Review Article

Nigerian Journal of Biotechnology and Life Sciences
ISSN: 2814-0281
Vol. 3 No 2a (2026) p. 218 - 233
http://www.njbls.fud.edu.ng/

Microbial Bioremediation of Wastewater: Mechanisms, Applications, Challenges, and Emerging Trends

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https://doi.org/10.67601/njbls.v3i2a.41

Article into

Date received
17/07/2026
Date accepted
25/08/2026
Available online
11/09/2026

Keywords

Heavy metals; Biosorption; Bioaccumulation; Bio-volatilization; Microbial consortia; Biodegradation; Bioaugmentation;

Abstract

Wastewater contamination resulting from rapid industrialization, urbanization, and agricultural activities has become a major global environmental and public health concern. Conventional physicochemical treatment technologies are often limited by high operational costs, incomplete pollutant removal, and the generation of secondary pollutants. Consequently, microbial-based wastewater treatment and bioremediation have emerged as sustainable, cost-effective, and environmentally friendly alternatives. This review comprehensively examines the role of microorganisms and microbial consortia, in the biodegradation, detoxification, and removal of organic pollutants, heavy metals, nutrients, pathogens, and emerging contaminants from wastewater. The major biological mechanisms involved, including biosorption, bioaccumulation, bioleaching, biotransformation, bio-volatilization, biomineralization, and bioaugmentation, are critically discussed alongside their underlying metabolic pathways. The review further highlights the application of microbial technologies in activated sludge systems, anaerobic digestion, nitrification-denitrification, enhanced biological phosphorus removal. Recent advances in molecular biotechnology, microbial consortia engineering, nano-bioremediation, and CRISPR-assisted microbial enhancement are also explored as promising approaches for improving remediation efficiency. Furthermore, current challenges such as pollutant bioavailability, environmental variability, scale-up limitations, and ecological risks are examined, supported by selected international and Nigerian case studies. Overall, microbial bioremediation represents a promising strategy for sustainable wastewater management and environmental restoration. Future research should focus on integrating advanced biotechnology, systems biology, and process optimization to enhance large-scale implementation and contribute to achieving global water sustainability goals.

Introduction

Pollution is the harmful alteration of the environment, caused entirely or partly by anthropogenic activities, through changes in the chemical and physical characteristics of the environment that negatively affect living organisms (Mukherjee et al., 2021). The contamination of water by heavy metals and hydrophobic organic compounds poses a significant threat to the environment (Gupta et al., 2022). Traditional physicochemical methods for remediation are often expensive and environmentally unfriendly, whereas bioremediation offers a more eco-compatible and economically feasible alternative (Ali, et al., 2023). Heavy metals, such as copper (Cu), cadmium (Cd), lead (Pb), nickel (Ni), chromium (Cr), and zinc (Zn), as well as hydrophobic organic compounds, cause soil and water contamination, leading to serious environmental problems (Ali, et al., 2023).

Microorganisms play a critical role in wastewater treatment by degrading organic pollutants, cycling nutrients, and removing toxic substances through various biological processes (Dharani et al., 2023; Kushkevych, 2021). These processes primarily utilize the metabolic activities of bacteria, algae, fungi, and protozoa to stabilize organic matter (Mathew et al., 2022). Microorganisms used in bioremediation have the potential to transform harmful contaminants into carbon dioxide (CO_2), water (H_2O), microbial biomass, and other products that are less toxic than the original compounds. Different microorganisms can be used for bioremediation. Examples include aerobic microbes such as Mycobacterium, which can contribute to the degradation of pesticides and hydrocarbons. Many of these microorganisms use pollutants as sources of carbon and energy (Mukherjee et al., 2021).

Wastewater refers to used water that has been degraded in quality due to human activities, including sewage, industrial effluents, and agricultural runoff. It contains pollutants such as suspended solids, organic matter, nutrients, heavy metals, and pathogens, which can harm ecosystems and public health if untreated. Modern perspectives view wastewater not only as waste but also as a valuable resource for energy, nutrients, and water reuse (Mukherjee et al., 2021) (Table 1).

This highlights the dual challenge of wastewater management: not only the removal of chemical pollutants but also the control of microbial pathogens to safeguard public health. Wastewater and its treatment have become major global concerns. Contamination of water is one of the key aspects of environmental pollution. The contaminants are mainly released from industries (fertilizers, mining, pesticides) or as domestic effluents. The release of hazardous waste affects human health and disturbs the aquatic ecosystems (Mishra et al., 2025).

According to Mishra (2025), based on the source from which wastewater is generated, there are various types of wastewater, some of which are sewage sludge, dairy wastewater, winery wastewater, tannery wastewater, textile wastewater, food wastewater, phenolic wastewater, carpet mill wastewater, slaughter house wastewater, pharmaceutical wastewater, beverage wastewater, paper industry wastewater, oil mill wastewater, and agricultural runoff.

Effects of Water Pollution

Anthropogenic activities and many industrial activities generate heavy metals, which contaminate water and cause severe harm to marine habitat. They are not biodegradable and harm animals and plants, which means they pose appreciable risk to both life and surroundings. Pollutants can exert different effects depending on their sources and types. Certain waste types, including dyes, heavy metals, and various organic contaminants, are known to be carcinogenic. Chemicals that damage the endocrine system and affect human and non-human animal reproduction and growth include some hormones, medicines, cosmetics, and waste generated from products of personal care (Mishra et al., 2025).

The following are some detrimental effects of contaminated water on human health and the environment: Health Impact: Contaminated water is an important source of waterborne diseases such as cholera, typhoid fever, hepatitis A, and dysentery. Cancer, neurological abnormalities, and disorders of reproduction are just a few of the severe health consequences that can result from exposure to harmful substances in contaminated water.

Environmental Effects: Water pollution may affect aquatic habitats, interfere with fish reproduction, and cause the death of fish. The loss of biodiversity is the result of all of these. Eutrophication, which results in algal blooms that lower water oxygen levels, can be brought on by an excess of nutrients from agricultural runoff (Mishra et al., 2025).

Table 1: Toxic effects of different heavy metals on human health (Mukherjee et al., 2021)

Heavy metals	Toxic form	Health risks
Cadmium	Cd^{2+}	Cd toxicity reduces cell viability, induces apoptosis, and damages the kidneys, liver, and bones.
Arsenic	As	As exposure can cause dermal lesions, including hyperkeratosis and pigmentation changes, and associated with an increased risk of skin cancer.
Mercury	Hg	Hg exposure can cause headache, hypertension, insomnia, altered neurological responses, cognitive impairment, and cardiovascular and renal dysfunction.
Lead	Pb	Pb toxicity can adversely affect the cardiovascular, renal, and nervous systems and can impair brain development, particularly in children.
Iron	Fe	Excessive iron exposure can cause gastrointestinal symptoms, including abdominal pain, vomiting, and diarrhea.
Copper	Cu	Cu toxicity caused gastrointestinal distress followed by abdominal pain, vomiting, and hypotension and it also affected the human brain, liver and kidney performances.
Chromium	Cr^{3+}	Cr^{6+} toxicity is highly toxic and carcinogenic, whereas Cr^{3+} is generally less toxic at environmental concentrations.
Aluminium	Al^{3+}	Al damaged central nervous system, kidney and liver dysfunction, and cause pulmonary fibrosis, osteomalacia and lung infections.
Vanadium	V	Vanadium toxicity caused nausea and throat injury, rashes and blacken the teeth and tongue.

Economic Impacts: Reduced agricultural output, higher medical expenditures, and lost tourism revenue are just a few of the substantial financial consequences that water contamination can have. Fish populations are impacted by water pollution, which lowers harvests and causes financial losses for the fishing sector. The cost of elimination of contaminants from waterways and regenerating harmed ecosystems can be substantial.

Microbial Pathogens in Wastewater and Their Public Health Implications

Wastewater can contain infectious agents, microbial toxins, and spores in water bodies that significantly affect daily water requirements. Some microbial pathogens responsible for water pollution are also the causative agents of waterborne diseases. These organisms include fungi, bacteria, protozoa, viruses, roundworms, and flatworms. Opportunistic pathogens such as *Enterococcus faecalis*, *Enterobacter cloacae*, *Klebsiella pneumoniae*, *Escherichia coli*, *Proteus vulgaris*, and *Pseudomonas aeruginosa* are frequently detected in wastewater. They pose serious risks to immunocompromised individuals, often leading to systemic infections. Moreover, pathogenic strains of *Shigella*, *Salmonella*, and *Escherichia coli* are recognized as leading causes of waterborne diseases globally (Mishra et al., 2025).

Wastewater Treatment Methodologies

Major methodologies involved in wastewater treatment include physical, chemical, and biological processes (Figure 1). Conventional physicochemical methods include precipitation, evaporation, osmosis, electrochemical treatment, ion exchange, and sorption. These methods can be costly and may have environmental limitations. Biological methods are often preferred because they can efficiently remove low concentrations of some metal ions and other contaminants.

Applications of Microbes in Wastewater Treatment

Activated sludge process heterotrophic bacteria degrade organic matter into carbon dioxide, water, and biomass, reducing biochemical oxygen demand (BOD) (Mishra et al., 2025). Biofilm-based systems (Trickling Filters, moving bed reactors) Microbes form biofilms on surfaces, breaking down organic pollutants as wastewater flows through (Kumar & Verma, 2025). Anaerobic digestion (Figure 2) methanogenic bacteria convert organic waste into biogas (methane + CO_2), providing renewable energy while stabilizing sludge (Mishra et al., 2025). Nitrification autotrophic bacteria (*Nitrosomonas*, *Nitrobacter*) oxidize ammonia to nitrate, reducing nitrogen pollution (Mishra et al., 2025). Denitrification is where facultative anaerobic bacteria convert nitrate into nitrogen gas, preventing eutrophication in receiving waters (Kumar & Verma, 2025).

Phosphorus removal (Enhanced Biological Phosphorus Removal – EBPR) Polyphosphate-accumulating organisms (PAOs) store phosphorus intracellularly, reducing phosphate levels in effluent (Mishra et al., 2025). Microalgae-based treatment, microalgae assimilate nutrients (N, P), produce oxygen for bacterial activity, and remove emerging contaminants such as pharmaceuticals. Specialized microbial consortia degrade dyes, heavy metals, and xenobiotics from industrial wastewater, reducing toxicity (Mishra et al., 2025).

Bioremediation

Bioremediation is an important field in environmental science that focuses on the use of living organisms to detoxify polluted environments (Abatenh et al., 2017). It offers a promising, eco-friendly solution by harnessing natural biological processes. Bioremediation employs microorganisms, including bacteria, fungi, and algae, to detoxify or transform contaminants in water and soil. These organisms utilize natural metabolic processes to adsorb, accumulate, transform, or otherwise immobilize contaminants, thereby reducing their mobility and toxicity (Etuk, et al., 2026).

Bioremediation is a technique used for the degradation, transformation, and removal of pollutants such as heavy metals, hydrocarbons, azo dyes, and pesticides into less toxic or less harmful forms with the help of biological agents. It is also widely used for the transformation of organic wastes into less toxic compounds (Mukherjee et al., 2021). There are two classes of bioremediation, which are as follows:

In situ bioremediation can involve either stimulation of indigenous microorganisms or introduction of selected microorganisms from external sources. These approaches are commonly described as biostimulation and bioaugmentation, respectively. For example, there may be soil that is contaminated. Rather than remove the soil from its point of origin, it is treated right where it is. The benefit of in-situ treatment is that it prevents the spread of contamination during the displacement and transport of the contaminated material (Etuk, et al., 2024). In-situ bioremediation could be categorized into two types based on whether the bioremediatory is within the polluted soil and is introduced from external source. These are intrinsic and engineered bioremediation (Alori et al., 2022). The Intrinsic bioremediation is carried out by the stimulation of indigenous microbes of the polluted sites. This remediation could be by both aerobic and anaerobic processes. It does not require application of any external force of any sort; hence, intrinsic bioremediation relies on naturally occurring microbial populations and environmental processes to reduce contaminant concentrations. Its effectiveness depends on the presence of microorganisms with appropriate metabolic capabilities and suitable environmental conditions (Alori, et al., 2022). While engineered In-situ bioremediation, non-indigenous microorganisms may be introduced into contaminated sites to enhance the degradation of target pollutants. The introduced microorganism improves the chemical and physical properties of the polluted site and, thereby, encourage the growth of the indigenous microorganisms. This, therefore, accelerates the degradation process of the pollutants (Alori, et al., 2022).

Ex-situ bioremediation: refers to treatment that occurs after the contaminated waste has been removed to a treatment area. To use soil as the example again, the soil may be removed and transported to an area where the bioremediation may be applied. The main advantage to this is it helps to contain and control the bioremediation products, as well as making the area that was contaminated available for use.

Microbial Remediation

Microbial remediation is a technique that utilizes microorganisms such as bacteria to transform or remove pollutants from various environments, including wastewater. In the context of inorganic pollutant extraction from wastewater, microbial transformation involves the metabolic activities of these microorganisms to either convert the pollutants into less harmful forms or accumulate them within their biomass. This environmentally friendly technique can be a sustainable approach to treating wastewater contaminated with heavy metals and other inorganic pollutants (Zaib, et al., 2023 Microorganisms can transform heavy metals through redox reactions, biosorption, bioaccumulation, biomineralization, and other mechanisms. Unlike organic pollutants, heavy metals cannot be metabolized as carbon sources because they are elements. Under heavy metals stress, some microbes also secrete different substances including polysaccharides, proteins, and lipids that can bind HMs ions and therefore reduce their availability (Adetunji et al., 2023).

Mechanism of Bacterial Bioremediation of Wastewater Pollutants

Bacteria employ various mechanisms for the degradation and removal of pollutants in wastewater. These mechanisms involve a combination of biochemical pathways, enzymatic reactions, and metabolic processes. The major mechanisms are described below.

Aerobic bacteria are most frequently employed for biological wastewater treatment, including trickling filters and activated sludge processes. Following equation describes the process:

Organic waste + O_2 $\rightarrow$ CO_2 +H_2O + Energy…. (1)

Aerobic bacteria facilitate the breakdown of organic matter under oxygen-rich conditions. They are widely used in biological wastewater treatment systems, including activated sludge and trickling filters. Process performance depends on factors such as pH, temperature, oxygen availability, nutrient concentrations, and microbial community composition. A major limitation of aerobic treatment is the production of excess biomass (sludge), which requires appropriate management and disposal (Ali, et al., 2025).

Anaerobic bacteria decompose organic pollutants present in wastewater and derive energy from nitrates and sulphates equations (2) and (3):

Organic waste + NO_3^- $\rightarrow$ CO_2 + N_2 + energy (bound to oxygen in nitrate) ……..(2)

Organic waste + SO_4^{2-} $\rightarrow$ CO_2 + H_2S + energy (bound to oxygen in sulphate) ……….(3)

Anaerobic processes generally have slower microbial kinetics than aerobic processes, but they offer important advantages, including lower energy requirements and the production of biogas. Under anaerobic conditions, organic matter can be converted into methane and carbon dioxide through a series of microbial processes. Integrated anaerobic–aerobic treatment systems can combine the advantages of both approaches and are used in the treatment of several industrial wastewaters (Ali et al., 2025).

Mechanisms of Microbial Remediation

Bioremediation is a sustainable environmental management strategy that employs microorganisms, plants, or their enzymes to detoxify and restore ecosystems contaminated by organic and inorganic pollutants. Its mechanisms are diverse and reflect the adaptability of biological systems to different contaminants and environmental conditions. Key pathways include bioaccumulation, biosorption, bioleaching, biotransformation, biomineralization, and bioaugmentation. These mechanisms collectively demonstrate the versatility of bioremediation as an alternative or complementary approach to conventional chemical and physical remediation methods (Dash et al., 2025)..

Figure 1: Wastewater Treatment Strategies (Mishra et al., 2025).

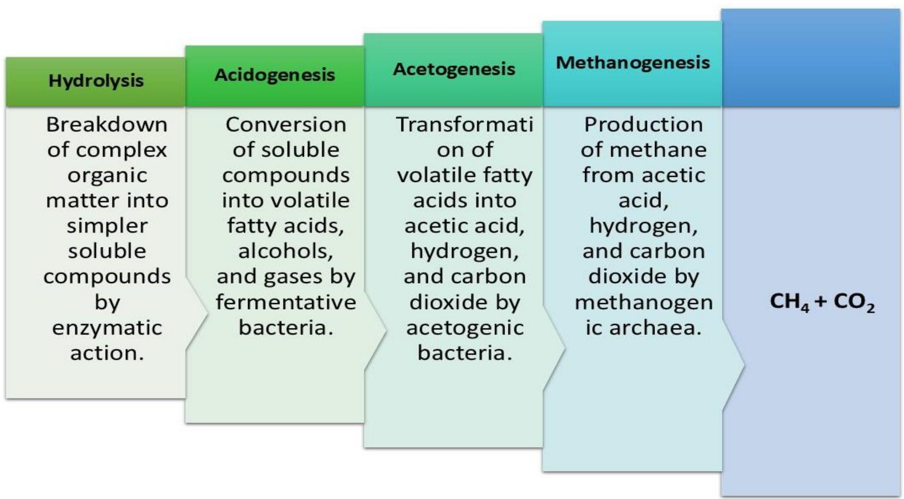

Figure 2: Stepwise of Anaerobic Digestion (Chatterji et al., 2025).

Biosorption

Bacterial cell-wall binding: Gram-negative bacterial cell envelopes contain functional groups, including carboxyl and phosphate groups that can contribute to the adsorption of metal ions and other contaminants. Fungal biosorption: chitin and glucans in fungal cell walls provide functional groups that can bind pollutants. Algal biomass: algal polysaccharides such as alginate and cellulose can act as binding matrices and ion exchangers (Torres, 2020).

Mechanism of Microbial Biosorption

The first step is diffusion and transport, during which pollutant molecules move from the bulk solution to the biosorbent surface, usually driven by concentration gradients (Figure 3). This is followed by surface adsorption, where functional groups on cell walls (e.g., carboxyl, hydroxyl, amino, and phosphate groups) bind pollutants. Ion exchange may also occur, in which cations such as Na^+ and Ca^{2+} associated with the biomass are exchanged with pollutant ions. For example:

$$2R\text{-}COOH + Pb^{2+} \rightarrow (R\text{-}COO)_2Pb + 2H^+$$

Complexation & Chelation causes the formation of stable complexes between pollutants and ligands on biomass. Fungal chitin and bacterial peptidoglycan act as binding matrices. Pollutants precipitate on the biomass surface is as a result of local pH changes. A key example of this technique in wastewater treatment, where *Saccharomyces cerevisiae* cell walls bind dyes and phenolic compounds through hydrogen bonding and van der Waals forces, reducing pollutant concentration significantly (Torres, 2020).

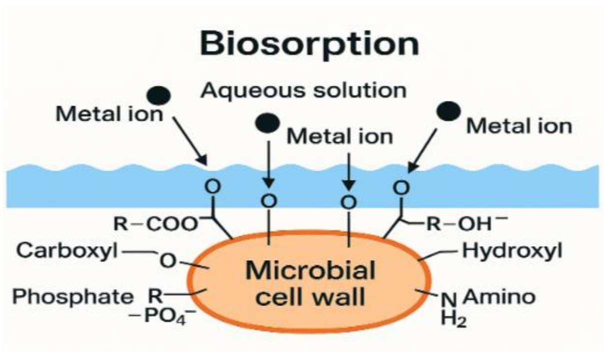

Figure 3. Biosorption Process (Torres, 2020).

Bioaccumulation

Bioaccumulation is a biologically active process in which pollutants gradually build up within living organisms over time. Unlike biosorption, which is passive and surface-based, bioaccumulation involves metabolic activity that enables organisms to take up, transport, and store contaminants internally. For example, *Microbacterium liquefaciens,* Certain microorganisms can accumulate chromium intracellularly, thereby reducing its concentration in the surrounding aqueous phase. This mechanism is particularly effective for metals such as Pb, Ni, Hg, Cd, and Cr (Adie et al., 2025).

Mechanism of Bioaccumulation

Bioaccumulation is a biologically active process in which pollutants gradually build up within living organisms over time (Figure 4). Unlike biosorption, which is passive and surface-based, bioaccumulation involves metabolic activity that enables the organism to absorb, transport, and store contaminants internally. The process begins with uptake, where pollutants enter the organism through diffusion or active transport mechanisms. Lipophilic compounds such as polychlorinated biphenyls (PCBs) and dioxins readily cross cell membranes due to their affinity for lipid environments. Once inside, the pollutants undergo transport through the cytoplasm or bloodstream. Specialized transport proteins may facilitate their movement into organelles, ensuring that contaminants reach specific cellular compartments. This leads to intracellular accumulation, where pollutants concentrate in tissues like fat, liver, or vacuoles. Some compounds bind to proteins or DNA, potentially disrupting cellular function and causing toxicity. The final stage is storage, where persistent pollutants are retained long-term, often in lipid-rich tissues. This retention is exacerbated by repeated exposure and slow metabolic degradation, making bioaccumulation a significant concern for ecological and human health. Over time, these stored pollutants can magnify through food chains, leading to biomagnification effects in top predators and humans (Adie et al., 2025).

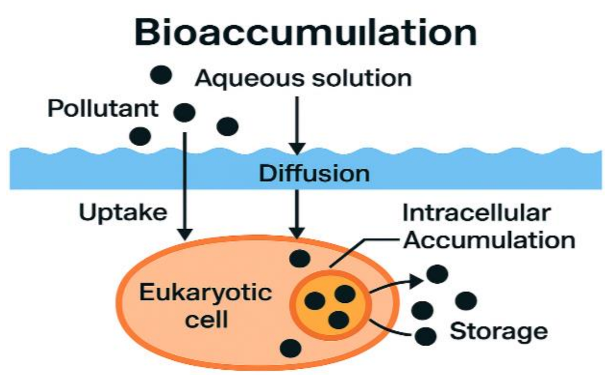

Figure 4. Bioaccumulation Reaction Process (Torres, 2020).

Bioleaching

Bioleaching is a microbial technique used to mobilize and recover metals from ores and contaminated materials through biochemical pathways involving microorganisms (Figure 5). It is especially useful for metals such as copper, zinc, uranium, and gold. The process may involve acidolysis, redoxolysis, and complexolysis.

In acidolysis, microorganisms such as *Acidithiobacillus ferrooxidans* can generate acidic conditions that dissolve metal-containing minerals. In many bioleaching systems, sulfuric acid is produced or involved in the process, facilitating the release of metal ions from sulfide minerals. This reaction liberates metal ions from sulfide minerals, as shown in the equation:

$MS + 2H^+ \rightarrow M^{2+} + H_2S$

Where MS represents a metal sulfide compound.

Redoxolysis involves microbial oxidation of metal sulfides, releasing metal ions through redox reactions. For example, pyrite can be oxidized by ferric ions in the presence of water, producing ferrous ions, sulfate, and protons:

$FeS_2 + 14Fe^{3+} + 8H_2O \rightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+$

Lastly, complexolysis occurs when microbial metabolites form soluble complexes with metal ions, enhancing their mobility and extraction. This pathway is particularly useful for metals that are otherwise poorly soluble in acidic conditions (Dash et al., 2025).

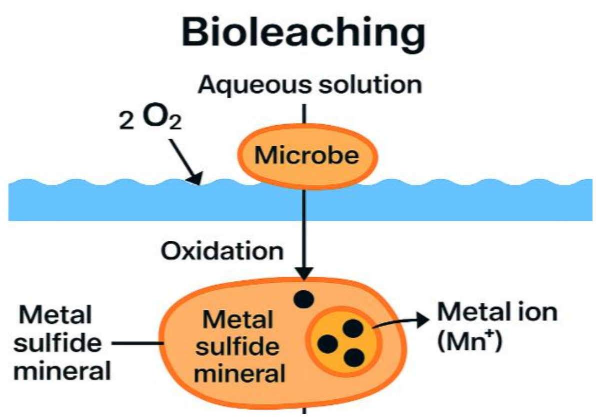

Figure 5. Bioleaching Process (Johnson, 2022).

Biotransformation

Biotransformation begins with the uptake of organic pollutants into microbial cells or their interaction with extracellular enzymes (Figure 6). This step is crucial because it determines the accessibility of the pollutant to enzymatic action. Lipophilic compounds often diffuse passively across cell membranes, while hydrophilic ones may require transport proteins (Ali, et al., 2023)..

Enzymatic Transformation in Biotransformation

Once inside the cell or in contact with microbial enzymes, the pollutant undergoes chemical modification. Microorganisms produce enzymes such as oxidases, reductases, hydrolases, and transferases that catalyse reactions like hydroxylation, dehalogenation, and conjugation. These reactions alter the pollutant's structure, often increasing its polarity and reducing toxicity (Khojasteha et al., 2022).

Intermediate Formation in Biotransformation

Some biotransformation pathways involve the formation of intermediate metabolites. These intermediates may be transient and undergo further transformation before reaching a stable, detoxified state. In some cases, intermediates can be more toxic than the parent compound, requiring additional enzymatic steps to neutralize them (Gómez, 2024). The end result of biotransformation is a less toxic, more biodegradable compound. This product may be excreted from the microbial cell or further metabolized into carbon dioxide, water, and biomass. In environmental applications, this step is critical for reducing pollutant load and restoring ecological balance (Khojasteha et al., 2022).

An example is the biotransformation of nitrobenzene to nitrosobenzene in *Saccharomyces cerevisiae*. This process begins with the uptake of nitrobenzene, which enters the yeast cell either by passive diffusion across the membrane or through facilitated transport. Once inside, reductase enzymes act on the compound, partially reducing the nitro group ($-NO_2$) to a nitroso group ($-NO$). This enzymatic transformation is represented by the reaction below, where nitrobenzene is converted into nitrosobenzene.

$$C_6H_5NO_2 \rightarrow C_6H_5NO$$

The resulting nitrosobenzene serves as an intermediate that may undergo further reduction depending on enzyme activity and environmental conditions. Under controlled circumstances, nitrosobenzene remains the stable product; however, in extended pathways, it can be reduced further to aniline, which is potentially less toxic and more biodegradable (Ajao et al., 2021).

Bio-volatilization

Bio-volatilization is a microbial process that transforms toxic elements into volatile, gaseous forms, enabling them to escape into the atmosphere and thereby reducing their concentration in soil and water (Figure 7). The mechanism begins with uptake, where microorganisms absorb toxic metal ions such as mercury (Hg), selenium (Se), or arsenic (As) from the environment, either through passive diffusion or active transport.

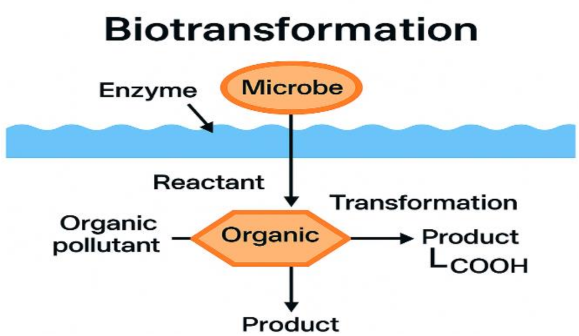

Figure 6: Biotransformation Process (Torres, 2020).

Once inside the cell, the metals undergo enzymatic conversion, typically mediated by enzymes like methyltransferases, which chemically modify the ions into volatile organic derivatives. For example, microorganisms can reduce Hg^{2+} to elemental mercury Hg, which can volatilize from aqueous environments, while selenium may be transformed into dimethylselenide. These transformed compounds are volatile and readily escape from the microbial cell during the volatile product formation stage. Finally, in the environmental release step, the gaseous products diffuse into the air, effectively detoxifying the contaminated environment, though their atmospheric fate must be considered for long-term ecological impact (Upadhyay et al., 2023).

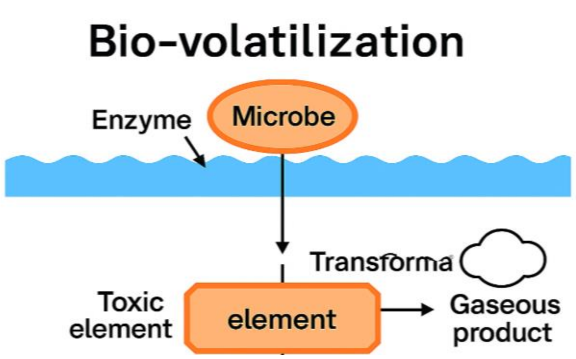

Figure 7. Bio-volatilization Process (Upadhyay et al., 2023).

Bio-Mineralization

Biomineralization is the biological process by which living organisms produce minerals, often resulting in hardened or stiffened structures such as bones, shells, teeth, and exoskeletons (Figure 8). It is a widespread phenomenon observed across all kingdoms of life, with over 60 different minerals identified in organisms. The mechanism of biomineralization generally involves several coordinated steps. First, organisms regulate ion uptake, drawing essential elements such as calcium, phosphate, or silica from their environment. These ions are then transported and concentrated at specific sites within cells or extracellular matrices. Next, nucleation occurs, where organic molecules such as proteins, polysaccharides, or lipids act as templates to initiate crystal formation. This is followed by crystal growth and organization, in which the mineral phase develops under biological control, often resulting in highly ordered structures with unique mechanical properties. Finally, the minerals are integrated into tissues, forming functional biomaterials like bone, dentin, or mollusk shells. This biologically controlled mineralization differs from purely chemical precipitation because it is tightly regulated by cellular activity, ensuring precise composition, structure, and function (Ali, et al., 2023).

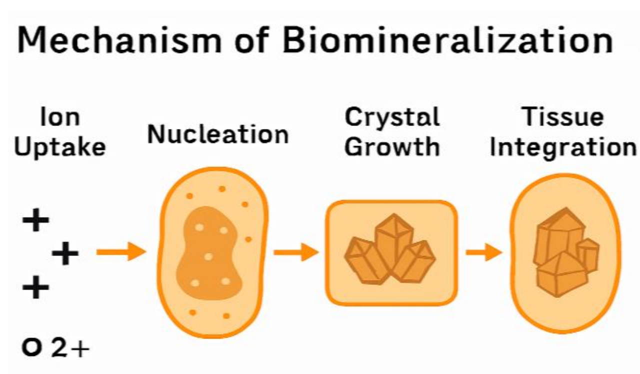

Figure 8. Mechanism of Biomineralization (Weiner, 2024).

Bioaugmentation

Bioaugmentation is a targeted bioremediation strategy that involves introducing specific microbial strains into a contaminated environment to accelerate pollutant degradation (Figure 9).

Unlike natural attenuation, which relies primarily on indigenous microorganisms, bioaugmentation adds microorganisms with demonstrated metabolic capabilities to degrade particular contaminants. The approach is used in wastewater treatment, soil remediation, and groundwater cleanup (Ghosh & Das, 2024).

The mechanism begins with the selection and cultivation of microbial strains possessing the enzymatic machinery required to degrade the target pollutant. These microorganisms are then introduced into the contaminated site, sometimes alongside nutrients or electron donors. Once established, they may perform enzymatic degradation through pathways such as oxidation, reduction, or hydrolysis. The success of bioaugmentation depends on microbial compatibility, environmental conditions (pH, temperature, and oxygen availability), and pollutant bioavailability (Singh et al., 2023).

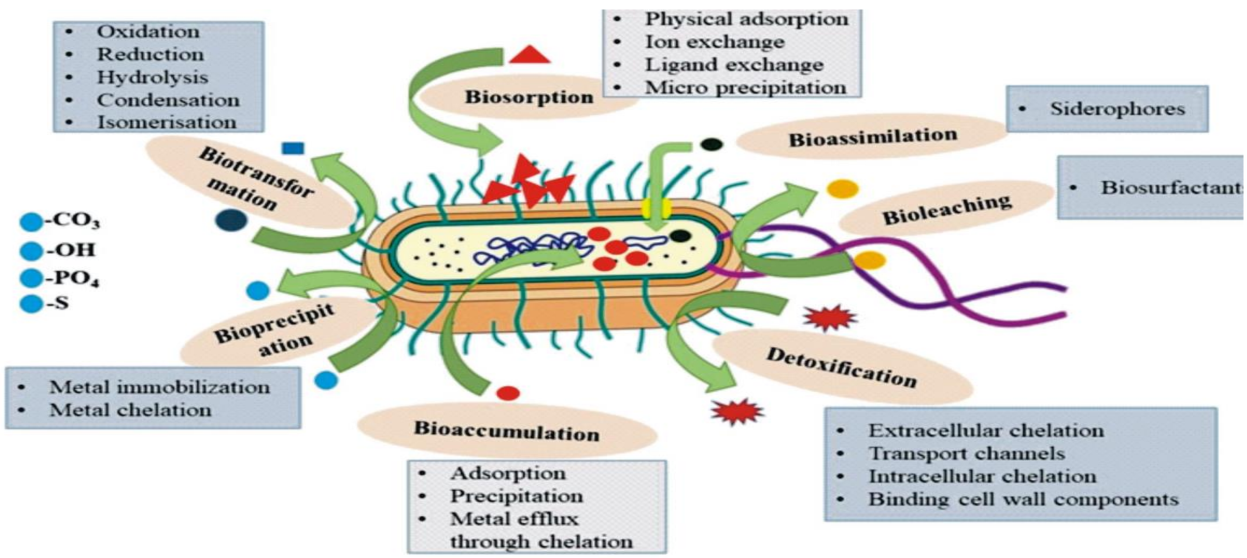

Figure 9: Mechanisms of Bioaugmentation (Singh et al., 2023).

Bioremediation efficiency depends on microbial capacity, environmental conditions, and contaminant properties. Optimal temperature, moisture, pH, nutrient balance, and oxygen availability can enhance microbial metabolism, while pollutant bioavailability and toxicity influence degradation success (Etuk et al., 2024).

Factors Affecting Bioremediation

Bioremediation is influenced by a complex interplay of biological, chemical, and environmental factors that determine the efficiency of pollutant degradation.

Biotic Factors: Microbial population size, diversity, and interactions (competition, predation, gene transfer, mutation) affect degradation rates. Also, enzyme activity and biomass growth are critical for pollutant breakdown.

Environmental Factors: Soil type, structure, moisture, redox potential, oxygen availability, nutrient levels, and pH strongly influence microbial metabolism and contaminant degradation (Abatenh et al., 2017).

Temperature: Optimal temperatures enhance microbial activity, while extremes reduce metabolic rates. Cold climates slow hydrocarbon degradation due to microbial inactivity (Etuk et al., 2024).

Moisture: Adequate soil moisture (25–85% of water-holding capacity) supports microbial survival and oxygen exchange, enhancing biodegradation (Eskander & Saleh, 2017).

pH: pH: Optimal biodegradation occurs within a suitable pH range that varies among microorganisms and contaminants. Soil pH also affects nutrient solubility and microbial activity (Ali, et al., 2023).

Nutrient Availability: Essential nutrients (C:N:P ratio) are required for microbial growth. Deficiency reduces degradation, while excess nutrients may inhibit metabolism (Etuk et al., 2024).

Oxygen: Aerobic and anaerobic conditions both support bioremediation. Oxygen is vital for respiration and enzymatic degradation pathways (Etuk et al., 2024).

Soil Characterization: Organic matter content and soil structure influence contaminant mobility and microbial growth, thereby affecting degradation rates (Etuk et al., 2024).

Bioavailability: Only bioavailable fractions of contaminants can be degraded. High molecular weight hydrocarbons and hydrophobic PAHs are less soluble, reducing microbial access (Etuk et al., 2024).

High pollutant concentrations can inhibit microbial metabolism. Hydrocarbon structure, including chain length and branching, influences ease of degradation; straight-chain alkanes are generally more readily degraded than highly branched or cyclic hydrocarbons under suitable conditions (Etuk et al., 2024).

Isolation and Characterization of Bacteria for Bioremediation

The isolation and characterization of bacteria for bioremediation involves several steps designed to identify strains capable of degrading pollutants in wastewater.

During sample collection, wastewater samples are collected from municipal sewage, industrial effluents, or sludge using sterile techniques to avoid contamination (Kulzhanova et al., 2024). Samples are inoculated into selective media containing pollutants such as hydrocarbons, dyes, or heavy metals. This enriches microbial populations capable of metabolizing contaminants (Mishra et al., 2025). Serial dilution and plating on nutrient agar or pollutant-specific media are used to obtain distinct colonies. Pure cultures are established by repeated sub-culturing (Sonune & Garode, 2018).

Characterization involves morphological tests (Colony shape, pigmentation, Gram staining), Biochemical tests (Catalase, oxidase, urease, nitrate reduction, carbohydrate fermentation), Molecular identification (16S rRNA sequencing for precise taxonomic classification), and Functional assays (Growth in pollutant-containing media and measurement of degradation efficiency) Okezie et al., 2020.

Laboratory scale cultivation and optimization before field application is where microbes undergo adaptation, where they are gradually exposed to increasing concentrations of the pollutant. Consortium Development Often, a single species cannot degrade a complex toxin. A mixed culture (consortium) is developed where different species perform successive steps in a metabolic pathway, preventing the buildup of toxic intermediates.

Scaling up (Fermentation) is the bioreactor production in a controlled environments (Stirred-tank or Airlift reactors) which allow for mass production of biomass. Media optimization is where parameters like Carbon:Nitrogen (C:N) ratios, pH, and dissolved oxygen are fine-tuned to maximize yield.

During bioremediation potential testing the isolates are tested in controlled conditions (batch cultures or bioreactors) to evaluate pollutant removal efficiency. Parameters measured include reduction in chemical oxygen demand (COD), biological oxygen demand (BOD), heavy metal concentration, or hydrocarbon degradation rate (Kulzhanova et al., 2024).

Bacillus subtilis reported in wastewater environments and studied for its ability to degrade organic matter and some dyes, *Pseudomonas aeruginosa* reported in industrial wastewater and studied for its ability to degrade hydrocarbons and phenolic compounds, *Enterobacter cloacae* reported in wastewater environments and investigated for its potential to reduce organic carbon and nitrogen loads, and *Klebsiella pneumoniae* reported in wastewater and sludge environments and investigated for heavy metal resistance and detoxification. These strains demonstrate the versatility of bacteria in wastewater bioremediation, with *Pseudomonas* and *Bacillus* being particularly well-studied due to their resilience and metabolic diversity (Mishra et al., 2025; Kulzhanova et al., 2024).

Advantages of Bioremediation

It is a natural process and generally acceptable by the public. It is eco- friendly, bioremediation can be less expensive than some conventional remediation technologies, depending on site conditions and treatment requirements. Bioremediation can often be carried out on site, often without causing a major disruption of normal activities. This also eliminates the need to transport quantities of waste off site and the potential threats to human health and the environment that can arise during transportation.

Disadvantages of Bioremediation

Bioremediation is limited to biodegradable compounds. Thus, not all compounds are susceptible to rapid and complete degradation. It is time-consuming compared to other treatment options, like excavation and removal of soil or incineration.

Limitations to bioremediation

According to Zaib et al. 2023, a number of factors can limit the effectiveness of bioremediation, including: No organism is known to degrade all organic wastes, and contaminated sites usually contain mixtures of contaminants. High concentrations of the contaminant or component of a complex mixture may be inhibitory or toxic to microorganisms. Binding of the contaminant to soil may occur, reducing bioavailability, exacerbated by poor contaminant solubility and pollutant 'ageing' to recalcitrant by-products. Limited availability of electron acceptors, nutrients and co-metabolites

Applications of Bioremediation

Bioremediation is applied to address organic and inorganic pollution in diverse environmental matrices, including wastewater, soil, groundwater, and sediments. Heavy metals like lead (Pb), cadmium (Cd), chromium (Cr), and arsenic (As) are common water pollutants from industrial effluents. Bioremediation is used in waste water treatment plants and to clean up contaminated groundwater and surface water. Agricultural and industrial activities often lead to the accumulation of heavy metals and other inorganic contaminants in soil. Bioremediation techniques can restore the fertility and health of the soil. Acid mine drainage (AMD) is a significant environmental issue at mining sites, releasing heavy metals and sulfur into the environment. Bioremediation can be used to neutralize the acidity and immobilize the metals. Certain microorganisms can interact with and reduce the mobility of radionuclides, such as uranium, making bioremediation a potential strategy for nuclear waste management.

Challenges experienced with Bioremediation

Despite its promising advantages, several challenges hinder large-scale bioremediation. Pollutant Complexity where some organics (e.g., polycyclic aromatic hydrocarbons, synthetic dyes) are highly recalcitrant and resist microbial degradation. Another challenge is environmental dependence. The success depends on pH, oxygen, moisture, nutrients, and temperature. Suboptimal conditions limit microbial activity (Sanjana et al., 2024).

Incomplete degradation can occur sometimes where toxic intermediates (e.g., aromatic amines from dye breakdown) are produced (Bala et al., 2022). Another challenge is bioavailability where pollutants adsorbed in soils or sediments may not be accessible to microbes. Also, laboratory success does not always translate to heterogeneous field conditions. Further, ecological concerns due to use of genetically modified or introduced organisms may disrupt native ecosystems (Ali et al., 2023). Lastly, monitoring challenge due to difficulties in tracking degradation progress and ensuring pollutants are fully mineralized into safe end products.

Case Study 1: Bacterial Bioremediation of Textile Wastewater Using *Bacillus subtilis*

A study conducted in India examined the use of *Bacillus subtilis* for treating textile wastewater contaminated with azo dyes. The bacteria were isolated from effluent discharge sites and tested in bioreactors. Results showed that *B. subtilis* achieved over 80% decolorization of azo dyes within 72 hours, while also reducing chemical oxygen demand (COD) and biological oxygen demand

(BOD) significantly. The mechanism involved enzymatic degradation through azoreductases and laccases, which broke down complex dye molecules into less toxic metabolites. This case highlights the effectiveness of bacterial strains in degrading persistent organic pollutants in industrial wastewater (Ayilara & Babalola, 2023).

Case Study 2: Algal-Microbial Consortia for Municipal Wastewater Treatment

In a 2025 case study, researchers applied a *consortium of microalgae (Chlorella vulgaris)* and bacteria (*Pseudomonas aeruginosa*) to municipal wastewater treatment. The system was designed to integrate photosynthetic oxygen production by algae with bacterial degradation of organic matter. The consortium removed 95% of nitrogen and phosphorus and achieved over 90% pathogen reduction within 10 days. Additionally, the process generated biomass that could be reused for biofuel production. This case demonstrates the synergistic potential of algal-bacterial systems in nutrient removal, pathogen control, and resource recovery from wastewater (Sharma, et al., 2025).

Case Study 3: Chromium Remediation

A former industrial site in the UK, contaminated with hexavalent chromium (Cr^{6+}), was successfully remediated using biostimulation. By injecting a carbon source (molasses) into the groundwater, native bacteria were stimulated to reduce the highly mobile and toxic Cr^{6+} to the less toxic and insoluble Cr^{3+}. This process effectively contained the plume of contamination and significantly reduced the concentration of chromium (Lovley & Coates, 2000).

Two notable case studies from Nigeria demonstrate how microbial bioremediation is being investigated and applied in wastewater treatment, particularly in Abuja and northern Nigeria, to address heavy-metal and organic pollution. These studies highlight the potential use of bacterial strains and microbial consortia for contaminant removal.

Case Study 4: Heavy Metal Bioremediation at Wupa Wastewater Treatment Plant, Abuja

A notable case of microbial bioremediation in Nigeria was reported at the Wupa Sewage Treatment Plant in Abuja, where *Pseudomonas aeruginosa* and *Bacillus subtilis* were investigated for their potential to remove heavy metals from wastewater. The study focused particularly on toxic metals such as cadmium (Cd), lead (Pb), and copper (Cu). The bacterial strains demonstrated considerable biosorption and bioaccumulation capacities, indicating their ability to reduce the concentration of heavy metals in contaminated wastewater. *Pseudomonas aeruginosa* achieved up to 82% removal of cadmium, while *Bacillus subtilis* demonstrated significant efficiency in immobilizing lead and copper. These findings indicate that indigenous bacterial strains have considerable potential for application in wastewater treatment and could provide a cost-effective and environmentally friendly approach to heavy-metal pollution management in Nigeria (Faruok et al., 2023).

Case Study 5: Bioremediation of Industrial Wastewater in Northern Nigeria

Another important case of microbial bioremediation was reported in Northern Nigeria, involving studies conducted by researchers from Kano and Wudil and published in the *FUDMA Journal of Sciences* in 2025. The studies investigated the use of mixed microbial consortia, comprising bacteria and fungi isolated from local wastewater environments, for the remediation of industrial wastewater contaminated with xenobiotics, persistent organic compounds, and heavy metals. The microbial consortia demonstrated the ability to degrade complex organic pollutants and significantly reduce chemical oxygen demand (COD) and biological oxygen demand (BOD). The study also emphasized the importance of microbial processes such as biosorption and bioleaching in the removal of toxic compounds from wastewater. The researchers concluded that microbial bioremediation represents a sustainable alternative to conventional physicochemical treatment methods, particularly in resource-limited settings such as Nigeria, where affordable and environmentally friendly wastewater treatment technologies are highly desirable (Umar et al., 2025).

Current Trends and Future Prospects

Recent advancements in molecular biology and genetic engineering are shaping the future of bioremediation include genetic engineering where sientists are modifying microorganisms and plants to enhance their remediation capabilities. This includes engineering microbes to increase toxin tolerance or to express specific enzymes that transform pollutants more efficiently (Asem et al., 2023). CRISPR-Cas9 technology is also being explored for precision gene editing to create enhanced bioremediation strains. Another trend is the microbial consortia where iInstead of using a single species, there is a growing trend toward using microbial consortia that can work synergistically to address complex pollutant mixtures. This approach can be more robust and effective.

Further trends are nano-bioremediation which is interdisciplinary field combines nanotechnology and bioremediation. Nanoparticles may be used to deliver nutrients or microorganisms to specific contaminated areas or may themselves act as catalysts for pollutant transformation. The future of bioremediation lies partly in integrating biological treatment with physical and chemical methods. For example, highly contaminated wastewater may first be treated ex situ in a bioreactor before further biological treatment of residual pollutants.

The future of bioremediation for inorganic pollutants is promising, with a shift towards more targeted, efficient, and integrated solutions. Continued research into the complex interactions between organisms and contaminants, coupled with technological innovation, will be key to unlocking its full potential.

Conclusion

Microbial bioremediation offers a sustainable, cost-effective, and eco-friendly alternative to conventional physicochemical wastewater treatments, which are often constrained by high operational costs and secondary pollution. As demonstrated through mechanisms such as biosorption, bioaccumulation, biotransformation, and bioaugmentation, microorganisms possess remarkable metabolic versatility to degrade persistent organic pollutants, heavy metals, and emerging contaminants. Furthermore, integrating advanced biotechnologies including genetic enhancements and optimized bioreactor systems—continues to significantly improve treatment efficiency. Despite these advantages, large-scale implementation remains challenged by environmental variability, pollutant bioavailability limitations, and scale-up bottlenecks. Overcoming these hurdles requires continued interdisciplinary research bridging molecular biotechnology and environmental engineering. Ultimately, optimizing these biological pathways will be crucial for achieving global water sustainability, protecting public health, and restoring ecological integrity.

Authors' Contributions

Salim Dan Saidu Idris: Conceptualization, literature search, manuscript drafting, visualization, and final manuscript preparation. Abdulmajid Ahmad: Supervision, critical revision of the manuscript, and validation. Ibrahim Shafiu Muhammad: Literature review, and manuscript editing. Maryam Abubakar: Literature review, proofreading, and manuscript editing. Hassan Hafsat: Critical review, supervision, and final approval of the manuscript. All authors read and approved the final manuscript.

Acknowledgements

The authors sincerely acknowledge the support and encouragement of their respective institutions during the preparation of this manuscript. The authors also appreciate the researchers whose published works formed the basis of this review.

Competing Interest

There are no competing financial interest, personal relationships or affiliations that could have influenced the outcome of this experiment.

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