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Bioremediation Techniques for Water and Soil Pollution: Review

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Abstract

Bioremediation is a novel and, environmentally benign technology that employs biological microbes to reduce pollution. Waterborne contaminants are a group of common materials that can enter rivers through a variety of entrance points, such as wastewater, the surrounding environment, ship emissions, and other sources. The majority of these dangerous compounds are consumed by marine life, whereupon they bioaccumulate in their body tissues and spread along the food chain through a process known as biomagnification. These practices may adversely affect the physiological processes of organisms, and the biochemical systems present in organic environments, which may have unintended negative effects concerning the overall wellness of humans, and animals, alongside the natural world. This review delves into various hazardous materials including a broad variety of chemical pollutants: including heavy metals, pesticides, and microplastics. Given the harmful consequences these toxins exert on environmental integrity, human health, and financial stability, immediate remediation is necessary. This review article provides a comprehensive analysis of bioremediation techniques used to address contamination of both soil and, water, emphasizing the intricate relationships between populations of microbes, environmental variables, and remediation efficacy. Therefore, various bioremediation methodologies are illustrated focusing on employing microbes in the procedure and investigating various technologies implemented. Furthermore, the metagenomic approach's potential to improve the effectiveness of bioremediation was highlighted. Ultimately, it highlights the necessity of bioremediation as an answer to organic contamination of soil and presents an overview of the various strategies and technologies accessible. The importance of this review is to deal with the cause of pollution (hazardous materials) and the solution (bioremediation). The goal and originality of this review are to provide the scientific community with an understanding and resolution to this global concern. Bioremediation will become increasingly important in the coming century due to global warming, increased mass production, and population growth.

Keywords:

Bioremediation, bioaugmentation, heavy metals, biostimulation, microplastics, soil pollution.

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Introduction

Bioremediation encompasses a broad spectrum of environmental biotechnologies, requiring multidisciplinary approaches and the application of innovative tools to natural biological processes in soil, water, and air (Muter, 2023). As a cutting-edge and ecologically sustainable technology, bioremediation employs biological microorganisms to break down and neutralize pollutants (Foroutan et al., 2023). It is an economical, straightforward, and competent method of destroying contaminants. This technique is pivotal in removing environmental toxins, thereby restoring ecosystems to their natural state and preventing further contamination.

Contaminants can be used by bacteria as a source of nutrition or energy in their natural operations, which can lead to bioremediation of polluted water (Muter, 2023). Both native and imported species that are employed for bioaugmentation might be considered biodegradative microorganisms (Vij & Prashant, 2024). The Kashmiri proverb "It's simple to put nearly anything into a river, and extremely difficult to retrieve it again" highlights the importance of water and the desire to minimize contamination(Khyade, 2018). Because of the continual developments in many forms of civilization, industry, and growing urbanization, sustainability needs to be fostered in order to ensure that individuals live healthier lives that are longer and happier (Sharma et al., 2022). Long, healthy, and happy lives are at risk because of the numerous human activities that introduce pollutants—hazardous elements or substances—into our ecosystem (Goswami et al., 2022).

Adherence to environmental management guidelines is critical for promoting sustainable and improved living conditions (Hussain & Taimooz, 2024). Addressing these challenges necessitates pollution control and the development of innovative treatment technologies (Goswami et al., 2022). As economies expand and countries industrialize, pollution is expected to rise (Malik, 2022; Sharma et al., 2021). According to UN-Water, issues related to polluting substances and their impact on water quality management are likely to intensify due to insufficient data, (Wang et al., 2024). Without proactive measures, water quality will continue to degrade, posing increased risks to human well-being, ecosystems, and sustainable development (Malik, 2022; Sharma et al., 2021).

While various remediation technologies have emerged, they differ in their applications and outcomes. Physicochemical treatments are fast and efficient but are often expensive, labour-intensive, and can disrupt soil functionality (Gladkov & Gladkova, 2021). On the other hand, biological treatments like bioremediation are environmentally friendly and enjoy greater social acceptance (Agarwal & Yadhav, 2023). They do not unintentionally harm the local wildlife, plants, or natural materials (Orhorhoro et al., 2016). A range of bioremediation strategies exists, involving on-situ and ex-situ techniques tailored to specific contamination patterns and ecological conditions (Sharma et al., 2021; Goswami et al., 2022).

For instance, bioaugmentation involves introducing exogenous microbial inoculants to enhance substrate specificity or accelerate degradation (Goswami et al., 2022). In contrast, biostimulation modifies environmental conditions, such as redox potential or nutrient availability, to stimulate the activity of native microorganisms (Raeisi, 2017).

Given these insights, this study will explore the following research questions through a comprehensive literature review:

1. What are the hazardous materials and their consequences effect?

2. How does the combination of pollutants affect the environment?
3. What are the bioremediation approaches, their drawbacks, and possible recommendations?

Understanding Soil and Water Pollution

Soil is a great source of nutrients and also serves as a natural filter of water. Soil pollution refers to the contamination of soil by waste products at higher-than-normal quantities, which has adverse impacts on the natural world and human health. Soil is essential to health in a variety of ways. Soil crops provide for almost 78% of worldwide per capita calorie consumption, with the remaining 20% coming from terrestrial food sources that rely on soil indirectly (Usman et al., 2023).

Pollutants in the soil and water can cause complicated and varied environmental issues when they enter aquatic and terrestrial ecosystem. These pollutants are produced by a wide range of human activities, including production, waste disposal, mining, farming, increasing urbanization, and transportation (Pimenov et al., 2022). Numerous chemical, physical, and biological pollutants are introduced into water and soil ecosystems on account of these operations, endangering the individual's well-being, ecosystem wellness, and biodiversity (AbuQamar et al., 2024).

2.1 Pollutant Types and Sources

Water and soil can get contaminated by several kinds of sources, both point and non-point. Airborne pollutants remain discharged into the natural world at their isolated sources, including chemical spills, dangerous waste dumps, treatment facilities for wastewater, and industrial exhaust pipelines.

On the other hand, diffuse inputs, which involve the dispersal of pollutants across large areas through a variety of pathways, are instances of non-point sources. These involve urban rainwater runoff, runoff from agriculture, air depositing, and contamination of groundwater, therefore, non-point source pollution is more difficult to control than point source pollution.

Mutually the water and soil include a wide range of contaminants, from chemical substances and harmful heavy metals to infections caused by microbes and recently identified toxic substances (21 Heavy metals for example lead, mercury, arsenic, cadmium, nickel, and chromium can be released by standard industrial processes such as extraction, melting, metallic plating, and waste annihilation (Lee et al., 2024). Because of the metals' propensity for bioaccumulation and biomagnification, they pose a threat to ecosystems and humans alike. They persist in the environment and can accumulate in soil and sediment ecosystems (Wang et al., 2024).

The chemical substances known as organic contaminants include pesticides, herbicides, chlorine-based chemical solvents, chemicals used in manufacturing, household products, and polycyclic aromatic hydrocarbons (PAHs) (Patel et al., 2020). These compounds remain hazardous to wildlife, humans, likewise aquatic life because they can linger in the environment for an extended amount of time. They come from domestic products, medications, agricultural practices, and industrial operations.

Microbial pollutants (protozoa, viruses, bacteria, and helminths) can contaminate soil and water by a variety of means, including waste from animals, sewage generated, runoff from agriculture, and faeces. These microbes increase the likelihood of contracting waterborne diseases, especially in places with poor sanitation infrastructure and management of water quality. These illnesses include gastroenteritis caused by viruses, typhoid fever, cholera, dysentery, giardiasis, and cryptosporidiosis.

There has been interest in the possible harm that a new class of pollutants known as novel pollutants might contribute to the natural environment and the public's health. Medication, microplastics, flame-resistant nanotechnologies, endocrine-disrupting chemicals (EDCs), and per- and polyfluoroalkyl substances (PFAS) are a few of these pollutants. It can be necessary to employ innovative strategies when recently found contaminants evade the detection, evaluation, and remediation techniques used in traditional monitoring programs.

2.2 Hazardous Materials and Their Impacts

Waste, particularly hazardous waste, is one of the priority areas for the Member States of the World Health Organization (WHO) Regional Office for Europe and was on the agenda of the Sixth Ministerial Conference on Environment and Health (Sharma et al., 2021). The pollutants could be categorized into three groups: inorganic Pollutants: Heavy metals (e.g., lead, mercury), nitrates, and phosphates, emerging Pollutants: Pharmaceuticals, personal care products, and microplastics, and organic Pollutants: Pesticides, hydrocarbons, and industrial solvents,

2.2.1 Inorganic Pollutants: Heavy Metals

Human activities continue to release a significant amount of pollutants, including heavy metals, into ocean waters (Usman et al., 2023), which is a very severe issue. Examples of human-caused metal sources encompass metropolitan runoff, automobile emissions, sewage, burning oil and coal, mining, industrial output, and ore melting (Usman et al., 2023). Marine animals consume food that contains heavy metal ions, and prolonged exposure to metallic materials at quantities beyond the threshold can be fatal. Many xenobiotics, including heavy metals (Wang et al., 2024), can have long-term effects that are not immediately noticeable, such as modifications to cellular and molecular reactions. Ecosystems appear to be significantly impacted by these changes. ((Wang et al., 2024).

One of the effects that has drawn the greatest study focus is oxidative stress. This is because being exposed to heavy metals (Ali et al., 2022) causes the production of Reactive Oxygen Species (ROS) (Ahmed et al., 2020). Recent studies show that the naturally occurring antioxidant enzyme metabolism of Mozambican tilapia (Oreochromis mossambicus) was altered when administered selenium. Metallothioneins (MT), Catalase blocking (CAT), Glutathione Peroxidase (GPx), Glutathione Reductase (GSH), Superoxide Dismutase (SOD), and Glutathione Reductase (GSH) had been among the antioxidant-producing digestive enzymes that showed elevated levels in the fish's liver and gills. These substances affect invertebrate species' metabolism and neurological systems since pollution-induced stressors modify their state of equilibrium (Lee et al., 2024; Gopi et al., 2021).

2.2.2 Emerging Pollutants: Micro/Nano Plastics

Microplastics are defined as particles of plastic and fragments that are smaller than 5 mm There are main and secondary sources for micro/nano plastic particles. The main types of microplastics originate from both residential and industrial sources, including laundry fibres along with personal hygiene products like toothpaste, shower gels, and shampoos. Macroscopic marine plastic waste breaks down into secondary microplastics. Waste appears to remain the primary basis of subordinate microplastics (Osman et al., 2023) along with fibres and plastic derived from organic materials (Ahmed et al., 2020).

2.2.3 Regarding Compounds in Personal Care Products

In addition, personal care products are one of the main sources of micro and macroplastics they contain other compounds that may be hazardous to the environment, which are used daily nowadays (Pimenov et al., 2022). These products have antimicrobial and antifungal ingredients that can build up globally if they get into water bodies. Triclosan is a prevalent organic micropollutant in aquatic systems worldwide. It is an antibacterial molecule found in soapy items, deodorant products, and gel showers (Pimenov et al., 2022). Because wastewater treatment plants use it extensively and only partially remove it, it can be found in sediments, surface water, and wastewater treatment facility effluents (Pimenov et al., 2022). The range of its average concentration is 0.0075 µg/L to 9.65 µg/L. Triclosan caused paralysis in numerous fish larval stages, for example, Cyprinus carpio(Pimenov et al., 2022), Labeo rohita, Ctenopharyngodon idella, and Cirrhinus mrigala , most likely because of oxidative stress-induced modifications in biochemistry and transcriptomic. Irregularities in the kidney and digestive system's function as usual (Wang et al., 2024), and impairment of typical metabolic functions.

2.2.4 Organic Pollutants: Insecticides

Pesticides are used primarily in agriculture, and they can affect aquatic life in both biological & ecosystem ways (Ahmed et al., 2020). These materials possess the ability to change behavior and decrease existence rates (Koyama et al., 2024).

Pesticides that are classified as herbicides are frequently used to manage the growth of algae. When heavy rain falls suddenly in the summer, unchecked algal development can obstruct water flow and cause flooding. Although the goal of these compounds is to decrease macrophytes (Lau & Hanson, 2023), They affect animals that are not targeted as well. They lose their habitat as well as their food. These surplus nutrients have the potential to cause huge algal blooms, which rob water of oxygen essential to marine life (Brêda-Alves et al., 2021).

2.3 The Pollutants' Combination Response

How several toxicants work together to impact animals and ecosystems is one element of pollution that has yet to receive enough attention (Evalen et al., 2024). The study of how pollutants interact in soil and water environments is crucial to comprehend their combined effects, which can be significantly different from their individual impacts. For instance, there are numerous research conducted on the issues brought on by the concurrent use of organochlorine insecticides & Polychlorinated Biphenyls (PCBs), a family of hazardous chemicals categorized through their biological & chemical steadiness (De Rosa et al., 2022). It has been noted that renal changes are caused by the combined effects of the two toxicants in crucian carp in their waters (Carassius carassius) (De Rosa et al., 2022).

The Bioremediation Theory

Bioremediation is an increasingly effective and environmentally friendly way to remove pollutants from the surrounding environment. This approach to getting rid of threatening contaminants is usually more affordable. A modern, optional method of controlling environmental contamination is called "bioremediation" (Koyama et al., 2024). Utilizing microbes' byproducts, different chemical wastes as well as hazardous substances are broken down, removed, immobilized, or detoxified from the surrounding environment (Atli & Sevgiler, 2024). Yeast, actinomycetes, fungi, and bacteria are examples of biological organisms that can be utilized in bioremediation to lessen or completely eradicate contamination (Dinakarkumar et al., 2024). Three basic components are needed for bioremediation (Kumar & Singh, 2024). Food, vitamins, and nutrients, & microbes are all three components (Evalen et al, 2024; Kumar & Singh, 2024). These three crucial components comprise the bioremediation triangle (Evalen et al., 2024).

Lack of nourishment and food is the most frequent missing element preventing successful bioremediation. Microorganisms get their nourishment from the soil or water in which they dwell. On the other hand, if pollutants are present, it can provide the microbes with another source of food. Two beneficial functions are fulfilled by the contamination of the bacteria ((Evalen et al., 2024; De Rosa et al., 2022). A supply of carbon, a substance necessary for growth, is first and foremost provided by pollution. Furthermore, to acquire energy, the microorganisms split chemical bonds and move electrons away from the pollutant. The term "oxidation-reduction" refers to this kind of reaction (Kuppan et al., 2024).

Environment-related organisms and contaminants are the three key components of bioremediation, and their many interactions are essential (Kuppan et al., 2024). Biodegradability, bioavailability, and physiological needs are all impacted by the interplay between these parameters and are crucial considerations when evaluating the feasibility of bioremediation (AbuQamar et al., 2024). The following are the key elements influencing the biodegradation procedures:

Contaminant Bioavailability

The bioavailability of a contaminant can be changed by its interactions with the environment, which can impact the accessibility it becomes to species that can degrade it. Depending on the kind of species and organism, a pollutant's degree of freedom to enter or adhere varies, which is defined as bioavailability. The process by which bacteria degrade organic pollutants in situ is dependent on the bioavailability of the organic pollutant & the catabolic activity of the microorganism (Fouad et al., 2022). Environmental factors that affect bioremediation include salinity, pH, pressure equal to oxygen, the outside temperature, water activity, vitamins and minerals, & moisture availability. These variables differ from location to location and function to limit the development of microorganisms that degrade pollutants. In unfavorable conditions, bacteria either develop slowly or die, leaving contaminants unremoved. Pollutant removal and microbial decomposition are influenced by the availability of nutrients. This includes the direct inhibition of the development process and the enzyme production of those living things that degrade pollutants. (Aziz et al., 2024). The soil's microbial population's ability to degrade contaminants depends on the number of microorganisms present and their overall catabolic potency (Atli & Sevgiler, 2024).

Metagenomic Approach To Biological Remediation

Genomic analysis is a rapid method for studying any material, including soil or water, that doesn't require a culture in order to advance sequencing technology. Next-Generation Sequencing (NGS) has been developed in recent decades (Atli & Sevgiler, 2024) , which enables the use of genomic, metagenomic, and bioinformatics technologies for the thorough research of microbial communities (Atli & Sevgiler, 2024). As a result, initially, unobtainable insights into the fundamental procedures underlying bioremediation were obtained. Nucleotide databases and silico approaches can be a tremendous help in research on how microorganisms help reduce pollution and uncover novel genes involved in microbial remediation (Atli & Sevgiler, 2024; Dinakarkumar et al., 2024).

When analyzing the relationship between soil microbes and ecological endeavors, metagenomics studies are a priceless means for graphical and analytical assistance in addition to offering new insights into the intricacies of the impacted region (Kumar & Singh, 2024). The genetic material extracted directly from samples from the environment is examined using a technique called "metabolomics" (Kuppan et al., 2024; Fouad et al., 2022). Thus, metagenomics uncovers details on the microbial communities of non-cultivable species in a niche habitat by employing sequence- and function-based research approaches.

Fermentation-Based Bioremediation

Fungi are known to decompose the majority of organic substances that are present in the environment. Additionally, bioremediation employing fungi is preferable to bioremediation employing bacteria due to their adaptability, diminishing enzymatic capabilities, and ability to function in a broad range of pH levels (Dinakarkumar et al., 2024). Fungal species, including those belonging to the White-Rot Fungi (WRF) family, have been used in soil and water bioremediation process systems since the 1980s. Consisting of an eco-physiological class of fungi that can break down lignin (Dinakarkumar et al., 2024), basidiomycetes constitute the majority of the WRF. This fungus group's Lignin-Modifying Enzymes (LME) are what break down wood and give lignin its characteristic breakdown. Since oxidoreductase enzymes are used by LME to chemically modify xenobiotic substances, WRF fungus is primarily responsible for the biodegradation of pharmaceutical company’s compounds. Because of the variation and non-specificity of WRF enzymes, these enzymes may be helpful tools for the biological remediation of antibiotics as a medication. (Dinakarkumar et al., 2024)

Microalgae-Based Bioremediation Technique

The capacity of microalgae to harness solar energy for biomass production while absorbing nutrients such as phosphorus and nitrogen, which aid in nutrient enrichment during photosynthesis, renders them especially beneficial for bioremediation (Tanvir et al., 2021). Because of their exceptional ability to absorb inorganic nutrients, microalgae are a cost-effective and efficient way to remove excess nutrients and contaminants from tertiary effluent. They can also produce biomass that could have market value (Amaro et al., 2023). Lately, certain studies have been conducted on the viability of employing microalgae-based bioremediation methods to eliminate microplastics from wastewater, and the resultant findings indicate that this approach offers numerous benefits, including efficient microplastic removal, lowered energy and operational costs, nutrient recovery from wastewater, and reduced environmental risks associated with microplastics compared to traditional methods. (Usman et al., 2023). For instance, Scenedesmus abundans was able to effectively eliminate polystyrene, polylactide, and poly(methyl methacrylate) microparticles, achieving removal efficiencies of 84%, 87%, and 98%, respectively.

Microbe-Based Bioremediation

The main source of energy for cell growth, CO_2 and H_2O, as well as metabolic intermediates, are produced when microbes mineralize some organic pollutants (Dinakarkumar et al., 2024). Microbes keep up a dual protection mechanism via:

(i) Producing enzymes that break down the specific contaminants; and
(ii) Preventing the relevant heavy metals from existing.

By binding heavy metals through volatilization, oxidation, transformation, and immobilization, microorganisms play a variety of roles in environmental replenishment (Kumar & Singh, 2024). Bacteria have evolved ways to use electron acceptors, including ferric ions, nitrates sulphate, and others to derive energy from almost any substance, both under aerobic and anaerobic circumstances (Aziz et al., 2024). The wide range of microorganisms involved in the aerobic degradation of xenobiotic contaminants is impressive in Table 1 (Dinakarkumar, et al., 2024).

Table 1. Typical instances of microorganisms that are engaged in xenobiotic chemical bioremediation

Xenobiotic compound group	**Name of xenobiotic pollutants**	**Degrading microorganisms**	**Ref.**
Aromatic hydrocarbon polycyclic elements	Naphthalene	*Pseudomonas putida*	(Wang et al., 2024)
	Pyrene	*Mycobacterium PYR-1*	(Lee et al., 2024)
	2,3,4-Chloroaniline	*Pseudomonas sp.*	(Gopi et al., 2021)
Pesticide compounds	End sulphate compounds	*Arthrobacter sp.*	(Osman et al., 2023)
	Endosulfan compounds	*Mycobacterium sp.*	(Osman et al., 2023)
	DDT	*Dehalospirilum sp.*	(Koyama et al., 2024)
	2,4-D	*Alcaligenes sp.*	(Koyama et al., 2024)
Halogenated organic elements	Vinyl chloride	*Dehalococcoides sp.*	(Lau & Hanson, 2023)
	PCE	Dehalococcoides entheogens 195	(Brêda-Alves et al., 2021)
	Atrazine	*Pseudomonas sp.*	(Evalen et al, 2024)
	PCB	*Rhodococcoides* RHA1	(De Rosa et al., 2022)
	Dioxins		
	Benzene	*Dehalococcoides sp.*	(AbuQamar et al., 2024)
		Dechloromonas sp.	(AbuQamar et al., 2024)
	Azo dyes	*Pseudomonas sp.*	(Atli & Sevgiler, 2024)
		Shingomonas sp.	(Dinakarkumar et al., 2024)
		Xanthomonas sp.	
	Petroleum products	*Achromobacter sp.*	(Kumar & Singh, 2024)
		Micrococcus sp.	
		Bacillus sp.	
		Flavobacterium sp.	

Certain nutrients that encourage the growth of beneficial bacterial species or the addition of terminal electron acceptors/donors can be added to these microorganisms to improve their growth and biodegradative capabilities. The stimulated microbial populations can change organic and inorganic pollutants into less dangerous or non-hazardous forms through oxidation or reduction. Frequently (Ancona et al., 2024), a group of microorganisms consisting of bacteria, yeast, and fungus carry out these procedures one after the other.

These microbial communities' genetic design enables the simultaneous biodegradation, biotransformation, biosorption, and bioaccumulation of pollutants. Genetic manipulation of metabolic and/or regulatory genes can further augment these natural capacities (Malik, 2022). Bacteria that are resistant to heavy metals and possess the enzyme S-adenosylmethionine methyltransferase (ArsM) may methylate harmful inorganic arsenic (III) into less harmful arsenic (V). By introducing ArsM overexpression into strains by genetic engineering, arsenic volatilization may be enhanced nine times (Ancona et al., 2024). Even though this method hasn't been used to treat arsenic-contaminated water yet, the results of the laboratory investigation offer encouraging information for dealing with arsenic-contaminated surroundings.

Among the various bioremediation methods discussed are ex-situ techniques, which involve the removal and treatment of contaminated materials in a controlled lab environment, and in-situ techniques, which address pollutants directly in their original surroundings (Ali et al., 2022). Bio-stimulation strategies modify environmental factors (e.g., redox conditions, nutrition supply) to boost the activity of native microbes, while bio-augmentation methods employ external microbial inoculation to enhance degradation rates or broaden substrate specificity (Davidson et al., 2021).

Bioremediation Methodologies

The word "bioremediation" describes a collection of several techniques that use the metabolic abilities of microorganisms to break down, modify, or sequester pollutants in contaminated settings. These tactics provide sustainable, cost-effective, and ecologically advantageous options to traditional remediation procedures by utilizing natural processes to clear up soil and water contaminants. The type of pollution, the characteristics of the site, the surroundings, and any relevant laws all have an impact on the selection of a method of bioremediation. The following are some of the most significant bioremediation techniques for removing pollution from soil and water:

- ***Bioaugmentation***

Adding specialized microbial cultures or microbial consortia to polluted environments can increase their capacity for breaking down pollutants. Certain naturally occurring microorganisms that degrade pollutants or strains of bacteria with genetic modifications that have been optimized for specific pollution could be microbial inoculants (Aziz et al., 2024) Bioaugmentation accelerates the breakdown rate of pollutants and improves the efficacy of remediation by introducing substantial amounts of decomposing organisms to the already existing microbial communities. Common applications for bioaugmentation include soils polluted with hydrocarbons, industrial wastewater, and petroleum leaks.

- ***Psychostimulant***

By giving electron-accepting co-substrates—basic nutrients required for the breakdown of pollutants—native microbial communities are kept alive through the process of biostimulation. This approach speeds up the removal of contaminants by enhancing microbial activity and the metabolic pathways associated with pollutant biodegradation. Additives including biological substrates (molasses, compost), inorganic elements (phosphorus, nitrogen), electron-accepting materials (nitrate, oxygen), or surfactants can be used in biostimulation techniques to increase the bioavailability and solubility of pollutants.

- ***Phytoremediation***

In phytoremediation, plants and the rhizospheric bacteria that live in them absorb, collect, or decompose contaminants from soil, water, or sediments. Plants absorb pollutants by the roots and transfer them to tissues above ground, which may undergo volatilization, metabolization, or sequestration. Common selections for phytoremediation include hyperaccumulators for metals (such as *Brassica juncea* for cadmium and *Alyssum spp.* for nickel) and rapidly spreading species for organic pollutants (like willows and poplar trees for PAHs and hydrocarbons).

- ***Rhizoremediation***

Rhizoremediation is a method of treating soil that increases microbial activity in the root zone—the portion of the soil that is impacted by the roots—to break down or detoxify contaminants (Wang et al., 2024). Rhizospheric microorganisms obtain their carbon and energy from various organic materials emitted by plant roots, including carbohydrates, amino acids, and organic acids. Additionally, rhizoremediation promotes the development of microorganisms that degrade pollutants in the vicinity of the roots, enabling them to metabolize pollutants and expedite the processes of soil biodegradation. This method is particularly effective for organic pollutants present in soils and particulate matter, including chemical pesticides, polychlorinated biphenyls (PCBs), and hydrocarbons from petroleum.

- ***Mycoremediation***

Mycoremediation breaks down refractory organic pollutants and xenobiotic substances in polluted environments by using fungi, primarily fungi with white rot. Comprising of the enzyme laccase, manganese peroxidase, and polyphenol peroxidase, extracellular ligninolytic enzymes generated through the white-rot fungus facilitate the breakdown of complicated aromatic substances present in contaminants including dioxins, PAHs, and PCBs. Mycoremediation appears to have potential applications in a range of contexts, such as commercial locations, fields of agriculture, and treatment plants for wastewater.

- ***Microbial Fuel Cells (MFCs)***

MFCs use a combination of electrochemical and microbial metabolic processes to produce power while decomposing organic contaminants. In MFCs, negative electrons from the oxidation of organic substances are transferred to the outer layer of the electrode by electrochemically aggressive microbes such as Shewanella and Geobacter organisms, which generate a current of electricity. This direct transfer of electrons technology breaks down organic contaminants such as organic detritus present in wastewater, while producing sustainable energy. MFCs are useful for subsurface remediation, treatment of wastewater, and the creation of environmentally friendly power since they provide the dual advantages of pollution elimination and generating electricity.

Challenges and Limitations of Bioremediation

Bioremediation offers a feasible way to clean up the environment, but there are a lot of barriers and limitations that might keep it from being extensively applied and working well. The complexity of the contaminants, the condition of the environment, the limitations of microorganisms, and technological constraints are some of the factors that contribute to these challenges (Davidson et al., 2021; Amaro et al., 2023). Pollutant complexity is a major barrier against the prosperous implementation of bioremediation. The nature of pollutants present in soil and water environments varies greatly in terms of their chemical makeup, toxicity, permanence, and bioavailability (Tanvir et al., 2021). Certain pollutants are resistant to degradation, such as polycyclic aromatic hydrocarbons (PAHs) & solvents that are chlorinated, and their cleanup requires certain enzyme systems and metabolic pathways .

Moreover, complex mixtures of pollutants may complicate bioremediation processes and necessitate specialized methods for effective cleanup. The effectiveness of bioremediation procedures is significantly influenced by the surrounding environment. The temperatures, water content, potential for redox reactions, pH (Haque & Gazi-Khan, 2025), and nutrition availability are some of the factors that have a significant impact on microbial activity & pollutant breakdown rates. Extreme environmental factors, for example, anaerobic environments, extremely elevated levels of dangerous metallic substances, or saline or acidic environments, can hamper microbial development and metabolic processes and restrict the effectiveness of bioremediation.

Different rehabilitation outcomes may arise from variations in the natural environment that impact the dynamics of communities of microbes and their metabolic processes. One challenge in bioremediation is the sluggish rates of pollutant breakdown caused by microorganisms. Some contaminants may not degrade fast, particularly those that are resilient to degradation (Davidson et al., 2021). This could result in longer remediation times as well as increased costs and durations for bioremediation projects. Furthermore, the continued presence of some poisons in the environment may require ongoing oversight and management to ensure complete cleanup and prevent recontamination from Nutrient limitations in bioremediation methods (Tanvir et al., 2021) may restrict microbial activity & breakdown of pollutants.

Access to essential nutrients like carbon, phosphorus, nitrogen, and trace metals is a typical restriction on microbial development and metabolic processes (Tanvir et al., 2021). More nutrient inputs may be required to enhance microbial activity and expedite bioremediation processes, even though doing so can result in eutrophication, algal blooms, as well as undesirable effects on the environment.

Opinions and Improvement for Future Bioremediation

The area of bioremediation processes has a bright future that awaits it as scientists and industry practitioners keep looking at cutting-edge methods and technologies to manage environmental pollution more effectively and sustainably. There are new opportunities to enhance the efficiency, versatility, and applicability of bioremediation techniques due to advancements in the domains of the field of biotechnology the ecology of bacteria, omics technologies, and nanotechnology (Amaro et al., 2023). Numerous noteworthy advancements and trends are influencing the direction of bioremediation in the future, including:

1. **Synthetic biology and microbiology:** The field of bioremediation is undergoing a revolution thanks to advancements in synthetic biology & microbial engineering, which have enabled the creation and enhancement of strains of bacteria with enhanced degrading capabilities (Grifoni et al., 2022).
2. **Biology of systems and omics technologies:** The integration of biological systems approaches with omics technologies—transcriptomics, metagenomics, proteomics, metabolomics, & genomes—is enhancing our understanding of microbial communities and their roles in bioremediation activities (Grifoni et al., 2022).
3. **Nanotechnology for Bioremediation:** Nanomaterials can be employed as carriers to promote microbial activity, immobilize enzymes, and make it easier for contaminants to be absorbed and broken down (Aziz et al., 2024). Nanoparticles are nanofibers, & nanocomposites are a few examples of these sorts of materials (Dinakarkumar et al., 2024).
4. **Designing Microbial Consortiums and Bioaugmentation:** To increase the effectiveness of bioremediation and accelerate the rate at which pollutants degrade, the application of exogenous microbial inoculants, also known as "bio augmentation," in polluted environments is gaining popularity (Tanvir et al., 2021). Engineered microbial consortia are designed to eliminate certain pollutants by metabolic pathway optimization and the mutually beneficial interactions of specialized degraders, syntrophic partners, and co-cultured species (Amaro et al., 2023).
5. **Plant-Microbe Interaction and Phytoremediation:** Phytoremediation, the process of treating Migration Letters-contaminated waters and soils using plants and related bacteria, is evolving as a result of developments in plant the field of biotechnology microbiome the field of engineering, and soil-plant-microbe interactions (Grifoni et al., 2022).
6. **Integrated and Sustainable Remediation Techniques:** Integrated remediation frameworks—like bio-stimulated natural and attenuation bio electrochemical in nature systems, and phytotechnology—combine biological, chemical, or physical processes to maximize the efficacy of pollutant removal, mitigate unfavorable impacts on the environment, and promote ecosystem recovery

Research Method

The review article's approach includes a careful and methodical evaluation of the literature to gather the most recent findings and state-of-the-art information on bioremediation techniques for lowering water and soil pollution (Postigo et al., 2021). A comprehensive search of electronic databases was conducted utilizing a multidisciplinary approach, covering PubMed, Scopus, Web of Science, Google Scholar, and specialized environmental science databases. A broad spectrum of terms and controlled phrases from the vocabulary were employed, such as "microbial deterioration," "bioremediation processes," "bio enhancement," "biological stimulation," "microbial fuel cells," "contaminant elimination," "pollutant fate," and "environmental microbiology," to ensure the regaining of relevant literature.

3.1. Data Collection and Fusion

It took a thorough search to locate academic resources on environmental microbiology in addition to bioremediation, including papers, books, conference proceedings, and peer-reviewed publications. Relevant information regarding bioremediation techniques, microbiological mechanisms, types of pollutants, environmental factors, case studies, and technological progress was gathered from a variety of thoroughly researched literary sources.

3.2. Integration of Results

The findings from the literature review were brought together and honed to tell a coherent tale that highlights the most current developments in the field of bioremediation . Priorities included understanding the major processes of microbial-driven pollutant deterioration, evaluating the efficacy and limitations of different bioremediation strategies, and figuring out what influences bioremediation efficiency (Ahmed et al., 2020).

3.3. Ethical Aspects

Upholding standards of academic credibility, openness, and accountability was necessary to guarantee that ethical concerns were given the utmost significance throughout the research procedure.The literature has been presented fairly and impartially, free from bias or inappropriate influence from other sources. Privacy, anonymity, and intellectual property rights were upheld throughout the whole data collection, processing, and dissemination procedure.

A Comparative Study

Understanding the interaction of pollutants interfering with the nature of water and soil is essential for mitigating their environmental and human health risks. Combined pollutant effects, such as those seen in the lower basin of the Llobregat River, highlight the need for comprehensive monitoring. A study conducted in the Llobregat River Lower basin employed a combination of pesticide occurrence patterns and stable isotope analyses to identify pollution sources. In this study, surface water contamination was primarily attributed to urban and industrial activities, while groundwater quality was influenced by both urban and agricultural pollution sources. In soil, heavy metals like lead and organophosphate pesticides reduce microbial diversity and enzyme activity, leading to diminished fertility and impaired crop growth. The combination of inorganic fertilizers and heavy metals exacerbates this issue by suppressing soil microbial activity, disrupting essential biochemical reactions critical to productivity. This comprehensive approach exemplifies investigative as planned in the Water Framework Directive. The research focused on combining data gathered from various sources to identify the source of two primary water pollutants, specifically nitrogen nutrients and pesticides, in a river basin experiencing multiple stresses (Postigo et al., 2021).

The co-presence of heavy metals and organophosphate pesticides in agricultural soils can adversely affect microbial diversity and enzyme activity, leading to reduced soil fertility and impaired crop growth. Research has shown that heavy metals like lead (Pb) diminish soil nutrients, microbial diversity, and overall fertility (Postigo et al., 2021). Additionally, the combined presence of inorganic fertilizers and heavy metals has been found to suppress soil microbial activities, further impacting soil health. These combined effects can disrupt essential soil biochemical reactions, resulting in decreased soil fertility and hampered crop growth.

Understanding these interactions is crucial for developing sustainable agricultural practices that maintain soil health and productivity. Due to the adverse effects of pollutants alone or combined with other pollutants, finding effective and sustainable approaches is crucial. Therefore bioremediation, bioaugmentation, and biostimulation approaches are discussed to address and evaluate them in the following paragraphs.

Evaluating how efficiently different bioremediation approaches break down hydrocarbon contaminants in soil was evaluated through three distinct therapies assessed: a control group that did not receive any additional therapies, bioaugmentation utilizing a cluster of microbes that decompose hydrocarbons, and biostimulation utilizing organic additives. The effectiveness of each approach was likely assessed by measuring the concentration of hydrocarbons before and after treatment, evaluating microbial population dynamics and enzyme activities to gauge how actively microbes were breaking down hydrocarbons, and assessing factors like pH, organic matter content, and nutrient levels to ensure the methods did not adversely impact soil quality(Ahmed et al., 2020).

While bioaugmentation strategies reported in various research can be replicated, it is crucial to keep in mind that they are not always comparable owing to variations in the experimental design, soil, feedstock, composition of water, measurement units, inoculum physiological state, etc. However, selecting the best course of treatment should benefit from thorough evaluations of diverse bioaugmentation trials. The dosage ratio and timing of administration greatly influence the bioaugmentation system's functional flora's capacity for coordination and adaptation. (Ancona et al., 2024) has detailed the dosing methodologies for the bioaugmentation of wastewater (WW) used in seafood processing by artificially produced mixed bacterial systems in a sequencing batch bioreactor. A total of eight hours were spent operating the reactor, which included five minutes for settling, five minutes for decanting (with a volumetric exchange percentage of 50%), five minutes for flopping, 105 minutes for anaerobic reaction, and 360 minutes for anaerobic reaction.

The success of bioaugmentation depends on factors like dosage ratios and timing, which critically impact microbial functionality and pollutant removal. Due to the addition of a bacterial agent as a dosage ingredient in the batches (supplementing 2.5% on day 1 and day 10, respectively), the elimination of NH4+-N and total nitrogen of seafood processing WW increased significantly in the winter, from 66 89% and 52.77% to 79 0.02% and 69.97%, respectively (Ancona et al., 2024). Furthermore, the rate at which anaerobic digestion happens is influenced by the dosage of bioaugmentation. Therefore, it was discovered that the optimal dose was 0.27 gVS bioaugmentation seed/gVS chicken dung. This might be used to either rapidly start-up or improve a current fermentation process used to treat chicken feces. Higher dosages of 0.34 g VSBS/g VSCM did not significantly increase the bioaugmentation efficiency. The findings of that study emphasized the importance of dosage ratio and timing that affect the results.

Bioremediation techniques, including bioaugmentation and biostimulation, offer promising solutions to address these challenges. Bioaugmentation employs targeted microbial inoculations, such as Methanosarcina thermophila or exogenous activated sludge, to enhance pollutant degradation A comparison was done by (Alori et al., 2022) between the outcomes of anaerobic digestion of food waste employing *Methanosarcina thermophila* alone and in conjunction with biochar. Particularly, 10% v/v of the microorganisms developed on biochar (1 g/L) were fed during reactor setup; in normal bioaugmentation, the same amount of supplements was provided throughout ten feeding cycles. The best regular reactor had 37% greater yield, whereas the top single reactor had 32% more yield. This approach has been shown to improve nitrogen removal efficiency by 15–35% and achieve hydrocarbon degradation rates of up to 90%. (Ahmed et al., 2020) demonstrated enhanced biomethane production when *Methanosarcina thermophila* was bioaugmented with biochar as a growth support particle. (Ahmed et al., 2020) Examined food waste digestion supplemented with Methanosarcina thermophila grown on biochar support particles, showing substantial yield improvements. Also, highlights the effectiveness of employing biochar as a support medium for Methanosarcina thermophila. The findings underscore that bioaugmentation with biochar-grown Methanosarcina thermophila significantly enhances methane yields and system stability. This approach optimizes the microbial community structure and bioavailability of substrates, demonstrating its potential to improve the efficiency and sustainability of food waste anaerobic digestion processes under thermophilic conditions. These findings validate the potential of biochar-mediated bioaugmentation to improve the efficiency, stability, and sustainability of food waste anaerobic digestion processes.

Researchers (Davidson et al., 2021) examined the effects of bioaugmentation with external active sludge on the nitritation anammox procedure in the sequencing of the batch reactor. Two methods of bioaugmentation were studied: adding exogenous sludge either instantly following the anammox-activated sludge inoculation or after nitrogen removal had stabilized. The scientists observed that bioaugmentation had a favorable impact when employed either at the bioreactor's beginning (a 15% rise in nitrogen RE) or afterward its longstanding process (a 21–35% increase in nitrogen RE); nevertheless, it had a short-term effect and should be used sparingly (Davidson et al., 2021). However, the benefits were transient, indicating that bioaugmentation should be strategically implemented for short-term enhancements rather than as a continuous treatment (Pimenov et al., 2022) highlighted the positive effects of bioaugmentation with nitrifying bacterial communities on nitrogen removal efficiency in sequencing batch reactors. That study underscores the potential of bioaugmentation with nitrifying bacterial communities to significantly enhance the nitrogen removal efficiency of sequencing batch reactors (SBRs). By introducing a complementary nitrifying community, the process achieved a more balanced and robust nitrogen cycle, improving the integration between nitritation and anammox pathways. This bioaugmentation approach not only accelerated the stabilization of nitrogen removal but also improved reactor resilience to operational fluctuations. These findings suggest that targeted bioaugmentation can be a powerful strategy for optimizing nitrogen removal in wastewater treatment, especially in systems facing performance instability or demanding nutrient loads.

Biostimulation, on the other hand, stimulates native microbial populations through organic additives like biosurfactants (e.g., Rhamnolipids) or fertilizers (e.g., Inipol EAP 22). Rhamnolipids have been demonstrated to improve pyrene bioaugmentation by acting as a biosurfactant and carbon source, encouraging the activity of pyrene degraders and microbial communities to be rebuilt(Ali et al., 2022). A greater RE can be obtained with biostimulation than through bioaugmentation. Therefore, throughout a 90-day trial (using 7.5 L bioreactors), the set that used biostimulation alone outperformed the one that used bioaugmentation in the biodegradation of 35 mg/kg benzo(a)pyrene (BaP) and 28 mg/kg dichlorodiphenyltrichloroethane (DDT). In contrast, toxicity decreased by 90% as a result of bioaugmentation, but only by 48% as a result of the biostimulation set (Atli & Sevgiler, 2024). While slightly slower than bioaugmentation, biostimulation supports steady, long-term pollutant degradation. For example, a 90-day trial demonstrated that biostimulation surpassed bioaugmentation in removing certain hydrocarbons, underscoring its role in sustained environmental recovery.

When natural sorbents like minerals (kaolinite, zeolite, diatomite, and vermiculite), carbonaceous materials (biochar), organic materials (peat), and mixed sorbents (diatomite and granular activated carbon) are added to soil contaminated (Chia et al., 2024) by crude oil, the hydrophobicity, toxicity, pH, and water-air regime all improve, which speeds up the oil degradation process considerably (Alori et al., 2020). Table 2 lists the commercial items for biostimulation and bioaugmentation.

Table 2. Commercial bioaugmentation and biostimulation products

Product	Composition	Results
DBC-plus™	Dry bacterial mixed cultures	Depending on the used cultures
Biosolve	Anionic biodegradable synthetic surfactant	A decrease of 66% was noted for total petroleum hydrocarbons within the initial 134 days.
S-200	Oleophilic fertilizer that contains urea, phosphoric esters, oleic acid, water, and a solvent	30% of linear alkanes and aromatics after 60 days
Surfactant AB01039	Blend of nonionic, biodegradable surfactants	40% of hydrocarbon depletion within 30 days
Inipol EAP 22	Oleophilic fertilizer having N source, oleic acid carrier, tri(laureth-4) phosphate, and butoxy ethanol	Improved biodegradation of the oil two-fold relative to untreated controls
TerraZyme™	Microbiological culture	Reduction at the area of oil covering the rocks from 91.0 to 13.7%

In the community of bacteria dynamics investigation, substantial changes in the number of bacteria associated with hydrocarbon degradation have been identified for each therapy (Tanvir et al., 2021). The effective inoculation of hydrocarbon-degrading bacteria, including Staphylococcus species, species of Bacillus, and Rhodococcus species, using bioaugmentation demonstrated the formation of the transplanted microbiological community.

Modifications in significant trial variables were found using information gathered from monitoring the environment. Throughout the year, variations in temperatures were connected with variations in the experimental environment, while all therapies kept pH values within the neutral range. The bioaugmentation therapy exhibited the greatest levels of oxygen, a sign of heightened metabolism and microbial respiration (Grifoni et al., 2022). The biostimulation treatments exhibited higher nutrient levels than the control, particularly phosphorus and nitrogen, that facilitated microbial metabolism and development.

The excellent repeatability and uniformity between therapies within duplicate experiment data demonstrated the resilience of the bioremediation results (Amaro et al., 2023). The frequency that hydrocarbons decompose is being demonstrated to be increased by bioaugmentation and biostimulation approaches, that validate statistically significant increases in contaminant removal effectiveness among bioremediation therapies and the control group.

Comparatively, bioaugmentation offers rapid contaminant removal, especially in heavily polluted environments, while biostimulation is better suited for gradual, sustainable restoration. Integrated approaches combining these techniques can optimize outcomes by leveraging their respective strengths. Such approaches are particularly effective in multi-contaminant environments, where they balance immediate action with long-term recovery.

To restore polluted ecosystems effectively, research has emphasized the importance of investigative techniques, such as combining pesticide occurrence patterns with stable isotope analyses, to trace pollution sources. Applications like biochar-mediated bioaugmentation enhance methane yields and accelerate hydrocarbon degradation in the soil through improved substrate bioavailability and microbial activity. Tailored bioremediation strategies, incorporating both bioaugmentation and biostimulation, can address specific contaminants and environmental conditions, ensuring sustainable outcomes while preserving soil health and productivity.

In conclusion, understanding pollutant interactions and employing targeted bioremediation strategies are crucial for reducing environmental risks and restoring ecosystems. Both bioaugmentation and biostimulation offer unique advantages, achieving significant pollutant reduction and fostering sustainable environmental recovery. Combining these methods in customized approaches ensures efficient and effective remediation across diverse contamination scenarios. Figure 1 shows the performance of the bioremediation process (Muter, 2023).

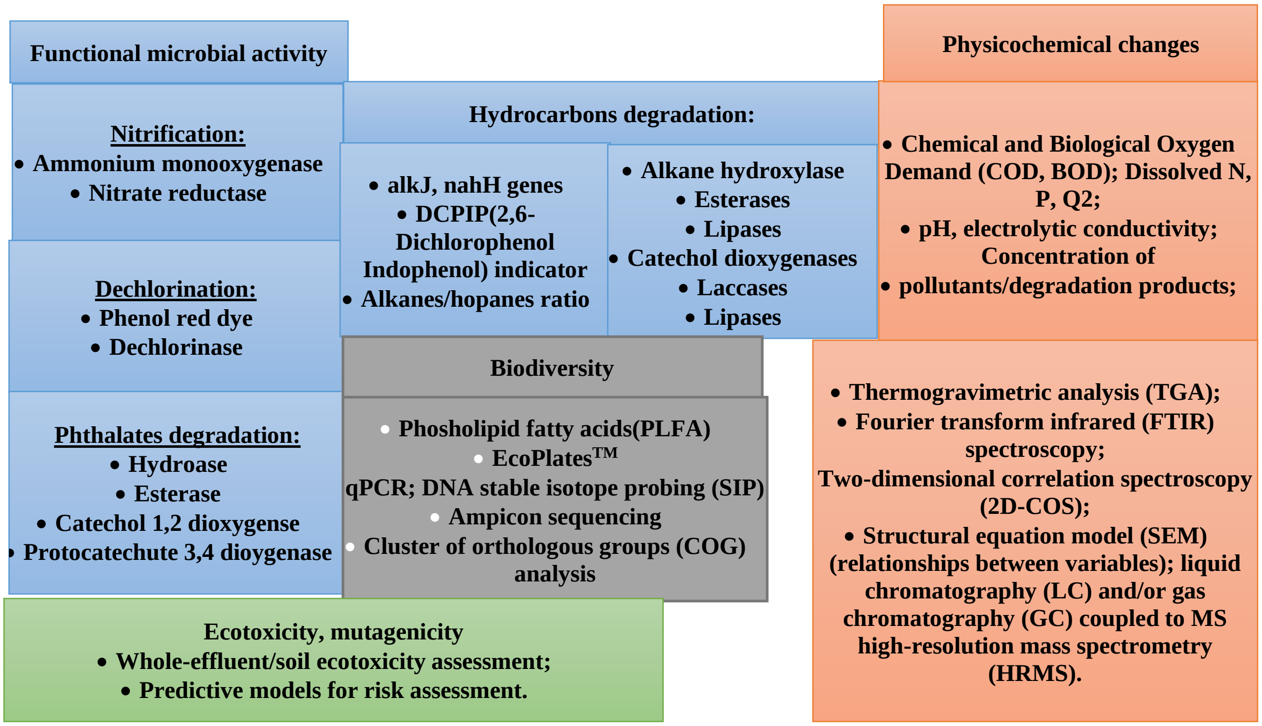

Figure 1. Performance of the bioremediation process (Muter, 2023)

Conclusion And Recommendation

Biological pollution not only has detrimental biological effects on aquatic life but also can disperse a variety of diseases. Aquatic ecosystem quality assessment is now important for environmental and health issues, and it is done through a set of deadline-driven rules and laws. Our review article indicates that bioremediation has a lot of possibilities as a practical and sustainable way to lessen pollution in the soil and water. The area of environmental research and remediation procedures will benefit from this study's significant new insights into microbial activity, environmental factors, and bioremediation strategies. Bioremediation techniques, like bioaugmentation and biostimulation, can dramatically reduce levels of pollutants and promote the development of microbial populations that can degrade a range of contaminants, as demonstrated throughout the review.

Bioaugmentation using specialized microbial consortia was very effective in raising pollutant breakdown rates, even though bio-stimulation treatment increased native populations of microbes and supported natural attenuation processes. It is critical to acknowledge the challenges and constraints associated with bioremediation, including the complexity of the contaminants, the limits of technology, and the constraints placed on the ecosystem. Multidisciplinary approaches, technological advancements, and adaptive management techniques are required to overcome these challenges and preserve the long-range viability of remediation operations while optimizing bioremediation outcomes.

Based on the findings of this review, many recommendations are offered for more research and practical applications:

1. Additional studies on the microbial ecology and metabolic capacity of significant pollutant-degrading microbes to identify novel biodegradation routes and enhance our understanding of bioremediation procedures.
2. The development of cutting-edge bioremediation approaches, for instance, microbial engineering, omics-based approaches, and nanotechnology, to overcome present limitations and expand the application of bioremediation in a variety of environmental scenarios.
3. Using complementary remediation approaches including chemical oxidation, physical treatments, and phytoremediation in conjunction with bioremediation to construct all-encompassing, cooperative remediation strategies that address challenging environmental issues and complex pollutant mixes.
4. The utilization of green chemistry concepts, life cycle analysis, and ecosystem services evaluation to apply sustainable remediation strategies that prioritize environmental preservation, minimize ecological disturbances, and value ecosystem services.
5. Using adaptive management strategies to ensure the long-term sustainability of bioremediation projects by optimizing remediation processes, including stakeholders, and incorporating real-time monitoring to improve decision-making.
6. Public engagement and awareness are crucial for initiating change and fostering effective mitigation strategies. Governments, companies, communities, and individuals need to collaborate to tackle the issues caused by environmental degradation. By adopting innovative mitigation strategies and emphasizing sustainable practices, we can reduce the negative effects of pollution on wildlife and human health, ensuring a healthier, more sustainable future for both the environment and society.

Author Contributions

All Authors contributed equally.

Conflict of Interest

The authors declared that no conflict of interest.

References

AbuQamar, S. F., El-Saadony, M. T., Alkafaas, S. S., Elsalahaty, M. I., Elkafas, S. S., Mathew, B. T., ... & El-Tarabily, K. A. (2024). Ecological impacts and management strategies of pesticide pollution on aquatic life and human beings. *Marine Pollution Bulletin*, *206*, 116613. https://doi.org/10.1016/j.marpolbul.2024.116613

Agarwal, A., & Yadhav, S. (2023). Structure and Functional Guild Composition of Fish Assemblages in the Matla Estuary, Indian Sundarbans. *Aquatic Ecosystems and Environmental Frontiers*, *1*(1), 16-20.

Ahmed, P. M., de Figueroa, L. I., & Pajot, H. F. (2020). Application of microbial consortia in degradation and detoxification of industrial pollutants. *Microorganisms for sustainable environment and health*, 401-418. https://doi.org/10.1016/B978-0-12-819001-2.00020-6

Ali, M., Song, X., Ding, D., Wang, Q., Zhang, Z., & Tang, Z. (2022). Bioremediation of PAHs and heavy metals co-contaminated soils: challenges and enhancement strategies. *Environmental Pollution*, *295*, 118686. https://doi.org/10.1016/j.envpol.2021.118686

Alori, E. T., Gabasawa, A. I., Elenwo, C. E., & Agbeyegbe, O. O. (2022). Bioremediation techniques as affected by limiting factors in soil environment. *Frontiers in Soil Science*, *2*, 937186. https://doi.org/10.3389/fsoil.2022.937186

Amaro, H. M., Salgado, E. M., Nunes, O. C., Pires, J. C., & Esteves, A. F. (2023). Microalgae systems-environmental agents for wastewater treatment and further potential biomass valorisation. *Journal of Environmental Management*, *337*, 117678. https://doi.org/10.1016/j.jenvman.2023.117678

Ancona, V., Cavone, C., Grenni, P., Gagliardi, G., Cosentini, C., Borello, D., & Caracciolo, A. B. (2024). Plant microbial fuel cells for recovering contaminated environments. *International Journal of Hydrogen Energy*, *72*, 1116-1126. https://doi.org/10.1016/j.ijhydene.2024.05.457

Atli, G., & Sevgiler, Y. (2024). Binary effects of fluoxetine and zinc on the biomarker responses of the non-target model organism Daphnia magna. *Environmental Science and Pollution Research*, *31*(19), 27988-28006. https://doi.org/10.1007/s11356-024-32846-5

Aziz, Z. S., Jazaa, S. H., Dageem, H. N., Banoon, S. R., Balboul, B. A., & Abdelzaher, M. A. (2024). Bacterial biodegradation of oil-contaminated soil for pollutant abatement contributing to achieve sustainable development goals: A comprehensive review. *Results in Engineering*, https://doi.org/10.1016/j.rineng.2024.102083.

Brêda-Alves, F., de Oliveira Fernandes, V., & Chia, M. A. (2021). Understanding the environmental roles of herbicides on cyanobacteria, cyanotoxins, and cyanoHABs. *Aquatic Ecology*, *55*(2), 347-361. https://doi.org/10.1007/s10452-021-09849-2

Chia, X. K., Hadibarata, T., Kristanti, R. A., Jusoh, M. N. H., Tan, I. S., & Foo, H. C. Y. (2024). The function of microbial enzymes in breaking down soil contaminated with pesticides: a review. *Bioprocess and biosystems engineering*, *47*(5), 597-620. https://doi.org/10.1007/s00449-024-02978-6

Davidson, C. J., Hannigan, J. H., & Bowen, S. E. (2021). Effects of inhaled combined Benzene, Toluene, Ethylbenzene, and Xylenes (BTEX): Toward an environmental exposure model. *Environmental toxicology and pharmacology*, *81*, 103518. https://doi.org/10.1016/j.etap.2020.103518

De Rosa, E., Montuori, P., Triassi, M., Masucci, A., & Nardone, A. (2022). Occurrence and distribution of persistent organic pollutants (POPs) from Sele River, Southern Italy: analysis of polychlorinated biphenyls and organochlorine pesticides in a water–sediment system. *Toxics*, *10*(11), 662. https://doi.org/10.3390/toxics10110662

Dinakarkumar, Y., Gnanasekaran, R., Reddy, G. K., Vasu, V., Balamurugan, P., & Murali, G. (2024). Fungal bioremediation: An overview of the mechanisms, applications and future perspectives. *Environmental Chemistry and Ecotoxicology*. https://doi.org/10.1016/j.enceco.2024.07.002.

Evalen, P. S., Barnhardt, E. N., Ryu, J., & Stahlschmidt, Z. R. (2024). Toxicity of glyphosate to animals: A meta-analytical approach. *Environmental Pollution, 347,* 123669. https://doi.org/10.1016/j.envpol.2024.123669

Foroutan, B., Bashi Amlashi, H. R., Partani, A., De los Ríos, P., & Nasrollahzadeh Saravi, H. (2023). Determination and comparisons of heavy metals (Cobalt and Iron) accumulation in muscle, liver, and gill tissues of Golden Mullet (Chelon aurata) in coastal areas of the Caspian Sea (Mazandaran and Golestan provinces of Iran). *International Journal of Aquatic Research and Environmental Studies*, *3*(1), 1-15. https://doi.org/10.70102/IJARES/V3I1/1

Fouad, F. A., Youssef, D. G., Shahat, F. M., & Abd El-Ghany, M. N. (2022). Role of microorganisms in biodegradation of pollutants. In *Handbook of biodegradable materials* (pp. 1-40). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-83783-9_11-1

Gladkov, E. A., & Gladkova, O. V. (2021). Plants and maximum permissible concentrations of heavy metals in soil. https://doi.org/10.7251/afts.2021.1325.077G

Gopi, N., Rekha, R., Vijayakumar, S., Liu, G., Monserrat, J. M., Faggio, C., ... & Vaseeharan, B. (2021). Interactive effects of freshwater acidification and selenium pollution on biochemical changes and neurotoxicity in Oreochromis mossambicus. *Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology*, *250*, 109161. https://doi.org/10.1016/j.cbpc.2021.109161

Goswami, R. K., Agrawal, K., Shah, M. P., & Verma, P. (2022). Bioremediation of heavy metals from wastewater: a current perspective on microalgae‐based future. *Letters in Applied Microbiology*, *75*(4), 701-717. https://doi.org/10.1111/lam.13564

Grifoni, M., Franchi, E., Fusini, D., Vocciante, M., Barbafieri, M., Pedron, F., ... & Petruzzelli, G. (2022). Soil remediation: Towards a resilient and adaptive approach to deal with the ever-changing environmental challenges. *Environments*, *9*(2), 18. https://doi.org/10.3390/environments9020018

Haque, S. E., & Gazi-Khan, L. (2025). Limitations and challenges of bioremediation approach: alternative solutions. In *Biotechnologies for Wastewater Treatment and Resource Recovery* (pp. 147-157). Elsevier. https://doi.org/10.1016/B978-0-443-27376-6.00023-2.

Hussain, L. I., & Taimooz, S. H. (2024). Measuring the Levels of Heavy Metal Pollution in Al-Diwaniyah River Water Using Oomycetes Fungus. *International Academic Journal of Science and Engineering*, *11*(1), 312-316. https://doi.org/10.9756/IAJSE/V11I1/IAJSE1136

Khyade, V. B. (2018). Review on biodegradation of plastic through waxworm (Order: Lepidoptera; Family: Pyralidae). *International Academic Journal of Economics*, *5*(4), 31-38. https://doi.org/10.9756/IAJE/V5I1/1810008

Koyama, H., Kamogashira, T., & Yamasoba, T. (2024). Heavy metal exposure: molecular pathways, clinical implications, and protective strategies. *Antioxidants*, *13*(1), 76. https://doi.org/10.3390/antiox13010076

Kumar, K., & Singh, D. (2024). Toxicity and bioremediation of the lead: a critical review. *International Journal of Environmental Health Research*, *34*(4), 1879-1909. https://doi.org/10.1080/09603123.2023.2165047

Kuppan, N., Padman, M., Mahadeva, M., Srinivasan, S., & Devarajan, R. (2024). A comprehensive review of sustainable bioremediation techniques: Eco friendly solutions for waste and pollution management. *Waste Management Bulletin*. https://doi.org/10.1016/j.wmb.2024.07.005

Lau, C., & Hanson, M. L. (2023). Recovery of freshwater aquatic macrophytes after exposure to herbicides and the implications for ecological risk assessment. *The ecotoxicology of aquatic macrophytes*, 137-170. https://doi.org/10.1007/978-3-031-27833-4_6

Lee, J. T., Bu, J., Senadheera, S., Tiong, Y. W., bin Abdul Majid, M., Yuan, X., ... & Tong, Y. W. (2024). Methanosarcina thermophila bioaugmentation with biochar growth support for valorisation of food waste via thermophilic anaerobic digestion. *Journal of Environmental Management*, *370*, 122869. https://doi.org/10.1016/j.jenvman.2024.122869

Malik, J. A. (Ed.). (2022). *Microbes and microbial biotechnology for green remediation*. Elsevier.

Muter, O. (2023). Current trends in bioaugmentation tools for bioremediation: a critical review of advances and knowledge gaps. *Microorganisms*, *11*(3), 710. https://doi.org/10.3390/microorganisms11030710

Orhorhoro, E. K., Atuma, E. V., & Adeniyi, A. S. (2016). Design and fabrication of compression molding machine for plastic waste recycling in Nigeria. *Int. Acad. Inst. Sci. Technol*, *3*(11), 1.

Osman, A. I., Hosny, M., Eltaweil, A. S., Omar, S., Elgarahy, A. M., Farghali, M., ... & Akinyede, K. A. (2023). Microplastic sources, formation, toxicity and remediation: a review. *Environmental Chemistry Letters*, *21*(4), 2129-2169. https://doi.org/10.1007/s10311-023-01593-3

Patel, A. B., Shaikh, S., Jain, K. R., Desai, C., & Madamwar, D. (2020). Polycyclic aromatic hydrocarbons: sources, toxicity, and remediation approaches. *Frontiers in microbiology*, *11*, 562813. https://doi.org/10.3389/fmicb.2020.562813

Pimenov, N. V., Nikolaev, Y. A., Dorofeev, A. G., Grachev, V. A., Kallistova, A. Y., Mironov, V. V., ... & Mardanov, A. V. (2022). Bioaugmentation of anammox activated sludge with a nitrifying bacterial community as a way to increase the nitrogen removal efficiency. *Microbiology*, *91*(2), 133-142. https://doi.org/10.1134/S0026261722020102

Postigo, C., Ginebreda, A., Barbieri, M. V., Barceló, D., Martín-Alonso, J., de la Cal, A., ... & de Alda, M. L. (2021). Investigative monitoring of pesticide and nitrogen pollution sources in a complex multi-stressed catchment: The lower Llobregat River basin case study (Barcelona, Spain). *Science of the Total Environment*, *755*, 142377. https://doi.org/10.1016/j.scitotenv.2020.142377

Raeisi, S. (2017). Subway expansion, the only way to treat air pollution in Tehran. *International Academic Journal of Social Sciences*, *4*(1), 63–69.

Sharma, J., Goutam, J., Dhuriya, Y. K., & Sharma, D. (2021). Bioremediation of Industrial pollutants. *Microbial Rejuvenation of Polluted Environment: Volume 2*, 1-31. https://doi.org/10.1007/978-981-15-7455-9_1

Sharma, P., Bano, A., Singh, S. P., Dubey, N. K., Chandra, R., & Iqbal, H. M. (2022). Recent advancements in microbial-assisted remediation strategies for toxic contaminants. *Cleaner Chemical Engineering*, *2*, 100020. https://doi.org/10.1016/j.clce.2022.100020

Tanvir, R. U., Zhang, J., Canter, T., Chen, D., Lu, J., & Hu, Z. (2021). Harnessing solar energy using phototrophic microorganisms: a sustainable pathway to bioenergy, biomaterials, and environmental solutions. *Renewable and Sustainable Energy Reviews*, *146*, 111181. https://doi.org/10.1016/j.rser.2021.111181.

Usman, G., Mashood, A. A., Aliyu, A., Adamu, K. S., Salisu, A., Abdullahi, A. K., & Sheriff, H. K. (2023). Effects of environmental pollution on wildlife and human health and novel mitigation strategies. *World Journal of Advanced Research and Reviews*, *19*(2), 1239-1251.

Vij, P., & Prashant, P. M. (2024). Analyzing Soil Pollution by Image Processing and Machine Learning at Contaminated Agricultural Field. *Natural and Engineering Sciences*, *9*(2), 335-346. https://doi.org/10.28978/nesciences.1575484

Wang, M., Bodirsky, B. L., Rijneveld, R., Beier, F., Bak, M. P., Batool, M., ... & Strokal, M. (2024). A triple increase in global river basins with water scarcity due to future pollution. *Nature Communications*, *15*(1), 880. https://doi.org/10.1038/s41467-024-44947-3