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Review Article

ADVANCES IN BIOREMEDIATION AGENTS AND PROCESSES FOR REMOVAL OF PERSISTENT CONTAMINANTS FROM ENVIRONMENT

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ABSTRACT

The development of bioremediation agents and processes-a sustainable solution to environmental pollution has advanced significantly. This is particularly valid when handling persistent pollutants such as Polycyclic Aromatic Hydrocarbons (PAHs). This study reviews the state-of-the-art in bioremediation technology, emphasizing the vital role that bacteria and their metabolic pathways play in the breakdown of pollutants. Microorganisms, which can be any type of fungus or bacteria, have been employed because of their unique capacity to break down a broad spectrum of contaminants. A thorough grasp of the metabolic subtleties of these bacteria is essential for optimizing bioremediation methods, especially with regard to PAH breakdown. The exploration of eco-friendly technologies, such bioaugmentation and biostimulation, emphasizes the commitment to eco-friendly approaches to environmental remediation. This review presents strong case studies and acknowledges ongoing issues to demonstrate the practical effectiveness of bioremediation. Future advancements in bioremediation-a crucial aspect of environmental management-may be possible through the combination of genetic engineering and artificial intelligence, which could assist overcome current obstacles.

Keywords: Bioremediation, PAH (Polycyclic Aromatic Hydrocarbons), Bioaugmentation, Biostimulation, Phytoremediation

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INTRODUCTION

Environmental contamination in the twenty-first century is creating hitherto unseen problems because persistent toxins are becoming a greater hazard to ecosystems and human health [1]. In the face of this oncoming calamity, bioremediation has emerged as a glimmer of hope since it offers a sustainable and environmentally friendly way to mitigate the consequences of pollution. This study looks at the current developments in bioremediation, with a focus on the critical role that bacteria and their metabolic pathways play in eliminating persistent pollutants, especially Polycyclic Aromatic Hydrocarbons (PAHs) [1, 2]. In order to promote a cleaner and healthier planet as the world struggles with the effects of industrialization, urbanization, and other anthropogenic activities, it is imperative to look into the most recent developments in bioremediation [3–5].

Bioremediation is a biological process that uses the natural characteristics of living organisms to remediate damaged environments [6]. Compared to conventional remediation approaches, which sometimes involve harsh chemicals and large equipment, bioremediation offers a sustainable alternative that upholds the principles of ecological balance [7, 8]. Microbes, including bacteria, fungi, and algae, are at the forefront of this biological army because they have the ability to metabolize and alter a broad variety of contaminants [3, 9]. The significance of microorganisms in environmental cleanup has been emphasized by recent advances in microbial ecology, genetics, and biotechnology, which have made it possible to identify and enhance microbial strains with unparalleled remediation capability [9].

The need to handle persistent contaminants is particularly critical when it comes to the class of organic pollutants known as Polycyclic Aromatic Hydrocarbons (PAHs), which are notorious for their resistance and environmental persistence [10]. The need to handle persistent contaminants is particularly critical when it comes PAHs, which are notorious for their resistance and environmental persistence. Their presence poses a serious risk to both human health and the environment because it is mutagenic and carcinogenic. Therefore, understanding how PAHs are broken down by microbial metabolism is crucial to developing effective and long-lasting bioremediation methods [11].

In the face of global environmental concerns, the convergence of bioremediation, sustainable technologies, and microbial metabolic pathways offers a glimmer of hope for a cleaner and more resilient Earth [12]. This review provides readers with an in-depth understanding of the cutting-edge tactics that are revolutionizing the environmental remediation landscape and walks them through recent advancements in these domains. With a particular focus on PAHs, we set out to investigate the intricate relationships that exist between bacteria and pollutants in order to fully realize the potential of bioremediation and its role in promoting a harmonious and sustainable coexistence between humans and the environment. The structure of the review article was designed based on keywords namely Bioremediation, PAH (Polycyclic Aromatic Hydrocarbons), Bioaugmentation, Biostimulation, Phytoremediation. Articles from peer-reviewed journals focusing on advancements achieved in the field of bioremediation for the last 20 y were considered. Articles discussing the development of bioremediation agents and processes as a sustainable solution to environmental pollution were selected.

Microbes as bioremediation agents

Microbes, including bacteria, fungus, and algae, are essential agents in the field of bioremediation because of their remarkable capacity to degrade and alter a wide range of pollutants. Microbial species' unique metabolic abilities and diversity make them effective tools for environmental restoration.

Bacterial bioremediation

Degradative Enzymes: Bacteria are essential to bioremediation because they produce a range of enzymes that help break down contaminants. As an illustration, certain bacteria produce oxygenases, which initiate the oxidation reactions that degrade hydrocarbons, including PAHs [13]. Formation of Biofilms: Bacterial biofilms improve the efficiency of pollutant decomposition. Because biofilms protect bacteria, they can multiply and efficiently degrade contaminants under unfavorable conditions [14, 15].

Fungal bioremediation

Hyphal Networks: Because of their extensive hyphal networks, fungi are very good at decomposing complex chemical compounds. These networks have the capacity to contaminate soil or water, increasing the accessibility of pollutants for fungi that generate fungal enzymes [16].

Ligninolytic Enzymes: Two ligninolytic enzymes that fungi produce are laccases and peroxidases, which are crucial for breaking down refractory pollutants like PAHs [17]. These enzymes aid in the oxidation and mineralization of aromatic compounds [16].

Algal bioremediation

Phycoremediation: Algae, particularly micro-and macroalgae, participate in bioremediation through a process known as phycoremediation [18]. Algae's capacity to take up and retain pollutants-especially heavy metals-from their surroundings helps lower the concentrations of pollutants [19].

Oxygen Production: As algae carry out photosynthetic processes, oxygen is released into the atmosphere. The aerobic conditions created by this oxygen can subsequently be used to benefit other bacteria that break down organic pollutants [20].

Genetic engineering and synthetic biology

Modified Microbial Strains: Advances in genetic engineering have made it feasible to produce genetically modified microorganisms with enhanced pollution-degrading abilities [21]. This entails altering microbes to express certain enzymes or metabolic pathways meant to combat persistent contaminants.

Synthetic Biology Approaches: Through the application of techniques unique to synthetic biology, researchers can design novel microbial systems that are primed for successful bioremediation. This technique has a great deal of promise for creating microbes that are especially suited to certain pollutants and environmental conditions [22].

Bioremediation consortia

Microbial Interactions: Bioremediation is often more successful when different microbial species work together in consortia. Microbial interactions within these consortia may provide synergistic effects, in which the metabolic activities of one species enhance the growth and function of others [23].

Complementary metabolic pathways among the microorganisms in a consortium can facilitate the gradual degradation of complex pollutants [24]. This collaborative approach enhances the overall efficacy of the bioremediation processes.

Understanding the intricate methods by which microorganisms act in bioremediation is essential to maximizing their use in a variety of environmental situations. Research on microbial communities and their metabolic pathways is still in its early stages, but it holds promise for novel and durable treatments for persistent environmental pollutants.

Metabolic pathways in bioremediation

Metabolic pathways are crucial to bioremediation procedures because they provide a comprehensive understanding of how microorganisms metabolize and alter pollutants. The effectiveness of bioremediation depends on bacteria's ability to use specific metabolic pathways that encourage the breakdown or transformation of contaminants into less dangerous forms. In this section, the details of metabolic pathways in bioremediation, highlighting its application in the elimination of persistent pollutants is discussed.

Initial recognition and uptake

The metabolic process in bioremediation commonly begins when microbial cells recognize and absorb pollutants. Pollutants can be absorbed by microbes through specialized receptors and transporters, which allows them to enter cells and interact with intracellular machinery [25].

Enzymatic degradation

Once the pollutants are inside the microbial cell, they are broken down by enzymes. When it comes to PAHs, which are complex chemical compounds that are often found in contaminated environments, certain enzymes, such as oxygenases and dehydrogenases, are crucial. These enzymes initiate the breakdown of the aromatic rings of PAHs, a process known as ring cleavage [26].

Aerobic and anaerobic pathways

In bioremediation, aerobic and anaerobic metabolic pathways can be discovered, depending on the oxygen content. Aerobic degradation requires oxygen to break down contaminants, whereas anaerobic processes occur in the absence of oxygen. It is well recognized that both aerobic and anaerobic bacteria are significant for PAHs, with each pathway offering certain advantages in various environmental conditions [27].

Intermediate metabolites

The degradation of pollutants often results in the formation of intermediate metabolites. These bridges may decompose even more into simpler compounds, or they may out to be less dangerous than the original contaminants [28]. Understanding what will happen to these intermediaries is crucial to ensuring that the bioremediation process results in the safe and complete removal of pollutants.

Co-metabolism

The process by which bacteria alter pollutants as a byproduct of their primary metabolic activities is known as co-metabolism [29]. Polycyclic Aromatic Hydrocarbons, or PAHs, are secondary carbon sources that some microorganisms use in their basic metabolism. This concept is particularly important when thinking about mixed microbial communities, in which a variety of species collaborate to increase the overall efficacy of bioremediation [30].

Genetic modification and engineering

Recent advancements in genetic engineering have made it possible for researchers to modify the genetic makeup of microorganisms to increase their bioremediation potential. This entails introducing genes that encode specific enzymes or metabolic pathways to boost microbial strains' efficiency and versatility in degrading certain pollutants, such as PAHs [31].

Cross-feeding and synergistic interactions

Microbial communities often generate compounds that serve as other species' substrates, a phenomenon called cross-feeding and synergistic interactions. The ability of bacteria to cooperate could improve the effectiveness of bioremediation since they play specialized functions in different phases of degradation [32].

Understanding these metabolic pathways is necessary to optimize bioremediation techniques. To develop tailored approaches that function in many environmental contexts, scientists are attempting to pinpoint the specific enzymes and genetic pathways implicated in the degradation of pollutants. As we learn more about microbial metabolism, the possibility of using these pathways to combat environmental pollution-including persistent pollutants like PAHs-is increasing.

Sustainable technologies in bioremediation

The incorporation of sustainable technology is crucial for enhancing the efficiency and environmental sustainability of bioremediation processes. Remedial actions are assured to be both successful in getting rid of pollutants and compliant with long-term ecological balance and environmental conservation principles when sustainable procedures are employed. Several environmentally friendly technologies utilized in bioremediation in are discussed below:

Bioaugmentation

Bioaugmentation is the process of introducing specific microbial strains or consortia into contaminated environments with the aim of increasing the ability of the existing microbial population for degradation [33]. This targeted approach lessens the need for external inputs like chemical supplements while promoting the microbial diversity that is already present in the environment. By selecting and enhancing natural microorganisms, bioaugmentation reduces the negative effects of introducing foreign species on the ecosystem [34].

Biostimulation

Enhancing the activity of native microorganisms by the provision of co-substrates, electron acceptors, or essential nutrients is the aim of biostimulation. This sustainable technique is based on the natural metabolic ability of the microorganisms at the contaminated location [33]. By boosting microbial activity using organic materials like compost, pollutants can be broken down naturally without the use of synthetic chemicals, which makes the remediation process more sustainable and eco-friendlier [35].

Phytoremediation

Phytoremediation uses the natural ability of plants to take in, hold, and decompose pollutants. When it comes to pollutants that are absorbed by plants, such as organic compounds and heavy metals, this approach is particularly beneficial. Once they have drawn contaminants from the soil or water, plants can be harvested and disposed of properly. Since phytoremediation eliminates the need for energy-intensive mechanical processes and chemical treatments, it is a sustainable and environmentally friendly way to clean up the environment [36].

Green and sustainable materials

Natural nanomaterials and bio-based sorbents are two examples of sustainable and green materials that can be used to make remediation processes more ecologically friendly [37]. These substances have the ability to effectively bond with contaminants and aid in their removal from the environment. By using sustainable materials, researchers and practitioners can reduce the bioremediation technology's overall environmental impact [4].

Energy-efficient techniques

Another top concern for sustainable bioremediation systems is their energy efficiency. This means that by optimizing operating parameters like temperature, pH, and nutrient concentrations, microbial activities can be maximized with the least amount of energy input. Additionally, using renewable energy sources like solar or wind power for cleanup operations reduces the carbon footprint associated with traditional energy-intensive techniques [38].

Integrated green engineering

The concept of designing cleanup processes to be naturally sustainable is known as "green engineering". This means producing as little waste as possible, utilizing low-impact technologies, and incorporating environmental safety principles into engineering solutions. By implementing green engineering techniques, bioremediation programmers can achieve their objectives while mitigating negative effects on the surrounding ecosystems [39].

In summary, as part of an all-encompassing strategy for environmental cleanup, eco-friendly bioremediation technologies highlight the need of minimizing environmental impact, maximizing natural processes, and promoting ecosystem health. The integration of these sustainable activities enhances the overall efficacy and acceptance of bioremediation as a feasible and environmentally desirable solution to persistent environmental pollutants.

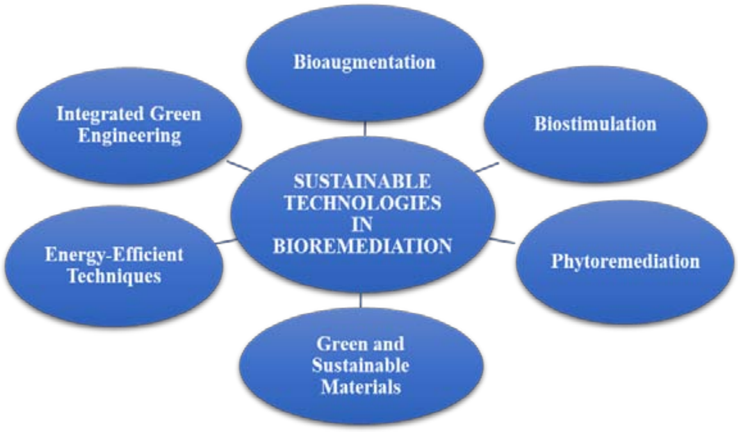

Fig. 1: Sustainable technologies in bioremediation (Created by Authors)

Case studies

Exxon valdez oil spill-bacterial remediation

Relating to the 1989 Exxon Valdez oil spill off the coast of Alaska, it was one of the worst environmental disasters ever documented. The application of bioremediation, particularly bacterial remediation, played a significant element in reducing the consequences. Scientists introduced the naturally occurring oil-eating bacterium Alcanivorax borkumensis into the affected areas. These particular bacteria expedited the natural restoration process by efficiently breaking down hydrocarbons using the crude oil spill as a source of carbon and energy. This case demonstrated the efficacy of microbial agents in the cleanup of large oil spills [40].

River thames-mycoremediation of heavy metals

The health of people and aquatic life in the United Kingdom is at risk due to heavy metal contamination in the river Thames. Mycoremediation, a form of bioremediation that makes use of fungi, was employed to address this issue. Researchers introduced Pleurotus ostreatus, a white-rot fungus known for its ability to absorb and accumulate heavy metals. The mycelium of the fungus served as a biofilter, removing contaminants from the water [41]. The effectiveness of mycoremediation in addressing metal contamination in aquatic environments is demonstrated by this case study.

Deepwater horizon oil spill-bioaugmentation with hydrocarbon-degrading bacteria

2010's Deepwater Horizon oil leak in the Gulf of Mexico sparked a huge cleanup effort to reduce ecological harm. The purposeful introduction of particular microbes, known as bioaugmentation, was used to accelerate the oil's natural breakdown process. Hydrocarbon-degrading bacteria, such as Alcanivorax and Pseudomonas strains, were introduced by researchers to the oil-contaminated sites. Because these bacteria were thriving in the hydrocarbon-rich environment, the breakdown of oil components was accelerated. The effective use of bioaugmentation in this instance highlighted the ability of specially designed microbial communities to handle intricate situations involving oil spills [42].

Industrial site contaminated with polycyclic aromatic hydrocarbons (PAHs)-biostimulation

A site contaminated by pervasive and highly hazardous Polycyclic Aromatic Hydrocarbons (PAHs) was selected for bioremediation by biostimulation. Organic additives were used by researchers to boost microbial activity and encourage PAH breakdown. The introduction of electron acceptors and nutrients produced the ideal environment for native microbes to degrade complex PAH compounds. PAH concentrations significantly decreased over time, demonstrating the efficacy of biostimulation in the remediation of persistent organic pollutants in industrial environments [43].

Landfill leachate treatment-phytoremediation

Leachate from landfills frequently contains a variety of contaminants, such as organic compounds and heavy metals. In one example study, landfill leachate was treated by phytoremediation with plants like Phragmites australis or common reed. Pollutants were taken up and stored by the plants' roots, and the breakdown of organic contaminants was aided by rhizospheric microbes that were connected to the plants [44]. This example showed how phytoremediation can be used to treat landfill leachate in an environmentally friendly and visually appealing way, reducing the negative effects of traditional leachate disposal on the environment.

Challenges and future prospects

Challenges in bioremediation

Microbial interactions and consortia complexity

Complex interactions are frequently exhibited by microbial populations involved in bioremediation. It can be difficult to comprehend and control these relationships for the best possible pollutant degradation. Improvements in metagenomics and systems biology can help us comprehend the dynamics of microbial consortia, which will help us create microbial communities that are more productive for a variety of contaminants [45].

Optimization of bioremediation conditions

Environmental factors, including pH, temperature, and nutrient availability have a significant impact on bioremediation efficacy. It is difficult to optimize these parameters for various contaminants and environments. By combining artificial intelligence, remote sensing technologies, and smart sensors, bioremediation parameters may be monitored and adjusted in real-time, increasing overall efficiency [46].

Regulatory hurdles and public perception

The challenge lies in the requirement for regulatory frameworks governing bioremediation to strike a balance between public safety and environmental conservation. Regulatory problems also arise from public opinion and adoption of Genetically Modified Organisms (GMOs) in bioremediation. Working together, researchers, authorities, and public education initiatives can assist allay worries and guarantee the morally and responsibly applied bioremediation technology.

Long-term stability and monitoring

Two major problems are sustaining bioremediation's long-term efficacy and keeping an eye on post-remediation situations. Remediated sites may not be as stable if there are abrupt changes in the surrounding environment or the introduction of new pollutants [47]. Creating long-term monitoring plans that incorporate ecological modelling and cutting-edge sensing technology can shed light on the long-term effectiveness of bioremediation techniques.

Genetic diversity and adaptation

Microbial populations may have trouble changing over time and adjusting to a variety of contaminants. The ability of microbial communities to digest particular pollutants can be influenced by genetic variety [48]. Genetic restrictions can be addressed by increasing the genetic diversity of microbial consortia and engineering microorganisms with improved adaptability through synthetic biology techniques.

Future prospects in bioremediation

Artificial intelligence and machine learning

Utilizing AI and machine learning algorithms to optimize bioremediation processes through data analysis, prediction, and optimization. This entails forecasting the best microbial consortiums, evaluating the surroundings, and creating customized bioremediation plans [49].

Genetic engineering and synthetic biology

Ongoing progress in genetic engineering to create customized microbes with improved capacity to degrade pollutants [50]. Through the use of synthetic biology techniques, designer microorganisms that are tailored to particular pollutants can be created [51].

Innovative bioremediation technologies

To increase the range of pollutants that may be efficiently addressed, research into new bioremediation technologies such as microbial fuel cells, electro-bioremediation, and nanotechnology-based techniques [49].

Global collaboration and knowledge sharing

To speed up the creation and application of efficient bioremediation techniques worldwide, there should be more international cooperation and knowledge exchange between academics, businesses, and regulatory agencies [49].

Circular economy integration

By incorporating bioremediation into circular economy models, contaminants can be converted into useful resources, promoting environmentally sound and financially feasible environmental remediation techniques [52].

Scientists, engineers, politicians, and the general public must work together in a multidisciplinary manner to address the issues facing bioremediation and embrace its future possibilities. To fully realize the potential of bioremediation for a cleaner and more sustainable environment, ongoing research, innovation, and cooperation will be essential.

CONCLUSION

Bioremediation appears as a ray of hope at the nexus of scientific advancement and environmental care. In addition to providing a workable solution for the removal of persistent toxins, bioremediation reflects the spirit of sustainable and ecologically harmonious technologies that can open the door to a cleaner and healthier planet via ongoing study, innovation, and cooperative efforts. However, it is crucial to acknowledge the current barriers, which range from legal restrictions to the need for a more comprehensive understanding of microbial ecology in complex environments. To solve these challenges and foster an environment that is conducive to the widespread use of bioremediation, scientists, policymakers, and industry participants must collaborate. In the future, integrating cutting-edge technologies like artificial intelligence could help improve bioremediation procedures and make more accurate outcome predictions. Another intriguing direction for future research is the creation of genetically modified organisms that are specifically engineered to target particular pollutants, thereby expanding the potential for bioremediation.

ABBREVIATION

Genetically Modified Organisms (GMOs), Polycyclic Aromatic Hydrocarbons (PAH).

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CONFLICTS OF INTERESTS

Declared none

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