen, H. Edwards, Bioleaching to reprocess sulfidic polymetallic primary mining residues: determination of metal leaching mechanisms, Hydrometallurgy 197 (2020), 105484, https://doi.org/10.1016/j.hydromet.2020. 105484.
[103] M. Arshadi, S. Yaghmaei, Bioleaching of basic metals from electronic waste PCBs, J. Mining Mech. Eng. 1 (2020) 51–58, https://doi.org/10.32474/JOMME.2020.01.000108.
[104] D. Rouchalova, K. Rouchalova, I. Janakova, C. Vladimir, J. Sarah, Bioleaching of iron, copper, lead, and zinc from the sludge mining sediment at different particle sizes, pH, and pulp density using *Acidithiobacillus ferrooxidans*, Minerals 10 (2020) 1013, https://doi.org/10.3390/min10111013.
[105] D. Kaliyaraj, M. Rajendran, V. Angamuthu, A.R. Antony, M. Kaari, T. Shanmugasundaram, G. Venogopal, J. Joseph, M. Radhakrishnan, Bioleaching of heavy metals from printed circuit board (PCB) by *Streptomyces albidoflavus* TN10 isolated from insect nest, Bioresour. Bioprocess. 6 (2019) 47, https://doi.org/10.1186/s40643-019-0283-3.
[106] A. Pathak, H. Srichandan, D.J. Kim, Column bioleaching of metals from refinery spent catalyst by *Acidithiobacillus thiooxidans*: effect of operational modifications on metal extraction, metal precipitation, and bacterial attachment, J. Environ. Manag. 242 (2019) 372–383, https://doi.org/10.1016/j.jenvman.2019.04.081.
[107] T. Naseri, N.B. Horeh, S.M. Mousavi, Environmentally friendly recovery of valuable metals from spent coin cells through two-step bioleaching using *Acidithiobacillus thiooxidans*, J. Environ. Manag. 235 (2019) 357–367, https://doi.org/10.1016/j.jenvman.2019.01.086.
[108] W. Gu, J. Bai, L. Lu, X. Zhuang, J. Zhao, W. Yuan, C. Zhang, J. Wang, Improved bioleaching efficiency of metals from waste printed circuit boards by mechanical activation, Waste Manag. 98 (2019) 21–28, https://doi.org/10.1016/j.wasman.2019.08.013.
[109] S.-Y. Chen, Y.-K. Cheng, Effects of sulfur dosage and inoculum size on pilot-scale thermophilic bioleaching of heavy metals from sewage sludge, Chemosphere 234 (2019) 346–355, https://doi.org/10.1016/j.chemosphere.2019.06.084.
[110] W. Wu, X. Liu, X. Zhang, M. Zhu, W. Tan, Bioleaching of copper from waste printed circuit boards by bacteria-free cultural supernatant of iron–sulfur-oxidizing bacteria, Bioresour. Bioprocess 5 (2018) 10, https://doi.org/10.1186/s40643-018-0196-6.
[111] M.G. Kiran, K. Pakshirajan, G. Das, Heavy metal removal from aqueous solution using sodium alginate immobilized sulfate reducing bacteria: mechanism and process optimization, J. Environ. Manag. 218 (2018) 486–496, https://doi.org/10.1016/j.jenvman.2018.03.020.
[112] Z. Liu, L. Li, Z. Li, X., Tian removal of sulfate and heavy metals by sulfate-reducing bacteria in an expanded granular sludge bed reactor, Environ. Technol. 39 (2018) 1814–1822, https://doi.org/10.1080/09593330.2017.1340347.
[113] A.E.D.M. Ibrahim, S. Hamdona, M. El-Naggar, et al., Heavy metal removal using a fixed bed bioreactor packed with a solid supporter, Beni-Suef Univ. J. Basic Appl. Sci. 8 (2019) 43088, https://doi.org/10.1186/s43088-019-0002-3.
[114] A. Giordani, R.R. Piacentini, S.G. Patrícia, H.E. Ayumi, B. Euzébio, B. Gunther, Effect of low pH and metal content on microbial community structure in an anaerobic sequencing batch reactor treating acid mine drainage, Miner. Eng. 141 (2019), 105860, https://doi.org/10.1016/j.mineng.2019.105860.
[115] K. Kamde, R. Dahake, R.A. Pandey, A. Bansiwal, Integrated bio-oxidation and adsorptive filtration reactor for removal of arsenic from wastewater, Environ. Technol. 40 (2019) 1337–1348, https://doi.org/10.1080/09593330.2017.1422547.
[116] J.P. Aguilar, V.R. Martínez, G.B. Francisco, J.A. Tapia, G.M. Meza, Ramiro V. Vargas, L. Alexander, M.T. Certucha-Barragán, K. Calderón, Removal of nickel (II) from wastewater using a zeolite-packed anaerobic bioreactor: bacterial diversity and community structure shifts, J. Environ. Manag. 279 (2021), 111558, https://doi.org/10.1016/j.jenvman.2020.111558.
[117] C. Tang, P. Sun, J. Yang, Y. Huang, Y. Wu, Kinetics simulation of Cu and Cd removal and the microbial community adaptation in a periphytic biofilm reactor, Bioresour. Technol. 276 (2019) 199–203, https://doi.org/10.1016/j.biortech.2019.01.001.
[118] M.E. Torbaghan, G.H.K. Torghabeh, Biological removal of iron and sulfate from synthetic wastewater of cotton delinting factory by using halophilic sulfate-reducing bacteria, Heliyon 5 (2019), e02948, https://doi.org/10.1016/j.heliyon.2019.e02948.
[119] Z. Wei, S. Yu, Z. Huang, X. Xiao, M. Tang, B. Li, X. Zhang, Simultaneous removal of elemental mercury and NO by mercury induced thermophilic community in membrane biofilm reactor, Ecotoxicol. Environ. Saf. 176 (2019) 170–177, https://doi.org/10.1016/j.ecoenv.2019.03.082.
[120] H. Chen, T. Xiao, Z. Ning, Q. Li, E. Xiao, Y. Liu, Q. Xiao, X. Lan, L. Ma, F. Lu, In-situ remediation of acid mine drainage from abandoned coal mine by filed pilot-scale passive treatment system: performance and response of microbial communities to low pH and elevated Fe, Bioresour. Technol. 317 (2020), 123985, https://doi.org/10.1016/j.biortech.2020.123985.
[121] K. Jokai, T. Nakamura, S. Okabe, S. Ishii, Simultaneous removal of nitrate and heavy metals in a continuous flow nitrate-dependent ferrous iron oxidation (NDFO) bioreactor, Chemosphere 262 (2021), 127838, https://doi.org/10.1016/j.chemosphere.2020.127838.
[122] D.K. Villa Gomez, A. Serrano, M. Peces, B. Ryan, H. Hofmann, G. Southam, A sequential bioreactor adaption strategy enhanced the precipitation of metals from tailings' leachates, Miner. Eng. 170 (2021), 107051, https://doi.org/10.1016/j.mineng.2021.107051.
[123] W. Miran, J. Jang, M. Nawaz, A. Shahzad, S.E. Jeong, C.O. Jeon, D.S. Lee, Mixed sulfate-reducing bacteria-enriched microbial fuel cells for the treatment of wastewater containing copper, Chemosphere 189 (2017) 134–142, https://doi.org/10.1016/j.chemosphere.2017.09.048.
[124] M.S. Wu, X. Xu, Q. Zhao, Z.Y. Wang, Simultaneous removal of heavy metals and biodegradation of organic matter with sediment microbial fuel cells, RSC Adv. 77 (2017) 53433–53438, https://doi.org/10.1039/C7RA11103G.
[125] A. Vijay, A. Khandelwal, M. Chhabra, T. Vincent, Microbial fuel cell for simultaneous removal of uranium (VI) and nitrate, Chem. Eng. J. 388 (2020), 124157, https://doi.org/10.1016/j.cej.2020.124157.
[126] J. Yan, W. Ye, Z. Jian, J. Xie, K. Zhong, S. Wang, H. Hu, Z. Chen, H. Wen, H. Zhang, Enhanced sulfate and metal removal by reduced graphene oxide self-assembled *enterococcus avium* sulfate-reducing bacteria particles, Bioresour. Technol. 266 (2018) 447–453, https://doi.org/10.1016/j.biortech.2018.07.012.
[127] F.S. Fadzli, M. Rashid, A.A. Yaqoob, M.N.M. Ibrahim, Electricity generation and heavy metal remediation by utilizing yam (*Dioscorea alata*) waste in benthic microbial fuel cells (BMFCs), Biochem. Eng. J. 172 (2021), 108067, https://doi.org/10.1016/j.bej.2021.108067.
[128] S. Zhao, Z. Chen, A. Khan, J. Wang, A. Kakade, S. Kulshrestha, P. Liu, X. Li, Elevated Cr (VI) reduction in a biocathode microbial fuel cell without acclimatization inversion based on strain *Corynebacterium vitaeruminis* LZU47-1, Int. J. Hydrog. Energy 46 (2021) 3193–3203, https://doi.org/10.1016/j.ijhydene.2020.05.254.
[129] A. Singh, A. Kaushik, Removal of Cd and Ni with enhanced energy generation using biocathode microbial fuel cell: insights from molecular characterization of biofilm communities, J. Clean. Prod. 315 (2021), 127940, https://doi.org/10.1016/j.jclepro.2021.127940.
[130] L. Huang, S. Song, Z. Cai, P. Zhou, G. Li Puma, Efficient conversion of bicarbonate (HCO_3^-) to acetate and simultaneous heavy metal Cr (VI) removal in photo-assisted microbial electrosynthesis systems combining $WO_3/MoO_3/g\text{-}C_3N_4$ heterojunctions and *Serratia marcescens* electrotroph, Chem. Eng. J. 406 (2021), 126786, https://doi.org/10.1016/j.cej.2020.126786.
[131] C. Amanze, X. Zheng, M. Man, Z. Yu, C. Ai, et al., Recovery of heavy metals from industrial wastewater using bioelectrochemical system inoculated with novel *Castellaniella* species, Environ. Res. 205 (2022), 112467, https://doi.org/10.1016/j.envres.2021.112467.
[132] Y. Dong, Z. Guo, N. Guo, T. Liu, One-step removal of calcium, magnesium, and nickel in desalination by *Alcaligenes aquatilis* via biomineralization, Crystals 9 (2019) 633, https://doi.org/10.3390/cryst9120633.
[133] S. Perazzoli, J.P. de Santana Neto, H.M. Soares, Anoxic-biocathode microbial desalination cell as a new approach for wastewater remediation and clean water production, Water Sci. Technol. 81 (2020) 550–563, https://doi.org/10.2166/wst.2020.134.
[134] M.J. Shahid, R. Tahseen, M. Siddique, S. Ali, S. Iqbal, M. Afzal, Remediation of polluted river water by floating treatment wetlands, Water Supply 19 (2019) 967–977, https://doi.org/10.2166/ws.2018.154.
[135] W. Tang, A.Y. Tang, Overexpression of *Arabidopsis thaliana* cysteine 2/histidine 2-type transcription factor 6 gene enhances plant resistance to a bacterial pathogen, J. For. Res. 32 (2021) 249–262, https://doi.org/10.1007/s11676-019-01093-7.
[136] N. Tara, A. Muhammad, Z. Hussain, M. Iqbal, Q.M. Khan, M. Afzal, On-site performance of floating treatment wetland macrocosms augmented with dye-degrading bacteria for the remediation of textile industry wastewater, J. Clean. Prod. 217 (2019) 541–548, https://doi.org/10.1016/j.jclepro.2019.01.258.
[137] G. Yu, G. Wang, J. Li, T. Chi, S. Wang, H. Peng, H. Chen, C. Du, et al., Enhanced Cd^{2+} and Zn^{2+} removal from heavy metal wastewater in constructed wetlands with resistant microorganisms, Bioresour. Technol. 316 (2020), 123898, https://doi.org/10.1016/j.biortech.2020.123898.
[138] Z. Hussain, M. Arslan, M. Malik, M. Hasan, M. Muhammad, S. Iqbal, M. Afzal, Treatment of the textile industry effluent in a pilot-scale vertical flow constructed wetland system augmented with bacterial endophytes, Sci. Total Environ. 645 (2018) 966–973, https://doi.org/10.1016/j.scitotenv.2018.07.163.
[139] N. Nawaz, S. Ali, G. Shabir, M. Rizwan, M.B. Shakoor, M.J. Shahid, M. Afzal, M. Arslan, A. Hashem, E.F. Abd Allah, M.N. Alyemeni, P. Ahmad, Bacterial augmented floating treatment wetlands for efficient treatment of synthetic textile dye wastewater, Sustainability 12 (2020) 3731, https://doi.org/10.3390/su12093731.
[140] M.J. Shahid, S. Ali, G. Shabir, M. Siddique, M. Rizwan, M.F. Seleiman, M. Afzal, Comparing the performance of four macrophytes in bacterial assisted floating treatment wetlands for the removal of trace metals (Fe, Mn, Ni, Pb, and Cr) from polluted river water, Chemosphere 243 (2020), 125353, https://doi.org/10.1016/j.chemosphere.2019.125353.
[141] A. Akram, N. Tara, M.A. Khan, S.A. Abbasi, M. Irfan, M. Arslan, M. Afzal, Enhanced remediation of Cr^{6+} in bacterial assisted floating wetlands, Water Environ. J. 34 (2020) 970–978, https://doi.org/10.1111/wej.12551.
[142] R. Kabeer, V.P. Sylas, C. Praveen Kumar, A.P. Thomas, V. Shanthiprabha, E. K. Radhakrishnan, K.R. Baiju, Role of heavy metal tolerant rhizosphere bacteria in the phytoremediation of Cu and Pb using Eichhornia crassipes (Mart.) Solms, Int. J. Phytoremediation (2021), https://doi.org/10.1080/15226514.2021.2007215.
[143] Z. Si, Y. Wang, X. Song, X. Cao, X. Zhang, W. Sand, Mechanism and performance of trace metal removal by continuous-flow constructed wetlands coupled with a micro-electric field, Water Res. 164 (2019), 114937, https://doi.org/10.1016/j.watres.2019.114937.
[144] C. Mu, L. Wang, W. Li, Removal of Cr (VI) and electricity production by constructed wetland combined with microbial fuel cell (CW-MFC): influence of filler media, J. Clean. Prod. 320 (2021), 128860, https://doi.org/10.1016/j.jclepro.2021.128860.

[145] S.K. Hwang, E.H. Jho, Heavy metal and sulfate removal from sulfate-rich synthetic mine drainages using sulfate reducing bacteria, Sci. Total Environ. 635 (2018) 1308–1316, https://doi.org/10.1016/j.scitotenv.2018.04.231.
[146] K. Elkarrach, M. Merzouki, S. Biyada, M. Benlemlih, Bioaugmentation process for the treatment of tannery effluents in Fez, Morocco: an eco-friendly treatment using novel chromate bacteria, J. Water Process Eng. 38 (2020), 101589, https://doi.org/10.1016/j.jwpe.2020.101589.
[147] L.C. Casalini, M. Vidoz, A. Piazza, C. Labanca, V.A. Pacini, J. Ottadoa, N. Gottig, Optimization of bacterial bioaugmentation for groundwater Mn removal using a waste-based culture medium and lyophilisation, Environ. Sci. Water Res. Technol. 6 (2020) 3255, https://doi.org/10.1039/d0ew00777c.
[148] J. Ji, S. Kulshreshtha, A. Kakade, S. Majeed, X. Li, P. Liu, Bioaugmentation of membrane bioreactor with *Aeromonas hydrophila* LZ-MG14 for enhanced malachite green and hexavalent chromium removal in textile wastewater, Int. Biodeterior. Biodegradation 150 (2020), 104939, https://doi.org/10.1016/j.ibiod.2020.104939.
[149] S. Tripathi, P. Sharma, R. Chandra, Degradation of organometallic pollutants of distillery wastewater by autochthonous bacterial community in biostimulation and bioaugmentation process, Bioresour. Technol. 338 (2021), 125518, https://doi.org/10.1016/j.biortech.2021.125518.
[150] S. Choudhury, A. Chatterjee, Microbial application in remediation of heavy metals: an overview, Arch. Microbiol. 204 (2022) 268, https://doi.org/10.1007/s00203-022-02874-1.
[151] Y. Li, L. Guo, Max M. Häggblom, R. Yang, M. Li, X. Sun, Z. Chen, F. Li, X. Su, G. Yan, E. Xiao, H. Zhang, W. Sun, *Serratia spp*. are responsible for nitrogen fixation fueled by As(III) oxidation, a novel biogeochemical process identified in mine tailings, Environ. Sci. Technol. 56 (2022) 2033–2043, https://doi.org/10.1021/acs.est.1c06857.
[152] V.H.T. Pham, J. Kim, S. Chang, W. Chung, Bacterial biosorbents, an efficient heavy metals green clean-up strategy: prospects, challenges and opportunities, Microorganisms 10 (2022) 610, https://doi.org/10.3390/microorganisms10030610.
[153] X. Hu, C. Wu, H. Shi, W. Xu, B. Hu, L. Lou, Potential threat of antibiotics resistance genes in bioleaching of heavy metals from sediment, Sci. Total Environ. 814 (2022), 152750, https://doi.org/10.1016/j.scitotenv.2021.152750.
[154] P.S. Chandrashekharaiah, Y. Gupte, P. Sarkar, S. Prasad, D. Sanyal, S. Dasgupta, A. Banik, Algae-bacterial aquaculture can enhance heavy metals (Pb^{2+} and Cd^{2+}) remediation and water re-use efficiency of synthetic streams, Resour. Conserv. Recycl. 180 (2022) 106211, https://doi.org/10.1016/j.resconrec.2022.106211.