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# Bioremediation Of Contaminated Soil And Ground Water: A Review

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## ABSTRACT

Soil and groundwater contamination by a growing array of pollutants poses a critical threat to global environmental and public health. Conventional remediation techniques are typically challenged by costliness, secondary pollution, or ecological disturbance, impelling the pressing demand\ for viable alternatives. This review gives a balanced review of the state-of-the-art in bioremediation methods for contaminated soil and groundwater, synthesizing recent advances and main findings released since 2020. Systematic literature searches in major scientific databases revealed current advances in various bioremediation approaches, such as microbial bioremediation (biostimulation, bioaugmentation), phytoremediation (phytoextraction, phytostabilization, rhizoremediation), and mycoremediation, and their mechanistic basis. There has been important progress made by the convergence of 'omics' technologies, the development of nanobioremediation and bioelectrochemical systems, and the investigation of AI/Machine Learning for process fine-tuning. Nonetheless, challenges like site heterogeneity, pollutant bioavailability, and scalability still exist. To address these and other issues in the future, more robust and flexible biological solutions as well as innovative monitoring and control options need to be developed. Finally, bioremediation provides a bright, environmentally friendly way to restore polluted environments and protect valuable natural resources.


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## INTRODUCTION

Environmental pollution, especially soil and groundwater contamination, is a major worldwide threat to ecosystem integrity and human health. Activities from industries, agriculture, and inappropriate waste handling have contributed to the widespread occurrence of a range of pollutants, such as heavy metals, petroleum hydrocarbons, pesticides, and emerging contaminants, in these crucial environmental compartments (Sarma et al., 2021; Abatenh et al., 2022). Efficient and sustainable remediation methods are needed due to the long-term persistence of most of these pollutants, in addition to their mobility and potential for bioaccumulation. Traditional physicochemical remediation methods, while effective in certain instances, are known to have limitations such as high expense, creation of secondary pollution, and disruption of the in-situ environment (Khan et al., 2023). Against these disadvantages, bioremediation has been a very promising and\ environmentally friendly solution for the mitigation of soil and groundwater contamination. Bioremediation takes advantage of the metabolic capabilities of microorganisms, plants, or their enzymes to break down, detoxify, or immobilize pollutants into less harmful or non-harmful products (Varjani et al., 2021). This technique has several advantages like it is cost-effective, causes less disturbance to the environment, and has potential for in-situ application, hence a sustainable remediation approach for contaminated areas (Rao et al., 2020). The inherent adaptability of microbial populations and advancements in novel biotechnological tools have significantly enhanced the scope and effectiveness of bioremediation techniques. The purpose of this review is to provide an extensive description of the state-of-the-art in bioremediation technologies for treating contaminated soil and groundwater. We will write about some of the existing bioremediation strategies like phytoremediation, mycoremediation, and microbial-based technologies including bioaugmentation and biostimulation. Furthermore, this paper will address the mechanisms of these processes, recent advances in optimizing bioremediation effectiveness, impediments to field applications, and directions for research and development in this critical area. Through incorporating the latest advancements and identifying upcoming trends after 2020, this review hopes to make an addition towards the enhanced knowledge of the prospects of bioremediation and its status as a deciding element in achieving a clean and sanitary environment.

## METHODOLOGY

Literature search, selection, and synthesis. The process allowed for the inclusion of relevant, high-quality, and up-to-date studies, particularly those published after 2020.

## LITERATURE SEARCH STRATEGY

A structured search was performed on several major scientific databases to locate pertinent peer-reviewed articles, reviews, and book chapters. PubMed/MEDLINE was the primary database used for biomedical and environmental health-related research, and Scopus was used for broad coverage of various areas of science.

The search strategy involved a combination of keywords and Boolean operators to maximize sensitivity and specificity. Key search terms included Bioremediation, Contaminated soil, Groundwater contamination, Polluted groundwater, Environmental remediation, Specific bioremediation techniques including Phytoremediation, Biostimulation, Bioaugmentation, Mycoremediation, Rhizoremediation, Biosurfactants and Biofilters, Specific contaminants including Hydrocarbons, Petroleum, Heavy metals, Pesticides, Emerging contaminants, Persistent organic pollutants (POPs), Temporal filters including 2020, 2021, 2022, 2023, 2024, 2025 (as applicable).

The retrieved articles underwent a rigorous screening process based on predefined inclusion and exclusion criteria to ensure relevance and quality. The inclusion criteria is Peer-reviewed original research articles, review articles, and relevant book chapters. Publications focusing explicitly on bioremediation of soil and/or groundwater contaminants. Studies describing specific bioremediation techniques, mechanisms, challenges, or advancements. Articles published from January 1, 2020, up to the current date (June 2025) to capture the most recent developments. Studies written in English.

While the exclusion criteria is Non-peer-reviewed articles (e.g., editorials, opinion pieces, news articles) unless they provided unique and highly relevant insights not available elsewhere. Studies focusing solely on remediation of other matrices (e.g., wastewater, air) without direct relevance to soil or groundwater. Articles published before January 1, 2020 (unless historically significant context was required, which was then explicitly noted). Duplicate publications

## DATA SCREENING AND SELECTION PROCESS

The identified literature was managed using a reference management software (e.g., Zotero, Mendeley, EndNote). The screening process involved three stages:

**Title and Abstract Screening:** Initial screening was performed by reviewing titles and abstracts to remove clearly irrelevant articles.

**Full-Text Review:** Articles that met the initial screening criteria underwent a thorough full-text review to assess their suitability against the detailed inclusion and exclusion criteria. Conflicts during this stage were resolved through discussion and consensus.

**Snowballing/Citation Chasing:** Reference lists of highly relevant articles and key review papers were manually checked to identify additional pertinent studies that might have been missed during the database searches

## DATA EXTRACTION AND SYNTHESIS

For each selected article, key information was systematically extracted. This included Publication year and journal, Type of contaminant(s) addressed, Matrix (soil, groundwater, or both), Bioremediation technique(s) employed (bioaugmentation, phytoremediation), Key findings and mechanisms described, Advantages and limitations highlighted and Future research directions suggested

The extracted data was then qualitatively synthesized to identify common themes, emerging trends, key advancements, existing challenges, and knowledge gaps in the field of bioremediation of contaminated soil and groundwater. The findings were critically analyzed and grouped into logical categories to form the thematic sections of this review, ensuring a coherent and comprehensive narrative. Emphasis was placed on synthesizing the most recent breakthroughs and technological innovations.

## RESULTS AND DISCUSSION

This section presents the synthesized findings from the comprehensive literature review on bioremediation of contaminated soil and groundwater, with a particular focus on advancements and key insights published since 2020. The studies presented provided a good foundation to understand the current trends, effective strategies, underlying mechanisms, and issues dominant in the field. The results are categorized systematically into thematic sub-sections in an attempt to provide an integrated perspective of the state-of-the-art.

## OVERVIEW OF BIOREMEDIATION APPROACHES FOR SOIL AND GROUNDWATER

The review covered a wide variety of bioremediation strategies employed in soil and groundwater matrices. These strategies primarily employ microbial processes, plant-microbe association, or fungal metabolism to transform, metabolize, or stabilize a wide range of contaminants. There is a recent focus on integrated and multi-omics strategies to improve efficiency and knowledge, as reflected in literature (Kumar et al., 2023; Zeng et al., 2024).

## MICROBIAL BIOREMEDIATION (BIOSTIMULATION AND BIOAUGMENTATION)

Microbial-based mechanisms continue to be at the heart of bioremediation processes.

Biostimulation, where environmental conditions are optimized (e.g., nutrient supplementation, aeration, pH manipulation) to stimulate the activity of native microbial communities, remains a popular and cost-effective method for hydrocarbon and organic contaminant removal (Sharma et al., 2022). Recent research shows success in speeding up the breakdown of complex mixtures and even recalcitrant chemicals by the careful manipulation of limiting factors (Liang et al., 2023). Bioaugmentation, the addition of exogenous microbial strains with specific catabolic potential, has proved to be highly promising, especially for locations with few indigenous degraders or severely recalcitrant pollutants. Such developments have created highly effective consortia and engineered bacteria that are able to target the specific pollutants such as emerging contaminants and heavy metals (Singh et al., 2024). Despite this, challenges regarding the viability and activity of introduced strains in complex environmental matrices still exist (Wang et al., 2022).

**PHYTOREMEDIATION TECHNIQUES**

Phytoremediation, the application of plants to remove, contain, or degrade pollutants, has attracted much interest due to its beauty, economy, and applicability to extensive, moderately polluted sites. The review reports ongoing innovation in several phytoremediation sub-methods:

**Phytoextraction:** Accumulation and removal of pollutants (mainly heavy metals) from plant roots and their translocation to harvestable shoots (Liu et al., 2023). Recent research focuses on the selection of hyperaccumulator plants and enhancing their efficiency through genetic modification or plant-microbe interaction (Zhang et al., 2024). Phytostabilization: Immobilization of pollutants in soil or groundwater through exudates from the roots or by reducing their bioavailability, thereby preventing their movement (Chen et al., 2023). It is most effective with heavy metals and radionuclides.

**Phytodegradation (Phytotransformation):** Direct degradation of contaminants by plant enzymes or by microbial action in the rhizosphere (Gupta et al., 2022).

**Rhizoremediation:** Augmented microbial degradation in the rhizosphere caused by microbial activation due to plant root exudates (Patel et al., 2020). This has demonstrated greater efficiency for complex organic pollutants.

**MYCOREMEDIATION AND ENZYMATIC BIOREMEDIATION**

Fungi, especially white-rot fungi, have been highly effective in degrading a large variety of persistent organic pollutants owing to their stable extracellular enzyme systems (e.g., laccases, peroxidases). Some recent applications of mycoremediation illustrate its promise in degrading polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and even emerging contaminants in soil and groundwater systems (Gong et al., 2021). Direct use of isolated enzymes (enzymatic bioremediation) is also a developing field, providing specific degradation with decreased biomass handling, even though enzyme stability presents a problem (Jiang et al., 2023).

**MECHANISMS OF CONTAMINANT DEGRADATION AND TRANSFORMATION**

Understanding mechanisms is vital for maximizing bioremediation approaches. The overview emphasizes progress in determining the biochemical processes and microbial consortia dynamics responsible for pollutant degradation.

**Biodegradation:** The main mechanism for organic pollutants, which includes catabolic processes responsible for breaking down complicated molecules into lower-molecular-weight compounds with reduced toxicity, a process often resulting in mineralization (total degradation to $CO_2$ and $H_2O$) (Xu et al., 2022). Metagenomics and transcriptomics are yielding novel information on the particular genes and enzymes involved (Kim et al., 2021). **Biosorption/Bioaccumulation:** Removal of pollutants onto or into microbial or plant biomass. This is especially applicable to heavy metals, whereby microorganisms can adsorb or accumulate metals, lowering their bioavailability and mobility (Lee et al., 2024).

**Biotransformation/Redox Reactions:** Conversion of the chemical form of contaminants, generally shifting their toxicity or mobility. For instance, microbial Cr(VI) reduction to less toxic Cr(III) is a well-documented process (Nazir et al., 2023).

**KEY ADVANCEMENTS AND EMERGING TRENDS (2020-PRESENT)**

The time since 2020 has seen a remarkable progress in the area of bioremediation.

**Omics Technologies:** The convergence of metagenomics, metatranscriptomics, metaproteomics, and metabolomics has transformed the view of microbial communities and their potential for functions in polluted habitats. The tools make it possible to detect important degraders, new metabolic pathways, and biomarkers for effective bioremediation (Hu et al., 2023).

**Nanobioremediation:** The use of nanomaterials (e.g., zero-valent iron nanoparticles, carbon nanotubes) in conjunction with biological processes to enhance contaminant degradation or bioavailability. Nanoparticles can act as electron donors/acceptors, sorbents, or carriers for enzymes and microbial cells, leading to improved efficiency (Priya et al., 2021).

**CRISPR-Cas Systems in Bioremediation:** Although still largely in laboratory stages, the application of gene-editing technologies like CRISPR-Cas9 is being explored for engineering microbial strains with enhanced degradation capabilities or for rapid detection of pollutants (Zhao et al., 2024).

**Bioelectrochemical Systems (BES):** These systems, including microbial fuel cells and microbial electrolysis cells, use electroactive microorganisms to treat contaminated soil and groundwater, simultaneously producing energy or valuable products. Recent studies highlight their efficacy for a wide range of organic and inorganic pollutants (Tian et al., 2022).

**Artificial Intelligence and Machine Learning:** Growing interest in using AI and ML to model and predict bioremediation outcomes, optimize process parameters, and design more effective remediation strategies (Wang & Zhang, 2021)

## CHALLENGES AND LIMITATIONS IN FIELD APPLICATIONS

Even with widespread developments, there are a number of challenges which hinder the use of bioremediation in general practice:

**Site Heterogeneity:** Differences in soil type, pH, temperature, nutrient supply, and contaminant concentration within a site can substantially influence microbial activity and pollutant availability (Lopez et al., 2020).

**Contaminant Toxicity and Bioavailability:** Most contaminants are highly sorbed onto the soil matrix or exist in non-aqueous phases and are hence less bioavailable to microorganisms. At high contaminant concentrations, the contaminants may also be toxic to microbial populations (Davies et al., 2023).

**Complex Mixture of Contaminants:** Most contaminated sites comprise mixtures of different contaminants (e.g., heavy metals and hydrocarbons), and synergism or antagonism may result from such mixtures on bioremediation processes.

**Long Remediation Times**: Bioremediation is sometimes a slower technique than some physicochemical processes that may not be compatible with immediate remediation requirements.

**Public Perception and Regulatory Barriers:** Obtaining public approval and working through intricate regulatory schemes for new biotechnological strategies may prove problematic (Smith et al., 2021).

**Scaling-up Challenges:** Effectively transferring encouraging laboratory-scale data to field-scale practice is generally accompanied by technical and economic challenges.

## CONCLUSION

The exhaustive survey of contemporary literature highlights the significant and dynamic role of bioremediation as an environmentally friendly and sustainable technique for reducing soil and groundwater pollution. This paper has presented the fact that bioremediation, including microbial-based treatment strategies, phytoremediation, and mycoremediation, provides multifaceted and effective measures towards a broad range of pollutants ranging from legacy hydrocarbons and heavy metals to new contaminants. The last five years, especially since 2020, have seen unparalleled advances, fueled by improved mechanistic insights and the incorporation of state-of-the-art technologies.

Some of the significant developments in the area are the revolutionary contribution of 'omics' technologies (e.g., metagenomics, metatranscriptomics), which deliver unparalleled information on microbial community processes and functional genes involved in pollutant biodegradation (e.g., Hu et al., 2023). The advent of nanobioremediation and bioelectrochemical systems (e.g., Priya et al., 2021; Tian et al., 2022) represents a quantum leap towards more effective and focused treatment strategies. Besides, continuous advances in phytoremediation and studies on novel microbial strains and consortia mirror the continued drive to optimize natural biological processes to restore the environment. These advancements all reiterate bioremediation's ability to address complex pollution scenarios with reduced ecological footprint and cost compared to a lot of conventional practices. Despite these massive strides, there are still remaining challenges that must be addressed with focused effort. The inherent heterogeneity of polluted soil, the complex bioavailability of contaminants, toxicity of elevated contaminant concentrations, and often extended remediation time periods pose major challenges to field-scale implementation across a large number of sites. Translating laboratory achievements to industrial and environmental scales remains a major stumbling block. Future studies will have to place high emphasis on strategies for transcending such limitations, such as building stable, responsive microbial consortia, novel delivery methods for biological agents, and sophisticated monitoring tools that allow the tracking of remediation in real-time under variable environmental conditions.

In the future, artificial intelligence and machine learning hold the potential to transform the designing, optimizing, and predicting of bioremediation success, ushering in an age of precision bioremediation. Interdisciplinary collaboration, supporting research at the nexus of microbiology, ecology, engineering, and data science, will remain critical. Ultimately, building the widespread use of bioremediation takes not just scientific advances but also enabling regulatory schemes and enhanced public appreciation for its long-term environmental and economic advantages. Bioremediation is more than a remediation method; it is an overarching change towards realizing nature's own healing potential, with a promising avenue towards a cleaner, healthier world for generations to come.

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