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Bioremediation of environmental wastes: the role of microorganisms

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The growing rate of urbanization and industrialization has led to an increase in several types of pollution caused by the release of toxic chemicals to the environment. This is usually perpetuated by the manufacturing industry (e.g. detergent and dye), agricultural sectors (e.g. fertilizers and pesticides), mining industry (e.g. cyanide and sulphuric acid) and construction companies (e.g. cement and metals). These pollutants have adverse effects on the health of plants, animals, and humans. They also lead to the destruction of the microbial population in both aquatic and the terrestrial regions, and hence, have necessitated the need for remediation. Although different remediation methods, such as the physical and chemical methods, have been adopted for years, however, the drawbacks and challenges associated with them have promoted the use of an alternative which is bioremediation. Bioremediation involves using biological agents such as plants and microbes to remove or lessen the effects of environmental pollutants. Of the two, microbes are more utilized primarily because of their rapid growth and ability to be easily manipulated, thus enhancing their function as agents of bioremediation. Different groups of bacteria, fungi and algae have been employed to clean up various environmental pollutants. This review discusses the types, mechanisms, and factors affecting microbial bioremediation. It also recommends possible steps that could be taken to promote the use of microbes as bioremediation agents.

KEYWORDS
microbial bioremediation, bioaugmentation, biostimulation, siderophores, biosorption

1 Introduction

The rise of urbanization and industrialization, has left the environment exposed to numerous pollutants which are toxic to living things. Pollutants arising from different industrial processes are major sources of pollution to the soil and aquatic environment. Different types and quantities of heavy metals are released during the industrial production process and as effluents after further industrial production. For instance, the wastewater from dye-producing companies are associated with antimony, chromium and mercury

(Methneni et al., 2021). The application of fertilizers, pesticides and herbicides in the agricultural sector generates pollutants that include aluminium, copper, zinc, nickel, lead and arsenic to the environment (Ayilara et al., 2020; Prabagar et al., 2021). Similarly, untreated pollutants from wastewaters of the agri-food industries disposed into river canals and other waterbodies have harmful effects on the environment (Siric et al., 2022a; AL-Huqail et al., 2022). Crude oil also serves as a major environmental pollutant particularly through pipeline vandalization, transportation leakage, and/or accidental spillage (Ogunlaja et al., 2019). During mining, some chemicals such as lead, arsenic, cadmium, and copper which are toxic to the immediate environment are released (Liu et al., 2020). Some other environmentally toxic chemicals including but not limited to cyanide and sulphuric acid are used during the mining process. (Ayangbenro et al., 2018; Orlovic-Leko et al., 2022). Equally, other industrial wastes such as those produced in cement-making industries release zinc, copper and cadmium and can be found in the top soils (Jafari et al., 2019). Chromium and lead from pharmaceutical effluents (Kumari and Tripathi, 2020), plastics containing lead, manganese, iron, copper, chromium, silver, cadmium, antimony and mercury all pollute water (Zhou et al., 2019). In addition, copper, arsenic, mercury, chromium, lead, nickel, cadmium and zinc from the coal industry serve as environmental pollutant (Sun et al., 2019). These heavy metals are very toxic to aquatic and terrestrial habitats and their inhabitants. In humans, mercury, cadmium and lead alters the central nervous system, especially in infants, while lead results in liver and kidney dysfunction, cardiovascular diseases, malfunctioning of the reproductive and immune system (Zwolak et al., 2019; Fashola et al., 2020a; Fashola et al., 2020b; Ayangbenro and Babalola, 2020). Cadmium causes cancers, skeletal disorders, neurotoxic and nefrotoxic complexities, and dysfunction of the reproductive system (Zwolak et al., 2019; Fashola et al., 2020a; Fashola et al., 2020b; Ayangbenro and Babalola, 2020). Wastes containing heavy metals are often improperly disposed into soil and water environments. When disposed into water bodies, they can lead to the death of fishes, and other aquatic inhabitants, otherwise, they are biomagnified and cause chronic diseases in humans and animals. Therefore, there is need for the remediation of these pollutants using physical, chemical, or biological methods. The physical and chemical methods have been used for years but they come with their drawbacks which include the need for an expert and special equipment for the chemical bioremediation procedure while the physical bioremediation procedure is expensive (Mahmood et al., 2021). This has called for the need for a better alternative which is the biological remediation (Bioremediation). Bioremediation is a most efficient, eco-friendly and cost effective technology for the transformation of contaminants (Sonune, 2021). Biological remediation can be carried out using both plants and microorganism, nonetheless, plants take a longer time to grow and cannot be easily manipulated like the microbes which makes the microbes more preferable (Hussain et al., 2022). In addition, microbes mitigates heavy metals and improve soil fertility and plant development (Chaudhary et al., 2023b). Hence, this review discusses the types, mechanism, challenges as well as the factors affecting microbial bioremediation, with recommendation on how to enhance the use of microbes in aquatic and terrestrial bioremediation.

2 Different pollutants and their toxicity on living things

Exposure of humans to air pollutants can cause developmental disorders, respiratory problems, cancers, cardiovascular diseases, and other health issues (Table 1). For instance, it has been reported that exposure to particulate matter in the air was associated with an increased risk of premature death in humans (Pope et al., 2019). Nitrogen oxides produced by combustion processes, are significant air pollutants. They irritate the respiratory system, cause cough, shortness of breath, and exacerbate asthma (Zhao et al., 2020). Equally, Sulfur dioxide, produced by burning fossil fuels, can cause respiratory and cardiovascular diseases, including bronchoconstriction, shortness of breath, and coughing. A recent study found that exposure to sulfur dioxide was associated with increased mortality from respiratory diseases in China (Luo et al., 2015). Volatile organic compounds (VOCs), emitted by various sources, including paints, cleaning products, and vehicle emissions, can cause eye, nose, and throat irritation, headaches, nausea, and dizziness. Some VOCs (such as benzene) are also carcinogenic, and are associated with an increased risk of leukemia (Bala et al., 2021). Water pollutants which include pesticides, heavy metals, and organic compounds are sometimes ingested by humans either directly or indirectly (through the consumption of aquatic animals). These pollutants can cause various health problems, including cancer, neurological disorders, and reproductive issues. It has been reported that exposure to heavy metals result in a higher risk of hypertension and kidney damage in humans (Wu et al., 2018; Rai et al., 2019).

Similarly, different animal diseases are caused by pollutants. Exposure to particulate matter (PM) can cause inflammation and damage to the respiratory system of animals, leading to respiratory diseases such as chronic obstructive pulmonary disease (COPD) and asthma (Manisalidis et al., 2020). When animals consume water contaminated with heavy metals, pesticides, and pharmaceuticals, it leads to reproductive disorders, liver damage, and cancer (Hitt et al., 2023). Nitrogen dioxide when present in the environment, reduces the growth of plants and the yield of crops while sulfur dioxide causes acid rain and acidification (Manisalidis et al., 2020). An impairment in the photosynthetic rhythm and metabolism is observed in plants exposed to ozone (Zuhara and Isaifan, 2018). In the aquatic environment, eutrophication occurs when there is a high concentration of nitrogen availability. This leads to algal bloom and cause death and disequilibration in the diversity of fish (Zuhara and Isaifan, 2018).

2.1 Types of remediation

There are different types of remediation, namely the physical, chemical and biological techniques. The physical remediation involves the use of skimmers, sorbent materials and booms.

TABLE 1 Effect of pollutants on living things.

Pollutants	Sources	Organism affected	Effect on the organism	References
Mercury	Mining and industrial production	Humans	Central Nervous System injury, hepatotoxicity and renal dysfunction	(Zhang et al., 2020)
Aluminium	Weathering, mining and industrial activities	Plants	Retardation of cell division, loosening of cell wall, destruction of plasma membrane, and the alteration of calcium homeostasis	(Rehman et al., 2021)
Pesticides (containing deltamethrin, fenthion, spinosyn, etc.) and heavy metals such as aluminum, copper and zinc	Agricultural and mining activities	Animals (bats)	DNA damage and morphology hepatocytes	(de Souza et al., 2020)
Cadmium	Agricultural amendments	Plants	Chlorosis, retarded growth, and alteration in water balance	(Rehman et al., 2021)
Chromium and lead	Industry and mining	Plants	Declined growth, reduced photosynthesis and root growth	(Zeng et al., 2012)
Lead	Industrial activities	Humans	Lung dysfunction, liver damage, central nervous system injury and cardiovascular dysfunction	(Balali-Mood et al., 2021)
Chromium	Industrial activities	Humans	Kidney disease, skin diseases and cancers	(Deng et al., 2019; Pavesi and Moreira, 2020)
Cadmium	Smoking and industrial activities	Humans	Liver damage, lung diseases, cancer and bone degeneration	(Fay et al., 2018; Wang Y. et al., 2018)
Arsenic	Industrial activity	Humans	CNS injury, skin and hair infection, cardiovascular dysfunction and liver damage	(Balali-Mood et al., 2021)
Chloride	Industrial activities	Animals (rats)	Kidney destruction and central nervous system injury	(Aragao et al., 2018)

Boom is a physical barrier made of materials that absorbs oil pollutants and prevents it from spreading before a further remediation procedure is carried out (Vocciante et al., 2019) (Figure 1). Skimmers and sorbents are methods that are further used to absorb and adsorb pollutants after booms (Kumari et al., 2019). The major challenge associated with the use of bloom remediation technique is that it is dependent on the buoyancy and roll response. When the boom is buoyant, it floats and remains longer on the water surface. The roll response refers to the torque required to rotate the bloom from its vertical position. That is, an

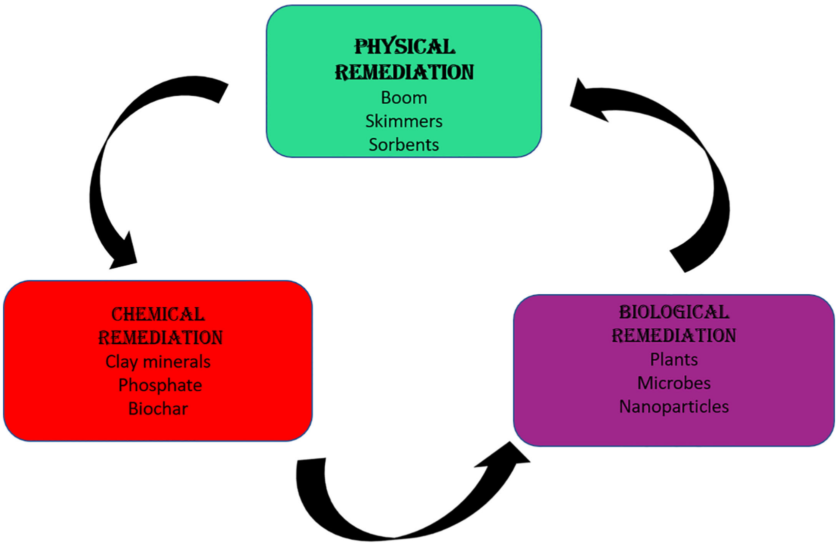

FIGURE 1
Types of bioremediations.

increased roll response results in a higher remediation process (Dhaka and Chattopadhyay, 2021).

Chemical remediation is the process of adding chemicals such as clay minerals, phosphate, biochar, aluminum salts, silicocalcium materials, and sulfide to stabilize and remove heavy metals from the environment. The mechanism behind the use of these chemicals include adsorption, reduction, oxidation, complexation, precipitation and ion exchange (Xu et al., 2022). Chemical remediation technique is an easy, simple, and rapid technique; however, the chemical used can also serve as a source of environmental pollution (Xu et al., 2022) (Figure 1).

Bioremediation is another method of pollution treatment, it is a sustainable, affordable and safe remediation technique (Kumar A. et al., 2021; Kumar G. et al., 2021; Patel A. K. et al., 2022). The technology involves the use of organics such as plants and microbes. The viability of this method depends on the nature, location and level of pollution (Patel A. K. et al., 2022). Microbes on the other hand have proved to be efficient in the remediation of environmental pollutants. They are preferred to plants in remediation, this is due to their ease of growth, rapid growth period and easy manipulation. It is therefore necessary to improve the use of microbes as agent of bioremediation to promote a sustainable environment.

3 Different microbes used as bioremediation agents

Microorganisms can convert toxic elements into water, carbon dioxide, and other less toxic compounds, which are further degraded by other microbes in a process referred to as mineralization (Mahmoud, 2021; Kumar G. et al., 2022). Bioremediation can be carried out using bacteria, fungi, algae, etc. (Table 2). Microbes are ubiquitous in nature, and they utilize a wide range of substrates as carbon source; hence, they are found in unusual environments where they can absorb a wide range of pollutants (Kour et al., 2022). Also, their ability to survive in odd environments promote their efficiency. For example the acidophiles survive in acidic environments, the psychrophiles thrive in cold climates and the halophiles survive in saline region (Perera and Hemamali, 2022).

4 Mechanisms of microbial bioremediation

Microbes can remove pollutants from the environment using different mechanisms. These mechanisms can be placed into two broad categories namely immobilization and mobilization (Ndeddy Aka and Babalola, 2016; Verma and Kuila, 2019). Mobilization process involves, enzymatic oxidation, bioleaching, biostimulation, bioaugmentation and enzymatic reduction procedure. On the other hand, immobilization includes bioaccumulation, complexation, biosorption, and precipitation (solidification) (Tak et al., 2012; Ayangbenro et al., 2019). During mineralization, microbes help transform pollutants into end products such as carbon dioxide and water or other intermediate metabolic substances. Similarly, immobilization is the conversion of compounds into a form where it will be unavailable in the environment. For instance, the conversion of nitrate nitrogen into organic nitrogen (Pratush et al., 2018). The method is usually utilized for the bioremediation of heavy metals, especially in highly contaminated environments.

Immobilization can be carried out using the *in-situ* and the ex-situ methods (Pratush et al., 2018). The ex-situ process involves the removal of polluted soils from the site of pollution to another location where it would undergo a microbial process to immobilize the metal ions responsible for the contamination (Ayangbenro and Babalola, 2017). On the other hand, in the *in-situ* procedure, the pollution is treated on site (Cao et al., 2020). Microbes such as *E. asburiae* and *B. cereus* have been reported to be involved in immobilization of heavy metals which pollute the environment (Fashola et al., 2020a). During microbial bioremediation, microbes protect themselves from toxic compounds by forming hydrophobic or solvent efflux pump that protects the outer membrane of the cell (Verma and Kuila, 2019).

4.1 Enzymatic oxidation

Enzymatic oxidation is the process of oxidizing pollutant compounds from a higher oxidation state to a lower one, during which heavy metals lose an electron and become less toxic. This process utilizes an enzyme (oxidoreductase) released by the microbes involved. This method is highly effective in the remediation of dyes, phenols, and other pollutants which are not easily degraded by bacteria (Unuofin et al., 2019). The oxidative enzymes form radicals which can be broken down into different fractions, eventually forming compounds with high molecular weight (Unuofin et al., 2019). An example of an oxidoreductase enzyme is laccase, which catalyzes the oxidation of aromatic amines (Gangola et al., 2018). Other examples are phenols and polyphenols, which cause the reduction of molecular oxygen to water (Kushwaha et al., 2018; Sahay, 2021). Laccase production has been reported in *Pycnoporus* sp. and *Leptosphaerulina* sp. where it was outlined to degrade heavy metals (Copete-Pertuz et al., 2018; Tian et al., 2020).

4.2 Enzymatic reduction

This process is the opposite of enzymatic oxidation, here, the pollutants are converted to a reduced oxidized state where they become insoluble. Obligate and facultative anaerobes carry out the process; this method is effective in the bioremediation of compounds such as polychlorinated dibenzo-p-dioxins and dibenzofurans (Zacharia, 2019). Equally, chrome reductase catalyzes the reduction of hexavalent chromium to trivalent chromium, and azoreductase reduces the azo compounds by cleaving to azo bonds (Saxena et al., 2020). Much more research is needed to unravel other organisms which are capable of bioremediating pollutants in the environment.

TABLE 2 Different microbes used in bioremediation.

Type of organism	Species	Pollutant remediated	References
Bacteria			
	Bacillus licheniformis JUG GS2 (MK106145) and *Bacillus sonorensis*	Naphthalene	(Rabani et al., 2022)
	Bacillus sp., *Rhodopirellula* sp., *Rhodovibrio* sp. and *Formosa* sp.	Hydrocarbon	(Machado et al., 2019)
	P. cepacia, *B. coagulans*, *B. cereus*, and *Serratia ficaria*	Diesel oil	(Miri et al., 2022)
	Pseudoalteromonas sp. and *Agarivorans* sp.	Hydrocarbons	(Dell'Anno et al., 2021)
	P. aeruginosa and *Aeromonas* sp.	Chromium, uranium, nickel and copper	(Gaur et al., 2022)
	E.coli	Hexavalent chromium	(Mohamed et al., 2020)
	Oscillatoria laete-virens, *Arthrospira platensis*, *Pseudochlorococcum typicum* and *Spirogyra insignis*	Lead	(Song et al., 2019)
	Microbacterium sp., *Micrococcus* sp., *Bacillus* sp., and *Shigella* sp.	Uranium and Arsenic	(Bhakat et al., 2019)
	Lysinibacillus sphaericus CBAM5	Lead, cobalt, copper crude oil and chromium	(Kharangate-Lad and D'Souza, 2021)
	Pseudomonas aeruginosa	Crude oil	(Mukjang et al., 2022)
	Cyclotella cryptica, *Pseudochlorococcum typicum*, *Spirogyra hyaline* and *Chlamydomonas reinhardtii*	Mercury	(Shah and Jain, 2020)
	Dehalococcoides sp.	Chloroethenes	(Dutta et al., 2022)
	Burkholderia sp. and *Myceliophthora thermophila*	N, N-dimethylpphenylenediamine and polycyclic aromatic hydrocarbons	(Mohapatra and Phale, 2021)
	Bacillus sp. and *Staphylococcus* sp.and	Endosulfans	(Liu et al., 2018)
	A. versicolor, *Cladosporium* sp., *Paecilomyces* sp., *A. fumigatus*, *Paecilomyces* sp., *Terichoderma* sp. and *Cladosporium* sp.	Cadmium	(Unuofin et al., 2021)
	Fusarium sp., *Corynebacterium propinquum*, *P. aeruginosa* and *Alcaligenes odorans*	Oils	(Pande et al., 2020)
	C. reinhardtii, *Ulothrix tenuissima* and *Spirulina* sp.	Chromium	(Aregbesola et al., 2020)
	Ralstonia sp., *Microbacterium* sp., *Pseudomonas* sp. and *Acinetobacter* sp.,	Aromatic hydrocarbons	(Basu et al., 2018)
	Aerococcus sp., and *Rhodopseudomonas palustris*	Cadmium, lead and chromium	(Sravya and Sangeetha, 2022)
	P. aeruginosa, Corynebacterium propinquum, Alcaligenes odorans and *B. subtilis*	Phenol	(Gaur et al., 2018)
	K. oxytoca, B. firmus, B. macerans, and *Staphylococcus aureus*	Vat dyes	(Sangkharak et al., 2020)
	Chlorella sp. and *Spirulina* sp.	Lead, nickel and dichromate	(Geetha et al., 2021)
	Saccharomyces cerevisiae and *Cunninghamella elegans*	Heavy metals and mercury	(Duc et al., 2021)
	Bacillus licheniformis	Dyes	(Mousavi et al., 2021)
	Bacillus subtilis and *Pseudomonas fluorescence*	Iron and zinc	(Siric et al., 2022b)
	Pseudomonas sp., *Bacillus* sp., *Escherichia* sp., *Shewanella* sp., *Enterobacter* sp. and *Thermus* sp.	Chromium	(Mousavi et al., 2021)
Fungi			
	Phanerochaete chrysosporium	N-heterocyclic explosives, benzene, xylene, ethylbenzene, toluene and organochlorines	(Singh et al., 2020)

(Continued)

TABLE 2 Continued

Type of organism	Species	Pollutant remediated	References
	Phanerochaete chrysosporium	4,4 dibromodiphenyl ether	(Sen et al., 2019)
	Saccharomyces cerevisiae	Arsenic	(Verma et al., 2019)
	Aspergillus sp.	Arsenic	(Mohd et al., 2019)
	Coprinus comatus	4-Hydroxy-3,5- dichlorobiphenyl	(Li et al., 2018)
	Aspergillus sp. and *Penicillium* sp.	Aliphatic hydrocarbons, polycyclic aromatic hydrocarbons and chlorophenols	(Li et al., 2020)
	Aspergillus sp.	N-hexadecane	(Al-Hawash et al., 2018)
	Phomopsis liquidambari	Phenanthrene	(Fu et al., 2018)
	Ganoderma lucidum	Pyrene	(Agrawal et al., 2018)
	Trichoderma sp., *Penicillium* sp. and *Aspergillus* sp.	Cobalt and copper	(Dusengemungu et al., 2020)
Algae			
	Microcystis aeruginosa	Arsenic	(Wang Z. et al., 2018)
	Chlamydomonas reinhardtii and *S. almeriensis*	Arsenic	(Saavedra et al., 2018)
	Fucus vesiculosus	Zinc	(Brinza et al., 2020)
	Chlorococcum humicola	Iron	(Chugh et al., 2022)
	Chlorella sp., *Isochrysis galbana* and *Phaeodactylum tricornutum*	Phenol	(Wu et al., 2022)
	F. vesiculosus	Chromium, nickel, cadmium and lead	(Moreira et al., 2019)
	Cystoseria indicant	Nickel and cadmium	(Moreira et al., 2019)
	Chlamydomonas reinhardtii	Chromium and cadmium	(Nowicka et al., 2020)
	Microcystis aeruginosa	Cadmium	(Deng et al., 2020)
	Scenedesmus accuminatus, Scenedesmus protuberans and *Cyclotella* sp.	Cadmium	(Vo et al., 2020)
	Chlorococcum humicola	Cobalt	(Chugh et al., 2022)

4.3 Bioaugmentation

Microorganisms are specially added to polluted sites to feed on toxic pollutants in a process referred to as bioaugmentation. It is a very effective, rapid and cost-effective method of bioremediation (Mahmoud, 2021). External microbes are added to polluted sites to augment the resident microbes. In other cases, it could also involve the isolation and genetic modification of microbes from the site of pollution before returning them to the same site for remediation. Genetic manipulation of resident microbes of polluted sites is carried out because the organisms may naturally not be capable of degrading the pollutant present at a site, and hence are modified to enhance their ability. In some other cases, non-resident microbes are added to polluted areas to promote the degradation of pollutants. The effectiveness of these new strains depends on some factors, which include the ability to compete with the resident microbes and the ability to adapt to the new environment (Fashola et al., 2016; Ayangbenro and Babalola, 2017; Goswami et al., 2018; Babalola et al., 2019). *Burkholderia* sp. FDS-1 which was added to a polluted site, has been reported to degrade nitrophenolic compound present in pesticides polluted soil to a less toxic form at a slightly acidic pH and a temperature of about 30° C (Goswami et al., 2018; Ojuederie et al., 2021) (Table 3).

4.4 Biostimulation

Biostimulation is the addition of nutrients (such as nitrogen, potassium, phosphorus), metabolites, electron donors, enzymes, electron acceptors, biosurfactants, etc., which are limiting to the soil to enhance the activity of the resident microbes and increase the remediation process (Ojuederie and Babalola, 2017; Ayangbenro and Babalola, 2018). It is an affordable, environmentally friendly and efficient process (Goswami et al., 2018). Compared to the bioaugmentation method, the biostimulation method is preferable because indigenous microbes are more competitive than the introduced ones (Sayed et al., 2021), and this method helps to maintain the natural microbial diversity balance of the environment. Nivetha et al. (2022) reported the effectiveness of *Bacillus* sp., *Rhodococcus* sp., *Staphylococcus* sp., *Klebsiella* sp.,

TABLE 3 Mechanism of Bioremediation.

Microorganism	Pollutant remediated	Mechanism of remediation	References
Bacillus sp.	Nickel	Biosorption	(Taran et al., 2019)
Lysinibacillus sphaericus	Azo dyes	Enzymatic reductase	(Lu et al., 2020)
Oudemansiella canarii	Congo red dye	Enzymatic reduction	(Iark et al., 2019)
Pseudomonas aeruginosa and *Bacillus cereus*	Lead and Cadmium	Bioaugmentation	(Nath et al., 2018)
Bacillus sp., *Lysinibacillus* sp. and *Rhodococcus* sp.	Aluminium, lead, cadmium, and copper	Bioaugmentation	(Nanda et al., 2019)
Cupriavidus sp.	Cadmium	Bioprecipitation	(Li et al., 2019)
Pseudomonas sp.	Copper and lead	Bioattenuation	(Nanda et al., 2019)
Bacillus subtilis	Lead	Bioimmobilization	(Qiao et al., 2019)
Desulfovibrio desulfuricans	Copper, zinc and cadmium	Extracellular sequestration	(Thakare et al., 2021)
Pseudomonas aeruginosa	Cadmium	Biosorption	(Chellaiah, 2018)
Sulfolobus solfataricus	Copper	Intracellular sequestration	(Thakare et al., 2021)

Pseudomonas sp., and *Citrobacter* sp. in bioremediation of heavy metals through the biostimulation technique. Unfortunately, as effective as this method of bioremediation may be, it could lead to some other environmental complications, including eutrophication due to the excess nutrient present in the environment. Also, if the sources of the nutrients are chemicals (synthetic), they can serve as a source of pollution to the environment defeating the initial purpose of bioremediation (Table 3).

4.5 Bioleaching

Bioleaching is the process of utilizing acidophilic microbes to promote the solubilization of heavy metals which are in a solid state from the sediment matrix. The process is particularly useful for iron or sulfur pollutants (Sun et al., 2021; Bhandari et al., 2023). Therefore, iron- or sulfur-oxidizing bacteria are majorly recruited for this process; examples of such organisms are *A. thiooxidans*, *Aspergillus* sp., *Mucor* sp., *Penicillium* sp., *Cladosporium* sp. and *Rhizopus* sp. (Medfu Tarekegn et al., 2020). These microbes create an acid environment and solubilize heavy metals in an immobilized state, into an aqueous solution (Medfu Tarekegn et al., 2020).

4.6 Biosorption

This is the adsorption of heavy metals from pollutants through proton and ion displacement, complexation, chelation and physical interaction with electrostatic forces (Mahmoud, 2021). It involves the removal of contaminants from solutions as a result of the outer cell shield of bacteria, fungi and algae which are bioremediation agents. Generally, metals are linked through the active groups of the compounds which exist at the cells surface layer. This results in the transfer of ion between metal cations and the negatively charged active group potentials present at the outer part of the microorganism structure. *Rhodococcus erythropolis*, *Streptomyces* sp. K11, and *Bacillus anthracis* have been reported to be capable of bioremediation through the biosorption process (Mathew and Krishnamurthy, 2018; Baltazar et al., 2019; Sedlakova-Kadukova et al., 2019). Oftentimes, heavy metal pollutants (e.g., gold, zinc and copper) have some economic importance and are very useful in industrial processes. Hence, the ability of the compounds to be recovered through a process called desorption (using the solution of weak mineral solution or chelating compounds), which is a reversible step in biosorption makes it a good process (Medfu Tarekegn et al., 2020).

Complexation involves using ligand to form a complex with inorganic metals, which are pollutants in the environment, especially solid wastes (Ayangbenro and Babalola, 2017). Complexation is carried out mainly through different agents, namely the high molecular weight ligands, siderophores and toxic metal-binding compounds as well as the low-molecular weight organic acids (alcohols, tricarboxylic acids and citric acids) (Pratush et al., 2018). Complexation occurs when extracellular polymeric substances, found on the surfaces of microbes interact with heavy metals which pollute the environment (Xie et al., 2020). Xiao et al. (2019) reported the removal of copper (II) oxide and hexavalent chromium from wastewater using biochar in a mechanism which includes complexation. The organisms that have been reported to be involved in complexation include *Rhodobacter blasticus* (Bai et al., 2019) and *B.lichenformisis* (Wang et al., 2019).

When microbes are exposed to a polluted environment where there is iron-deficiency, they produce siderophores which are iron chelators. The siderophores have binding groups such as hydroxamate, catecholate and phenolates that form complexes with heavy metals and increase their solubility (Khan et al., 2018). Siderophores are capable of producing reactive oxygen species, which also enhance their function as bioremediation agents for organic contaminants (Albelda-Berenguer et al., 2019). Cyanobacteria have been reported to be effective as bioremediation agents due to the production of siderophores; for example, they are capable of bioremediating complex compounds like polythene and are capable of producing different types of siderophores, which include the anachelin, synechobactin and schizokinen (Arstol and Hohmann-Marriott, 2019; Sarmah and Rout, 2020) (Table 3).

4.7 Bioaccumulation

Bioaccumulation refers to the process where the rate of absorption of a compound is more than the rate at which the compound is lost. This process leads to the (toxic) build-up of compounds in the intracellular portion of the microbes. (Sharma et al., 2022a). Heavy metals move across the membrane of microbes using different mechanisms such as carrier-mediated transport, protein channel and ion pumps (Mir-Tutusaus et al., 2018). Many organisms have been reported to be very active in bioaccumulation of heavy metals. For example, *Rhizopus arrhizus*, bioremediates mercury, *Pseudomonas putida*, bioremediates cadmium and *Aspergillus niger* bioremediates thorium (Sharma et al., 2022a).

4.8 Precipitation

This is the conversion of heavy metals or pollutants into precipitates or crystals, resulting in a reduced toxicity level; this process can occur during the biogeochemical cycling to form deposing of metals (iron and manganese), mineralized manganese and silver as well as microfossils, due to the activity of enzymes and galactosis of secondary metabolites (Sharma et al., 2022a). For instance, sulfate-reducing bacteria are capable of converting organo-phosphate to ortho-phosphate when the pH is alkaline (i.e. above 7) (Pratush et al., 2018). Similarly, *Bacillus subtilis* and *Oceanobacillus indicireducens* have also been reported to be associated with the precipitation of heavy metals in the environment (Maity et al., 2019).

5 Factors affecting microbial bioremediation

The ability of microbes to bioremediate heavy metals is determined by different factors, which include the total metal ion concentration, redox potential, chemical forms of the metals, competition among microbes, pH, temperature, soil structure, presence of oxygen, moisture content, nature of the soil and the solubility of the heavy metal in water (Medfu Tarekegn et al., 2020). At acidic pH, free ionic species are formed by heavy metals, leading to the availability of more protons which would saturate the binding site of the metals. The pH of an environment affects the structure of the pollutant and also determines the ability of the microbe to survive in such an environment; the optimum pH that enhances bioremediation falls between 6.5 and 8.5 (Kharangate-Lad and D'Souza, 2021).

Microbes compete for carbon which is a limited resource and serve as an energy source for microbes. Therefore, the inherent ability of the microbes, which compete better to degrade heavy metal pollutant, would affect the biodegradation rate. In addition to carbon, microbes responsible for biodegradation also require nitrogen (N) and phosphorus (P), thus it is important to balance the C:N:P ratio to enhance the rate of biodegradation, in environment when these essential nutrients are limited. They can be added to increase microbial activities (Bala et al., 2022). The type and population of microbes determine the rate and success of a bioremediation process, for instance in the laboratory, a strain of organism might successfully bioremediate a particular heavy metal, which becomes problematic in a field situation where a consortium of microbes would be needed (Patel A. B. et al., 2022). The molecular nature, gene and enzyme induction, metabolite production, growth efficiency and survival rate affect the ability of individual microbes as bioremediation agents (Kebede et al., 2021). In addition, the ionization of the cell wall's chemical moieties, the configuration of the microbial cell wall and sorption site also affect the rate of microbial biodegradation (Mahmoud, 2021).

The amount of moisture present in an environment affects the solubility of the heavy metals in water, as well as their availability, pH and osmotic pressure (Medfu Tarekegn et al., 2020). At a high moisture content, the microbial biodegradation rate is very low. This might be a result of an anaerobic condition that is created, which prevents the survival of aerobic microbes. Also, at a low moisture content, microbes might not be able to survive; hence an optimum moisture content is required for a successful microbial biodegradation process. In the cold regions where only psychrophiles can survive, the rate of microbial degradation of heavy metals is slow. This is because metabolic activities are reduced as the microbial transport channels is freezed by the sub-zero water; the degradation of each compound also occurs at different temperature even though most bioremediation processes are favored by high temperature (Ren et al., 2018; Bala et al., 2022; Sharma et al., 2022c). At an increased temperature, the rate of heavy metal solubility is increased, which consequently increases their rate of availability as well as the rate of microbial biodegradation (Mahmoud, 2021).

Similarly, the chemical structure, bioavailability, concentration, toxicity and stability of the metal or pollutant determines the rate at which microbial biodegradation takes place (Kebede et al., 2021). For instance, heavy metals with a simple chemical structure and low concentration would be easier to be remediated by microbes compared to those with a complex chemical structure and high temperature. Cycloalkane compounds that are highly condensed as well as high molecular weight polymatic hydrocarbons (those containing four rings and above) are more difficult to degrade compared to the lighter polyhydrocarbons (anthracene, naphthalene and phenanthrene) and unbranched alkanes (alkanes with intermediate length of about C_{10}–C_{25}) (Kebede et al., 2021). Hence, in order of ascending degradation, the n-alkanes are more easily degraded compared to the branched alkanes, low molecular weight aromatics, high molecular weight hydrocarbons and the asphaltenes (Imam et al., 2019). Biodegradation is carried out aerobically and anaerobically. The ability of an organism which degrades a particular nutrient to survive in such an environment depends on the nature of the organism (Jacob et al., 2018). For example, oxygenase associated with organisms that are active in aerobic regions is only produced in the presence of oxygen.

Different soil parameters, including the soil region, moisture-holding capacity texture and particle size, affect the rate of microbial biodegradation (Alvarez et al., 2020). There is a higher population and diversity of microbes at the top layer of the soil (0-10cm). This is due to the increased availability of oxygen and organic matter, which is the opposite of what happens in sediment soils (Ndeddy Aka and Babalola, 2017). In soils with fine particles, such as clayey soils, hydrocarbon retention takes place more at the surface, which renders the nutrient of the soil and oxygen unavailable. Therefore the best soil texture that promotes increased microbial biodegradation is the well-drained soil which supports oxygen availability and inhabits more soil microbes (Huang et al., 2019). The presence of salinity has an effect on the hydrocarbonoclastic activity of the halotolerant and halophilic microbes, and it also exposes the soil microbes to stress conditions. The osmotic pressure of microorganisms increases as the saline concentration of an environment increases. This has a direct negative impact on the metabolic activities, of the microbes as well as the transportation system and solubility of the heavy metals (Imron et al., 2020; Kebede et al., 2021).

6 Microbial enzymes used in bioremediation

Different microbial enzymes have been reported to be helpful in the removal of pollutants (especially heavy metals) in the environment (Verma and Kuila, 2019; Bhatt et al., 2021a; Chaudhary et al., 2023a) (Table 4). Mechanisms such as elimination, oxidation, ring-opening and reduction are used by enzymes in bioremediation (Bhandari et al., 2021). Different factors which include temperature, contact time, concentration and pH affect the potency of microbial enzymes (Bhandari et al., 2021). Enzyme bioremediation is expensive and time-consuming and therefore cannot be used when there is an urgent need for bioremediation (Narayanan et al., 2023). Equally, the stability and activity of the pollutants, affects the potency of the bioremediation process. It is difficult to determine and discover multiple sources of a particular type of enzyme which might make the procedure unsustainable (Narayanan et al., 2023).

7 Molecular approaches for validating microbial remediation

Molecular mechanisms help to unravel the microbial metabolism, genes, nature, diversity and dynamics of microbes involved in microbial remediation. Diverse molecular mechanisms are utilized in the study of microbes used in bioremediation. Metabolic and protein profiling, sequencing as well as the use of advanced bioinformatics resources are particularly used to unravel the different groups of microbes and the factors affecting them in bioremediation process (Sharma et al., 2022b). On the other hand, conventional and culture-dependent molecular methods are also used in the monitoring of microbial communities during bioremediation. These methods include the use of terminal-restriction fragment (T-RF) length polymorphism, amplified ribosomal DNA restriction analysis, temperature gradient gel electrophoresis, randomly amplified polymorphic DNA analysis, length heterogeneity polymerase chain reaction, amplified fragment length polymorphisms, denaturing gradient gel electrophoresis, length heterogeneity polymerase chain reaction, automated ribosomal intergenic spacer analysis and single strand conformation polymorphism (Bharagava et al., 2019).

TABLE 4 Enzymes used in Microbial Bioremediation.

Enzyme	Microbial sources	Pollutant remediated	References
Hydrolases	*T. fusca* *Pseudomonas* sp., *Burkholderia* sp., *Ralstonia* sp., *Achromobacter* sp., *Sphingomonas* sp. *and Comamonas* sp.	Polyester plastics Hydrocarbons	(Gricajeva et al., 2022) (Dave and Das, 2021)
Oxidoreductase	*Bacillus safenis*	Xenobiotics	(Malakar et al., 2020)
Phosphotriesterase	*Brevundimonas diminuta*	Pesticides	(Thakur et al., 2019)
Lipase	*Bacillus pumilus*	Oil containing industrial wastewater	(Saranya et al., 2019)
Laccase	*Pseudomonas putida*	Synthetic dyes	(Bhandari et al., 2021)
Lignin peroxidase	*Escherichia coli* and *Bacillus* sp. F31	Synthetic dyes	(Dave and Das, 2021)
Dehydrogenase	*E. coli* *S. rhizophila*	Steroids Polyvinyl alcohol	(Ye et al., 2019) (Wei et al., 2018)
Protease	*Bacillus subtilis*	Casein and feather	(Bhandari et al., 2021)
Amylase	*Bacillus cereus*	Waste water pollutants	(Sonune and Garode, 2018)
Oxygenase	*Pseudomonas* sp.	Pesticides	(Malakar et al., 2020)
Lipase	*Bacillus pumilus*	Palm oil	(Saranya et al., 2019)

Moreover, omics approaches such as transcriptomics, proteomics and metagenomics have greatly contributed in this field. Metagenomics involve the extraction of genomic DNA from all forms of life residing in a sample. Thereafter, the DNA will be fragmented, cloned, transformed and screened in the metagenome library (Bharagava et al., 2019). The approaches to metagenomics include metabolomics, metatranscriptomics, fluxomics and metabolomics. Metatranscriptomics involve the use of metagenomic mRNA which unravel the function and expression of microbes present in a sample (Mukherjee and Reddy, 2020). Metaproteomics involved the assessment of all the protein samples that comes from environmental samples (Bargiela et al., 2015). Metabolomics is the identification and quantification of all the metabolites released into an environment (Liu et al., 2022). Fluxomics refers to the different approaches used to study the rate of metabolic activities in a biological sample (Kumar V. et al., 2022). More recently, the use of Next-Generation sequencing which is viewed as the most powerful technology for gene sequencing has become more popular (Eisenhofer et al., 2019).

8 Other bioremediation metabolites produced by microbes

Microbes produce metabolites such as organic acids, biosurfactants and polymeric substances which are also used in bioremediation. Organic acids improve the bioavailability, mobility and solubility of metals; examples of organic acids include citric acids, malate and acetic acids (Saha et al., 2021). Polymeric substances are beneficial in bioremediation by enhancing the phytostabilization of metals (through mobility), examples of polymeric substances include polyesters, polysaccharides and polyphosphates. Equally, biosurfactants which include viscosin, polymixin, glycoprotein and gramicidin help to solubilise, mobilise and increase the bioavailability of hydrophobic substrates (Ojuederie and Babalola, 2017; Saha et al., 2021).

9 Recent advancements in microbial bioremediate

Lately, many improvements have been observed with the use of microbes as agents of bioremediation. Microbial glycoconjugates help to reduce the surface tension, increase the bioavailability, and create a solvent interface of organic pollutants. This helps to enhance the removal of the pollutants in the environment (Bhatt et al., 2021b). Atakpa et al. (2022) reported the use of microbial glycoconjugates from *Scedosporium* sp. and *Acinetobacter* sp. in the biodegradation of petroleum hydocarbons.

Microbial biofilms which consist of polysaccharides, extracellular DNAs and proteins are also lately used in the bioremediation of organic pollutants (Sonawane et al., 2022). They are particularly used in the remediation of recalcitrant pollutants. The technology is presently being made better by improving on the quorum sensing, environmental factors and surface of adhesion (Sonawane et al., 2022). In a research carried out by Andreasen et al. (2018), it was revealed that *Exiguobacterium profundum* was able to significantly reduce the concentration of arsenic in synthetic wastewater after 48 hours of incubation.

Bioelectrochemical system is another emerging technology which combines the use of biological and electrochemical methods in the control of pollutants (Ambaye et al., 2023). This technology helps to majorly remediate petroleum hydrocarbon pollutants and its efficiency depends mainly on the syntrophic and cooperative interactions between the members of the microbial groups involved (Ambaye et al., 2023). Sharma et al. (2020) stated that *Pseudomonas* sp., *Ralstonia* sp., *Rhodococcus* sp., and *Thauera* sp. are capable of remediating phenanthrene from petroleum hydrocarbon polluted soils.

Nanotechnology is a thriving method of pollution control globally. Nanomaterials can be sourced from different sources which include the physical and chemical sources (Shanmuganathan et al., 2019). The efficiency of nanoparticles as bioremediation agents is dependent on different factors such as the size, chemical nature, surface coating and shape of the nanoparticles (Tan et al., 2018). Other factors such as the nature of the pollutants, type of media, temperature and the environmental pH affect the potency of nanoparticles in the bioremediation process (Tan et al., 2018). For instance, carbon dots nanoparticles have recently gained attention in the remediation of environmental pollutants owing to their abundance, low toxicity and unique optical properties (Long et al., 2021). It is therefore necessary to carry out further research to unravel technologies and mechanisms to improve the efficiency of the bioremediation process.

10 Future perspectives and conclusions

A number of research endeavours have been carried out on the use of microbial enzymes for bioremediation of waste materials; however, it is very important to improve the process to ensure a safer and more sustainable environment. It is imperative to intensify research to unravel novel microbes that can effectively and rapidly bioremediate different pollutants, especially from industrial sources. Perhaps the novel microbes and their enzymes may have the inherent ability to bioremediate pollutants better than the presently used ones. It is also very important to carry out more studies to innovate rapid detection methods to reveal the progress or help to confirm total biodegradation of pollutants in the environment. Similarly, microbes presently used in bioremediation can be genetically modified to produce more enzymes which will enhance their biodegrading ability. A combination of different microbial consortium other than a single microbial consortium would be a better approach to bioremediation, as this would bring about the presence of different organisms which utilizes different substrate, consequently increasing the rate of microbial biodegradation.

Often, microbes are majorly used to degrade organic substrates, leaving out the persistent inorganic pollutants. Hence, research should be intensified to discover microbes that are capable of degrading inorganic (synthetic) pollutants. In recent years, nuclear wastes generated from the research sectors, hospitals, fuel processing plants and nuclear reactors have remained a global source of pollution. Therefore, the use of microbes and microbial enzymes in the bioremediation of nuclear wastes should be seriously taken into consideration. Occasionally, microbes themselves serve as a source of pollution instead of remediating pollutants. An example of such can be found when microbial biostimulation which results in algal bloom is carried out Consequently, methods to prevent this should be devised to ensure a sustainable environment.

Furthermore, in nature (outside the laboratory), the degradation of different compounds occurs at a different temperature, while the survival of microbes in nature are also environment-specific (temperature). It is therefore essential to carry out more field research to determine the optimum temperature for the degradation of different compounds in nature. In addition, it is also essential to find a balance between the environmental temperature and the temperature for the survival of different microbes in the environment. This would help to prevent bioremediation failure when external microbes are to be recruited or introduced to an environment. As positive and effective microbes might be recruited in the bioremediation of pollutants, it is important to carry out follow-up research to understand their effects on the environment after bioremediation, as some organisms which are introduced to an environment might later constitute pollution to the environment through mutation and other means. Hence, there should be regulatory bodies which would monitor the potential risk associated with microbes in specific environments.

Finally, if enzymes or microbes are directly applied to the soil, they might die or lose their potency before the remediation process begins; therefore, their combination with other agents, such as the nanoparticle could enhance their activity. More awareness is needed on the adoption of microbial degradation, and this will help policymakers as well as the populace to utilize this method. Many people unaware of this procedure might use the available conventional method, which might not be as safe and effective as the microbial biodegradation.

Author contributions

MA and OB conceptualized, wrote, reviewed, and edited the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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