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Review on the bioremediation of waters contaminated with native strains of the genus Pseudomona

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Abstract
Introduction: Bioremediation has emerged as an effective strategy to mitigate environmental pollution, especially in water and soil, using microorganisms to degrade or transform contaminants. Hydrocarbons and other pollutants such as heavy metals and persistent organic chemicals pose serious threats to biodiversity and human health. Methodology: A literature review was conducted focusing on bioremediation with Pseudomonas, collecting scientific articles and case studies. Studies presenting empirical results and theoretical analysis on the efficiency of Pseudomonas in the remediation of contaminants such as hydrocarbons and heavy metals were included. Sources were searched in scientific databases using relevant keywords. Results: Pseudomonas stand out for their ability to degrade a variety of contaminants due to their metabolic versatility. Mechanisms such as the production of degradative enzymes, the formation of biofilms, and the regulation of gene expression allow these bacteria to efficiently break down contaminants. Factors such as nutrient availability, pH, temperature, and redox conditions significantly affect its efficacy. In practical applications, Pseudomonas aeruginosa has shown high efficiency in the degradation of hydrocarbons in soils and waters, removing up to 90% of short-chain hydrocarbons. Furthermore, in the bioremediation of heavy metals, P. aeruginosa has demonstrated a high capacity to adsorb metal ions, removing up to 60% of arsenic from groundwater. In conclusion, bioremediation with Pseudomonas is promising for treating water and soil contamination by hydrocarbons and heavy metals, under various conditions.
Keywords: Bioremediation; Pseudomonas; Contamination; Hydrocarbons; Heavy metals; Degradation.

Introduction

In recent decades, bioremediation has emerged as a promising strategy for mitigating environmental pollution, especially in the remediation of natural resources such as water and soil. This technique takes advantage of the ability of microorganisms to absorb, degrade or transform pollutants, thus reducing their impact on the environment. The versatility of bioremediation lies in its ability to address a wide variety of chemical compounds, each with different characteristics, molecular weight, composition, structure, toxicity, and biodegradability (Cota-Ruiz et al., 2019).

Among the most important pollutants are hydrocarbons, whose presence in water, in particular, poses a serious threat to biodiversity and human health. Activities related to the production, refining, and distribution of oil have increased water pollution, generating negative ecological and economic effects on surrounding communities (López Naranjo & Luyando Cuevas, 2018).

However, there are other non-oil pollutants that also cause serious environmental and public health problems (Blaya Delgado, 2021).
It is important to emphasize that the bioremediation technique dates back to the 1960s, when the American engineer George M. Robinson developed a method using microorganisms to remediate oil contamination (Salamone, 2018). Bioremediation is defined as any process that uses living organisms such as bacteria, fungi or plants to degrade or transform pollutants and eliminate them from the environment, inactivating them or reducing their impact on soil, water and air (Garzón, 2017). This approach is based on the metabolic activity of bacteria, fungi and other microorganisms capable of degrading harmful substances and organic matter (Cota-Ruiz et al., 2019).

Characteristics of Pseudomonas bacteria

Bacteria of the genus Pseudomonas are a diverse and widely distributed group of Gram-negative microorganisms that exhibit a number of distinctive morphological, physiological, and genetic characteristics.

Morphological characteristics

1. **Shape and size:** The Pseudomonas they are Gram-negative bacilli, elongated in shape, with lengths between 0.5 and 3 micrometers.
2. **Mobility**: Many species are mobile thanks to the presence of polar flagella.
3. **Appearance in crops**: In agar, colonies are usually irregular, smooth, and mucoid, with colors ranging from whitish to greenish.
4. **Biofilm formation**: They have the ability to form biofilms, which influences adhesion to pollutant particles and resistance to cleaning agents (Girard et al., 2021).

Physiological characteristics

1. **Metabolic versatility:** They use a wide variety of organic and inorganic compounds as sources of carbon and energy.
2. **Adaptability:** They survive in a wide range of environmental conditions, including extreme pH, high salt concentrations, and variable temperatures.
3. **Exoenzyme secretion:** They degrade complex organic compounds such as hydrocarbons, pesticides, and chemical pollutants.
4. **Nitrogen fixation**: Some species can fix atmospheric nitrogen, contributing to soil biogeochemistry and the nitrogen cycle (Girard et al., 2021).

Genetic characteristics

1. **Large, flexible genomes:** They contain a variety of genes related to environmental adaptation, degradation of pollutants, and antibiotic resistance.
2. **High genomic plasticity:** They can adapt quickly to changes in their environment and acquire new genes through horizontal gene transfer.
3. **Genetic diversity:** They exhibit great diversity within the genre Pseudomonas, with different species and strains showing various physiological and metabolic adaptations (Hou et al., 2024).

Metabolic versatility of Pseudomonas and their ability to degrade a wide variety of contaminants.

Bacteria in the genus Pseudomonas are known for their impressive metabolic versatility, allowing them to use a wide variety of compounds as sources of carbon and energy. This metabolic

versatility is critical to its ability to degrade a wide range of pollutants in contaminated environments (Lei et al., 2020). Highlights of this metabolic versatility include:
Pseudomonas bacteria are noted for their ability to degrade a wide variety of organic compounds, such as hydrocarbons, pesticides, nitrogenous compounds, and phenolics. They use complex compounds as carbon and energy sources, breaking down large molecules into simpler products using specialized metabolic pathways. These bacteria are highly adaptable and can survive in extreme conditions, including extreme pH, high salt concentrations, and varying temperatures, as well as in the presence of toxic compounds. In addition, some species have developed resistance to various antibiotics, allowing them to thrive in contaminated environments. Thanks to their metabolic versatility, Pseudomonas are widely used in bioremediation processes to clean contaminated soil, groundwater, and surface water (Paz-Zarza et al., 2019).

Common contaminants in water and soil.

Some common pollutants present in waters and their impacts on the environment and human health are listed below:
Heavy Metals: Lead, mercury, cadmium, arsenic, these elements cause soil and water pollution, toxicity to aquatic life, bioaccumulation in the food chain. When in contact with humans, they cause acute and chronic toxicity, affects the nervous, renal and cardiovascular systems, and carcinogenicity (Moreno-Rivas et al., 2018).

Hydrocarbons: Petroleum, petroleum derivatives, BTEX (benzene, toluene, ethylbenzene, xylenes). The environmental impact it causes is water and soil pollution, damage to aquatic biodiversity, and a decrease in the quality of water for human and agricultural consumption. In humans, it causes acute and chronic toxicity, cancer, respiratory disorders, liver and kidney damage (García González et al., 2019).
Persistent Organic Chemicals (POPs): DDT, PCBs, dioxins. It produces accumulation in the environment, chronic toxicity for wildlife, alteration of aquatic ecosystems. Being in contact with humans affects the endocrine and reproductive system, neurodevelopmental disorders (Castro López et al., 2024).

Excessive nutrients: nitrates, phosphates. It causes eutrophication of water bodies, algae and phytoplankton blooms, decreased dissolved oxygen, and the death of aquatic organisms. If there is contamination of drinking water sources, this will lead to an increase in toxic algae, becoming a risk of gastrointestinal diseases (Luque Tumiri, 2020).

Industrial and Pharmaceutical Chemicals: Solvents, pesticides, pharmaceuticals, personal care products. At the environmental level, it produces contamination of surface and groundwater, affecting the quality of the aquatic habitat. Being in contact with humans produces possible adverse effects such as acute and chronic toxicity, development of bacterial resistance, endocrine disruption (Blaya Delgado, 2021). In this context, bioremediation has emerged as a viable alternative to treat pollution caused by various agents (Garzón, 2017).

Analysis of Bioremediation Mechanisms.

Identification of Mechanisms: The biochemical and genetic mechanisms used by Pseudomonas to degrade different types of pollutants were identified and described.

Environmental and Operational Factors: Environmental (pH, temperature, nutrient availability, redox conditions) and operational (biostimulation, bioaugmentation) factors that affect the efficacy of Pseudomonas bioremediation were analyzed.

Mechanisms of Bioremediation by Pseudomonas Bacteria.

According to Bedoya Vélez et al. (2019), Pseudomonas are known for their ability to degrade a wide variety of pollutants, thanks to their various biochemical and genetic mechanisms. Below is an analysis of some of the main mechanisms used by Pseudomonas to break down different types of pollutants:

1. **Production of degradative enzymes:** The Pseudomonas They produce enzymes such as oxidases, peroxidases, and monooxygenases, which break down pollutants such as hydrocarbons and pesticides.
2. **Specialized metabolic pathways:** They possess metabolic pathways such as phenol and benzoate to degrade specific compounds.
3. **Acquisition of additional genes:** Through the horizontal transfer of genes and mutations, they acquire the ability to degrade new pollutants such as polycyclic aromatic hydrocarbons.
4. **Biofilm formation:** They adhere to surfaces forming biofilms, which allows degradative enzymes to concentrate and colonize contaminated soils and waters.
5. **Regulation of gene expression**: They respond to environmental signals by regulating the expression of degradation genes, increasing their effectiveness in the breakdown of pollutants (Espinoza Pesantez & Esparza Sanchez, 2021; Paz-Zarza et al., 2019).

Microbial bioremediation.

Bacteria are highly effective in bioremediation due to their ability to degrade a wide range of organic and inorganic compounds. This process can be carried out both in situ and ex situ, depending on the site conditions and the nature of the contaminant. Microorganisms can break down contaminants through processes such as oxidation, reduction, hydrolysis, mineralization, and biochemical transformation (García González et al., 2019).

In such a way, the different methods of microbial bioremediation are described below:

Aerobic Bioremediation; In aerobic bioremediation, microorganisms degrade contaminants in the presence of oxygen. This method is effective for the degradation of hydrocarbons and simple organic compounds in soils and surface waters (Rodríguez-Gonzales et al., 2022).

Anaerobic Bioremediation; In anaerobic bioremediation, microorganisms degrade contaminants in the absence of oxygen. This technique is useful for the degradation of more complex organic compounds, such as chlorinated pollutants, in soils and groundwater (Rodríguez-Gonzales et al., 2022).

Biostimulation: Biostimulation involves the addition of nutrients and other compounds that stimulate the growth and activity of degrading microorganisms in the environment. Additional nutrients may include carbon, nitrogen, phosphorus, and trace elements necessary for microbial metabolism (Rivera Ortiz et al., 2018).

Bioaugmentation: Bioaugmentation involves the addition of specific degrading microorganisms to the environment to increase bioremediation capacity. The added microorganisms can be native strains selected for their ability to degrade the target contaminant or genetically modified strains to improve their efficacy (Ome Barrera & Zafra Mejía, 2018).

Microorganism-Assisted Phytoremediation (FAM): Microorganism-assisted phytoremediation combines the use of plants (phytoextraction) with microorganisms that enhance the degradation of contaminants in soil or water. Microorganisms can help break down pollutants released by plant roots and increase the effectiveness of phytoremediation (Mendarte-Alquisira et al., 2021).

Having analysed all of the above, bioremediation offers an effective and environmentally friendly solution to address water pollution caused by petroleum derivatives. Despite being an old technique, its low operating cost and effectiveness make it attractive for the remediation of contaminated water (Garzón et al., 2017; Cota-Ruiz et al., 2019).

Bioremediation, especially using bacteria such as Pseudomonas, is a promising strategy for treating water pollution caused by hydrocarbons. Its ability to degrade a wide range of pollutants and its versatility in different environmental conditions make it a valuable tool for environmental recovery and the protection of human health. However, it is crucial to consider and control the environmental and operational factors that influence the effectiveness of bioremediation to ensure optimal results in the remediation of contaminated natural resources (Cota-Ruiz et al., 2019).

Among the microorganisms most commonly used in bioremediation are Pseudomonas bacteria, recognized for their metabolic versatility and ability to degrade a wide range of pollutants, including hydrocarbons (Mayz and Manzi, 2017; Rodríguez, 2017). Pseudomonas, especially P. aeruginosa, stand out for their ability to use petroleum-derived substrates and for their production of biosurfactants such as rhamnolipids, which allows them to degrade pollutants under various environmental conditions (Cota-Ruiz et al., 2019).

The effectiveness of bioremediation is highly dependent on a number of environmental and operational factors. Nutrient availability, medium pH, temperature, redox conditions, and the presence of inhibitors can significantly influence the activity of Pseudomonas bacteria and thus the efficacy of the bioremediation process (Pojmaevich et al., 2023). These factors must be carefully controlled and optimized to maximize the efficiency of microbial degradation of contaminants.

In addition to Pseudomonas, other bacterial genera such as Xanthomonas, Ferroxidans and Ralstonia also have interesting capabilities as remedial agents, especially in the extraction of metals from solid substrates and the treatment of industrial effluents (Ramírez, 2017). The mechanisms of hydrocarbon degradation depend on the dominant chemical fraction and the microorganisms involved. In microbial biodegradation of hydrocarbons, multiple metabolic pathways interact to oxidize pollutants, involving genes that code for the synthesis of enzymes such as monooxygenases, dioxygenases, and dehydrogenases (Cota-Ruiz et al., 2019).

In this context, we have focused on analysing the bacterium Pseudomonas and its bioremediation capacity, in order to improve our understanding of microbial degradation processes and optimise the application of bioremediation in contaminated environments.

Methodology

Literature Review.

Selection of Sources: Scientific articles, reviews and relevant case studies on bioremediation were collected, focusing on the use of Pseudomonas for the remediation of different types of pollutants (hydrocarbons, heavy metals, nitrogenous pollutants).

Inclusion Criteria: Studies that present empirical results, systematic reviews and theoretical analyses on the efficiency and mechanisms of bioremediation by Pseudomonas were included. Recent and relevant articles were prioritized to ensure the topicality and relevance of the content.

Databases: Sources were searched in scientific databases such as PubMed, Google Scholar, Scopus, and Web of Science, using keywords such as "bioremediation," "Pseudomonas," "pollution," "hydrocarbons," "heavy metals," and "nitrogenous contaminants."

Case Studies and Practical Applications.

Efficiency of Pseudomonas in Bioremediation: Case studies and practical experiments demonstrating the efficiency of different strains of Pseudomonas in the bioremediation of contaminated soils and waters were reviewed.
Comparison of Results: The results of different studies were compared to evaluate the consistency and variability in the efficiency of bioremediation by Pseudomonas under different conditions.
Information Synthesis: A thematic organization was carried out, addressing first the types of pollutants, then the bioremediation mechanisms, and finally the factors that influence the efficiency of these processes. Areas where research is limited or where more information is required were also identified, and recommendations for future research were made.

After all the review; Of a total of 59 bibliographies used, 5 correspond to degree theses and 54 correspond to scientific articles.

Results and discussion

Factors That Affect the Effectiveness of Pseudomonas Bacteria

According to Castillo Rogel et al. (2020), environmental and operational factors play a crucial role in the efficacy of Pseudomonas bacteria in bioremediation. Here is a description of some of the most important factors:

1. **Nutrient availability:** The Pseudomonas They require nutrients such as carbon, nitrogen, and phosphorus to grow and degrade pollutants. Biostimulation with additional nutrients can improve degradation.
2. **pH of the environment**: It influences their activity and survival. Some species tolerate wide pH ranges, while others do not, so optimizing pH is crucial.
3. **Temperature**: It significantly affects your metabolism. Most of the Pseudomonas they grow best between 20-40°C, and extreme fluctuations can reduce their effectiveness.
4. **Redox conditions:** They influence their activity, since some carry out oxidation-reduction processes important for the degradation of pollutants. Anaerobic conditions can limit the activity of aerobic strains.
5. **Presence of inhibitors**: Heavy metals and toxic compounds can negatively affect its activity, although tolerance varies between strains.
6. **Interactions with other microorganisms**: Competition or cooperation with other microorganisms can influence the ability of Pseudomonas to access nutrients and degrade pollutants effectively (Bedoya Vélez et al., 2019).

Practical Applications and Case Studies

Biodegradation of hydrocarbons by Pseudomonas aeruginosa

Pseudomonas aeruginosa has proven to be one of the most ecological and profitable methods for cleaning oil and its derivatives, as it converts hydrocarbons into harmless byproducts such as carbon dioxide and water (Luján, 2019). In contaminated soils, this bacterium has shown remarkable efficiency, managing to remove 90% of short-chain hydrocarbons (C10) and 69% of long-chain hydrocarbons (C20+) (Safdari et al., 2017).

Emulsification in coastal areas:
In the bioremediation of petroleum pollutants in coastal areas, P. aeruginosa has demonstrated a 100% emulsification index against crude oil, in addition to reducing surface tension to 26.5 mN/m, which facilitates the degradation of oil in marine environments (Cheng et al., 2017).
Biostimulant in soils:
P. aeruginosa has also been shown to be quite effective as a biostimulant in soils contaminated with pure crude oil, showing better results than when treated crude oil is used (Ojewumi et al., 2018).
Bioremediation in saline soils:
In the bioremediation of oil-contaminated saline soils, P. aeruginosa has been able to reduce hydrocarbon levels by up to 30% compared to untreated soils (Ebadi et al., 2017).
Biostimulation with rhamnolipids:
In a study that evaluated biostimulation with rhamnolipids of Pseudomonas sp. Y3-B1A in the degradation of hydrocarbons, it was found that, in the laboratory, rhamnolipids increased the degradation of total petroleum hydrocarbons (HTP) by 61.7%. In microcosms and soil plots, the degradation of HTP and aromatic compounds increased between 33% and 40%, with no toxic effects on the ecosystem (Barrios San Martín et al., 2022).
Biodegradation in marine environments:
In marine environments contaminated by Diesel-2 oil, biodegradation by P. aeruginosa in 5 days was low compared to its interaction with an endogenous microbial consortium (Mendoza-Avalos & Guerrero-Padilla, 2015).
Use of surfactants produced by Pseudomonas spp.:
In contaminated soil, 78 isolates of Pseudomonas spp. were obtained, where 84.62% used petroleum as a carbon source, and 92.42% produced biosurfactants with emulsion diameters of 10-30 mm, achieving yields of 35%, 31%, and 19% (Ugaz-Hoyos et al., 2020).
Biodegradation by Pseudomonas putida
Efficiency in WWTPs (Wastewater Treatment Plants):
Pseudomonas putida ATCC 49128 has shown a significant reduction in BOD5 (5-day Biological Oxygen Demand) and COD (Chemical Oxygen Demand) in wastewater from WWTP effluents, with maximum reductions of 54.79% and 51.62% respectively. The pH varied between 6.60 and 8.23, considered optimal for the purification process. The temperature remained constant between 25.36 and 27.47°C (Bazán-Suárez and Chiclla-Salazar, 2023).

Heavy Metal Bioremediation

High bioremediative capacity of Pseudomonas aeruginosa
Pseudomonas aeruginosa has a high capacity for the bioremediation of heavy metals, preventing these, in quantities above certain limits, from being extremely harmful to the soil and biota. In specific studies, P. aeruginosa has demonstrated its efficacy in the remediation of waste ponds with low concentrations of Copper (Cu), removing 30% of the metal from 160 ppm (Baltazar et al., 2014). In addition, it has been able to remove arsenic (As) from groundwater by up to 60%, reducing its concentration from 1.0 to 0.4 mg/L (Pellizari et al., 2015).
Metal ion adsorption:
P. aeruginosa efficiently detects and adsorbs metal ions such as Hg2+ by up to 80%, and also acts on Cu2+, Pb2+, Co2+, Cd2+, and Cr3+ (Yin et al., 2016). In another study, this bacterium showed remarkable efficiency in the remediation of several metal ions, the main ones being Zn2+ with a removal of 57.5% (648.4 mg/L), Cu2+ with 51.3% (518.9 mg/L) and Fe3+ with 48.5% (298.6

mg/L) (Sindu & Gautam, 2017). In addition, it has an efficiency of 76.1% in the removal of Cesium (Cs) from wastewater (Kang et al., 2017).

Adsorption capacity of Cadmium:

P. aeruginosa adsorbs Cadmium (Cd) with a maximum capacity of 131.9 μmol/g (Tang et al., 2018).

Bioremediation of Nitrogenous Contaminants using Pseudomonas:

Pseudomonas stutzeri has demonstrated high efficiency in the removal of nitrogenous contaminants in industrial wastewater, achieving removal rates of 91.1% of NH4+-N at concentrations of 1500.0 and 2000.0 mg/L in 120 hours (Chen et al., 2020).

Heterotrophic nitrification and aerobic denitrification using Pseudomonas tolaasii:

Pseudomonas tolaasii strain Y-11 has shown remarkable efficiency in the removal of ammonium, nitrate, and nitrite, with removal rates of 93.6%, 93.5%, and 81.9% respectively, and removal rates of up to 2.04, 1.99, and 1.74 mg/L/h (Sun et al., 2016).

Adapted to cold by Pseudomonas putida Y-9

Pseudomonas putida Y-9, adapted to cold, has demonstrated efficiency in nitrogen removal at 15°C, eliminating ammonium, nitrate, and nitrite at average rates of 2.85 mg, 1.60 mg, and 1.83 mg NL^{-1} h^{-1}, respectively (Xu et al., 2017).

Other Relevant Studies

Bioaugmentation in soils and water

In a study that evaluated bioremediation techniques for oil-contaminated areas in Iquitos, landfarming was used for soils and aeration injection for water, employing native bacteria such as Pseudomonas sp. to restore the environment. The results showed a biodegradation of 30% in soils and 50% in water. These techniques are recommended to eliminate hydrocarbon residues, benefiting the local population, flora and fauna (Julián Benites & Rivero Méndez, 2023).

Cyanide removal

Microorganisms and algae: In Colombia, microorganisms with high cyanide degradation potential (up to 96% removal) were identified, including fungi of the genus Fusarium, Hasenula, and bacteria of the genera E. coli, Pseudomonas fluorescens, Citrobacter, Bacillus subtilis, Pseudomonas, Acinetobacter, Bacillus and Alcaligenes. In addition, some algae such as Arthrospira maxima, Chlorella sp. and Scenedesmus obliquus managed to remove between 86% and 90% of the cyanide in polluted waters (Cartagena, 2019).

Influence of Pseudomonas aeruginosa on benzene reduction

In the Paca lagoon, the influence of Pseudomonas aeruginosa on benzene reduction by bioremediation was remarkable. Using a factorial experimental design, 93.63% of benzene (0.043 mg/L) was removed in 48 hours, with a pH of 6 and a concentration of 18,108 CFU/mL, exceeding environmental quality standards (Yaranga-Piñares, 2022).

Future Perspectives of the Use of Pseudomonas

Bioremediation with Pseudomonas spp. has considerable potential in various areas due to its adaptability and efficiency in degrading pollutants. Future prospects in this field can be approached from several angles:

Development of Bioengineering Techniques:

Genetic engineering could further enhance the capabilities of Pseudomonas spp. by introducing genes that enhance the degradation of specific pollutants. For example, genetic manipulation to increase biosurfactant production or improve tolerance to extreme conditions could lead to greater efficiency in bioremediation.

Applications in Extreme Environments:
The use of Pseudomonas spp. in extreme environments, such as saline, cold soils or soils contaminated with heavy metals, can be optimized. Future research could focus on identifying and developing strains adapted to these conditions to maximize their efficacy.
Microbial Consortia Improvement:
The combination of Pseudomonas spp. with other microorganisms in microbial consortia can enhance bioremediation. The study of microbial interactions and the selection of optimal consortia could lead to a more complete and rapid degradation of contaminants.
Large-scale applications:
The scalability of bioremediation techniques is a crucial challenge. Future research should focus on transitioning from laboratory studies and microcosms to large-scale applications in contaminated fields, water bodies, and coastal environments.
Monitoring and Evaluation Technologies:
The development of advanced monitoring and evaluation technologies, such as real-time sensors and metagenomic analysis, could improve the efficiency of bioremediation processes by enabling continuous and accurate monitoring of microbial activity and contaminant degradation.
Industrial Applications:
The use of Pseudomonas spp. in industrial wastewater treatment and oil spill mitigation could be expanded. Collaboration with industry to develop tailor-made solutions that comply with environmental regulations and are economically viable will be crucial.
Environmental Impact and Safety:
Although bioremediation is generally safe and environmentally friendly, it is essential to continue to assess the potential long-term effects on the environment. Biosafety research and minimization of environmental risks will be key areas to ensure that bioremediation applications are sustainable.

Conclusions

Bioremediation using Pseudomonas spp. represents a promising and versatile technology to address environmental pollution. The studies and cases analyzed show the effectiveness of these bacteria in the degradation of hydrocarbons, heavy metals, and nitrogenous contaminants in a variety of environments, from soils and waters to marine and saline environments.

Pseudomonas aeruginosa and Pseudomonas putida, in particular, have demonstrated remarkable capabilities for the degradation of toxic compounds, offering sustainable and ecological solutions for the remediation of contaminated sites. The high adsorption capacity of metal ions and the efficiency in the removal of nitrogenous compounds highlight its versatility and usefulness in different bioremediation applications.

Advancement in research and development in this field will open up new opportunities to improve existing techniques and expand their application on a larger scale. The integration of biotechnology, bioengineering and advanced monitoring techniques will be crucial to maximize the efficiency and effectiveness of bioremediation.

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