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Microbial Solutions for Sustainable Environmental Restoration

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ABSTRACT

There has been a surge in pollution of many types due to the release of harmful compounds into the environment, resulting from the acceleration of industry and urbanization. Usually, this is the result of the mining business (such as cyanide and sulphuric acid), the building industry (such as cement and metals), the manufacturing sector (such as detergent and dye), and the agriculture sector (such as fertilizers and pesticides). Certain toxins have a detrimental effect on the health of people, animals, and plants. Furthermore, they lead to the eradication of the microbial population in both aquatic and terrestrial settings, compelling remediation. Bioremediation has gained popularity over chemical and physical methods due to their inherent flaws and challenges in environmental restoration. Bioremediation is the use of biological agents, such as plants and microbes, to reduce or eliminate the effects of environmental toxins. Because they may be easily manipulated and grow quickly, microbes are used more frequently than other types of agents for bioremediation. Various fungal, bacterial, and algal communities have been employed to eradicate a range of environmental pollutants. The review examines microbial bioremediation types, procedures, and influencing factors, and suggests initiatives to promote bacteria as effective remediation agents.

KEYWORDS: *Pollution, Bioremediation, Microbes, Environmental toxins, Remediation approaches, Industrial pollutants*

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INTRODUCTION

Growing industrialization and urbanization have exposed the environment to a wide range of toxins that are harmful to all living creatures. Significant causes of contamination to the aquatic and soil environments include pollutants originating from various industrial processes. Heavy metals are emitted in a variety of forms and concentrations both during and after industrial production when they are used as effluents. For example, antimony, chromium, and mercury have been linked to wastewater from dye manufacturing industries (Methneni et al, 2021). The use of fertilizers, pesticides, and herbicides in the agriculture sector results in the production of environmental contaminants such as lead, copper, arsenic, zinc, aluminum, and nickel (Prabagar et al, 2021; Babalola et al, 2020). Similarly, the ecosystem is harmed when untreated contaminants from the agri-food businesses' effluent are dumped into river canals and other bodies of water (Siric et al, 2022; AL-huqail et al, 2022). Furthermore, the transportation of crude oil results in leaks, pipeline vandalism, and unintentional spills that greatly increase environmental contamination

(Ogunlaja et al, 2019). Lead, arsenic, cadmium, and copper are among the dangerous elements released into the surrounding environment during mining operations (Liu et al, 2020). Several other environmentally hazardous substances, including sulfuric acid and cyanide, are employed in the mining process (Ayangbenro et al 2018; Orlovic-Leko et al, 2022). On the other hand, other industrial wastes, including those generated by the cement industry, release cadmium, copper, and zinc and are present in the top soils (Jafari et al, 2019). Water is contaminated by lead and chromium from pharmaceutical effluents, and plastics containing lead, manganese, iron, copper, chromium, silver, cadmium, antimony, and mercury (Kumari and Tripathi 2020; Zhou et al, 2019). Moreover, environmental pollutants from the coal industry include copper, arsenic, mercury, chromium, lead, nickel, cadmium, and zinc (Sun et al, 2019). For both terrestrial and aquatic ecosystems, as well as the people who live there, these heavy metals are extremely harmful. Lead causes cardiovascular disorders, liver and kidney failure, immune system dysfunction, and abnormalities in the reproductive and reproductive systems. Mercury, cadmium, and lead affect the central nervous system in humans, particularly in new-borns (Zwolak et al, 2019; Fashola et al, 2020a; Fashola et al, 2020b; Ayangbenro and Bablola 2020). According to Zwolak et al, 2019; Fashola et al, 2020a; Fashola et al, 2020b; Ayangbenro and Bablola 2020), cadmium causes malignancies, skeletal diseases, neurotoxic and nephrotoxic complexity, and reproductive system malfunction. Oftentimes, wastes that contain heavy metals are disposed of incorrectly into soil and aquatic habitats. If discarded into bodies of water, they have the potential to kill fish and other aquatic life; if not, they become biomagnified and can infect humans and other animals with chronic illnesses. Consequently, physical, chemical, or biological remediation techniques must be used to remove these contaminants. Although the chemical and physical approaches have been utilized for many years, they have certain disadvantages. For example, the chemical bioremediation process requires specialized equipment and an expert, and the physical bioremediation procedure is costly (Mahmood et al, 2021). This has made biological remediation (bioremediation) a more suitable option that is now required. One of the most effective, economical, and environmentally benign technologies for changing pollutants is bioremediation (Sonune, 2021). Microbes are preferred over plants for biological remediation because microbes are easier to manipulate and take longer to grow than plants. However, both can be used for biological remediation (Hussain et al, 2022). In addition, microbes mitigate heavy metals and improve soil fertility and plant development (Chaudhary et al, 2023b) Thus, this study addresses the various forms of microbial bioremediation, its mechanisms, obstacles, and contributing variables, and offers suggestions for improving the application of microorganisms in both terrestrial and aquatic bioremediation schemes.

PRINCIPLE OF BIOREMEDIATION

Microorganisms are used in bio-remediation to break down organic pollutants found in solids, sludge, groundwater, and soil. By co-metabolizing pollutants with an energy source or using them as an energy source, the microorganisms degrade pollutants. More precisely, bio-remediation is the process by which energy is produced in microbial cells through a redox reaction. Respiration and other biological processes required for cell upkeep and reproduction are included in these responses. Typically, one or more of the following must be provided by the delivery system: nutrients, an electron acceptor, and an energy source (electron donor). Bio-remediation can incorporate many microbial electron acceptor classes, such as those that reduce carbon dioxide, oxygen, nitrate, manganese, iron (III), sulfate, or sulfate, along with their accompanying redox potentials.

MECHANISM OF BIOREMEDIATION

Microbes utilize several methods to eliminate contaminants from their surroundings, which can be broadly classified into two categories: immobilization and mobilization processes (Ndeddy & Babalola 2016; Verma & Kuila 2019). According to Tak et al, 2012 and Ayangbenro et al, 2019, immobilization includes bioaccumulation, complexation, biosorption, and precipitation (solidification), whereas mobilization entails enzymatic oxidation, bioleaching, biostimulation, bioaugmentation, and enzymatic reduction. While immobilization makes molecules unavailable in the environment, such as transforming nitrate nitrogen into organic nitrogen, mineralization turns pollutants into innocuous end products like carbon dioxide and water (Pratush et al, 2018). Immobilization can be done in situ or ex-situ; the former treats pollution on-site, while the latter transports contaminated soils to another place for microbial processing (Pratush et al, 2018; Ayangbenro and Bablola 2017; Cao et al, 2020). Microbes that use defense mechanisms like hydrophobic or solvent efflux pumps to defend against hazardous substances, such as *E. asburiae* and *B. cereus,* contribute to the immobilization of heavy metals (Zwolak et al, 2019; Verma & Kuila 2019).

Enzymatic Oxidation

Enzymatic oxidation is a vital process in bioremediation, where pollutant compounds undergo oxidation from a higher to a lower oxidation state, reducing heavy metal toxicity as they lose electrons. This mechanism relies on oxidoreductase enzymes released by microbes. Particularly effective for pollutants like dyes and phenols resistant to bacterial degradation, oxidative enzymes generate radicals that break down into various fractions, ultimately forming high molecular weight compounds (Unuofin et al, 2019). For instance, laccase, an oxidoreductase enzyme, catalyzes the oxidation of aromatic amines (Gangola et al, 2018), while phenols and polyphenols facilitate the reduction of molecular oxygen to water (Sahay 2021). *Pycnoporus sp.* and *Leptosphaerulina sp.* have been noted for laccase production, contributing to heavy metal degradation (Copete-Pertuz et al, 2018; Tian et al, 2020).

Enzymatic Reduction

In contrast to enzymatic oxidation, this process converts the contaminants into an insoluble reduced oxidized state and is carried out by facultative and obligatory anaerobes (Zacharia 2019). In a similar vein, azoreductase reduces the azo compounds by cleaving them into azo linkages, and chrome reductase catalyzes the reduction of hexavalent chromium to trivalent chromium (Saxena et al, 2020). Additional research is needed to determine which other animals can be bio-remediated environmental contaminants.

Bioleaching

The technique known as "bioleaching" involves using acidophilic microorganisms to encourage the solubilization of solid heavy metals from the sediment matrix. Iron or sulfur pollution is especially well-suited for this procedure (Sun et al, 2021; Bhandari et al, 2023). As a result, bacteria that can oxidize iron or sulfur are primarily used in this process; *A. thiooxidans, Aspergillus sp., Penicillium sp., Mucor sp., Rhizopus sp., and Cladosporium sp.* are a few examples of these organisms (Medfu Tarekegn et al, 2020). These microorganisms provide an acidic environment that dissolves adsorbed heavy metals into an aqueous solution.

Bioaugmentation

A powerful bioremediation technique known as "bioaugmentation" involves introducing microorganisms into contaminated areas to digest harmful contaminants (Mahmoud 2021). This procedure can involve genetically altering local microorganisms to increase their capacity for pollutant degradation or introducing foreign microbes to boost resident microbial populations (Fashola et al, 2016; Ayangbenro and Bablola 2017; Goswami et al, 2018; Babalola et al, 2019). It is frequently required to manipulate DNA because natural bacteria may not be able to efficiently digest certain contaminants. For best results, introduced strains need to coexist with local bacteria and adjust to their surroundings (Fashola et al, 2016). For example, *Burkholderia sp.* FDS-1 has demonstrated competence in breaking down nitrophenolic chemicals in soil contaminated by pesticides at particular pH and temperature levels (Goswami et al, 2018; Ojuederie & Babaloa 2017).

Biostimulation

Biostimulation involves supplementing the soil with nutrients, electron donors, and other substances to boost resident microbe activity and expedite remediation processes (Ojuederie & Babaloa 2017; Ayangbenro and Bablola 2017).

This method is considered cost-effective and eco-friendly (Goswami et al, 2018), and enhances natural microbial diversity while promoting competitiveness over introduced species (Sayed et al, 2021). Nivetha et al, (2022) demonstrated the efficacy of various bacteria, including *Bacillus sp. and Pseudomonas sp.,* in heavy metal bioremediation via biostimulation. However, excessive nutrient supplementation can lead to eutrophication, and synthetic nutrient sources may introduce additional pollution (Nivetha et al, 2022).

Bioaccumulation

Bioaccumulation occurs when the absorption rate of a compound exceeds its elimination rate, resulting in the toxic accumulation of compounds within microbial cells (Sharma et al, 2022a). Various mechanisms such as carrier-mediated transport, protein channels, and ion pumps facilitate the movement of heavy metals across microbial membranes (Mir-Tutusaus et al, 2018) Several organisms exhibit significant bioaccumulation capabilities for specific heavy metals, such as *Rhizopus arrhizus* for mercury, *Pseudomonas putida* for cadmium, and *Aspergillus niger* for thorium (Sharma et al, 2022a).

Precipitation

Biogeochemical cycling, which is aided by enzymes and secondary metabolites, transforms heavy metals or other contaminants into precipitates or crystals, lowering their toxicity (Sharma et al, 2022a). Silver, microfossils, mineralized manganese, iron, and manganese are among the metal deposits that are created as a result of this process. At alkaline pH levels, sulfate-reducing bacteria can change organophosphate into orthophosphate (Pratush et al, 2018). Furthermore linked to the precipitation of heavy metals in the environment include *Bacillus subtilis* and *Oceanobacillus indicireducens* (Maity et al, 2019).

Factors Affecting Bioremediation

Several factors affect the capacity of microbes to remove heavy metals from the environment, such as the concentration of total metal ions, redox potential, chemical forms of the metals, competition between microbes, pH, temperature, soil structure, oxygen content, moisture content, soil nature, and the solubility of the heavy metal in water (Medfu Tarekegn et al, 2020).

1. ***The impact of pH on bioremediation*:** Heavy metals produce free ionic species at acidic pH levels, which saturate binding sites and reduce microbial viability. For bioremediation, a pH between 6.5 and 8.5 is ideal (Kharangate-Lad & D'Souza 2021)
2. ***Microbial competition and nutrient balance*:** Microbial competition for phosphorus, nitrogen, and carbon influences the rates of biodegradation. It's important to maintain a balanced C: N: P ratio and providing these nutrients can increase microbial activity (Bala et al, 2022)
3. ***Microbial diversity and bioremediation effectiveness*:** The kind and quantity of microorganisms involved in a given bioremediation process dictate its efficacy. In the field, a group of microorganisms is frequently required, even though a single strain might be effective in the lab (Patel et al, 2022)
4. ***Microbial properties influencing bioremediation*:** Microbial efficaciousness in bioremediation is influenced by various factors, including molecular nature, induction of genes and enzymes, metabolite production, growth efficiency, survival rate, ionization of cell wall moieties, and configuration of sorption sites (Kebede et al, 2021; Mahmou 2021)
5. ***Moisture content and microbial activity*:** The solubility of heavy metals, pH, and osmotic pressure are all impacted by moisture levels, which in turn affect microbial activity. Microbial biodegradation can be hampered by both high and low moisture levels (Medfu Tarekegn et al, 2020)
6. ***The effect of temperature on bioremediation*:** Microbial metabolic rates and the solubility of heavy metals are influenced by temperature. Generally speaking, biodegradation processes are favored by higher temperatures (Ren et al, 2018; Bala et al, 2022; Sharma et al, 2022b; Mahmou 2021).
7. ***Chemical characteristics of pollutants*:** Microbial biodegradation rates are determined by the chemical composition, stability, toxicity, concentration, and bioavailability of pollutants. Remediation is usually simpler for simple chemicals at lower doses (Kebede et al, 2021).

8. ***Microbial activity and soil characteristics*:** Microbial biodegradation is influenced by soil properties such as moisture-holding capacity, texture, region, and particle size. Increased microbial activity is encouraged by well-drained soils that have better oxygen availability (Álvarez et al, 2020; Ndeddy & Babalola et al, 2017; Huang et al, 2019).
9. ***The effect of salinity on microbiological activity*:** Microbes are exposed to stress and microbial hydrocarbonoclastic activity is affected by salinity. Elevated salt levels prevent heavy metal solubility and microbial metabolic processes (Imron et al, 2020; Kebede et al, 2021).

ROLE OF ENZYMES IN MICROBIAL BIOREMEDIATION

Numerous microbial enzymes are essential for eliminating contaminants from the environment, particularly heavy metals, as demonstrated by studies (Verma & Kuila 2019; Bhatt et al, 2021a; Chaudhary et al, 2023a). These enzymes utilize mechanisms such as elimination, oxidation, ring-opening, and reduction, as outlined in studies like that of (Bhatt et al, 2021a). However, according to Bhandari et al, 2021, variables including temperature, contact time, concentration, and pH affect how effective they are. There are obstacles to overcome for enzyme-based bioremediation, notwithstanding its potential. According to Narayanan et al, 2023, it is costly, time-consuming, and inappropriate for urgent remedial needs. Furthermore, the stability and activity of pollutants can affect the potency of enzyme bioremediation, while sourcing diverse enzymes for different pollutants may prove unsustainable. These challenges underscore the complexity of enzyme-based approaches to bioremediation (Table 1).

Table 1: Various enzyme's action in Bioremediation

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

CURRENT DEVELOPMENTS IN THE FIELD OF MICROBIAL BIOREMEDIATION

Microbial glycol-conjugates have been used in recent bioremediation advances to lower surface tension, boost bioavailability, and form solvent interfaces for the removal of organic pollutants (Bhatt et al, 2021b). With continuous advancements in quorum sensing and environmental conditions, microbial biofilms comprising polysaccharides, extracellular DNA, and proteins are also utilized, particularly for resistant contaminants (Sonawane et al, 2022). Furthermore, in artificial wastewater, *Exiguobacterium profundum* exhibits arsenic reduction (Andreasen et al, 2018).

Utilizing microbial group interactions, bio-electrochemical systems integrate biological and electrochemical techniques to regulate pollutants, mainly petroleum hydrocarbons (Ambaye et al, 2023). Many bacteria are useful for remediating phenanthrene, including *Pseudomonas sp., Ralstonia sp., Rhodococcus sp.,* and *Thauera sp* (Sharma et al, 2020).

Globally, nanotechnology presents promising approaches to pollution prevention; the performance of nanoparticles depends on their size, shape, surface coating, and chemical makeup, as well as environmental variables including pH and temperature (Shanmuganathan et al, 2019; Tan et al, 2018). Because of their abundance, low toxicity, and distinctive optical features, carbon dot nanoparticles in particular offer promise in the clean-up of environmental pollutants (Long et al, 2021). To improve the efficacy of bioremediation, more research is necessary.

DISCUSSION AND CONCLUSION

A safer and more sustainable environment is the goal of research on microbial enzymes for waste bioremediation. It is hoped that novel bacteria would increase bioremediation efficacy and potentially even outperform existing techniques. Monitoring progress requires the use of rapid detection techniques. Microbe enzyme production can be increased through genetic manipulation. Microbial consortia combined increase the rate of biodegradation. Microbes that break down inorganic pollutants are essential for thorough cleanup, even concerning radioactive waste. It is imperative to take action against inadvertent contamination caused by microbiological activity. The best temperatures for deterioration and circumstances for microbial survival are found through field study. Microbial concerns are observed by regulatory agencies after bioremediation. The combination of nanoparticles and enzymes/microbes increases their activity. Growing awareness encourages the use of microbial degradation in place of traditional techniques for efficient pollution control.

Data Availability Statement
The data supporting this study's findings are available on request from the corresponding author. The data are not publicly available due to privacy and ethical restriction

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