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DEVELOPMENT IN THE SECTOR OF AGRICULTURE AND  
TOURISM“



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## MICROBIAL BIOREMEDIATION OF SOILS FOR SUSTAINABLE DEVELOPMENT IN AGRICULTURE

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### ABSTRACT

Modern society is highly dependent on industrial activity. While industry provides significant benefits, it also releases a variety of pollutants into the environment. These contaminants can enter the human body through the food chain, via soil, water, plants, and animals, and may exhibit carcinogenic, teratogenic, or mutagenic properties. Their toxic effects are often cumulative. To mitigate adverse environmental and biological impacts, numerous decontamination and remediation techniques have been developed. Currently, a wide range of physical, chemical, and thermal methods are employed to separate, transform, or degrade pollutants. In comparison to these approaches, biological techniques such as bioremediation are considered more cost-effective, do not generate waste, and are often described as environmentally friendly. Bioremediation utilizes microorganisms that can survive in contaminated environments and degrade pollutants. These microorganisms use contaminants as sources of carbon and electrons for growth and reproduction. For optimal results, bioremediation procedures typically employ consortia of autochthonous microorganisms isolated directly from the contaminated site. The metabolic versatility of these microorganisms and their interactions with both organic and inorganic pollutants are most pronounced within such consortia, where two or more species co-metabolically degrade specific components. The end products of bioremediation, including carbon dioxide, water, and microbial biomass, are non-toxic, resulting in an environment that is remediated without the generation of additional waste. Bioremediation of contaminated soils is of particular importance in agriculture, as it contributes to the restoration of soil fertility, reduces the risk of toxic substances entering the food chain, and preserves the quality of agroecosystems.

The application of microbial technologies represents a sustainable and environmentally friendly solution that supports safe food production and long-term environmental protection.

**Keywords:** industry, pollutants, environment, bioremediation, microorganisms.

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## **INTRODUCTION**

Modern industrial and technological development has significantly contributed to economic growth and improved quality of life, but has also led to increased pressure on the environment. Environmental degradation caused by industrial activities, intensive agriculture, and inadequate waste management poses a serious threat to rural ecosystems, agricultural productivity, and the sustainable development of local communities. Soil contamination by various organic and inorganic pollutants can degrade its physicochemical and biological properties, with long-term consequences for fertility, food quality, and human health. Pollutants can enter the food chain through soil, water, plants, and animals, exerting toxic effects that are often cumulative, including carcinogenic, mutagenic, and teratogenic effects. Therefore, sustainable remediation strategies for contaminated sites to mitigate their impact have become a key challenge in environmental protection and the sustainable management of natural resources (Singh & Singh, 2017; Correia & Rasteiro, 2025).

### **Bioremediation and factors influencing the bioremediation process**

The detrimental effects of pollutants on the environment require the implementation of remediation strategies (Ou et al., 2025). Remediation processes focus on contaminant removal, reduction, degradation, and restoration of land properties and functions, which are essential for ecosystem recovery (Imam et al., 2019; Imron et al., 2020; Kumar et al., 2022; O'Brien et al., 2017; Okoh et al., 2020).

Remediation techniques are classified according to the agent employed, including physico-chemical, chemical, thermal, electromagnetic, radiation, and biological methods (Arghiropol et al., 2025).

The application of biological agents for environmental remediation represents a cost-effective biotechnological strategy that is increasingly adopted and offers certain advantages over alternative techniques. Bioremediation can be categorized based on the agent utilized: phytoremediation (plants), microbial remediation (microorganisms), and mycoremediation (fungi) (Sarfaraz et al., 2025). This article focuses on the use of microorganisms for soil remediation; therefore, microbial remediation will be discussed in detail. In this process, microorganisms degrade, transform, and convert pollutants into non-toxic forms. The success of bioremediation depends on specific environmental and biological conditions. Microbial activity in soil is influenced by factors such as texture, permeability, oxygen availability, humidity, temperature, pH, nutrient content, salinity, and pressure. Additionally, the bioremediation efficiency depends on substrate characteristics, bioavailability, and the quality and composition of the microbial consortium (Ajona & Vasanthi, 2021; Das & Kazy, 2014; Imron et al., 2020; Khalid et al., 2021; Madhavi et al., 2021; O'Brien et al., 2017; Okoh et al., 2020; Ossai et al., 2020).

### **Bioremediation processes**

Bioremediation processes are commonly classified based on the location of implementation into in situ and ex situ procedures. In situ bioremediation occurs directly at the site of contamination, whereas ex situ methods involve excavating contaminated soil or sediment, or extracting groundwater, followed by treatment at a separate location.

In situ treatment preserves the structure of the contaminated material but requires the construction of infrastructure at the contamination site. This approach presents challenges in controlling parameters such as temperature, humidity, and aeration, and typically requires a longer treatment duration compared to ex situ methods. Ex situ treatment allows for greater control over environmental parameters and generally reduces treatment time. However, the excavation and transfer processes may alter the

characteristics of the contaminated material (Ajona, 2021; Madhavi et al., 2021; O'Brien et al., 2017; Okoh et al., 2020).

Bioremediation strategies are further categorized into biostimulation and bioaugmentation. Biostimulation involves enhancing the activity of indigenous microorganisms capable of degrading contaminants by modifying abiotic factors and introducing nutrients to accelerate degradation rates. In addition to nutrients, stimulatory agents may include biosurfactants, biopolymers, and fertilizers. Bioaugmentation refers to the introduction of specialized microorganisms that efficiently degrade pollutants (Ajona & Vasanthi, 2021; Imam et al., 2021; Madhavi et al., 2021; O'Brien et al., 2017; Okoh et al., 2020; Ossai et al., 2020).

A variety of bioremediation technologies are described in the literature, including natural attenuation, bioventing, biosparging, bioslurping, land farming, biopiles, composting, and bioremediation in bioreactors (bioslurry) (Ossai et al., 2020; Raju & Scalvenzi, 2018).

### **Procedure for selecting a bioremediation treatment**

Selecting an optimal bioremediation treatment requires careful evaluation of the interactions between biotic and abiotic factors, economic considerations, and regulatory requirements associated with the chosen process. Biotic and abiotic factors are mutually dependent. Microbial activity is influenced by contaminant properties, which in turn are shaped by environmental conditions. The selection process should account for the contaminant's nature, origin, composition, and characteristics, as well as the properties of the polluted environment, contaminant distribution, ecological factors, and interactions with living systems. The initial step involves analyzing the site and assessing the suitability of the technology for the specific conditions. The second phase focuses on regulatory compliance and feasibility. The third phase evaluates additional factors such as the efficiency of the technology, cost, and implementation timeframe (Kuppusamy et al., 2019; Ossai et al., 2020).

### **Microorganisms and pathways of contaminant degradation: The case of petroleum hydrocarbons**

Microorganisms capable of utilizing petroleum hydrocarbons as an energy source are highly diverse and abundant in the environment (Imam et al., 2019; Kumar et al., 2022). This group includes Gram-positive bacteria such as *Arthrobacter*, *Bacillus*, *Corynebacterium*, *Micrococcus*, *Mycobacterium*, *Nocardia*, *Rhodococcus*, *Staphylococcus*, and *Streptomyces*, as well as Gram-negative bacteria including *Achromobacter*, *Acinetobacter*, *Alcaligenes*, *Burkholderia*, *Flavobacterium*, *Klebsiella*, *Pseudomonas*, *Sphingomonas*, and *Xanthomonas*. Fungi from the genera *Aureobasidium*, *Aspergillus*, *Candida*, *Mortierella*, *Penicillium*, *Rhodotorula*, *Sporobolomyces*, and *Trichoderma* also possess this capability (Chandra et al., 2013; Imron et al., 2020; Kumar et al., 2022). The application of microorganisms for the biotransformation and biodegradation of pollutants is steadily increasing (Al-Sayegh et al., 2015; Beškoski et al., 2011; Jednak Berić et al., 2023; Lješević et al., 2019; Lukić et al., 2024; Žerađanin et al., 2022).

Aerobic degradation of petroleum hydrocarbons is generally more efficient than anaerobic processes, although both pathways are documented (Li et al., 2025). The use of microbial consortia is preferred over individual microorganisms because consortia exhibit enhanced enzymatic capabilities and can degrade a broader spectrum of hydrocarbon substrates (Pereira et al., 2025). Microorganisms employ various

mechanisms to adapt to hydrophobic substrates, and evolutionary changes have altered bacterial surface characteristics. The initial step in petroleum hydrocarbon degradation involves emulsification by microbial surfactants. Effective degradation requires direct physical contact between the microbial cell and the hydrocarbon, facilitated by hydrophobic fimbriae, fibrils, outer membrane proteins, lipids, and small molecules such as gramicidin S and prodigiosin. The presence of negatively charged exopolysaccharides and a capsule can inhibit this contact. Certain bacteria can modify lipopolysaccharides and porins on their outer membrane to enhance interaction. Following contact, hydrocarbons are transported into the cell via active or passive mechanisms and endocytosis, where they undergo enzymatic degradation. Key enzymes involved include oxygenases, monooxygenases, dioxygenases, and hydrolases (Chandra et al., 2013; Imam et al., 2019; Imam et al., 2021; Khalid et al., 2021; Mekonnen et al., 2024; Raju & Scalvenzi, 2018; Shakya et al., 2021; Xu et al., 2018). Complete biodegradation results in the formation of carbon dioxide, water, and biomass (Chandra et al., 2013; Imam et al., 2019; Imron et al., 2020).

The efficiency of petroleum hydrocarbon degradation decreases in the following order: straight-chain alkanes, branched alkanes, low molecular weight aromatic compounds, and high molecular weight aromatic compounds (Imam et al., 2019; Xu et al., 2018).

Short-chain alkanes containing up to nine carbon atoms are highly volatile, and a significant portion evaporates into the atmosphere before biodegradation can occur. Microorganisms most rapidly biodegrade medium-length n-alkanes with 10 to 24 carbon atoms (Chandra et al., 2013). Compounds such as monoaromatic steroids, diasteranes, C21-C22 steranes, diahopanes, 25-norhopanes, tricyclic terpenes, oleananes, and gamaceranes are highly resistant to biodegradation. Similarly, C27-C35 hopanes and C27-C29 regular steranes exhibit considerable resistance (Head et al., 2003).

### **Advantages and limitations of bioremediation technology**

Bioremediation is a widely recognized and promising technology for environmental remediation. As an environmentally friendly technique, it does not negatively impact the environment, demonstrates high efficiency in contaminant removal, applies to a wide range of contaminated sites, and is characterized by low implementation costs. In comparison, physical and chemical remediation methods are less efficient and more costly (Chandra et al. 2013; Imron et al., 2019; Okoh et al., 2020; Shakya et al., 2021). Furthermore, the application of bioremediation to polluted soil promotes the humification process and produces valuable microbiological products (Avdalović et al., 2021; Žerađanin et al., 2020).

In addition to the significant advantages over other methods, bioremediation has several disadvantages that should be considered before application to contaminated areas. The bioremediation process is significantly slower because microbial degradation depends on the growth and metabolism of the consortium's microorganisms, as well as on environmental conditions.

Sometimes bioremediation cannot achieve complete degradation of pollutants, leading to the accumulation of intermediate metabolites, while in some polluted environments, high concentrations of heavy metals or pollutants can inhibit the activity of microorganisms (Dar & Naseer, 2022; Jabbar et al., 2022).

## CONCLUSIONS

Bioremediation represents an environmentally acceptable, efficient, and economically viable approach to remediating polluted environments. This process reduces contaminant concentrations and transforms pollutants into non-toxic products. The effectiveness of bioremediation is influenced by both biotic and abiotic factors, including soil properties, contaminant characteristics, and the composition of the microbial consortium. Selection of an appropriate bioremediation technology requires evaluation of site location, technical feasibility, treatment duration, cost, and regulatory considerations. Both in situ and ex situ approaches are available, with the choice determined by site-specific conditions. Microorganisms play a central role in degrading pollutants, transforming and mineralizing them through complex enzymatic pathways. Beyond contaminant removal, bioremediation enhances soil quality and yields valuable microbial products. In conclusion, bioremediation is a sustainable and promising technology within contemporary strategies for environmental protection and restoration.

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