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Bioremediation of Environmental Pollutants: Microbial Tactics for Sustainable Ecosystem Restoration

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ABSTRACT

Environmental pollution from industrial growth, urbanization, and farming has become a serious global issue. Among different cleanup strategies, bioremediation stands out as a sustainable and low-cost approach that uses microorganisms to transform or remove pollutants. This paper reviews the roles of microorganisms such as bacteria, fungi, algae, and yeast in breaking down contaminants under both aerobic and anaerobic conditions. Special attention is given to microbial enzymes such as laccases, peroxidases, and monooxygenases, which play a central role in the degradation of persistent compounds, including pharmaceutical residues. The review also covers in situ and ex situ methods—such as bioventing, composting, and bioreactors—and discusses the environmental factors that affect their efficiency, including pH, pollutant levels, nutrient supply, and soil properties. Bioremediation is a sustainable method for cleaning up the environment. It supports SDG 6 (Clean Water and Sanitation), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). Using this approach at local, industrial, and global levels shows its ability to reduce pollution, lower chemical waste, and restore ecosystems while promoting sustainable development. Recent developments, including microbial biofilms, bio electrochemical systems, nanomaterials, and omics-based tools, show promise in improving efficiency and extending the range of pollutants that can be treated. Although bioremediation offers clear environmental and economic benefits, it still faces challenges related to speed, specificity, and the formation of harmful byproduct.

KEYWORDS: Bioremediation, Microbial degradation, Environmental pollutants, Nanotechnology and omics tools.

INTRODUCTION

Environmental pollutants: The population of human beings and the industrial growth demand is ever-growing. This strains our natural resources including air, water, and land. Additionally, environmental maintenance has been lacking since industrial and technological advancements. Subsequently, the increase in population, an abrupt upsurge in industrialization, and lack of control in agriculture has increased environmental pollution in the last few decades. Environmental pollutants are harmful substances that are released into the environment, damaging air, water, and land quality. They can be natural, like volcanic ash, or generated by human activities, such as trash or factory runoff (Persson *et al.*, 2022). The anthropogenic activities have led to the accumulation of significant types of waste, namely hospital waste (which contains pharmaceutical residues and pathogens), e-waste (which contains heavy metals such as lead and mercury), agricultural waste (which contains pesticides and fertilizers), domestic waste (which contains plastics and rubber), and industrial waste (which contains toxic chemicals

and solvents) (Methneni *et al.*, 2021). To address this issue, biological remediation methods are being used to detoxify and break down biodegradable waste such as food waste, paper, agricultural residues, sewage, and other organic matter that can be decomposed by microbial activity (Hussain *et al.*, 2022).

Bioremediation: Bioremediation is whereby living organisms are involved in the removal of undesirable garbage and aid in the recovery of the environment (Modupe and Olubukola., 2023). Bioremediation involves the utilization of living organisms (i.e. plants) to stain and detoxify toxic substances within the environment. They change these pollutants into carbon dioxide (CO₂), water (H₂O), microbial biomass and less toxic by-products like biosurfactants, enzymes and organic acids. Biodegradation depends on the wide range of factors such as the environment, the nature and dissolvability of the contaminant (Tegene *et al.*, 2020). The principle is based on enzymatic catalysis, microbial growth, and substrate use. These can be improved through bioaugmentation, biostimulation, or designed microbial groups. Recent studies have highlighted the importance of microbial and fungal

bioremediation strategies for petroleum hydrocarbons, heavy metals, and synthetic chemicals around the world (Persson *et al.*, 2022). There are two main processes of biodegradation: aerobic degradation, which involves oxygen as the terminal electron acceptor, and anaerobic degradation, which involves other electron acceptors, including nitrate, sulfate, or carbon dioxide. The effectiveness of these bioremediation methods is highly dependent on the type of microorganisms used, which are explained in the following section.

Microorganisms in bioremediation: Since the creation of the universe biological balance is based on microorganisms known as decomposers a pivotal component of food chains. Therefore, members of this group (bacteria, algae, fungi, and yeast) are also employed for decomposition of contaminants (Enerijiofi *et al.*, 2024). Various microbes are able to survive in extreme temperatures, ranging from -196 degrees Fahrenheit to 1200 degrees Fahrenheit even amongst the unsafe compounds or waste. They are very versatile and would be the most useful in angel cleanup. *Achromobacter*, *Alcaligenes*, *Xanthobacter*, *Arthrobacter*, *Pseudomonas*, *Bacillus*, *Flavobacterium*, *Nitrosomonas*, and other microorganisms are examples of such useful microbes (Hussain *et al.*, 2022). This description of aerobic degraders sets the stage for discussing anaerobic microorganisms, which play a crucial role in pollutant degradation in oxygen-deficient environments.

Aerobic microorganisms: The organisms that decompose complex organic compounds aerobically are basically bacteria such as *Bacillus subtilis*, *Bacillus cereus*, *Pseudomonas*, *Sphingomonas*, *Flavobacterium*, *Nocardia*, *Rhodococcus* and *Mycobacterium* (Figure. 1). They can break down materials such as pesticides, alkane hydrocarbons and polyaromatic compounds and usually utilize them as carbon and energy sources (Giri *et al.*, 2021). Besides the bacteria, aerobic fungi like white-rot fungi (*Phanerochaete chrysosporium*, *Trametes versicolor*) are also essential as they provide extracellular enzymes like laccases and peroxidases to degrade complex aromatic compounds which might not be effectively broken down by bacteria. Microalgae such as *Chlorella sp.* and *Scenedesmus sp.* also play a part in metabolizing organic pollutants and supplying oxygen to the aerobic activity of microbes through photosynthesis (Enerijiofi *et al.*, 2024). These microbial communities tend to be synergistic: fungal enzymes break down large, recalcitrant molecules into smaller intermediates which bacteria can further process, and algae increase the availability of oxygen and nutrient cycles. This complementary interaction increases the maximum biodegradation efficiency and preconditions the study of anaerobic microorganisms in the following section (Tripathi *et al.*, 2022).

Anaerobic microorganisms: The use of amphibious bacteria capable of degrading pollutants into less toxic phases is becoming popular as a method of

bioremediation, particularly in the presence of such highly toxic substances such as polychlorinated biphenyls (PCBs), chlorine compounds, and chlorinated solvents, trichloroethylene and chloroform. Types of bacteria (Figure. 1) employed in bioremediation under anaerobic conditions include *Pseudomonas stutzeri*, *Aeromonas hydrophila*, and *Desulfovibrio species* (sulfate-reducing bacteria), which are commonly employed in bioremediation under anaerobic conditions (Saroj *et al.*, 2022).

In sediment-rich habitats, anaerobic fungi ferment complex organic matter into simpler compounds, which can be further broken down by anaerobic bacteria; such as *Neocallimastix* species break down plant biomass into acetate and hydrogen that sustain bacterial activity. Some algae, including *Chlorella vulgaris*, can also mediate anaerobic degradation through the production of substrates to microbial consortia and the fixation of toxic metals (Hussain *et al.*, 2022). The synergistic effect of bacteria, fungi and algae points to the relevance of mixed microbial communities in efficient removal of pollutants. The knowledge of these synergistic interactions would give a basis of developing specific bioremediation strategies and this is discussed in the next section on bioremediation techniques world (Persson *et al.*, 2022).
Classification of bioremediation techniques: Bioremediation comes in two types based on removal and transportation of the waste to undergo treatment (Kashif Hussain *et al.*, 2021).

In-Situ Bioremediation

Ex-Situ Bioremediation

In-situ bioremediation: In-situ bioremediation involves treating contaminants directly at the site using biological agents. This cleanup method facilitates a direct interaction between microbes and the contaminants to be bio transformed (Gurkok, 2021). There are two main types of in situ bioremediation.

Intrinsic bioremediation: Intrinsic bioremediation, sometimes called natural attenuation, is a passive process of treating a contaminated location, based on natural microbial populations in nature without human action.

It uses the natural abilities of microorganisms to transform environmental pollutants into non-toxic or less toxic forms without any engineering enhancements.

Intrinsic bioremediation is mostly used in the control of contaminants in waste sites.

They have to be monitored to evaluate the contribution of native microorganisms in removing all the pollutants by running tests on soil, sediment or water samples collected at the site.

Some of the environmental factors can be conducive to intrinsic bioremediation such as pH, pollutant concentration, temperature, as well as nutrient availability.

It is a cheap approach; the weakness is that, it may require more time to achieve the anticipated degree of

concentration of the pollutant (Kashif Hussain *et al.*, 2021)

Engineered bioremediation: Engineered bioremediation, European: accelerated bioremediation is a high-tech process that incorporates engineered structures to augment the microbial energy in the remediation of pollutants to the environment.

In cases where intrinsic bioremediation cannot be used, the process is conducted by either allowing substrates or nutrients to cause faster growth of microorganisms that can deal with the contaminants faster.

This process optimizes physical and chemical conditions to support the rapid growth of microbes, thereby speeding up biodegradation.

Typically, the microorganisms used are indigenous to the site, but highly effective strains may also be introduced to target specific contaminants.

Engineered bioremediation is often preferred over intrinsic bioremediation due to time constraints and liability concerns.

However, a limitation of this approach is its reduced effectiveness with metal contaminants when mixed with organic compounds (Sharma, 2019).

In Situ bioremediation techniques: The techniques used for in situ bioremediation (Fig. 2) are as follows:

Phytoremediation

Bioventing

Bio slurping

Bio sparging

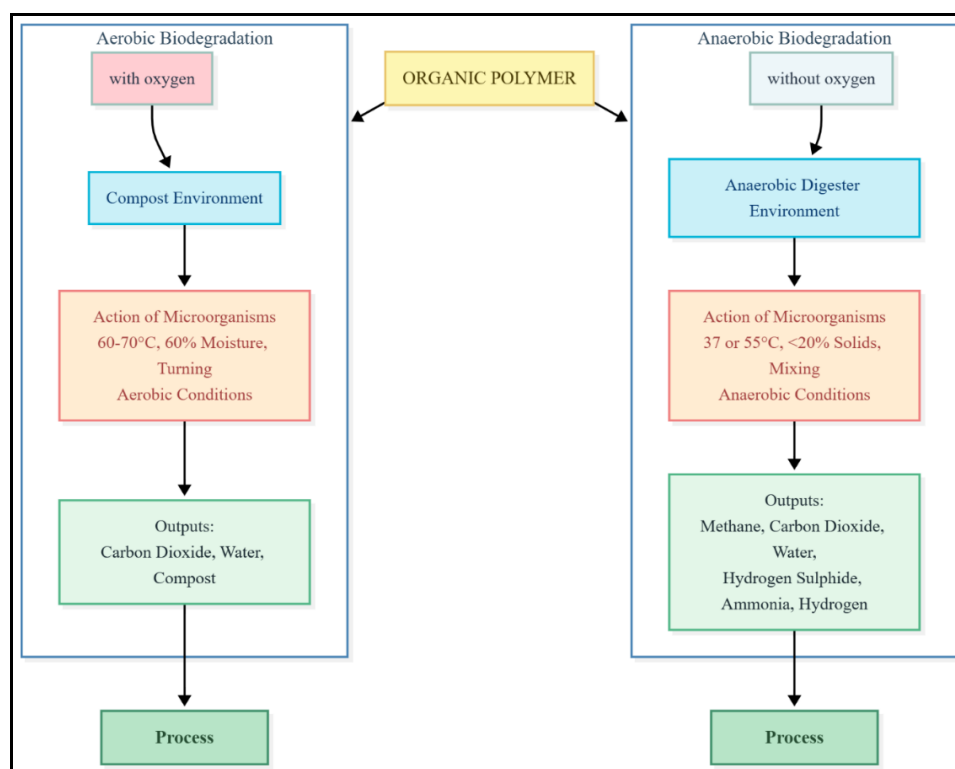


Figure 1. Aerobic and anaerobic degradation pathways for organic polymers.

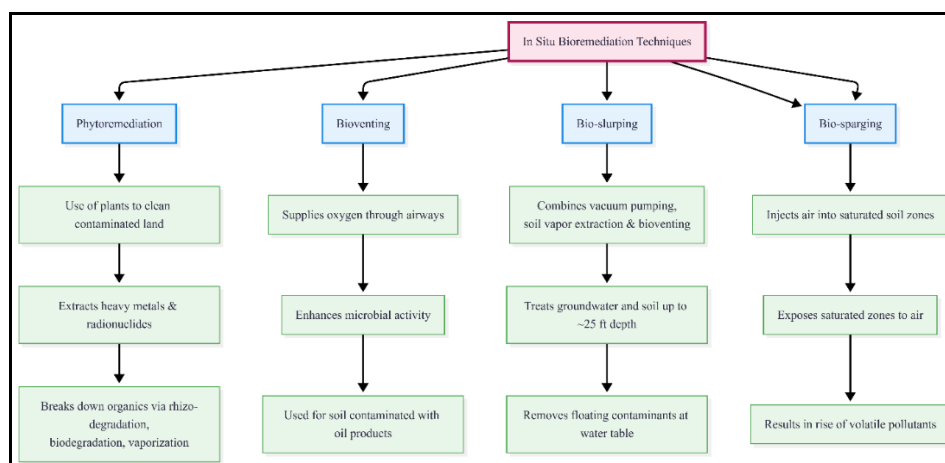


Figure 2: Common in situ bioremediation techniques, including phytoremediation, bioventing, bio-slurping, and bio-sparging.

Phytoremediation: Phytoremediation refers to the application of plants in cleaning up contaminated lands. Plants help in reducing the toxicity of harmful substances through various natural processes. Their mode of action depends on the type of pollution. For heavy metals and radioactive materials, plants mostly extract and keep them integrated these elements. For organic pollutants, they mainly break them down or remove them through processes like rhizo-degradation, biodegradation, and vaporization (Sales da Silva *et al.*, 2020).

Bioventing: Bioventing is the procedure the airways were designed to bring oxygen that enhances micro-action and enhances bioremediation (Kashif Hussain *et al.*, 2021). Nutrients and moisture are frequently used in order to render the causal agents of pollution less harmful. This technique has been successfully used to clean up soils contaminated with oil products (Saxena *et al.*, 2020).

Bio-slurping: The process of cleaning the ground water and soil is referred to as bio-slurping or multi-phase extraction. It integrates a combination of vacuum pumping, soil vapor extraction and bioventing to make oxygen supply and assist in decomposing pollutants (Sales da Silva *et al.*, 2020). This method is effective to a depth of 25 feet in the ground because at that depth it is impossible to place the contaminants out. It works best to eliminate floating contaminants contaminating the water table.

Bio-sparging: Bio sparging entails incorporation of air in the soil with the aim of aiding microorganisms to decompose wastes. Unlike bioventing, which adds air to unsaturated soil, bio sparging exposes saturated region to air resulting in the rise of volatile pollutants (Saxena *et al.*, 2020).

Ex-Situ bioremediation techniques: In this approach, the contamination is removed and disposed of in established facilities off-site. Once the soil that has been polluted is excavated, it is carried to a different place where it is treated. Choosing an ex-situ bioremediation technique depends on factors like cost,

the level and depth of contamination, the type of pollutant, and the site's location and geology (Narendra *et al.*, 2024). The techniques used in ex situ bioremediation (Fig. 3) are as follows:

1. Bioreactor
2. Landfarming
3. Biopiling
4. Composting

Bioreactors: Every equipment set up to sustain biological processes is referred to as a bioreactor. One of the safe methods of cleaning up the pollution is through the use of sludge bioreactors taken to treat hydrocarbon pollutants. The vessel containing the pollutants in these systems is put in another chamber that has sludge mixing equipment, which forms a mixture of solid, liquid and gaseous phases. This mixing encourages the growth of biofilm, which helps to break down pollutants and increases the amount of biomass (Preethi Chandran *et al.* 2025).

Landfarming: A landfarming is a site of bioremediation of soil in which there is a mixture of contaminated soil with hydrocarbons to promote biological, physical and chemical remediation. It is a simple and cost-effective bioremediation technology with a low environmental impact. Landfarming can be done either ex-situ, where treatment occurs away from the original site, or in-situ, where treatment happens at the site itself (Sejal Mahalle *et al.* 2025).

Composting: Composting is defined as decomposition and break down of organic matter through the action of waste degrading microorganisms in favorable controlled conditions. The microbial population decomposes the organic matter in liquid waste during composting. This process can decrease the original volume by up to 50 percent to produce an end-product called compost or humus (Manea *et al.*, 2024). Compost is a nutrient rich soil that is highly fertile and can be applied to the plants and crops to enable their healthy growth.

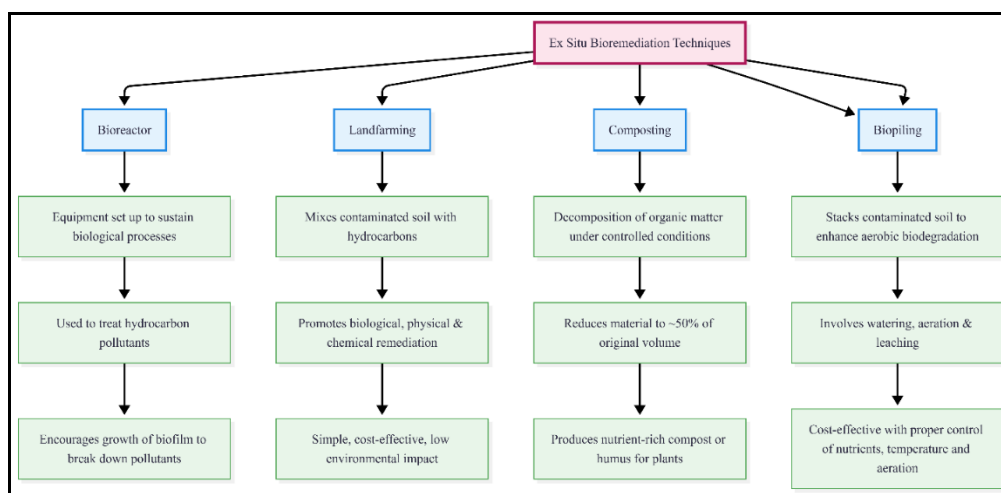


Figure 3: Common ex situ bioremediation techniques, including bioreactors, landfarming, composting, and biopiling.

Biopiling: Biopiling is the process of piling up the contaminated soil and encouraging the microbial activity under aerobic conditions to promote biodegradation. This method includes elements like watering, aeration, and leaching. Its popularity is growing due to its construction advantages and good

cost-effectiveness, as long as there is proper control of nutrients, temperature, and aeration (Ostovar *et al.*, 2025). These bioremediation methods are based on the particular microbial metabolic pathways, such as enzymatic reactions, which are discussed in the next section

Table 1: Comparison of in-situ and ex-situ bioremediation techniques based on key operational and environmental parameters

Parameter	In-Situ bioremediation	Ex-Situ bioremediation	References
Application Site	Contaminants are treated directly at the site using biological agents.	Contamination is excavated and disposed of/treated in established facilities off-site.	Kashif Hussain <i>et al.</i> (2021); Narendra <i>et al.</i> (2024)
Cost	Generally, a cheap approach, particularly intrinsic bioremediation.	Choosing a technique depends heavily on the cost of excavation and transportation.	Gurkok (2021); Narendra <i>et al.</i> (2024)
Timeframe	Intrinsic methods can require more time to reach anticipated results.	Often preferred when there are time constraints (engineered) or controlled (bioreactors).	Kashif Hussain <i>et al.</i> (2021); Sharma (2019)
Technical Approach	Can be passive (natural attenuation) or high-tech (engineered) involving added nutrients.	Uses equipment like sludge bioreactors with mixing devices to sustain biological processes.	Sales da Silva <i>et al.</i> (2020); Manea <i>et al.</i> (2024)
Monitoring	Requires surveillance and tests on soil, sediment, or water samples collected at the site.	Efficacy depends on controlled conditions like nutrients, temperature, and aeration.	Kashif Hussain <i>et al.</i> (2021); Ostovar <i>et al.</i> (2025)
Depth / Scale	Bio-slurping is effective to a depth of 25 feet; phytoremediation is used for large-scale land cleanup.	Volume can be synthesized to 50% (composting); biopiling involves stacking contaminated soil.	Kashif Hussain <i>et al.</i> (2021); Preethi Chandran <i>et al.</i> (2025)

Microbial enzymatic mechanisms in bioremediation: Various microbial enzymes have been effective in removing pollutants. For example, laccases from *Trametes versicolor*, peroxidases from *Phanerochaete chrysosporium*, and monooxygenases from *Pseudomonas* species are crucial in breaking down aromatic compounds, hydrocarbons, and industrial dyes (Ayilara *et al.*, 2023). Enzyme mechanisms in bioremediation include elimination, oxidation, ring-opening and reduction of compounds (Fig. 4). Enzyme bioremediation is costly and time consuming and cannot be adopted in situations where one requires bioremediation immediately. Similarly, the stability and activity of the pollutants influence the efficacy of the bioremediation process. It can also be hard to identify and locate several sources of a specific kind of enzyme that could render the process unsustainable. (Narayanan *et al.*, 2023).

Fungi, which are the main agents of decomposition in natural habitats, are rich in enzymes used for bioconversion of complex substrates (Kango *et al.*, 2019). Enzymes from fungi have shown great effectiveness in breaking down pharmaceutical active compounds (PhACs) found in different waste streams and under various conditions as shown in figure 3. Thus, it is inexpensive and more natural when compared to conventional treatment techniques (Vaksmas *et al.*, 2023). The enzymes facilitate the modification and catabolism of these drug substances through numerous mechanisms: the reduction-oxidation, hydroxylation-dehalogenation, dehydrogenation, and deamination among others (Narayanan *et al.*, 2023). The most researched fungal

enzymes that break down PhACs are discussed in detail.

Laccases: Laccases belong to a family of enzymes also called the multicopper enzymes. Yoshida first described them in 1883, which makes them some of the earliest identified enzymes (Loi *et al.*, 2021). In nature, laccases play an important role in lignin synthesis, plant cell wall degradation, and in pathogenicity, stress responses and the formation of fungal fruiting bodies. The wide spectrum of substrates is associated with the application of fungi to detoxify water, combat wastewater pollution, and decolorize industrial waste (Zhai *et al.*, 2024).

As demonstrated by different researchers, fungal laccases can degrade pharmaceuticals and personal care products (PhACs). Laccases in the genus *Trametes* produce the best results. For example, laccases from *T. versicolor* can bioremediate the antibiotics tetracycline, chlortetracycline, doxycycline, and oxytetracycline (Suda *et al.*, 2012). Likewise, the enzyme from another species in the same genus, *Trametes polyzona*, has also been shown to break down tetracycline, as well as some β -lactam and quinolone antibiotics, in a system without redox mediators (Lueangjaroenkit *et al.*, 2019). Fungal laccases working together have also been shown to break down PhACs. To provide an example, *T. versicolor* and *Myceliophthora thermophila* enzymes were effective in the biodegradation of steroid hormones namely estrone, 17 β -estradiol, estriol, and 17 α -ethinyl estradiol even at average enzyme activity (Becker *et al.*, 2017).

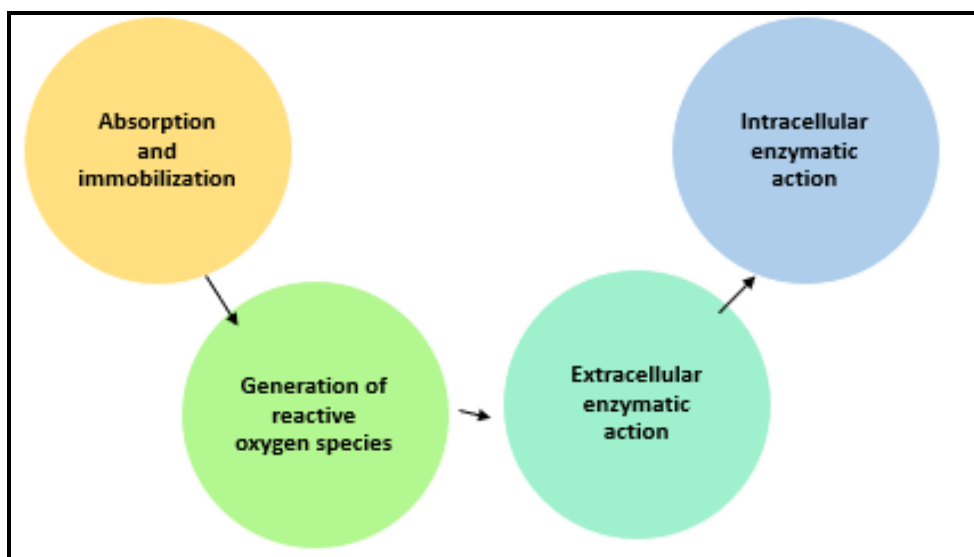


Figure 4. Mechanism of fungal bioremediation of hospital waste.

Peroxidases: The fungal peroxidases are not only diverse in substrates but capable of degrading several inert compounds which are difficult to treat using normal bioremediation techniques. These compounds include synthetic dyes, herbicides, pesticides, and PhACs, among others (Saikia *et al.*, 2022). Different studies have shown that various types of peroxidases can break down different pharmaceutical compounds. To illustrate, the manganese peroxidase of *T. polyzona* has been identified to degrade tetracycline, β -lactam and quinolone classes. It especially prefers to oxidize dimethoxy-substituted phenol at the ortho position (Lueangjaroenkit *et al.*, 2019). A versatile peroxidase from *Bjerkandera adusta* was previously found to break down 100% of diclofenac and estrogens at very low enzyme concentrations. This peroxidase also bioremediated 80% of sulfamethoxazole and naproxen (Eibes *et al.*, 2011). Peroxidase of Manganese *Pleurotus spp.* was quite active in breaking steroid hormones. This includes the synthetic estrogen 17 α -ethinylestradiol (Santosa *et al.*, 2012). Similarly, in the study by Wen *et al.* (2009), Lignin peroxidase extracted from *P. chrysosporium* was employed in the in vitro degradation of tetracycline and oxytetracycline, achieving nearly 100% removal within 5 minutes (Amobonye *et al.*, 2023).

Monooxygenases: The fungal oxidoreductase superfamily involves fungal monooxygenases. They can catalyze biological oxidation and reduction reactions with different substrates (Hussain *et al.*, 2020). They have been acknowledged for their versatility. They have different uses in biotechnology, medicine, food, and bioremediation, including breaking down pharmaceutical and personal care products (PhACs) (Vaksmas *et al.*, 2023). As the best fungal source of bioremediating enzymes, *T. versicolor* can secrete a monooxygenase. This enzyme significantly breaks down norfloxacin and ciprofloxacin (Efremenko *et al.*, 2024). Other fungal

monooxygenases have also demonstrated great potential to eliminate PhACs.

Recently, a cytochrome P450 monooxygenase from *Phanerochaete chrysosporium*, which is another white-rot fungus, helps in breaking down acetamiprid through an N-alkylation reaction mechanism (Mori *et al.*, 2021). Fungal monooxygenases from different species have also been reported to work together to improve the efficiency of removing pharmaceuticals and personal care products (PhACs). The monooxygenases from *P. chrysosporium* and *Pycnoporus sanguineus* worked together to remove ciprofloxacin, norfloxacin, and sulfamethoxazole. They achieved removal rates of 98.5%, 96.4%, and 100%, respectively (Cheute *et al.*, 2024).

Factors affecting microbial bioremediation:

Biological reactions in the biodegradation mainly rely on enzymatic activity. As enzymes are sensitive and work optimally in narrow ranges of environment, so several factors affect the bioremediation process. These comprise physical, chemical and biological conditions, type of soil, microorganisms and sources of carbon and nitrogen they utilized, alone or together. Microbial consortia often exhibit greater functionality and resilience as different species collaborate to optimize substrate utilization, enhancing bioremediation efficiency compared to single microorganisms. Additionally, bioremediation typically relies on organic carbon more than other additives. In environments without oxygen, many microorganisms can ferment organic carbon to produce hydrogen gas (Table. 2) (Khalid *et al.*, 2021). The success of the bioremediation process depends on different factors that help remove contaminants, including:

Concentration of the contaminant: The concentration of contaminants directly affects microbial activity. A lower concentration of contaminants results in a lower rate of degrading enzymes produced by soil bacteria. However, the decomposition rate of catabolic enzymes can improve

through cooperative interactions among the different components of the contaminants (Mishra *et al.*, 2021).

pH: Heavy metals produce the free ionic species in acid condition. This results in an increase of protons to fill the affixing sites of the metals. The pH level of an environment influences the composition of the pollutant and the survival chances of the microbes in an environment. The best pH range for improving bioremediation is between 6.5 and 8.5 (Kharangate-Lad *et al.*, 2021).

Nutrient availability: As primary energy source of many heterotrophic bacteria is carbon and its usually scarce so microbes compete for it and results in increased rate of heavy metal contaminants deposition. While some heterotrophic bacteria and fungi require nitrogen (N) and phosphorus (P) along with carbon for successful biodegradation. Thus, it is also necessary to maintain the C:N:P ratio when improving the biodegradation rates, particularly where these key nutrients are low. (Bala *et al.*, 2022). The rate and success of a bioremediation process depend on the type of microbes involved and their population usually the consortium of microbes works better as each microbe type absorbs specific heavy metal.

Amount of moisture: The amount of water in an environment also influences the dissolution of heavy metals in water. It also impacts their availability, pH, and osmotic pressure (Medfu Tarekegn *et al.*, 2020). At high moisture levels, the rate of microbial biodegradation drops a lot, as aerobic microbes could not survive only aerobic continuous degradation process. On the other hand, at low moisture content both type of microbes can't survive therefore, to ensure biodegradation, the moisture content must be moderate. Heavy metal degradation is slow in cold areas in which only psychrophilic microorganisms are capable of living. The reason behind this is that low temperatures slow down the metabolic activity of microbes and sub-zero temperatures may freeze the transport channels of microorganisms. Each compound also degrades at different temperatures, but generally, higher temperatures favor most bioremediation processes (Bala *et al.*, 2022; Ren *et al.*, 2018). High temperatures increase Dissolution of heavy metals making these available in more quantity resulting in active biodegradation (Mahmoud, 2021).

Chemical structure, bioavailability, toxicity and stability of the pollutant: Microbes degrade pollutant at different speeds depending on the chemical structure, toxicity, concentration, bioavailability and stability of a metal or pollutant. For instance, heavy metals with a simpler chemical structure and lower concentration are easier for microbes to clean up than those with a complex structure and higher concentration. In the same way, highly condensed cycloalkane compounds and high molecular weight polycyclic hydrocarbons, which have four or more rings, are harder to degrade than lighter polycyclic hydrocarbons like anthracene, naphthalene, and phenanthrene, as well as unbranched alkanes with intermediate chain lengths (around

C10–C25) (Kebede *et al.*, 2021). Thus, in order of increasing degradation difficulty, n-alkanes are the easiest to break down. They are followed by branched alkanes, low molecular weight aromatics, high molecular weight hydrocarbons, and asphaltenes.

Soil physical characters and depth: The depth of the soil, soil-textures and soil-particles affects moisture retention ability that determines the rate of microbial biodegradation. The topsoil layer (0-10 cm) usually has a higher microbial population and diversity because of better oxygen availability and more organic matter. This is different from what is found in sediment soils (Ndeddy Aka and Babalola, 2017). In soils with fine particles, such as clayey soils, hydrocarbons usually build up at the surface. This deprives them of nutrients and oxygen. As a result, well-drained soil is the best type for improving microbial biodegradation. It allows more oxygen to be available and supports a larger population of soil microbes (Huang *et al.*, 2019). Salinity strongly influences the hydrocarbon-degrading activity of halotolerant and halophilic microbes by imposing osmotic stress that disrupts cellular homeostasis. The more the salt concentration in the environment rises, the greater the osmotic pressure exerted on the microbial cells, which subsequently causes dehydration, enzyme inactivity and change in membrane transport. These changes compromise metabolic activity, reduce nutrient uptake, and can modify the solubility and bioavailability of heavy metals, ultimately affecting overall microbial growth and pollutant degradation efficiency (Kebede *et al.*, 2021).

Advancements in microbial bioremediation: Recently, microbial glycoconjugates, microbial biofilms, bioelectrochemical system, Nanotechnology, Omics-based tools are being employed for efficient bioremediation of organic pollutants or waste (Ambaye *et al.*, 2023; Wang *et al.*, 2026).

Microbial glycoconjugates: Microbial glycoconjugates are essential for reducing surface tension, improving the availability of organic pollutants, and creating a solvent interface. This helps in removing pollutants from the environment. The application of microbial glycoconjugates of *Scedosporium sp.* And *Acinetobacter sp.* to degrade petroleum hydrocarbons is documented (Bhatt *et al.*, 2021).

Microbial biofilms: Recently, microbial biofilms, made of polysaccharides, extracellular DNA, and proteins, have been used in cleaning up organic contaminants, especially those that are hard to break down. Ongoing advancements in this technology focus on enhancing quorum sensing, environmental conditions, and adhesion surfaces (Sonawane *et al.*, 2022). In a study by Xiao *et al.* (2024), researchers found that *Exiguobacterium profundum* could greatly lower the level of arsenic in synthetic wastewater after 48 hours of incubation.

Bioelectrochemical system: A bioelectrochemical system is a new technology that combines biological

and electrochemical methods to control pollutants (Ambaye *et al.*, 2023). It operates through microbial fuel and electrolysis systems. In these systems, electroactive microbes transfer electrons from contaminants to electrodes. This process allows for oxidation at the anode and reduction at the cathode. The efficiency of the system depends on factors like electrode material, redox conditions, and nutrient availability. This technology works well in removing

petroleum hydrocarbon pollutants. Its efficiency depends mostly on the teamwork and interactions between the microbial groups involved (Ambaye *et al.*, 2023). It has been reported that *Pseudomonas sp.*, *Ralstonia sp.*, *Rhodococcus sp.*, and *Thauera sp.* can effectively clean phenanthrene from soils contaminated with petroleum hydrocarbons.

Table 2: Factors affecting microbial bioremediation.

Factor	Optimal range condition	Impact on the bioremediation Process	References
pH	6.5 to 8.5	Influences pollutant composition and microbial survival. Acidic conditions increase protons to fill metal affixing sites.	(Kharangate-Lad <i>et al.</i> , 2021)
Temperature	Higher temperatures (generally)	Generally, favors most processes by increasing dissolution of heavy metals. Sub-zero temperatures freeze transportation channels, slowing metabolic activity.	(Khalid <i>et al.</i> , 2021)
Moisture	Moderate levels	High moisture drops biodegradation rates as aerobic microbes cannot survive. Low moisture prevents the survival of both aerobic and anaerobic microbes.	Bala <i>et al.</i> , 2022; Ren <i>et al.</i> , 2018)
Nutrient Availability	Balanced C:N:P ratio	Microbes compete for carbon as an energy source. Nitrogen (N) and phosphorus (P) must be maintained for successful biodegradation, especially when naturally low.	(Bala <i>et al.</i> , 2022; Mahmoud, 2021).
Contaminant Concentration	Cooperative interactions among components	Directly affects microbial activity. Lower concentrations result in lower rates of degrading enzyme production by soil bacteria.	(Mishra <i>et al.</i> , 2021)
Soil Texture & Depth	Well-drained soil; Topsoil (0-10 cm)	Topsoil has higher microbial diversity due to better oxygen availability. Fine particles (clay) deprive sites of nutrients and oxygen. Well-drained soil supports larger populations.	(Ndeddy Aka and Babalola, 2017)
Salinity	Low (non-halophilic environments)	Increases osmotic potential, which harms metabolic activities and transport systems. It also leads to the stressing of soil microbes and affects heavy metal solubility.	(Huang <i>et al.</i> , 2019)

Nanotechnology: Nanotechnology is a novel tool that is applied in pollution control across the globe. Nanomaterials may be obtained as a result of both physical and chemical sources (Beni and Jabbari 2022). Nanoparticles work effectively as cleaning agents for many pollutants. These include heavy metals, petroleum hydrocarbons, pesticides, dyes, and pharmaceutical compounds. Their effectiveness depends on factors such as size, chemical composition, surface coating, and shape. Nanotechnology improves bioremediation by using nanomaterials with a high

surface area and reactivity. These enhance the breakdown of pollutants and increase removal efficiency. Such materials also boost contaminant bioavailability and support microbial activity, allowing for faster and more targeted cleanup processes. The effectiveness of nanoparticles in the bioremediation process is also determined by some other conditions among them being the nature of the pollutants, nature of the medium, temperature, and environmental pH. Organic pollutants in soil such as petroleum hydrocarbons and PAHs lose a lot of their solubility and mobility in the result of sorption, thus having little

effect on the environment. Polymeric nanoparticles are produced with the help of poly (ethylene) glycol-modified urethane acrylate (PMUA) precursor chains. These nanoparticles of PMUAs are designed to maintain their properties on exposure to diverse aspects of bacterial population (Tripathi *et al.*, 2022).

Carbon dot nanoparticles have recently become the focus of interest as the environmental pollutant remediation material since they are abundant, least toxic, and possess unique optical properties (Long *et al.*, 2021). Therefore, further studies are needed to understand the long-term stability of nanoparticles in complex environments. Researchers should also evaluate their possible environmental risks, the best synthesis methods for large-scale use, and how nanoparticles interact with pollutants and microbial communities. This knowledge could improve the overall effectiveness of the bioremediation process.

Bioremediation tools based on omics: The Genomics, transcriptomics, proteomics, metabolomics are molecular bioremediation tools based on omics provide critical insights into microbial community dynamics, metabolic pathways, and functional potential for pollutant degradation. Such technologies are accessible as next-generation sequencing (NGS) and mass spectrometry, which allow identifying key microorganisms and optimizing or bioaugmentation strategies to cleanse the environmental environment effectively and in a biostimulative manner (Wang *et al.*, 2026).

Genomics: Diverse genomic techniques are used to analyze the biodegradation process better and these are PCR, isotope distribution, DNA hybridization, molecular connectivity, metabolic foot printing, and metabolic engineering. In doing the study of the soil microbial communities, one can determine related bacterial species closely, build up the functional structural models and create the genetic fingerprints using the random amplified polymorphic DNA analysis (RAPD). Research on soil microbes and their interactions with natural factors can also leverage a combination of molecular techniques, such as genetic fingerprinting, microradiography, fluorescence in situ hybridization (FISH), stable isotope probing, and quantitative PCR. Additionally, techniques for analyzing an individual's DNA utilize amplified PCR products as the basis for directly examining specific molecular biomarker genes. Cluster-assisted analysis can be used to compare fingerprints between different samples to gain a better insight into the association of different microbial communities (Yunusa *et al.*, 2021).

Transcriptomics: Transcriptomics is a technique that examines the entire sample of RNA transcripts that are present in microorganisms that are in a given environmental condition. This method shows the genes that are actively expressed in the process of pollutant degradation aiding to determine the important metabolic pathways used in the process of bioremediation. The measurement of the level of gene expression is often done by techniques like RNA

sequencing (RNA-Seq) and reverse transcription quantitative PCR (RT-qPCR). Transcriptomics has effectively been used in monitoring changes in the expression of microbial genes in response to heavy metals, hydrocarbons and pharmaceutical contaminants, which has allowed researchers to gain insight into how microbes respond to the toxic environment through changes in their metabolism (Freyria *et al.*, 2025).

Proteomics: Proteomics is the study of proteins at a large scale in a community of microbes. Proteins are the functional molecules that execute degradation reactions, so, proteomics is a direct evidence of enzyme activity that is involved in the breakdown of the pollutants. Proteins are identified and quantified using techniques like two-dimensional gel electrophoresis (2D-PAGE) and mass spectrometry (LC-MS/ MS). Proteomics has been employed to characterize enzymes such as laccases and peroxidases and monooxygenases in pollutant-degrading microorganisms, and also to discover new proteins in the metabolism of new contaminants such as microplastics and pharmaceuticals (Chandramouli & Qian, 2009).

Metabolomics: Metabolomics examines the small-scale metabolites that are created by microbes in the process of bioremediation. This methodology is a functional readout of cellular activity and the pathways of pollutant transformation. Gas chromatography-mass spectrometry (GC-MS) and nuclear magnetic resonance (NMR) spectroscopy are the most common methods of profiling metabolites. Metabolomics can be used to determine the breakdown products of pollutants that are intermediate and to determine the toxicity of the transformation products and the overall efficiency of the biodegradation process. Recent works have used metabolomics to trace the breakdown of petroleum hydrocarbons, pesticides and pharmaceutical residues in polluted surroundings (Qiu *et al.*, 2023).

Advantages of bioremediation:

It is extremely easy and can be performed in-situ without interfering with the normal activity of the microorganisms.

There is no use of hazardous chemicals, nutrients, especially fertilizers, are introduced to enhance a faster growth in microorganisms.

The processes that take place under nature make it simple, less manpower and economical.

Contaminants are eliminated rather than merely relocated to different environments.

It is non-intrusive, allowing for continued use of the site.

It is a modern method for remediating large-scale contamination and represents eco-friendly, sustainable opportunities.

It is also energy-efficient since bioremediation is based on natural microbial metabolism, and not on energy-consuming physical or chemical treatment. Bioremediation is a process that can be conducted at ambient conditions unlike incineration or chemical

oxidation, which may require high temperatures or pressures, consumes much less energy, and is thereby less costly.

As one of the most efficient, handy and easy-to-use methods, it has gained the universal consent of both the population and the government agencies (Sharma et al., 2022).

Disadvantages of bioremediation

Only biodegradable compounds can be targeted.

Biodegradation can produce some byproducts that are potentially more lethal as compared to the original compound and may remain in the environment.

The bioremediation technologies are commonly used in sites that are polluted with complexes of pollutants. These pollutants can be irregularly located in the environment, and it becomes difficult to treat. So, more studies are required to come up with and streamline bioremediation methods in such mixed environments.

Close surveillance is to be performed.

As a biological process, specificity poses a significant drawback, influenced by factors such as environmental growth conditions, types of microorganisms, nutrient

Altogether, it is quite a time-consuming process (Sharma I, 2020).

FUTURE PERSPECTIVE AND CONCLUSION:

Stress studies on the use of microbial enzymes on the bioremediation of wastes have been intensively conducted. Nonetheless, it is essential to take these processes to the next higher level to be able to provide a safer and more sustainable environment. More research activities should be conducted to find the new efficient microbial strains that can bioremediate the industrial sources.

Also, more research needs to be undertaken to come up with quicker methods of detecting the direction of biodegradation or ensuring the ultimate destruction of pollutants in the environment. Genetic modification of existing microbes utilized for bioremediation is needed to yield more enzymes for efficient biodegradation process. Employing a consortium of diverse microbes rather than relying on a single strain would be used, for complete degradation.

Bioremediation has also its limitations. These include the slow breakdown of persistent pollutants, sensitivity to environmental conditions, and possible ecological risks from the introduction of new microbes. Overcoming these challenges will require engineered consortia, improved bioreactors, and strong monitoring systems for large-scale use.

There is dire need to discover microbes with degradation ability for inorganic (synthetic) pollutants. While beneficial microbes may be employed for pollutant bioremediation, follow-up research is needed to assess their long-term environmental effects, as some introduced organisms could become pollutants themselves through mutations or other processes. Thus,

the responsibility of potential threats of microbes within particular conditions should be controlled by regulatory bodies.

Lastly, the direct application of enzymes or microbes to the soil can cause their death or deactivation of their activities before the remediation process of the soil can begin. Combining these agents with other substances, such as nanoparticles, could enhance their activity. There is a need for greater awareness regarding microbial degradation methods, which will aid policymakers and the public in adopting this approach. Without adequate awareness, stakeholders may continue relying on conventional treatment methods that are often less safe and effective than microbial biodegradation.

CONFLICTS OF INTEREST

We declare no competing interests affecting the work reported in this study.

AUTHORS' CONTRIBUTION

M.A designed and wrote the initial draft, M.I and U.E.H performed data collection, formatting and wrote the manuscript. M.A critically revised the manuscript for intellectual content and proofread the manuscript. S.M, S.N and S.F assisted in data organization and manuscript editing along with overall coordination of the manuscript submission. All authors proofread and approved the final manuscript.

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