



A Comprehensive Review on the Role of Bioremediation in Heavy Metal Contamination

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Nat. Env. & Poll. Tech.
Website: www.neptjournal.com

Received: 03-04-2024

Revised: 11-05-2024

Accepted: 19-05-2024

Key Words:

Bioremediation
Heavy metals
Microorganisms
Metal tolerance

ABSTRACT

Heavy metal contamination, along with other pollutants, presents significant environmental hazards. These substances not only endanger human health but also disrupt natural ecosystem. Bioremediation emerges as a sustainable and economically viable approach to tackling pollution. It harnesses the capabilities of microorganisms, plants, and their enzymes to degrade or neutralize pollutants. This paper categorizes bioremediation into two primary types: ex-situ and in-situ. Ex-situ bioremediation treats contaminated material away from its original location, while in-situ bioremediation addresses contamination directly at the site. This paper also explores how microbes tolerate heavy metals through various mechanisms. These mechanisms encompass extracellular barriers, efflux pumps, enzymatic reduction, and intracellular sequestration. Extracellular barriers function to block the entry of metals into the cell, whereas efflux pumps work actively to expel metals from the cell. Enzymatic reduction facilitates the conversion of metals into less harmful forms, while intracellular sequestration involves storing metals within the cell. Moreover, the paper examines diverse applications of bioremediation in environmental restoration. These applications encompass natural attenuation, enhanced reductive dechlorination, sewage treatment, bioleaching, biosorption, constructed wetlands, biostimulation, and bioaugmentation. This paper emphasizes the need for further research to optimize bioremediation technologies for broader real-world environmental management applications.

INTRODUCTION

The substantial increase in human population is negatively impacting the environment. The rate of industrialization and other human activities is rising daily, leading to contamination. The presence of contaminants in the environment may cause harm or upset the natural balance of ecosystem referred to as pollutants. These pollutants can be solid, liquid, or gaseous particles and can come from various human operations, industrial operations, or environmental factors Organic solvents, herbicides, pesticides, textile dyes, PAHs (polycyclic aromatic hydrocarbons), nitrates and nitrites, personal care products, and heavy metals are the sources of pollution (Martinez et al. 2019, Shah et al. 2021). The primary sources of PAHs are human activities, including incomplete fossil fuel combustion, burning of biomass, oil spills, and some industrial processes (Li et al. 2010, Bezza & Chirwa 2016). Soils from a variety of locations, including coal storage regions, coke oven plants, produced gas plants, and coal tar spill sites, have high levels of PAH pollution (Li et al. 2010, Bezza & Chiwra 2016). Herbicides and pesticides are crucial for farming but can heavily pollute the

environment. They might seep into drinking water sources, affecting people's health by potentially messing with the nervous, hormonal, and immune systems (Rahman 2018, International Federation of Organic Agriculture Movements 2009). Textile dyes pollute waterways, harming aquatic ecosystems (Dutta et al. 2024). Chemicals like nitrates and nitrites from farm runoff can get into our drinking water and make it unsafe (Prickett et al. 2023). Personal care products (PCPs) are the main types of new pollutants coming from cities. They're getting into the soil and water systems through untreated or treated wastewater, polluting the environment (Bester 2004). Chlorinated aliphatic chemicals, particularly chlorinated solvents, are typically found in soil and groundwater near hazardous waste sites (Barbee et al. 1994)

Improper waste management procedures, industrial waste, and agricultural runoff into the environment are the sources of organic pollutants. The permanent existence of these substances in nature poses a major threat to the health and safety of both humans and animals (Pavlostathis et al. 2001). One of the hardest materials for life in the environment is heavy metal (Siddiquee et al. 2015, Maddela

& García 2021). Heavy metals are classified as elements with a specific density greater than 5 g/cm³ (Jarup et al. 2003). Heavy metals are not polymers or biodegradable and have detrimental effects (Malik et al. 2022). Toxic heavy metals including mercury, chromium, cadmium, arsenic, lead, and others in high quantities can cause a variety of health problems as well as harm the ecosystem. Metal-containing contaminants are either indirectly or directly introduced into the environment, threatening the health of people, soil, and sediment (Siddique et al. 2011). Additionally, the maximum amount of dangerous heavy metals in irrigation water was permitted by the Food and Agricultural Organisation.

Heavy metals pose a grave threat to human health through various exposure routes such as inhalation, ingestion, and skin contact, leading to a myriad of health issues including neurological impairment, kidney dysfunction, cardiovascular complications, and increased cancer risks (Mahurpawar 2015). Certain heavy metals, such as lead, arsenic, mercury, cadmium, copper, nickel, and tin, have different harmful effects on the body. Consumption of arsenic can cause serious gastrointestinal issues, and long-term exposure can cause diseases like hypertension and black foot disease (Mahurpawar 2015, Bharti & Sharma 2022). Exposure to lead destroys various organs, but cadmium mostly harms the kidneys and bones. There is a danger of neurotoxicity from mercury, particularly from methylmercury in shellfish. Overconsumption of copper can damage the kidneys and liver, while exposure to nickel is associated with several malignancies and respiratory problems (Martin & Griswold 2009).

The effects of metal pollution on marine ecosystems are significant, even though it may not be as readily apparent as other types of marine pollution. The level of metals present in fish can vary depending on factors such as species, age, developmental stage, and physiological conditions (Singh & Kalamdhad 2011). Fish tend to accumulate significant amounts of mercury in their tissues, making them a primary dietary source of this element for humans (Singh & Kalamdhad 2011). Fish serve as the primary sources of mercury and arsenic exposure for humans. Mercury, a well-known human toxin, is primarily introduced into human systems through fish consumption (Singh & Kalamdhad 2011).

Heavy metal toxicity in plants occurs when metal concentrations within the plant surpass acceptable limits and indirectly and directly impact the plant (Tyagi et al. 2022). Excessive amounts of metal can block cellular enzymes and cause oxidative stress-induced cellular structural damage (Van Assche & Clijsters 1990, Uchenna et al. 2020).

Heavy metals' deleterious impact on the growth and function of soil microorganisms has an indirect impact on

the development of plants. Excessive metals may reduce the amount of helpful soil microorganisms, resulting in a decrease in organic matter breakdown and poorer soil fertility (Hossain et al. 2022). Enzyme activities are critical for plant metabolism; yet, they are hampered by heavy metal interactions with soil microbial activity. These negative impacts (both direct and indirect) reduce plant development, which finally leads to plant death (Hossain et al. 2022).

Even though these materials are often resistant, under the right circumstances, microbially mediated processes can transform and eliminate them (Ferguson & Pietari 2000). Various approaches and techniques have been researched and implemented to eliminate these pollutants. Some of the most used methods include phytoremediation, chemical precipitation, electrochemical treatment, ion exchange, adsorption, membrane filtration, soil washing, stabilization, solidification, and bioremediation. Bioremediation is often considered a more environmentally safe remediation method based on self-generated biological processing rather than adding chemicals. The use of dangerous chemicals can be reduced or even eliminated with the help of bioremediation. Bioremediation employs biomass, both alive and dead, and mineralizes organic contaminants to form carbon dioxide, nitrogen gas, water, and other compounds.

BIOREMEDIATION

Bioremediation is one way to reduce or replace harmful chemicals (Manorma et al. 2023). Bioremediation utilizes alive or dead biomass to break down organic contaminants into carbon dioxide, nitrogen gas, water, and other chemicals. Additionally, it can be utilized to get rid of dangerous pollutants including heavy metals and poisonous elements from contaminated surroundings (Arya et al. 2023, Manorma et al. 2023, Kapahi & Sachdeva 2019, Alori et al. 2022).

Bioremediation is the procedure of restoring polluted sites into less hazardous or innocuous forms by using biological organisms, mainly microorganisms, green plants, and their enzymes, to remove, break down, mineralize, change, and detoxify pollutants from the environment and hazardous waste elements (Vishwakarma et al. 2023, Jain et al. 2023, Azubuiké et al. 2016, Tyagi & Kumar 2021). Bioremediation is frequently less expensive than other cleanup procedures. Its implementation takes fewer resources, equipment, and energy. Bioremediation proves advantageous across various pollutants and environments, effectively eliminating substances such as pesticides, heavy metals, petroleum hydrocarbons, and chlorinated solvents from soil, water, and subterranean aquifers. Bioremediation technologies are frequently non-intrusive and can be done without interfering with the natural ecosystem.

FUNDAMENTALS OF ENVIRONMENT RESTORATION THROUGH BIOREMEDIATION

The fundamental concept of bioremediation is to use living things, such as plants, fungi, algae, and bacteria (Saxena et al. 2020) to decrease and detoxify toxic chemicals in the environment and transform them into less toxic substances, like CO₂, H₂O, microbial biomass, and metabolites (Tyagi & Kumar 2021) (Fig. 1). Hot springs, glaciers, salt lakes, deserts, and oceans are just a few of the various environments where microorganisms can be found. Degradable microbes are capable of breaking down a variety of toxins when isolated from polluted habitats, including heavy metal-polluted areas, waste landfills, pesticide-contaminated sites, and wastewater treatment plants.

Microorganisms from the genera *Bacillus*, *Enterobacter*, *Flavobacterium*, *Alteromonas*, *Arthrobacter*, *Achromobacter*, and *Pseudomonas* are the main ones used in bioremediation procedures (Ojuederie & Babalola 2017, Xu et al. 2018). *Alcanivorax*, *Marinobacter*, *Thalassolituus*, *Cycloclasticus*, and *Oleispira* are examples of hydrocarbonoclastic bacteria (OHCB), renowned for their distinctive capacity to degrade hydrocarbons (Yakimov et al. 2007).

Certain enzymes, such as laccases, peroxidases, and catalases (Varjani et al. 2018), have been reported to be produced by fungi and can either break down organic contaminants or immobilize inorganic ones. Moreover, microbes are also capable of producing these enzymes (Morel et al. 2013, Durairaj et al. 2015, Shah et al. 2021).

Several fungal taxa are capable of degrading aromatic hydrocarbons, including *Aspergillus*, *Fusarium*, *Curvularia*, *Lasiodiplodia*, *Drechslera*, *Mucor*, *Penicillium*, *Rhizopus*, and *Trichoderma* (Lladó et al. 2013, Balaji et al. 2014, Chang et al. 2016).

It has been shown that microalgae, primarily green algae from the genera *Scenedemus*, *Selenastrum*, or *Chlorella*, may immobilize metals and break down certain polycyclic aromatic hydrocarbons like phenanthrene, pyrene, and naphthalene (Lei et al. 2007, Takáčová et al. 2014, García et al. 2016, Ghosal et al. 2016).

CATEGORIES OF BIOREMEDIATION

Ex-situ bioremediation and in situ, bioremediation are two widely recognized classifications for the bioremediation process as shown in Fig. 2 (Gkorezis et al. 2016).

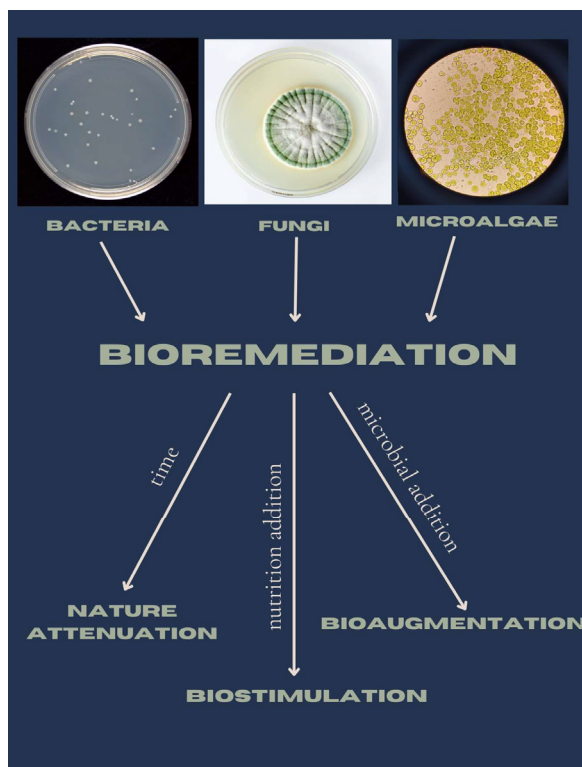


Fig. 1: General framework for bioremediation techniques using various microbial species.

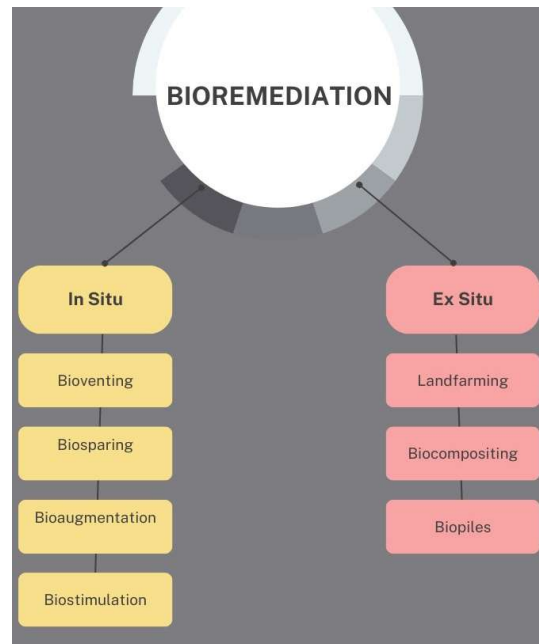


Fig. 2: Techniques of bioremediation.

MECHANISM OF HEAVY METAL TOLERANCE

Now, four basic mechanisms of heavy metal tolerance were determined, as depicted in Fig. 3, and they can even be present in the same microbe (Cánovas et al. 2003, Cazorla et al. 2002, Cervantes et al. 2001, Cervantes & Gutierrez-Corona 1994, Cha & Cooksey 1991, Antonucci et al. 2017, Lin et al. 2006, Kumar & Thakur 2022).

1. **A selectively permeable system, the extracellular barrier:** The heavy metals subsequently bind to different chemical structures on the cell wall. The metal-binding capability of Gram-positive bacteria and Gram-negative bacteria is determined by a peptidoglycan layer containing various groups. Carboxyl groups bind metal cations avidly because they are numerous and negatively charged (Doyle et al. 1980). However, some metal ions penetrate the cell by crucial element ingestion pathways; As an example, the sulfate transport system is responsible for bringing Cr(II) into the cell (Gilotra & Srivastava 1997). The magnesium transport mechanism facilitates the entry of Cd(II), Zn(II), Co(II), Ni(II), and Mn(II) into cells (Nies & Silver 1989). Furthermore, As(V) is transported via phosphate transport systems, whereas As(III) is transported by glucose permeases (Yang & Rosen 2016). Recent studies indicate that capsular polysaccharides in both Gram-positive and Gram-negative bacteria can contribute to the extracellular heavy metal barrier, in addition to the well-established involvement of peptidoglycan in Gram-

positive bacteria. Divalent and trivalent cations can be bound by these intricate sugar molecules (Grass et al. 2010). In addition to the physical barriers, efflux pumps are another crucial component of the extracellular barrier. Heavy metals are actively transported out of the cell by these specific membrane proteins, which decreases the accumulation of heavy metals inside cells. Two such examples are the ArsB arsenic efflux pump in *S. cerevisiae* and the CadA cadmium efflux pump in *E. coli* (Nies et al. 2003, Wysocki et al. 2006).

2. **Transport of Metal Ions:** Efflux Systems: Efflux systems in thermophiles are a series of molecular mechanisms that allow these organisms to remove poisonous or undesired chemicals from their cells. It is essential for thermophile survival in severe environments by maintaining cellular homeostasis and protecting them from external stresses. The function of specialized membrane proteins known as efflux pumps, which actively transport chemicals across the cell membrane, is often involved in these systems. Genetic determinants of the efflux system are present in chromosomes and plasmids. Bacteria have three main efflux systems: CDF (cation diffusion facilitator) proteins, RND (resistance, nodulation, and cell division), and P-type ATPases (Nies et al. 2003). The passage of particular substrates across the cell membrane and into the periplasm of Gram-negative bacteria is facilitated by P-type ATPases and CDF proteins. The three domains of life are home

to metal transporters found in these bacteria, which go by the name of CDF proteins. Divalent metal ions like Zn(II), Co(II), Ni(II), Cd(II), and Fe(II) are handled by these CDF proteins. It is possible to export metals by using a chemiosmotic gradient produced by H⁺ or K⁺ (Paulsen & Saier 1997, Kolaj-Robin et al. 2015, Joshi et al. 2023). P-type ATPases can transfer both monovalent and bivalent metal ions, in contrast to CDF proteins. By hydrolyzing ATP, these ATPases may move ions like Cu(I)/Ag(I) and Zn(II)/Cd(II)/Pb(II) across cellular membranes. They also show a great affinity for sulfhydryl groups (Nies et al. 2003). These three domains make up these efflux systems: i) a soluble ATP binding domain with a transiently phosphorylated aspartate residue; ii) a soluble actuator domain (AD). The transmembrane helix bundle facilitates substrate translocation. P1B-type ATPases can eliminate hazardous metals like Ag(I), Cd(II), and Pb(II) as well as necessary transition metal ions like Zn(II), Cu(I), and Co(II). This helps maintain cellular homeostasis. Members of the RND family are efflux pumps classified into subfamilies according to the substrates they transport. These pumps are primarily found in Gram-negative bacteria. They actively eliminate hydrophobic substances, heavy metals, and nodulation factors (Tseng et al. 1999). Another common family of efflux pumps that is present in both Gram-positive and Gram-negative bacteria is the MacA/B family. These pumps are very good at moving substances that are amphiphilic, such as some heavy metals (Paulsen et al. 1997). Moreover, newer studies indicate that RND efflux pumps may have

a bigger function in heavy metal efflux than previously thought. Research has indicated that the CzcCBA RND pump in *Escherichia coli* is capable of effluxing a wide variety of heavy metals, such as lead, zinc, cobalt, and cadmium. (Valencia et al. 2013).

3. **Metal ion reduction by enzymatic means:** Specialised enzymes, such as reductases or metal reductases, catalyze the reduction of metal ions once within the bacterial cell (Martinez et al. 2019). To promote the reduction reaction, these enzymes use electron donors, which are frequently produced from cellular metabolic activities (Ranawat & Rawat 2018). Metal ions are often reduced from a higher oxidation state to a lower oxidation state, transforming them into a less hazardous form. To develop heavy metal resistance, many thermophilic bacteria use internal enzymatic transformations in conjunction with efflux mechanisms. A wide range of additional heavy metal ions, including Cr(V), Mo(VI), and V(V) (Smirnova 2005), which act as terminal acceptors of electrons during their anaerobic respiration (Poli et al. 2009), can also be reduced by the thermophilic bacteria isolated from diverse ecological settings. Safer versions of metal ions can be produced by enzymatic reduction; for instance, Cr(V) can be changed into Cr(III) and Hg(II) to Hg(0). (Ranawat & Rawat 2018). The flavoprotein MerA from *Sulfolobus solfataricus* catalyzes the transformation of poisonous mercury ions into comparatively benign elemental mercury by reducing Hg(II) to volatile Hg(0) (Schelert et al. 2004).

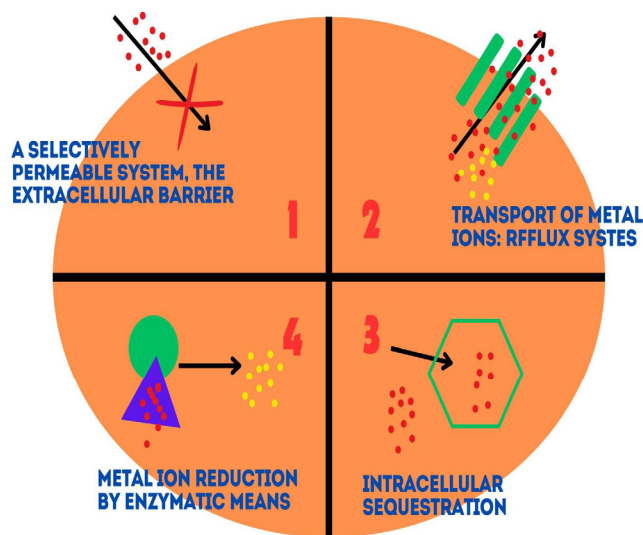


Fig. 3: A generalised interpretation of the genetic pathway underlying microorganism resistance to toxic metals: 1) A selectively permeable system, the extracellular barrier. 2)Transport of metal ions: Efflux systems; 3) Metal ion reduction by enzymatic means;4) Intracellular sequestration.

4. **Intracellular sequestration:** The process by which thermophilic bacteria store or sequester various chemicals within their cells is referred to as intracellular sequestration. This technique enables thermophilic bacteria to protect themselves from potentially hazardous molecules or to amass beneficial substances for diverse purposes. Peptides containing cysteine residues that bind metal ions through sulfhydryl groups are called Phytochelatins and Metallothioneins (Kumar et al. 2022, Ranawat & Rawat 2018). A superfamily of short cytosolic proteins with an average length of 25–82 amino acids is known as the metallothioneins. They have seven to twenty-one conserved cysteine residues, which contributes to their high cysteine concentration. Even in the lack of aromatic amino acids and histidine residues, metallothioneins can bind metal ions, specifically Cd(II), Zn(II), and Cu(I), by forming metal-thiolate clusters (Coyle et al. 2002). The creation of the adaptable proteins known as metallothioneins is triggered by a variety of ecological stresses and environmental contaminants such as heavy metals. Based on the findings of this study, scientists developed a whole-cell biosensor that can detect heavy metals by using the *Tetrahymena* thermophiles metallothionein activator (Amaro et al. 2011, Mehta et al. 2016). In addition to these protein-based methods, thermophiles employ inorganic polyphosphates for intracellular sequestration. These linear polymers of inorganic phosphate residues can bind heavy metals, among other cations (Rao et al. 2009). Interestingly, there is a close relationship between polyphosphate metabolism and heavy metal tolerance, as polyphosphate levels are elevated in cultivated bacteria and fungi in the presence of heavy metal cations. Polyphosphate functions in bacteria by binding heavy metals, and some metal cations even enhance the activity of exopolyphosphatase, which liberates phosphate from polyphosphates and subsequently transports MeHPO_4^- ions out of cells for excretion and storage (Kulakovskaya 2018). Polyphosphate builds up in cytoplasmic inclusions, vacuoles, and cell walls in fungi to produce cation/polyphosphate complexes that help them overcome heavy metal stress (Gajewska et al. 2022, Kulakovskaya 2018). Inclusion bodies are structured intracellular formations consisting of aggregated proteins. These bodies serve as repositories for either vital or potentially harmful metals such as cadmium (Cd) (Magalhães et al. 2007).

APPLICATIONS OF NATURAL CLEANUP

Bioremediation is not a recent concept, but recent advancements in process engineering and molecular biology

have given rise to innovative techniques (Bonaventura & Johnson 1997). Among the contemporary bioremediation methods employed for site cleanup, natural attenuation, and enhanced reductive dichlorination stand out as cutting-edge approaches. The natural removal of pollutants from a site occurs through organic, inorganic, and biological processes without human intervention (Rysz et al. 2010). Electron donors such as lactic acid, molasses, volatile fatty acids, or commercial goods must be added in situ to enhance reductive dechlorination. This promotes biological hydrogen production and facilitates the dechlorination of organic molecules like trichloroethene (TCE) (Evans et al. 2002).

Processing biological nitrogen waste from people and the animals they eat, such as feces and urine, is one well-known, well-established, and getting the harder and harder field of bioremediation. The development of the human population, industrial output, and chemical use have all contributed to the expansion of animal populations (Bonaventura & Johnson 1997). Twenty-five thousand tonnes of nitrogen, thirteen thousand tonnes of phosphorus, and thirteen thousand tonnes of potassium were produced by feed animals in North Carolina alone in 1993, totaling almost 27,000,000 tonnes of fresh manure (Barker & Zublena 1995).

Sewage Treatment Plants (STPs) are the largest and most important bioremediation firms in the world because of the requirement for clean water for human health (Bonaventura & Johnson 1997). Thirty billion cubic meters of raw wastewater is processed annually by the sixteen thousand municipal STPs that make up the United States. Raw wastewater mostly consists of suspended particles, nitrogen, organic debris, phosphorus, pathogenic bacteria, and chemicals (such as pesticides and toxic metals). Certain components are reduced even in the most basic STPs (Bonaventura & Johnson 1997).

The atomic structure of metals is intrinsically harmful, unlike organic contaminants, and they cannot be further transformed or mineralized into an entirely safe state. Despite variances in the solubility, oxidizing state, and relationships with other substances, both organic and inorganic, bacteria and larger organisms can improve bioremediation by concentrating metals to minimize their accessibility and potential hazard (Bonaventura & Johnson 1997). Microbial bioleaching can be applied to different metals and mineral wastes, including contaminated soil, for recycling, metal recovery, and bioremediation (Purchase et al. 2016, White et al. 1998, Xu & Sparks 2013). Sulfide generated by sulfate reduction has been used in leachates and waters for metal bioremediation (White & Gadd 1998, White & Gadd 2000, White et al. 2003 Tabak et al. 2005). Recovery of precious metals like gold is another application for the bioremediation technique called biosorption (Gadd et al. 2009, Volesky

et al. 1990, Wang & Chen 2009). Biosorption is also one of the bioremediation mechanisms used to treat metal contamination. Many bacteria and algae have cell walls or envelopes that can passively absorb relatively high amounts of metallic substances, usually by charge-mediated attraction (Mohamed et al. 2001, Macaskie & Dean 1990).

Interest in mercury pollution has grown significantly since the 1950s, when eating seafood tainted with methylmercury resulted in hundreds of serious illnesses and deaths in Japan. Several states in the US now regularly check the mercury levels in freshwater fish, including North Carolina. The World Health Organisation and the US Food and Drug Administration have set warning standards for mercury levels, which are exceeded in a large number of freshwater and saltwater species (Bonaventura & Johnson 1997). The edible (fillet) part of fish in North Carolina recorded mercury levels higher than 1 part per million (ppm), within a range of 1 to 6.9 ppm (Bonaventura & Johnson 1997). Constructed wetlands are artificial habitats primarily composed of vascular vegetation and algal colonies (Bonaventura & Johnson 1997). These habitats offer structural and nutritional support to a diverse range of microorganisms inside the area. One extremely promising application for artificial wetlands is in situ bioremediation of heavy metal pollution (Bonaventura & Johnson 1997).

Biostimulation and bioaugmentation are two commonly employed processes that promote the bioremediation of soils contaminated with hydrocarbons. Biostimulation is the process of adding nutrients (Betancur-Galvis et al. 2006) humic compounds (Nam & Kim 2002), or other substances that could affect the bacterial state to increase the activity of various bacterial strains that are present in the contaminated soil (Kalantary et al. 2014).

According to certain research, soil bioaugmentation is effective in eliminating pesticides that include triazine (Cycoń et al. 2017). Researchers investigated the impact of biostimulation using *Pseudomonas sp.* ADP (at concentrations of 107–108 viable cells/g of soil) and citrate (up to 4.8 mg/g of soil) on the biodegradation of atrazine in soil contaminated with Atrazera FL, at levels 20 and 200 times higher than the recommended doses (RD) (Lima et al. 2009, Cycoń et al. 2017). Oil biodegradation in the United States was accelerated after the 1989 oil disaster by the utilization of fertilizers and bioaugmentation, which involved the application of naturally occurring bacteria that break down oil. In a matter of years, the joint strategy dramatically decreased oil contamination (Betancur-Galvis et al. 2006).

Although biostimulation is one of the most well-established techniques for bioremediation of hydrocarbons, recent developments in stable isotope analysis, molecular

microbiology, and geophysics promise to significantly expand the breadth, depth, and throughput of biostimulation approaches (Upton et al. 2002). In Washington's Creosote-Contaminated Soil Creosote-contaminated soil at a former wood processing facility was successfully remedied through biostimulation with nitrogen and phosphorus and the addition of native fungi (Betancur-Galvis et al. 2006).

Naturally occurring biodegradation, albeit a slow one, is frequently the means of bioremediation. Some argue that the best course of action for cleaning up certain types of pollution, especially marine oil spills, is to "do nothing" if time-scale concerns are disregarded (National Academy Press 1989).

CONCLUSIONS

In conclusion, bioremediation emerges as a potent and sustainable approach for addressing environmental contamination, particularly in the realm of heavy metals. By harnessing the natural capabilities of microorganisms, this method offers a plethora of advantages, including environmental friendliness, cost-effectiveness, and adaptability to various pollutants and site conditions. Metal-ion transport proteins and specialized microbial mechanisms play crucial roles in enhancing the efficiency of bioremediation processes. Additionally, the integration of microbial processes with engineering techniques has paved the way for innovative strategies that promise to refine soil and water remediation. While challenges such as the lengthy treatment times and the necessity for monitoring persist, the continuous advancement in understanding microbial resistance mechanisms and the development of biostimulation and bioaugmentation techniques hold promise to overcome these hurdles. Future research focused on optimizing these bioremediation technologies will be essential in transitioning from theoretical applications to practical, real-world solutions for environmental management.

ACKNOWLEDGMENT

We express our gratitude to professor Dr. Mamta Arya and emphatically express our indebtedness to Ms. Anjali Patil (Research scholar) for her suggestions and needful help in different stages.

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