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Bioremediation of Hazardous Wastes

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Abstract

The remediation of the contaminated environment using the physical, thermal, or chemical methods has been criticized due to their high-cost implication, non-eco-friendly and inability to meet remediation objectives. Bioremediation offers the application of environmentally benign and cost-effective biological techniques for the remediation of contaminated sites. This chapter provides an overview of bioremediation technologies for the remediation of hazardous substances in the environment while highlighting the application of bioturbation as a promising bioremediation tool for the effective treatment of organic and inorganic contaminants. Given the success of bioremediation, most of these technologies are yet to be applied on a large scale which presents a drawback to this technique. Challenges and prospects for the effective application of bioremediation technologies were discussed.

Keywords: bioaugmentation, biostimulation, bioturbation, bioventing, genetically engineered microbes, phytoremediation

1. Introduction

The increase in human activities triggers environmental pollution through the generation and disposal of hazardous wastes in aquatic and terrestrial habitats [1]. Most of these pollutants include inorganic (heavy metals) and organic matter (polyaromatic hydrocarbons (PAH), petroleum hydrocarbons compounds (PHC)) which may cause negative effects on the ecosystem and possibly react with other abiotic factors that attribute to the effect on the structural arrangement of terrestrial and aquatic habitats [2].

In terms of the environment and ecology system, the proper and safe disposal of these hazardous wastes is a key priority for a sustainable ecosystem. This involves the use of various treatment procedures to clean up hazardous waste. For detoxifying heavy metals, radionuclide and organic polluted soils, physicochemical techniques such as filtration, precipitation, electrochemical treatment, soil washing and chelating, oxidation/reduction, ion exchange, reverse osmosis, and stabilization/

solidification have been employed. These environmental clean-up procedures have various disadvantages, including inefficiency, the need for a large number of chemical reagents, energy, and high cost, as well as the formation of secondary by-products [3].

Bioremediation is a cost-effective and environmentally tolerable technology that employs a biological process to reduce environmental risks caused by toxic substances and other hazardous pollutants. To treat polluted multiphase systems and sustain the native ecosystem, a combination of bioremediation techniques will be effective. The fundamental premise of bioremediation is to reduce contaminant solubility by adjusting pH, modifying redox processes, and adsorbing toxic substances from polluted sites [3]. Environmental remediation always requires human assistance to achieve effective remediation of contaminants and restoration of ecological balance. However, remediation can be destructive to the ecosystem [4], if the application is not properly addressed to meet the eco-friendly standard required to combat the contemporary issues of pollution [4, 5]. Most small-scale applications of bioremediation approaches using bioremediation agents such as bacteria, fungi, plants, and organic materials have been successful with variation in results, although bioremediation on a large scale has not been widely validated [4]. This chapter aims to propose a cost-effective and eco-friendly bioremediation strategies that could reduce or remove contaminants from the environment and thus stabilizing the ecosystem from heavy metal pollution and oil spills.

1.1 Bioremediation technologies

1.1.1 Bioattenuation or natural attenuation

There are a lot of different physical, chemical, and biological processes commonly termed bioattenuation, which make pollutants smaller in terms of their size and toxicity as well as how much of them there are. Some examples of these processes are sorption, volatilization, chemical or biological stabilization, and the transformation of contaminants. This entails removing pollutant concentrations from the surrounding through biological methods or perhaps incorporating (oxic and anoxic biodegradation, plant and animal sorption), physical occurrences (changes in weather conditions, dispersion, dilution, diffusion, volatilization, sorption/desorption), and chemical reactions (ion exchange, complexation, abiotic change) [6–8]. For instance, natural biodegradation and biotransformation are incorporated within the broader notion of common restriction [9, 10]. At the point when the site is contaminated with chemicals, the environment acts in 4 different approaches to facilitate remediation [11]:

- Microbes or microorganisms living in soil and groundwater may consume just a small number of chemical or manmade chemicals available as dietary nutrients. When they have completely digested the chemical, they can convert it to water and non-toxic gases.
- Chemical compounds can stick to or sorb to the soil, which prevents them from contaminating groundwater or escaping the location.
- As contamination travels through soil and groundwater, it can blend in with clean water. This diminishes or weakens the contamination.

- Certain chemicals, such as oil and solvents, can disappear, hence, they can transform from liquids to gases within the soil or groundwater. As a result, if these gases reach the earth surface via the air, they may be pulverized by sunlight.

Additionally, if natural attenuation is insufficiently rapid or complete, bioremediation will be accelerated or augmented via biostimulation, bioaugmentation, bioventing, or biopile [11, 12].

1.1.2 Biostimulation

This bioremediation approach invigorates the activity of native microbes by adjusting the environmental parameters or the introduction of nutrients [11, 13]. This is carried out with the incentive of natural or normally prevailing parasites or microbial communities [7, 11, 13]. Successive steps involve providing manures, development enhancements and minor elements. Also, by giving other natural prerequisites including pH, temperature and oxygen to enhance their digestion rate and degradation pathway [10, 12]. Similarly, the presence of pollutants even in small quantities can act as a stimulant by spinning for bioremediation proteins. Typically, this type of deterioration is followed by the provision of organic or inorganic nutrients and oxygen to promote the metabolism of native microbes for effective remediation [6]. These nutrients are the fundamental building blocks of life, enabling microorganisms to synthesize vital components such as enzymes, energy, and cell biomass required to degrade the toxin [6, 14]. However, nitrogen, phosphorous and carbon are significantly required to enhance metabolism.

1.1.3 Bioaugmentation

This procedure entails sequentially adding contaminant-degrading microbes (inherent/non-native/genetically modified) to improve the biodegradative efficiency of the native microbial community in the polluted site [8, 11]. Thus, to rapidly grow the natural microbial population and accelerate breakdown at the pollutant's location. Microorganisms that predominate in polluted sites on a global scale, may surely change significant amounts of harmful substances into non-poisonous structures. This process converts pollutants to by-products like carbon (IV) oxide and water, as well as metabolic intermediates that serve as critical nutrients for cell development [15, 16]. Microorganisms can also be isolated from the remediation environment, cultured autonomously, genetically engineered, and then reintroduced to the site [8, 11]. For persuade, all basic microbes are prevalent in locales where soil and groundwater are polluted with chlorinated ethenes, for example, tetrachloroethylene and trichloroethylene [7, 8, 11]. These are employed to facilitate the effective removal and conversion of these pollutants to non-poisonous ethylene and chloride by in situ microbes [10].

Additionally, genetically modified microbes have been shown to degrade a broad range of environmental contaminants effectively. Since the metabolic pathway can be altered to produce less puzzling and harmless end products [8, 17]. Genetically engineered microorganisms (GEM) have shown viability in bioremediation of soil, groundwater and activated sludge, proving effective degradation abilities of extensive integration of chemical and physical contaminations. GEMs have better enzyme abilities, which makes them better at breaking down a wide spectrum of aromatic hydrocarbons and making the soil more fertile [14, 18]. There are several types of hydrocarbon-degrading microorganisms that include the genera *Alanivorax* and

Bacillus, *Pseudomonas* and *Bravibacillus*, *Acinetobacter* and *Methylobacterium*, and *Candida* as well. Biodegradation of the benzene, toluene, ethylbenzene, and xylene (BTEX) isomers may be discovered in situ using the polymerase chain reaction, and nucleotide sequence analysis of BTEX degraders in the environment [7–9, 14, 18].

1.1.4 Bioventing

It is the practice of venting oxygen through the soil to encourage the development of natural or injected microbes and fungus in the soil by supplying oxygen to the soil microbes, which has been termed as bioventing [8, 11, 14]. The use of low air flowrates to supply sufficient oxygen to sustain microbial movement has long been a typical practice in aerobic degradation of substances, and it has been for many years. For example, several scientists have demonstrated that bioremediation of oil-contaminated soil utilizing bioventing may be achieved with reasonable success [19]. Consequently, petroleum residuals and their by-products are biodegraded, and volatile organic compounds, when destroyed, release vapors that slowly permeate through the biologically dynamic soil environment.

1.1.5 Biopiles

Biopile, also known as biocells, bioheaps, biomounds and composts piles are employed to minimize the toxicity of total petroleum hydrocarbon constituents via microbial respiration. Biopiles are an ex-situ bioremediation technology that consists of piling polluted soil onto a compost pile (biopiles) or cells (biocells) or mounds (biomounds) or heaps (bioheap) and stimulating oxic metabolism in the soil via aeration or introduction of minerals or nutrients, bulking agents, and subsequently confining it in a treatment bed with polyethylene material to avoid evaporation, surface runoff, and volatile emissions. Biopiles treatments can transform pollutants into low-toxic by-products through biological processes by utilizing already existing microorganisms to breakdown fuels and oils into carbon dioxide and water.

The biopile technology is made up of commercial roll-off dumpsters or containers that have been turned into fully contained bioremediation units. The biopile units have an impermeable liner to decrease the possibility of leachate movement to the subsurface ecosystem. Excavated soils are combined with soil additives and placed on a treatment area with leachate collecting devices and some type of aeration to maximize and regulate the rate of biodegradation. Air is introduced to the biopile mechanism of piping and pumps, which either power air into the heap under a specific tension or draw air through the heap under a negative tension [8, 20]. Microbial movement, for instance, can boost the adsorption and degradability of petroleum pollutants during funneling and siphoning operations. Biopiles, such as biocells, bioheaps, biomounds, and compost, might alleviate public concern about excavated soil contaminated by vigorously remediable hydrocarbons [8, 13, 19].

1.1.6 Phytoremediation

Utilizing plants for bioremediation is highly dependent on their ability to break down certain pollutants [21–24]. Phytoremediation is the process of utilizing plants to degrade, eliminate, or convert contaminants to less hazardous chemicals [25]. Even though plants have been used for soil purification for centuries, scientists have contributed to its advancement and expanded its scope of application throughout the

- iii. Phytodegradation: this process includes the degradation or modification of pollutants in the plant tissue by enzymes.
- iv. Phytoextraction: this approach involved the extraction of contaminants from the soil and their accumulation in the shoots. Upon that, these plants' leaves are gathered, burned for energy, and the metals retrieved from the ash are regenerated.
- v. Phytofiltration or rhizofiltration use roots to accumulate and sequester contaminants from polluted water.
- vi. Phytostimulation or rhizodegradation: plant roots are employed to digest organic pollutants in the rhizosphere environment and through microbial activity.

1.1.7 Combinative bioremediation

This is when two or more bioremediation methods work together to remove contaminants from the environment. This kind of bioremediation technique can be effectively applied in a multi-contaminated environment. The combinative strategy most likely to be suitable and effective in boosting bioremediation of bauxite residue is a combination of bioaugmentation (incorporation of inocula) [8, 11] and biostimulation (introduction of nutrients to enhance the activity of microorganisms) of the indigenous community in bauxite residue [11, 13].

In this scenario, for instance, biostimulation using organic or inorganic compounds can be applied as the first or basic treatment while bioventing or bioaugmentation using engineered microbes can be applied subsequently as a secondary or tertiary treatment to facilitate the removal or degradation of recalcitrant compounds. Combinations of bioaugmentation and biostimulation have also proven effective, albeit they do not always show significant improvements over bioaugmentation alone. Given the nearly consistent advancement seen with bioaugmentation technology, it is anticipated that bioaugmentation will improve on the outcomes obtained so far with biostimulation for bauxite waste cleanup (provided an appropriate choice of the microbes and adequate trials are prioritized). Based on the simplicity of obtaining and introducing the inoculum, the most suited approach for future research and field trials is combinative bioremediation using biostimulation and bioaugmentation technology.

1.2 Bioremediation mechanisms for contaminant removal

Several bioremediation mechanisms for reducing or oxidizing contaminants have been discovered over time, such as adsorption, physio-biochemical (biosorption and bioaccumulation) bioleaching, biotransformation, biomineralization, and molecular mechanisms [7, 11].

1.2.1 Adsorption bioremediation mechanism

Environmental pollutants (both organic and inorganic) can be absorbed by microorganisms at specific sites in their cell structure that do not require the dissipation of energy. There are many various kinds of chemicals connected with bacterial cell walls,

but their extracellular polymeric substances (EPS) are of particular importance since they have been shown to have significant effects on corrosive base characteristics and metal adsorption [10, 26]. Several studies on the metal binding behavior of EPS have revealed that it has a remarkable capacity to absorb complex metals by a variety of processes that combine ion exchange and micro-precipitation of metals [10, 13]. Bioremediation research and application are still limited in the present scenario due to a lack of understanding of the genetic traits and genome-level properties of the organisms used in metal adsorption, the metabolic route, and the kinetics of metal adsorption [7].

1.2.2 Physio-biochemical mechanism

In microscopic organisms, inhibition is advanced through two mechanisms: detoxifying (changing the detrimental metal's state and rendering it inaccessible) and dynamic efflux (siphoning poisonous heavy metals from cells) [7, 9]. In wastewater or soil, the fundamental redox (oxidation and reduction) reaction occurs between hazardous metals and microorganisms. Additionally, microbes oxidize heavy metals, causing them to lose electrons, which are recognized by active electron acceptors (nitrate, sulphate and ferric oxides) [26]. Additionally, the biosorption process, which consists of a biosorbent's increased affinity for sorbate (metal ions), is repeated till a balance between the two components is established [18, 26]. For instance, *Saccharomyces cerevisiae* acts as a biosorbent for Zn (II) and Cd (II) removal via the ion exchange process [10, 26]. *Cunninghamella elegans* is also reported as a potential sorbent against substantial metals delivered by textile wastewater [12, 17].

Bioaccumulation is a term referring to the combination of active and passive techniques of hazardous metal bioremediation. Additionally, bioremediation may entail aerobic or anaerobic microbial activity [10, 12, 13]. Aerobic degradation frequently involves the addition of oxygen atoms to the reactions via monooxygenases, dioxygenases, hydroxylases, oxidative dehalogenases, or chemically active oxygen molecules produced via catalysts including ligninases or peroxidases [10–13]. Anaerobic contaminant corruptions comprise initial enactment reactions followed by oxidative degradation with the assistance of anaerobic electron acceptors. The act of Immobilization refers to the process of reducing the activation of significant metals in a polluted environment by modifying their physical or synthetic state [7, 12]. Microbes muster metals from polluted sites through leaching, filtering, chelation, methylation and redox transformation of harmful metals [12, 17]. Since significant metals cannot be entirely eliminated, the cycle modifies their oxidation state or organic complex to make them more soluble, less poisonous and precipitated [9, 14].

1.2.3 Bioleaching

In bioleaching, naturally occurring microorganisms such as bacteria and fungi solubilize metal sulphides and oxides from ores and secondary wastes. Adsorption, ion exchange, membrane separation, and selective precipitation are some of the processes used to purify solubilized metals. It is a cost-effective and environmentally beneficial technique because it consumes less energy and produces no hazardous gases. It has been applied to leach metals from low-grade ores, and it now provides a substantial global business in the extraction of metals like copper, cobalt, gold, nickel, uranium, zinc, and other elements [27].

1.2.4 Biotransformation

This is the procedure for altering the structure of a chemical substance to produce a molecule with higher polarity. Moreover, this metal-microbe interaction process converts hazardous metal and organic chemicals into a less poisonous form. This mechanism has emerged in microorganisms to assist them in adjusting to variations in their surroundings. Bacterial cells have a significant surface-volume ratio, a rapid pace of proliferation, a rapid rate of metabolic activities, and are easy to keep sterile [27]. As a result, they are perfect for biotransformation. Various methods, such as condensing and hydrolyses, forming new carbon bonds, isomerization, inserting functional groups, and oxidation, reduction, and methylation, can be used to attain this objective. Metals may be volatilized, reducing their lethal nature, as a result of these interactions.

1.2.5 Biomineralization

Biomineralization refers to the mechanisms by which microbes produce minerals, and it can lead to metal extraction from solution, which can be used for decontamination and biorecovery. Dead biota and related products may also serve as a model for mineral deposition, with physicochemical parameters determining whether the process is reversible or not. There are several prevalent microbe-precipitated biominerals with unique chemical features such as high metal sorption capacities and redox catalysis. However, some biominerals can be deposited at nanoscale dimensions, resulting in additional physical, chemical, and biological features that can be used in practical applications [28].

1.2.6 Molecular mechanisms involved in bioremediation process

Different components of genetically altered bacteria, such as *Deinococcus geothermalis*, are active in the removal of heavy metals [9, 14, 18]. Hg^{2+} reduction has been recorded at high temperatures as a result of the expression of mer operon from *Escherichia coli* coded for Hg^{2+} reduction [18]. Two distinct components for Hg reduction by microscopic organisms (*Klebsiella pneumonia* M426) are mercury volatilization by the decrease of Hg (II) to Hg (0) and mercury precipitation as insoluble Hg attributed to unstable thiol (H_2S) [7, 18]. Genetic of *Deinococcus radiodurans* (radiation tolerant bacterium) which usually decreases Cr (IV) to Cr (III) has been done for toluene (fuel hydrocarbon) reduction by cloned genes of *tod* and *xyl* operons of *Pseudomonas putida* [9, 11, 18]. Microbial metabolites including metal-bound coenzymes and siderophores are usually part of the degradation pathway.

2. Bioturbation

The promising bioremediation technique involves the application of bioturbators. Bioturbation is made up of a series of processes triggered by microbenthic fauna that influences sediment physicochemical characteristics and affects the microbial population which partake in the distribution of nutrients [29]. Bioturbation involves a series of activities such as the reworking of particles, bioirrigation, and other benthic biota related behaviors (i.e. nutrition mode and grazing by animals and organisms) that were responsible for transportation and distribution of porewater and particles along the water-sediments interface [30]. The distribution of dissolved contaminants

can be a reworking of sediments by bioturbators through facilitating transportation and biomixing efficiency from overlying water and porewater to deep layers of the sediment [31–33].

The term “bioturbation” relates to the procedure of completely transforming dangerous hazardous substances into harmless or naturally occurring chemicals. Bioturbation can be done in situ (for example, in field conditions) or ex-situ (for instance, in a microcosm or under controlled conditions). Both scenarios entail the utilization of plants, parasites/fungi, and microorganisms as bioremediators for the biodegradation of toxic pollutants, even though individualized end product may be a different component [34–36]. Thus, complete breakdown of the contaminants by the bioremediators directly or indirectly may influence the residue structure [34, 37]. **Figure 2** presents significant types of contaminant improvement approaches by bioturbators (benthic fauna) in the contaminated environment to facilitate residue treatment.

Figure 2 illustrates the following:

- i. Biodiffusors: this is performed through microorganisms’ activities, which often result in the biomixing of uniform and irregular sediments over short separations, resulting in particle interchangeability via molecular diffusion.
- ii. Upward conveyors: these are organisms that live vertically head-down in the sediments. They transfer particles from the residue’s deep horizons to its surface. Gravity then returns the particles to the base under the influence of feces pellet agglomeration at the sediment surface.
- iii. Downward conveyors: these are head-up feeders that actively pick and consume particles near the surface, as well as discharge in deeper residual layers.
- iv. Regenerators: these microorganisms dive into the leftovers and constantly maintain burrows, so transferring dirt from depth to the surface.

Figure 2.
Schematic representation of bioturbators activities in sediments (i) biodiffusors, (ii) upward conveyors, (iii) downward conveyors, and (iv) regenerators.

2.1 The role of bioturbation in bioremediation of organic and inorganic contaminants

The role and effectiveness of bioturbators in bioremediation is dependent on several conditions, such as the chemical type and quantities of contaminants, the physicochemical properties of the environment, and their accessibility to microbes [38]. Bioturbators are responsible for vital changes in the biological and physicochemical aspects of soils and water [38, 39]. Additionally, aerobic bioturbation can increase benthic digestion and supplement components by stimulating oxygen-consuming bacterial networks that are concerned with pollutant mitigation [8, 11]. In other words, bioturbators are well-suited for a dual-purpose mechanism, namely the production of degradative enzymes for specific contaminants and resistance or protection from significant relative dangerous substances such as heavy metals [15, 38, 39]. Controlling and simplifying bioremediation procedures is a difficult process due to a large number of components including the presence of a microbial community with the ability to detoxify pollutants, the contaminants' accessibility to the microbial community, and abiotic conditions (soil type, temperature, pH, oxygen or other electron acceptors, and substrates) [6, 16, 39].

Bioturbation influences the sediment-water interface's biological, physical, and chemical properties which accounts for the high rate of mineralization of organic matter in the aquatic environment [40]. This operation changes the sediment column distribution of the contaminants [41]. Bioturbation and biotransport can affect the physicochemical characteristics of sediments and sediment pollutants [42–44]. Bioturbation controls the organic matter and nutrient digestion enhances pollutant mobility and transformation [45–48]. The biosorption of organic contaminants into the organic matter during bioremediation reduces its bioavailability for plants (phytoremediation) or degrading organisms (bioaugmentation) [49]. Atrazine removal from sediments is promoted and positively influenced by the adjustment of organic matter and earthworm bioturbation activities, which increases contaminant bioavailability and atrazine sorption rate on their microsites [46, 50]. Previous studies reported positive contributions of earthworm bioturbation to organic pollutant transformation and biodegradation [51, 52] by modifying pore size and metabolism of degrading bacteria groups or accelerating mineralization in bioaugmented soils [50].

Moreover, several studies showed that bioturbation alters the physicochemical characteristics of the water-sediment boundary which promotes the bioavailability of inorganic pollutants to degrading organisms. This is achieved through the modification of sediment particle sizes, pore spaces, moisture content, nutrient content, turbidity, and total organic carbon of the vadose water-sediment [41, 43, 53]. Also, the bioturbation of benthic invertebrates through the mixing of sediments in the underground zone enhanced the electron acceptors (oxygen, nitrate and sulphate) entrance into the vadose zone which triggers geochemical changes that influence metal behavior [54]. The presence of these electron acceptors in the unsaturated zone can activate the RedOx reaction to change the chelating of metals affinities between liquid and solid phases to enhance the quantitative distribution and bioavailability of metal in the sediment [55]. The changes created by the bioturbation-attributed redox potentials, pH, organic content, pore spaces can affect metal sorption capacity and improve metal conversion from one phase to another e.g. Cd, Zn [56–58].

2.2 Factors that influence bioremediators or bioturbators for pollutant remediation

The activities of bioturbators are affected by some factors which modulate the rate of bioturbation for effective remediation of polluted environments. These factors include the variation in salinity, temperature, density, sediment grain size pH, and concentration.

2.2.1 Variation in salinity level

Variation in salinities in the aquatic environment can influence the metabolism of nutrient and metal releases [59, 60], whether naturally and/or through human-related activities. Remaili et al. [61] noted that hypersalinity has a negative effect on the larger bioturbators which affects the activities of benthic organisms. Gonzalez et al. [62] study found that the salinity levels and tolerance of various bioturbators are distinct. The findings however suggest that ammonia release in the aquatic environment is significantly modified due to the effect of modulating conditions and distinguished by a higher salinity than other nutrients such as phosphorus [62, 63].

2.2.2 Temperature variation

Regional variability in temperature is also a crucial factor that regulates the impact of bioturbation in pollutant remediation. In microbial response, metabolism, and degradation of organic matter and metals, temperatures played a fair modulatory function [64]. In the presence of bioturbation activities, the rise in temperatures increases the production of ammonium from the sediment, possibly due to the high level of hydrogenase in microbial species and the increased aerobic conditions in the sediment [64, 65]. Gonzalez et al. [62] reported that an increase in temperature is indirectly proportional to the nutrient dispersion as high temperature decreases nutrient flux (phosphorus) in the sediment but extreme temperatures may be devastating to the microbes. However, an increase in temperature corresponds to the increased rate of metal resuspension and metal solubility as a result of higher bioturbation rates [66, 67].

2.2.3 Bioturbator density

The bioturbator density influences bioturbation, control bioturbation efficiency for contaminant remediation, which correlates with the increased aerobic microbial activity and emission of pollutants. The increased bioturbation density increased phosphorus release and induced aerobic microbial activity but did not increase the release of ammonia. Animal density is a highly imperative factor, as study reveals that higher densities contribute toward greater degradation and mineralization of organic matter but may also increase nutrients in the overlying water and can, depending on the ecosystem studied, have counterproductive effects on recovery [66]. In response to pollution, the population of certain benthic species such as polychaetes [68] may increase as several systems are deprived of the use of other larger bioturbators.

2.2.4 Sediment grain size

Another element that influences the high level of organic matter and metals accumulation and the structure and metabolism of microbial communities and their

metabolism is the sediment grain size [69, 70]. A recent study also shows a positive association between ammonia, phosphorus release, and aerobic microbial activity for the sediment grain size as Martinez-Garcia et al. [70] noted that the grain size showed less effect at low organic enrichments, but instead, at higher enrichments, coarse sediments contain less organic matter and nutrients while metabolism rate is enhanced. The contaminant bioavailability assessment can be affected by the susceptibility, grain size and behavior of microbes used in bioassays or observed on the ground, and the interaction between various species and microbial populations in highly polluted sediments depauperated by larger invertebrates [1, 71].

2.2.5 Contaminant pH and concentration in the sediment

The concentration of organic or inorganic contaminants is another factor that regulates the activities of the benthic organisms [72] which tend to either reduce or hinder the activities of the benthic organism at a high concentration, beyond the tolerable limit, which can result in the death of these organisms at extreme condition due to toxicity [5]. Benthic organisms have varying tolerance limits for sediment contaminations and tend to possess special features or activities (such as bioaccumulation or biosorption) to enable them to adapt and function effectively in high pollutant concentrations. For metal remediation, abiotic factor-like pH which works closely with concentration may be a crucial modulating variable that determines the impact of bioturbation in the marine environment which can alter metal speciation and reactivity [66].

Therefore, sediment properties like particle size and concentration as well as contaminant shape (sulphides or organic carbon) can affect the bioavailability of the contaminant. Also, in most environments, temperature and type of organism activity or population density can increase or decrease contaminant exposure or bioavailability for bioremediation [61, 73–75].

3. Challenges in bioremediation application

Notwithstanding the benefits (such as environmental friendliness, selectivity, adaptability, self-reproducibility, and the ability to recycle bioproducts) of the bioremediation technique, some setbacks have hindered the successful application of this technology. The delay of the operations and the complexity in managing the procedures are the two most significant disadvantages of this technique of treatment. Since the elimination of significant concentrations of heavy metals is a priority, and that the world has become more aware of the environmental concerns caused by other approaches, microbial procedures offer the most rational and long-term answer for treatment. As previously stated, while a variety of microbial contaminant bioremediation techniques to address contamination have been developed, their extensive use and application on a commercial scale are still restricted by some factors. A further point to mention is that the long-term viability of microbial decontamination is still a subject of significant importance, given the paucity of investigations into its long-term performance. Due to the extremely high accumulation of inorganic contaminants (heavy metals) in heavily inhabited places of the world, updating existing microbial bioremediation technologies to an industrial level by making the procedures quicker, more reusable, and easier to regulate will be a big issue in the future. Furthermore, another limitation of bioremediation is that not all substances

are biodegradable while some hydrocarbon components are recalcitrant to microbial breakdown, which restricts the scope of the remediation technique. Even when a material is biodegradable, its downstream operation and breakdown can result in the production of harmful by-products in some situations.

4. Future approach of bioremediation technology

4.1 Genetically engineered microorganisms (GEMs)

The potential for microorganisms to remediate water and soil pollutants to increase treated water consumption and soil fertility for agricultural output is gaining attention [11, 38]. Recently, research has been conducted to enhance the application of altered organisms delineated specifically to boost their affectability toward hazardous metals [11, 16, 38]. An organism whose genetics have been transformed by the use of synthetic methods, which are driven by an artificial genetic exchange between bacteria, is referred to as a “genetically engineered microorganism [11, 18]. By developing GEM, genetic engineering has enhanced the application and disposal of hazardous wastes in laboratory settings. In addition, the following protocols must be considered during the GEM process: (a) alteration of enzyme selectivity and affinity, (b) pathway development and modulation, (c) bioprocess advancement, surveillance, and control, and (d) bioaffinity bioreporter sensor utilization for chemical detecting, toxicity reduction, and endpoint evaluation [13, 18].

As there are several possibilities for improving degradation performance through genetic engineering approaches, such as genetically controlling the rate kinetics of known metabolic pathways to increase degradation rate, or completely infusing bacterial strains with new metabolic pathways for the degradation of previously recalcitrant compounds [6, 8]. Despite important genes for microorganisms are carried on a single chromosome, defining the specific genes needed for the catabolism of some of these novel substrates may be carried on plasmids [18, 76, 77]. Plasmids were entangled in the catabolism process. As a result, GEM can be successfully used for biodegradation purposes, necessitating immediate research and large-scale deployment. Genetically engineer microbes offer the benefit of developing microbial strains which can tolerate unfriendly upsetting circumstances and can be utilized as a bioremediation tool under different and complicated natural conditions [18, 37, 76, 77]. Additionally, GEM has encouraged the development of “microbial biosensors” capable of precisely quantifying the degree of pollution in a contaminated site.

4.2 Engineered plants approach

The current advancement in omics technologies, including genomics, proteomics, transcriptomics, and metabolomics, play a critical role in finding characteristics that optimize remediation solutions [7, 11, 78]. Consequently, phytoremediation was developed, a process for eliminating toxins or their metabolites from plant tissues. This usually shortens the life of the plant and finally volatilizes the toxins into the atmosphere [78]. This disadvantage can be mitigated by managing plants’ metal resistance, accumulation, and breakdown capacity in the presence of various inorganic toxins. To improve metal decomposition in plants, bacterial genes responsible for metal reduction can be integrated into plant tissues. As a result, plant-based bioremediation for a variety of significant metal poisons is cutting-edge due to its

eco-friendliness. They are more effective at reducing dangerous substances than Physicochemical approaches, which are less environmentally friendly and potentially detrimental to human health [7, 8].

Notwithstanding, microbial genes can bridge in the transgenic plant for decontamination and collection of inorganic pollutants [7, 11]. The metal-detoxifying chelators, for example, metallothioneins and phytochelatins can give resistance to the plant by upgrading take-up, transport and amassing of different heavy metals [14, 78]. Similarly, transgenic plants with bacterial reductase can augment the volatilization of Hg and Se while absorbing the arsenic in plant shoots [17, 78]. Also, high-biomass-producing plants including poplar, willow and *Jatropha* can be applied for both phytoremediation and energy generation [7, 14, 26, 78]. Nonetheless, metals can only be removed from soil or water, which is why consuming metal-contaminated plants is advantageous. Thus, metal-accumulating biomasses should be properly preserved or disposed of to avoid posing an environmental hazard [20, 78].

4.3 Engineered Rhizosphere approach

Bioremediation methods include the introduction of growth stimulators (electron acceptors/donors) or nutrients to the rhizosphere to promote microbial growth and bioremediation characteristics of microbes or genetically engineered plants [6, 26, 78]. Multiple small organisms were generated with heavy metals by drainage using synthesized catalysts such as chromate and uranyl reductase in a particular rhizosphere [19, 26, 78]. Although genomics has been studied and applied mostly in microbial genetics and agriculture, such as genetic crops, and now serve as a bioremediation instrument [26, 76]. The application of genomics to bioremediation enables the microorganism to be dissected based on biochemical constraints as well as sub-atomic levels associated with the component [26, 76, 77].

4.4 Integrated bioturbation: phytoremediation process

Bioturbation is a very prolific and appealing technology for remediation, cleaning, management, and recovery of environmental contamination caused by microbial activity [11]. Furthermore, phytoremediation is successful at removing both inorganic and organic pollutants from residues or soils [7, 11, 12]. Nonetheless, investigation of resourceful bioremediation approaches for damaged aquatic environments that are based on these two processes to improve wastewater and soil treatment is necessary [10, 17]. Nonetheless, investigation of resourceful bioremediation technologies based on these two processes is important to improve soil and wastewater treatment [11, 17]. In addition, phytoremediation has been generally illustrated as a bioremediation process for heavy metals, such as lead, cadmium, copper, arsenic removal from contaminated soil or water [76, 77]. In essence, aquatic bioturbation combined with phytoremediation is a more effective and alternative method of removing heavy metals by improving cadmium transfers from overlying water to sediment and then into the root system of plants [15, 38].

Additionally, studies have demonstrated that earthworm movement greatly boosted phytoavailability by increasing soil macroporosity and generating cast around plant roots (**Figure 3**), implying that the physical effect of the earthworm's bioturbation is a viable mechanism [20, 26]. Interaction between plants and soil-dwelling microorganisms can also enhance phytoremediation known as rhizosphere bioremediation. The study by Leveque et al. [52] to investigate the contribution of

Figure 3.
Proffered approach to illustrate metal phytoavailability in earthworms' activities (adapted from [20, 26]).

earthworm (as bioremediator or bioturbation agent) to phytoremediation showed that earthworms significantly increased the phyto-availability of metal by generating soil macroporosity and developing cast near plant roots in which the main mechanism appears to be the physical impact of earthworm bioturbation. Moore et al. [21], demonstrated the contribution and the effect of bioturbators in the remediation of organic contaminants using the phytoremediation technique. In the study, *Typha latifolia* plant species recorded rapid growth in high pollutant concentrations in the environs due to its appreciable efficiency in the phytoaccumulation of contaminants from the sediments, which showed the ability to extract atrazine molecules by producing flux between the soil and the plant root. This plant was able to transform contaminants from atrazine to lower metabolites such as hydroxyatrazine, DEA and DIA [79].

4.5 Nano-biotechnology for bioremediation

The use of nanomaterials is extensively gaining attention for components remediation of heavy metals and recovery of valuable via nanotechnology [8, 34]. Conversely, nanobioremediation, which employs nanoparticles to stimulate microbial activity to clear hazardous chemicals from groundwater and soil [14, 17]. Not only can this nanotechnology greatly cut the cost of cleaning contaminated regions, but it also significantly shortens the procedure's duration. Metal chelating polymers require damaging solvents for mixing and ultrafiltration for division, which can be avoided by inventing metal limiting substances that can be reclaimed by adjusting their pH, temperature, or form, among other parameters [13, 19, 20]. One of the materials is nanoscale modified biopolymers, produced by microorganisms' intrinsic and protein structure, and whose size can be adjusted at the subatomic level [13]. For instance, polymers and magnetosomes are fabricated proteins for the remediation of infections, *Deinococcus radiodurans*, a radioactive-safe form of life, can resist radiation well past the naturally prevailing levels [13, 34, 37]. This is mostly used in radioactive

waste remediation activities financed by the USA Division of Energy (DOE) [34, 38]. This technology seems to be very promising to address the rising concerns about heavy metals and other emerging contaminants in the aquatic environment.

4.6 Ecological engineering

The technique entails using ecological and environmental engineering expertise to create and monitor a sustainable ecosystem or biological system that benefits both humans and the environment. **Table 1** and **Figure 4** illustrate how to apply ecological engineering in a way that is more beneficial to humanity while maintaining the natural balance. Nevertheless, the majority of these technologies are typically designed with the following objectives in mind: (i) conservation, (ii) ecosystem restoration,

Ecological-engineering approaches	Terrestrial examples	Aquatic examples
Using ecosystems to solve a pollution problem	Phytoremediation	Wastewater wetland
Imitating or copying ecosystems to reduce or solve a problem	Forest restoration	Replacement wetland
Recovering an ecosystem after significant disturbance	Mine land restoration	Lake restoration
Existing ecosystems are modified in an ecologically sound way	Selective timber harvest	Bio-manipulation
Using ecosystems for benefit without destroying the ecological balance	Sustainable agroecosystems	Multi-species aquaculture

Table 1.
Application of ecological engineering approach for terrestrial and aquatic systems.

Figure 4.
Graphical representation of ecological engineering application to balance the ecosystem.

(iii) expanding ecological systems to the quantity, quality, and maintainability of their production, and (iv) assembling new ecological systems that would provide routine types of assistance [16, 39, 76, 77, 80].

5. Conclusion

Bioremediation is a cutting-edge and promising approach for treating contaminated soil and water. Microorganisms are also known to generate and use a variety of detoxification methods, including biosorption, bioaccumulation, biotransformation, and biomineralization for the remediation of the contaminated site during the bioremediation process. However, recent bioremediation research, such as bioturbation, which uses live organisms (macrofauna) directly or indirectly with the environment to eliminate toxins, is gaining momentum. The use of organisms to detoxify and recover polluted soil and water has emerged as the most robust, straightforward, and profitable technique. Microorganisms in water and soil have been studied and equipped to eliminate or detoxify harmful compounds discharged into the ecosystem due to anthropogenic processes such as mineral mining, oil and gas production, pesticides, pigments, plastic, organic solvents, fuel, and industrial operations. Nevertheless, a lack of data on microorganisms' cell reactivity to minor components and heavy metal poisons precludes their successful implementation. As such, the application of molecular genetic technology will enhance the efficiency and address most of the challenges in the large scale application of bioremediation technology.

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References

- [1] Chapman PM, Wang F. Assessing sediment contamination in estuaries. *Environmental Toxicology and Chemistry*. 2001;**20**(1):3-22
- [2] Johnston EL, Roberts DA. Contaminants reduce the richness and evenness of marine communities: A review and Meta-analysis. *Environmental Pollution*. 2009;**157**(6):1745-1752
- [3] Jain S, Arnepalli D. Biomineralisation as a remediation technique: A critical review. *Geotechnical Characterisation and Geoenvironmental Engineering*. 2019;**16**:155-162
- [4] Boopathy R. Bioremediation of explosives contaminated soil. *International Biodeterioration & Biodegradation*. 2000;**46**(1):29-36
- [5] Boopathy R. Factors limiting bioremediation technologies. *Bioresource Technology*. 2000;**74**(1):63-67
- [6] Ron EZ, Rosenberg E. Biosurfactants and oil bioremediation. *Current Opinion in Biotechnology*. 2002;**13**(3):249-252. DOI: 10.1016/S0958-1669(02)00316-6
- [7] Kumar A, Joshi V, Dhewa T, Bisht B. Review on bioremediation of polluted environment: A management tool. *International Journal of Environmental Sciences*. 2011;**1**(6):1079-1093
- [8] Megharaj M, Ramakrishnan B, Venkateswarlu K, Sethunathan N, Naidu R. Bioremediation approaches for organic pollutants: A critical perspective. *Environment International*. 2011 Nov 1;**37**(8):1362-1375. DOI: 10.1016/j.envint.2011.06.003
- [9] Watanabe K. Microorganisms relevant to bioremediation. *Current Opinion in Biotechnology*. 2001;**12**(3):237-241. DOI: 10.1016/S0958-1669(00)00205-6
- [10] Viswanath B, Rajesh B, Janardhan A, Kumar AP, Narasimha G. Fungal laccases and their applications in bioremediation. *Enzyme Research*. 2014;**2014**:1-21. DOI: 10.1155/2014/163242
- [11] Adams GO, Fufeyin PT, Okoro SE, Ehinomen I. Bioremediation, biostimulation and bioaugmentation: A Review. *International Journal of Environmental Bioremediation & Biodegradation*. 2015;**3**(1):28-39. DOI: 10.12691/ijebb-3-1-5
- [12] Iwamoto T, Nasu M. Current bioremediation practice and perspective. *Journal of bioscience and bioengineering*. 2001;**92**(1):1-8
- [13] Dixit R, Wasiullah, Malaviya D, Pandiyan K, Singh UB, Sahu A, et al. Bioremediation of heavy metals from soil and aquatic environment: An overview of principles and criteria of fundamental processes. *Sustainability (Switzerland)*. 2015;**7**(2):2189-2192. DOI: 10.3390/su7022189
- [14] Dzionek A, Wojcieszynska D, Guzik U. Natural carriers in bioremediation: A review. *Electronic Journal of Biotechnology*. 2016;**23**:28-36. DOI: 10.1016/j.ejbt.2016.07.003
- [15] Vidali M. Bioremediation. An overview. *Pure and Applied Chemistry*. 2001;**73**(7):1163-1172. DOI: 10.1351/pac200173071163
- [16] Mary Kensa V. Bioremediation—An overview. *Journal of Industrial Pollution Control*. 2011;**27**(2):161-168
- [17] Ayangbenro AS, Babalola OO. A new strategy for heavy metal polluted

environments: a review of microbial biosorbents. International journal of environmental research and public health. 2017;**14**(1):94

[18] Pieper DH, Reineke W. Engineering bacteria for bioremediation. Current Opinion in Biotechnology. 2000;**11**(3):262-270. DOI: 10.1016/S0958-1669(00)00094-X

[19] Samanta SK, Singh OV, Jain RK. Polycyclic aromatic hydrocarbons: Environmental pollution and bioremediation. Trends in Biotechnology. 2002;**20**(6):243-248. DOI: 10.1016/S0167-7799(02)01943-1

[20] Farhadian M, Vachelard C, Duchez D, Larroche C. In situ bioremediation of monoaromatic pollutants in groundwater: A review. Bioresource Technology. 2008;**99**(13):5296-5308. DOI: 10.1016/j.biortech.2007.10.025

[21] Moore MT, Tyler HL, Locke MA. Aqueous pesticide mitigation efficiency of *Typha latifolia* (L.), *Leersia oryzoides* (L.) Sw., and *Sparganium americanum* Nutt. Chemosphere. 2013;**92**(10):1307-1313

[22] Fulekar M. Global status of environmental pollution and its remediation strategies. Bioremediation Technology. Dordrecht: Springer; 2010. pp. 1-6

[23] Murphy IJ, Coats JR. The capacity of switchgrass (*Panicum virgatum*) to degrade atrazine in a phytoremediation setting. Environmental Toxicology and Chemistry. 2011;**30**(3):715-722

[24] Qu M et al. Distribution of atrazine and its phytoremediation by submerged macrophytes in lake sediments. Chemosphere. 2017;**168**:1515-1522

[25] Vangronsveld J, Herzig R, Weyens N, Boulet J, Adriaensen K, Ruttens A, et al. Phytoremediation of contaminated soils and groundwater: Lessons from the field. Environmental Science and Pollution Research. 2009;**16**(7):765-794

[26] Malik A. Metal bioremediation through growing cells. Environment International. 2004;**30**(2):261-278. DOI: 10.1016/j.envint.2003.08.001

[27] Tayang A, Songachan L. Microbial bioremediation of heavy metals. Current Science. 2021;**120**(6):00113891

[28] Gadd GM, Pan X. Biomineralization, Bioremediation and Biorecovery of Toxic Metals and Radionuclides. Taylor & Francis; 2016;**33**(3-4):175-178

[29] Biles CL, Paterson DM, Ford RB, Solan M, Raffaelli DG. Bioturbation, ecosystem functioning and community structure. Hydrology and Earth System Sciences. 2002;**6**(6):999-1005

[30] Kristensen E, Penha-Lopes G, Delefosse M, Valdemarsen T, Quintana CO, Banta GT. What is bioturbation? The need for a precise definition for fauna in aquatic sciences. Marine Ecology Progress Series. 2012;**446**:285-302

[31] He Y, Men B, Yang X, Li Y, Xu H, Wang D. Relationship between heavy metals and dissolved organic matter released from sediment by bioturbation/bioirrigation. Journal of Environmental Sciences. 2019;**75**:216-223

[32] Teal LR, Parker ER, Solan M. Coupling bioturbation activity to metal (Fe and Mn) profiles in situ. Biogeosciences. 2013;**10**(4):2365-2378

[33] Timmermann K, Banta GT, Klinge L, Andersen O. Effects of bioturbation on

the fate of oil in coastal sandy sediments– An in situ experiment. *Chemosphere*. 2011;**82**(10):1358-1366

[34] Azubuike CC, Chikere CB, Okpokwasili GC. Bioremediation techniques–classification based on site of application: Principles, advantages, limitations and prospects. *World Journal of Microbiology and Biotechnology*. 2016;**32**(11):1-8. DOI: 10.1007/s11274-016-2137-x

[35] Concetta Tomei M, Daugulis AJ. Ex situ bioremediation of contaminated soils: An overview of conventional and innovative technologies. *Critical Reviews in Environmental Science and Technology*. 2013;**43**(20):2107-2139. DOI: 10.1080/10643389.2012.672056

[36] Guerin TF. Ex-situ bioremediation of chlorobenzenes in soil. *Journal of Hazardous Materials*. 2008;**154**(1-3): 9-20. DOI: 10.1016/j.jhazmat.2007.09.094

[37] Juwarkar AA, Singh SK, Mudhoo A. A comprehensive overview of elements in bioremediation. *Reviews in Environmental Science and Biotechnology*. 2010;**9**(3):215-288. DOI: 10.1007/s11157-010-9215-6

[38] Hazen TC. Bioremediation. In: *The Microbiology of the Terrestrial Deep Subsurface*. 1997;**1**:1-20. DOI: 10.1201/9781351074568

[39] Boopathy R. Factors limiting bioremediation technologies. *Bioresource Technology*. 2000;**74**(1):63-67. DOI: 10.1016/S0960-8524(99)00144-3

[40] Gerino M, Aller R, Lee C, Cochran J, Aller J, Green M, et al. Comparison of different tracers and methods used to quantify bioturbation during a spring bloom: 234-thorium, luminophores and chlorophylla. *Estuarine, Coastal and Shelf Science*. 1998;**46**(4):531-547

[41] Anschütz P, Ciutat A, Lecroart P, Gérino M, Boudou A. Effects of tubificid worm bioturbation on freshwater sediment biogeochemistry. *Aquatic Geochemistry*. 2012;**18**(6):475-497

[42] Gilbert F, Stora G, Cuny P. Functional response of an adapted subtidal macrobenthic community to an oil spill: Macrobenthic structure and bioturbation activity over time throughout an 18-month field experiment. *Environmental Science and Pollution Research*. 2015;**22**(20):15285-15293

[43] Mermillod-Blondin F, Rosenberg R, François-Carcaillet F, Norling K, Mauclaire L. Influence of bioturbation by three benthic infaunal species on microbial communities and biogeochemical processes in marine sediment. *Aquatic Microbial Ecology*. 2004;**36**(3):271-284

[44] Pigneret M, Mermillod-Blondin F, Volatier L, Romestaing C, Maire E, Adrien J, et al. Urban pollution of sediments: Impact on the physiology and burrowing activity of tubificid worms and consequences on biogeochemical processes. *Science of the Total Environment*. 2016;**568**:196-207

[45] Farenhorst A, Topp E, Bowman B, Tomlin A. Earthworm burrowing and feeding activity and the potential for atrazine transport by preferential flow. *Soil Biology and Biochemistry*. 2000;**32**(4):479-488

[46] Farenhorst A, Topp E, Bowman B, Tomlin A. Earthworms and the dissipation and distribution of atrazine in the soil profile. *Soil Biology and Biochemistry*. 2000b;**32**(1):23-33

[47] Hoelker F, Vanni MJ, Kuiper JJ, Meile C, Grossart H-P, Stief P, et al. Tube-dwelling invertebrates: Tiny

ecosystem engineers have large effects in lake ecosystems. *Ecological Monographs*. 2015;**85**(3):333-351

[48] McCall P, Fisher J. Effects of tubificid oligochaetes on physical and chemical properties of Lake Erie sediments. In: *Aquatic Oligochaete Biology*. Boston, MA: Springer; 1980. pp. 253-317

[49] Binet F, Kersanté A, Munier-Lamy C, Le Bayon R-C, Belgly M-J, Shipitalo MJ. Lumbricid macrofauna alter atrazine mineralization and sorption in a silt loam soil. *Soil Biology and Biochemistry*. 2006;**38**(6):1255-1263

[50] Monard C, Martin-Laurent F, Vecchiato C, Francez A-J, Vandenkoornhuyse P, Binet F. Combined effect of bioaugmentation and bioturbation on atrazine degradation in soil. *Soil Biology and Biochemistry*. 2008;**40**(9):2253-2259

[51] Kersanté A, Martin-Laurent F, Soulas G, Binet F. Interactions of earthworms with atrazine-degrading bacteria in an agricultural soil. *FEMS Microbiology Ecology*. 2006;**57**(2):192-205

[52] Leveque T, Capowicz Y, Schreck E, Xiong T, Foucault Y, Dumat C. Earthworm bioturbation influences the phytoavailability of metals released by particles in cultivated soils. *Environmental Pollution*. 2014;**191**:199-206

[53] Ciutat A, Widdows J, Readman JW. Influence of cockle *Cerastoderma edule* bioturbation and tidal-current cycles on resuspension of sediment and polycyclic aromatic hydrocarbons. *Marine Ecology Progress Series*. 2006;**328**:51-64

[54] Aller JY, Woodin SA, Aller RC. *Organism-sediment Interactions*.

Columbia: University of South Carolina Press eSC SC; 2001

[55] De Jonge M, Teuchies J, Meire P, Blust R, Bervoets L. The impact of increased oxygen conditions on metal-contaminated sediments part I: Effects on redox status, sediment geochemistry and metal bioavailability. *Water Research*. 2012;**46**(7):2205-2214

[56] Cheng J, Wong MH. Effects of earthworms on Zn fractionation in soils. *Biology and Fertility of Soils*. 2002;**36**(1):72-78

[57] Yu C, Zhang J, Pang XP, Wang Q, Zhou YP, Guo ZG. Soil disturbance and disturbance intensity: Response of soil nutrient concentrations of alpine meadow to Plateau pika bioturbation in the Qinghai-Tibetan Plateau, China. *Geoderma*. 2017;**307**:98-106

[58] Zorn MI, Van Gestel CA, Eijsackers H. The effect of *Lumbricus rubellus* and *Lumbricus terrestris* on zinc distribution and availability in artificial soil columns. *Biology and Fertility of Soils*. 2005;**41**(3):212-215

[59] Nowicki BL. The effect of temperature, oxygen, salinity, and nutrient enrichment on estuarine denitrification rates measured with a modified nitrogen gas flux technique. *Estuarine, Coastal and Shelf Science*. 1994;**38**(2):137-156

[60] Rysgaard S, Thastum P, Dalsgaard T, Christensen PB, Sloth NP. Effects of salinity on NH₄⁺ adsorption capacity, nitrification, and denitrification in Danish estuarine sediments. *Estuaries*. 1999;**22**(1):21-30

[61] Remaili TM, Simpson SL, Bennett WW, King JJ, Mosley LM, Welsh DT, et al. Assisted natural recovery of hypersaline sediments: Salinity

thresholds for the establishment of a community of bioturbating organisms. *Environmental Science: Processes & Impacts*. 2018;**20**(9):1244-1253

[62] Gonzalez SV, Johnston E, Gribben PE, Dafforn K. The application of bioturbators for aquatic bioremediation: Review and meta-analysis. *Environmental Pollution*. 2019;**250**:426-436

[63] Magalhães CM, Joye SB, Moreira RM, Wiebe WJ, Bordalo AA. Effect of salinity and inorganic nitrogen concentrations on nitrification and denitrification rates in intertidal sediments and rocky biofilms of the Douro River estuary, Portugal. *Water Research*. 2005;**39**(9):1783-1794

[64] Bernard G, Duchene J-C, Romero-Ramirez A, Lecroart P, Maire O, Ciutat A, et al. Experimental assessment of the effects of temperature and food availability on particle mixing by the bivalve *Abra alba* using new image analysis techniques. *PLoS One*. 2016;**11**(4):e0154270

[65] Berkenbusch K, Rowden AA. Factors influencing sediment turnover by the burrowing ghost shrimp *Callinassa filiholi* (Decapoda: Thalassinidea). *Journal of Experimental Marine Biology and Ecology*. 1999;**238**(2):283-292

[66] Amato ED, Simpson SL, Remaili TM, Spadaro DA, Jarolimek CV, Jolley DF. Assessing the effects of bioturbation on metal bioavailability in contaminated sediments by diffusive gradients in thin films (DGT). *Environmental Science & Technology*. 2016;**50**(6):3055-3064

[67] Andres S, Ribeyre F, Boudou A. Effects of temperature and exposure duration on transfer of cadmium between naturally contaminated sediments and burrowing mayfly nymphs (*Hexagenia rigida*). *Archives*

of Environmental Contamination and Toxicology. 1998;**35**(2):295-301

[68] Dafforn KA, Kelaher BP, Simpson SL, Coleman MA, Hutchings PA, Clark GF, et al. Polychaete richness and abundance enhanced in anthropogenically modified estuaries despite high concentrations of toxic contaminants. *PLoS One*. 2013;**8**(9):e77018

[69] Jackson CR, Weeks AQ. Influence of particle size on bacterial community structure in aquatic sediments as revealed by 16S rRNA gene sequence analysis. *Applied and Environmental Microbiology*. 2008;**74**(16):5237-5240

[70] Martinez-Garcia E, Carlsson MS, Sanchez-Jerez P, Sánchez-Lizaso JL, Sanz-Lázaro C, Holmer M. Effect of sediment grain size and bioturbation on decomposition of organic matter from aquaculture. *Biogeochemistry*. 2015;**125**(1):133-148

[71] Eggleton J, Thomas KV. A review of factors affecting the release and bioavailability of contaminants during sediment disturbance events. *Environment International*. 2004;**30**(7):973-980

[72] Mulsow S, Landrum P, Robbins J. Biological mixing responses to sublethal concentrations of DDT in sediments by *Heteromastus filiformis* using a ¹³⁷Cs marker layer technique. *Marine Ecology Progress Series*. 2002;**239**:181-191

[73] Cadée GC, Checa AG, Rodriguez-Tovar FJ. Burrows of *Paragnathia* (Crustacea: Isopoda) and *Bledius* (Arthropoda: Staphylinidae) enhance cliff erosion. 2001;**8**(3-4):255-260. DOI: 10.1080/10420940109380193

[74] Levinton J. Bioturbators as ecosystem engineers: Control of the sediment fabric, inter-individual interactions, and

material fluxes. In: *Linking Species & Ecosystems*. Boston, MA: Springer; 1995. pp. 29-36

[75] Remaili TM, Simpson SL, Amato ED, Spadaro DA, Jarolimek CV, Jolley DF. The impact of sediment bioturbation by secondary organisms on metal bioavailability, bioaccumulation and toxicity to target organisms in benthic bioassays: Implications for sediment quality assessment. *Environmental Pollution*. 2016;**208**:590-599

[76] Gadd GM. Metals, minerals and microbes: Geomicrobiology and bioremediation. *Microbiology*. 2010;**156**(3):609-643. DOI: 10.1099/mic.0.037143-0

[77] Lovley DR. Cleaning up with genomics: Applying molecular biology to bioremediation. *Nature Reviews Microbiology*. 2003;**1**(1):35-44. DOI: 10.1038/nrmicro731

[78] Chibuike GU, Obiora SC. Heavy metal polluted soils: Effect on plants and bioremediation methods. *Applied and Environmental Soil Science*. 2014;**2014**: 1-12. DOI: 10.1155/2014/752708

[79] Mezzari MP, Schnoor JL. Metabolism and genetic engineering studies for herbicide phytoremediation. In: *Phytoremediation Rhizoremediation*. Dordrecht: Springer; 2006. pp. 169-178

[80] Singh R, Paul D, Jain RK. Biofilms: Implications in bioremediation. *Trends in Microbiology*. 2006;**14**(9):389-397. DOI: 10.1016/j.tim.2006.07.001