MICROBIAL BIOACTIVES REVIEWS

Biodegradation as a Sustainable Solution for Environmental Restoration: Bridging the Gap

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Abstract

Microbial biodegradation, as a sustainable solution for environmental restoration, has gained significant attention in recent years. With growing concerns about pollution, waste management, and the depletion of natural resources, there is a pressing need to explore eco-friendly approaches to mitigate environmental degradation. Biodegradation offers a promising avenue for addressing these challenges by harnessing the power of nature's own processes to break down and eliminate pollutants. Enzymatic processes, such as those involving hydrolases, oxidases, and dehydrogenases, are what allow them to biodegrade contaminants into less toxic forms. The genetic foundation of microbial biodegradation has been better understood because to developments in genomics and molecular biology. Techniques such as biostimulation and bioaugmentation are used to improve the performance of microbial communities. While bioaugmentation adds specialized microbial consortia to speed up pollution breakdown, biostimulation includes adding nutrients and electron acceptors to encourage natural microbial populations. Temperature, nutrition availability, and pH all affect how well microorganisms biodegrade materials. Optimizing the results of biodegradation requires customizing these settings to particular pollutants and habitats. The environmentally acceptable and economical method of cleaning up the environment is microbial biodegradation. We can solve pressing pollution challenges while preserving and restoring ecosystems by utilizing the potential of microbial communities. The importance of microbial biodegradation is emphasized in this abstract, which also calls for more study and practical implementation of these communities for a better, cleaner Earth.

Keywords: Microbial biodegradation, Environmental cleanup, Pollutant biodegradation, Microbial communities, Biostimulation.

Significance | This review describes CRISPR-Cas systems as an advanced tool in microbial biotechnology with a great potential for genetic manipulation and disease intervention.

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Editor Md Fakrudin. and accepted by the Editorial Board Feb 11, 2024 (received for review Dec 03, 2023)

Introduction

Biodegradation, defined as the physiologically accelerated reduction in chemical compound complexity, is a fundamental process where living microbial organisms break down organic compounds into simpler substances (San et al., 1994; Lacatusu et al., 2009). The subsequent conversion of these degraded products into inorganic molecules is termed mineralization, although any biological-mediated alteration of a substrate is broadly referred to as biodegradation (Wunch et al., 2002). Understanding the microorganisms involved in biodegradation is crucial for comprehending this process, wherein microbial enzymes and metabolic activities transform organic contaminants, using them as sources of energy and carbon during growth (Hofrichter & Fritsche, 2008).

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Please cite this article:
Mahfoudh A.M. Abdulghani, Fouad Saleh AL Suede et al. (2024). Biodegradation as a Sustainable Solution for Environmental Restoration: Bridging the Gap, Microbial Bioactives, 7(1), 1-11, 9377

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(http://microbialbioactives.emanresearch.org).

https://doi.org/10.25163/microbbioacts.719377

A diverse array of microorganisms including bacteria, yeasts, and fungi participate in biodegradation, while algae and protozoa play lesser-known roles (Chandran et al., 2011). Despite variations in biodegradation mechanisms, carbon dioxide typically represents the final metabolic endpoint (Ramesh et al., 2012). Biodegradation occurs under anaerobic (without oxygen) or aerobic (with oxygen) conditions, influencing how organic materials decompose (Labuzek et al., 2012).

Biodegradable materials encompass a wide range, from synthetic substances akin to plant and animal matter to natural organic compounds. Microbes possess diverse catabolic activities enabling them to degrade or convert numerous substances, such as metals, PCBs, hydrocarbons, and PAHs (Leitão et al., 2009). Biodegradation finds extensive application in environmental restoration, often termed bioremediation, and ecological studies (Lacatusu et al., 2009).

Bioremediation processes typically progress through three stages: natural attenuation, biostimulation, and bioaugmentation (Figure 1). Natural attenuation involves indigenous microorganisms attenuating pollutants without external intervention. Biostimulation supplements these systems with nutrients and oxygen to enhance degradation efficiency, while bioaugmentation introduces specialized microorganisms to accelerate pollutant breakdown beyond natural capabilities (Diez et al., 2010).

Effective bioremediation hinges on the ability of microorganisms to rapidly adapt and utilize target contaminants under specific environmental conditions, influenced by factors like temperature, pH, and nutrient availability (Keum et al., 2009; Hofrichter & Fritsche, 2008). Genetically modified microbes (GEM) show promise for enhancing degradation capabilities, yet face regulatory and environmental challenges for widespread application (Menn et al., 2008).

This review explores biodegradation's pivotal role in environmental sustainability, elucidating microbial mechanisms involved in contaminant breakdown across diverse ecosystems. By examining biodegradation within the context of bioremediation strategies and the variables impacting its efficacy, this article aims to underscore its potential as a sustainable approach for environmental conservation. Understanding the complexities and benefits of biodegradation is essential for harnessing its full potential in safeguarding and restoring our fragile ecosystems.

Microorganisms play a crucial role in the biodegradation of pollutants, facilitating environmental bioremediation processes. Biodegradation refers to the natural breakdown of organic matter into simpler nutrients that can be recycled by other species, primarily mediated by a diverse array of living organisms, including bacteria, yeast, and fungi (Lesley et al., 2012). These microorganisms utilize their enzymatic and metabolic diversity to degrade, accumulate, or transform various substances such as metals, radionuclides, polychlorinated biphenyls (PCBs), polyaromatic hydrocarbons (PAHs), and hydrocarbons like oil (Lesley et al., 2012).

Several classes of biodegradable pollutants pose environmental challenges due to their persistence and toxicity. Hydrocarbons, which include aliphatic and aromatic compounds like PAHs, are prevalent pollutants derived from industrial activities (McMurry, 2000; Piotrowska et al., 2003; Okere & Semple, 2012). PAHs, in particular, are known for their persistence in soil and water environments, posing risks to ecosystems and human health through bioaccumulation (Piotrowska et al., 2003).

PCBs, historically used in various industrial applications for their chemical stability and insulation properties, are another group of persistent pollutants linked to environmental contamination and health hazards such as endocrine disruption and carcinogenicity (Méndez et al., 2010). Pesticides, employed extensively in agriculture, undergo degradation primarily through microbial action in soil, where fungi and bacteria metabolize these chemicals over time (Vargas, 1975).

Synthetic dyes, essential in industries like textiles and printing, present challenges due to their complex aromatic structures, which hinder complete biodegradation and often necessitate physical or chemical treatment methods for wastewater disposal (Raffi et al., 1997; Bianchi et al., 1998; Verma et al., 2003). Radionuclides, characterized by unstable nuclei emitting radiation during decay processes, require specialized microbial strategies for remediation and containment (Harwood & Herring, 2002).

Heavy metals, distinct from organic pollutants, undergo bioremediation processes like biosorption, bioleaching, biomineralization, and enzymatic transformation facilitated by microbial interactions, aiming to immobilize or transform these metals into less toxic forms (Lloyd et al., 2001).

The study and application of microbial biodegradation capabilities in bioremediation strategies highlight their potential for mitigating environmental contamination. Understanding these processes is essential for developing sustainable solutions that safeguard ecosystems and human health from the impacts of industrial pollutants. By harnessing microbial diversity and metabolic activities, biodegradation offers promising avenues for achieving environmental sustainability and restoring polluted environments.

Bacterial degradation

The degradation of environmental contaminants by microorganisms is extensively documented in the literature, highlighting their pivotal role in bioremediation processes. Hydrocarbon-degrading bacteria, such as those described by Yakimov et al. (2007), specialize in consuming hydrocarbons as their primary energy and carbon source. Both aerobic and

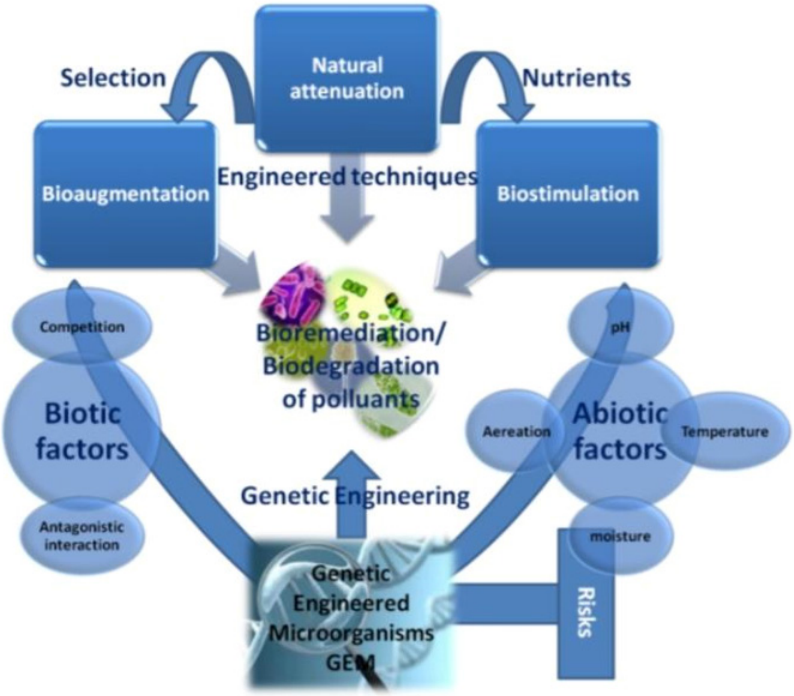

Figure 1. Natural attenuation is included in bioremediation of pollutants using microorganisms' biodegradation abilities. However, it may be improved by designed procedures, such as the addition of certain microbes (bioaugmentation) or biostimulation, which involves the provision of nutrients. GEM also uses genetic engineering to enhance microorganisms' capacity for biodegradation. However, there are several variables influencing this procedure's effectiveness as well as the dangers connected to using GEM in the field. (https://images.app.goo.gl/ALLAQ3m7ouHozB1T9).

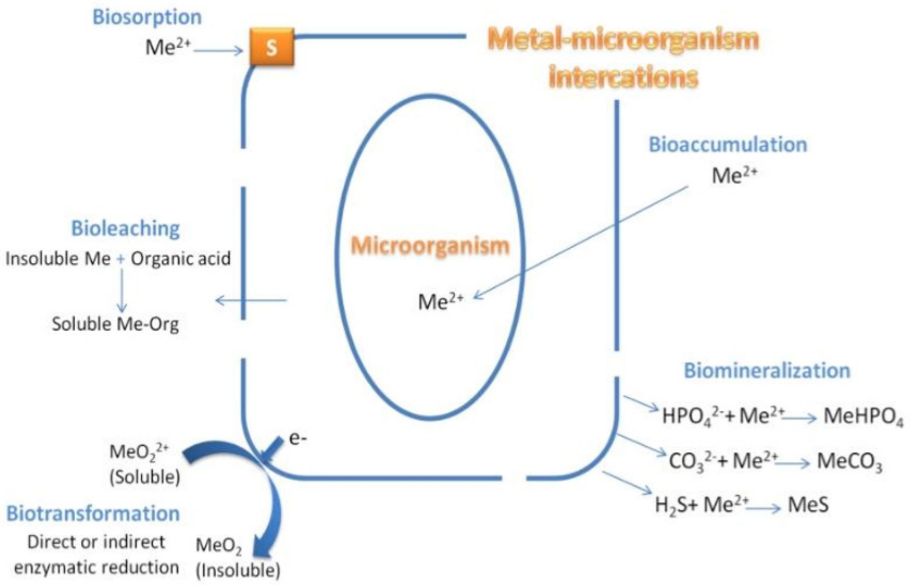

Figure 2. Microbial processes used in bioremediation technologies modified from Lloyd and Lovley.

anaerobic environments support the biodegradation of hydrocarbons, as evidenced by studies on nitrate-reducing bacterial strains like Pseudomonas sp. and Brevibacillus sp. isolated from petroleum-contaminated soil (Boronin et al., 2000). Anaerobic biodegradation, emphasized by Wiedemeier et al. (1984), is particularly significant in certain contexts.

In marine environments, Floodgate et al. (1984) identified 25 species of hydrocarbon-degrading bacteria, underscoring the diversity and ecological importance of these microbes. Kafilzadeh et al. (2011) further classified 80 bacterial strains into 10 genera, including Alcaligenes, Shigella, Escherichia, Acinetobacter, Enterobacter, Klebsiella, Bacillus, and Corynebacterium, with Bacillus demonstrating superior hydrocarbon degradation capabilities. Gram-negative bacteria, particularly those from the genus Pseudomonas, are frequently noted for their proficiency in breaking down aromatic hydrocarbons (Bisht et al., 2015).

Moreover, microbial communities comprising diverse species are often more effective in degrading complex organic contaminants than individual strains due to their collective enzymatic capacities (Fritsche et al., 2005). For instance, anaerobic bacteria engage in reductive dehalogenation of PCBs, while aerobic bacteria oxidize lower chlorinated biphenyls (Seeger et al., 2001). Both Gram-negative (e.g., Burkholderia, Pseudomonas) and Gram-positive bacteria (e.g., Rhodococcus, Bacillus) have been studied for their ability to degrade PCBs, reflecting the diverse metabolic pathways employed in these processes (Petric & Hrak, 2007).

Beyond hydrocarbons, microorganisms play crucial roles in pesticide degradation, with bacterial strains like Providencia stuartii identified for their ability to break down chlorpyrifos in agricultural soils (Lakshmi et al., 2008). Similarly, bacteria from genera such as Bacillus, Staphylococcus, and Stenotrophomonas exhibit capabilities in degrading dichlorodiphenyltrichloroethane (DDT) in various environmental contexts (Kanade et al., 2012).

Azo dyes, widely used in industries such as textiles and printing, pose challenges due to their complex structures, but microbial consortia involving species like Pseudomonas sp., Enterococcus sp., and Proteus sp. have shown promise in their biodegradation and decolorization (Chaube et al., 2010). However, specific bacteria like Shewanella decolorationis are noted for their exceptional efficacy in azo dye removal (Hong et al., 2007).

In the realm of heavy metals, microorganisms utilize diverse mechanisms such as adsorption, absorption, methylation, oxidation, and reduction for bioremediation (Khalid et al., 2010). Dissimilatory metal reduction, a process where bacteria use metals as terminal electron acceptors in anaerobic respiration, exemplifies one effective strategy for reducing metal toxicity (Fern et al., 2012). This approach includes the reduction of Cr(VI) to Cr(III) and Se(VI) to elemental Se, demonstrating microbial versatility in environmental detoxification (Yee et al., 2007; Zhu et al., 2008).

In summary, microorganisms exhibit diverse metabolic capabilities that make them indispensable in the biodegradation of environmental pollutants, offering promising avenues for sustainable environmental management and restoration.

PGPR and PGPB degradation

Plant-associated bacteria, including rhizospheric bacteria (which inhabit the vicinity of plant roots) and endophytic bacteria (non-pathogenic bacteria naturally occurring within plants), play pivotal roles in the biodegradation of toxic organic compounds in contaminated soil, and they also enhance phytoremediation processes (Divya et al., 2011). Specifically, plant growth promoting rhizobacteria (PGPR), a type of naturally occurring soil bacteria, colonize plant roots and stimulate plant growth, thereby contributing to enhanced biodegradation and remediation of pollutants (Saharan et al., 2011).

Certain plants facilitate the growth of bacteria capable of breaking down hydrocarbons and polycyclic aromatic hydrocarbons (PAHs) by releasing structural analogs like phenols. Notably, Pseudomonas spp. are significant in these plant-microbe systems due to their dual capability of hydrocarbon degradation and PGPR activity (Hontzeas et al., 2004). In polluted environments, the rhizosphere of plants harbors a diverse array of PAH-degrading bacteria; for instance, Chen et al. (2010) identified two strains of Lysini bacillus from such communities. Additionally, members of genera such as Luteibacter, Williamsia, and Rhodococcus have been found to degrade polychlorinated biphenyls (PCBs) in the rhizosphere and root zone of mature trees, underscoring the potential of rhizoremediation strategies to enhance PCB biodegradation in situ (Leigh et al., 2006).

In agricultural contexts, Azospirillum lipoferum, a free-living nitrogen-fixing bacterium commonly found in the rhizoplane of plants, has been utilized for the breakdown of malathion, a widespread organophosphorus insecticide (Saharan et al., 2011). Moreover, research indicates that rhizobacteria promoting plant growth can aid in the removal of heavy metals from polluted soils. By leveraging plant growth promoting bacteria (PGPB) in metal phytoremediation, it is possible to mitigate the inhibitory effects of high metal concentrations on plant development, thereby enhancing overall remediation efficacy (Glick et al., 2010). Rhizoremediation, which integrates specific bacteria with plant systems, represents a promising technology to improve pollutant extraction efficiency (Jing et al., 2007).

In summary, plant-associated bacteria play crucial roles in enhancing the biodegradation of pollutants and improving the effectiveness of phytoremediation strategies. By harnessing the symbiotic relationships between plants and specialized bacteria, researchers are advancing environmentally sustainable approaches to address contamination in diverse ecosystems.

Microfungi and mycorrhiza degradation

Microfungi represent a diverse class of eukaryotic organisms, encompassing both extensively mycelial molds and unicellular yeasts (Spellman et al., 2008). Molds typically develop as true hyphae that form mycelia, whereas yeasts generally grow as single cells or generate pseudomycelia. As crucial agents in the carbon cycle, fungi play a pivotal role in the biosphere by metabolizing dissolved organic materials, akin to bacteria, thereby contributing significantly to the cycling of nutrients and organic matter (Matavuly et al., 2009).

Unlike bacteria, fungi thrive in environments with low moisture and acidic conditions, which enables them to effectively degrade organic materials (Matavuly et al., 2009). Fungi are particularly efficient due to their possession of extracellular multienzyme complexes, which are essential for breaking down complex organic compounds such as polymeric materials found in nature (Khan et al., 2006). Their hyphal structures facilitate nutrient transfer and redistribution within their mycelium, allowing fungi to colonize and penetrate substrates rapidly (Khan et al., 2006).

A notable symbiotic relationship exists between fungi and the roots of vascular plants, known as mycorrhiza. In mycorrhizal associations, fungi colonize plant roots either extracellularly (ectomycorrhizal fungi) or intracellularly (arbuscular mycorrhizal fungi), significantly influencing soil chemistry and enhancing plant nutrition and resilience (Khan et al., 2006). Mycorrhizoremediation, the application of mycorrhizal fungi in bioremediation processes, underscores their potent capabilities in mitigating environmental pollution and recycling recalcitrant polymers like lignin (Fritsche et al., 2005).

In conclusion, fungi represent powerful agents in the degradation of hazardous pollutants and play a crucial role in the sustainability of ecosystems through their unique metabolic capabilities and symbiotic relationships with plants. Their ability to thrive in diverse environmental conditions makes them invaluable contributors to bioremediation efforts aimed at restoring contaminated environments.

Bioremediation and biodegradation

Bioremediation, a biotechnological approach employing microorganisms, has gained prominence in microbiological research due to its effectiveness in addressing various environmental contaminants through biodegradation (Demnerova et al., 2005). Microorganisms offer significant advantages over other remediation techniques, making them valuable tools for pollutant removal from soil, water, and sediments (Demnerova et al., 2005). Bioremediation via biodegradation is particularly advantageous due to its cost-effectiveness, rendering it a highly viable method for environmental cleanup (Olaniran et al., 2006). According to Olaniran et al. (2006), the core principles of bioremediation include bioaugmentation, biostimulation, and natural attenuation. Natural attenuation, the simplest form of bioremediation, relies on monitoring changes in pollutant concentrations in soils to confirm their degradation (Kaplan et al., 2004).

In cases where indigenous microbial communities are insufficiently active, bioaugmentation becomes essential by introducing specialized organisms capable of degrading specific pollutants, thereby accelerating biodegradation rates (Fantroussi et al., 2005). However, adapting foreign strains with high pollutant degradation potential to new environments presents a significant practical challenge (Fantroussi et al., 1999).

Furthermore, enhancing the metabolic capabilities of local microbial communities through the provision of nutrients or electron acceptors can boost their capacity to degrade pollutants effectively (Olaniran et al., 2006). These strategies underscore the versatility and applicability of bioremediation as a sustainable approach to mitigating environmental pollution, offering promising solutions for contaminated sites worldwide.

Natural attenuation

Bioattenuation, also known as natural attenuation, refers to the reduction of pollutant concentrations in the environment through physical, chemical, and biological processes. Physical phenomena such as dispersion, advection, diffusion, dilution, volatilization, and sorption/desorption, along with chemical reactions like complexation, abiotic transformation, and ion exchange, contribute to natural attenuation (Washington et al., 1995). Biological processes, such as aerobic and anaerobic biodegradation, as well as uptake by plants and animals, are also critical components of natural attenuation.

Biodegradation, which involves the transformation of chemicals by microorganisms into less harmful forms, is particularly significant within natural attenuation processes. Microbes initiate or facilitate chemical processes that alter pollutants, thereby reducing their potential health risks. Natural attenuation occurs spontaneously in many contaminated areas, contingent upon the appropriate subsurface conditions. Monitoring these conditions is crucial to ensuring the effectiveness of natural attenuation, a practice known as Monitored Natural Attenuation (MNA) (EPA, 2001).

MNA involves monitoring and assessing the progress of natural processes that break down pollutants in soil and groundwater. If the rate of pollutant degradation is sufficiently rapid to protect human health and the environment, MNA can be implemented as a standalone remediation method or in combination with other remediation strategies as a final treatment option. Regular monitoring of soil and groundwater confirms reductions in residual contamination achieved through natural processes (EPA, 2001).

Nature employs various mechanisms to cleanse contaminated environments (Wong et al., 2010). These mechanisms include:

Microbial Degradation: Microscopic organisms in soil and groundwater use certain chemicals as food sources, converting them into harmless gases and water through digestion.

Sorption: Chemicals can bind or sorb onto soil particles, immobilizing them and preventing their migration, thereby limiting groundwater contamination.

Dilution: Pollutants may become diluted as they percolate through soil and mix with groundwater, reducing their concentration.

Volatilization: Certain substances like oils and solvents can evaporate from soil into the atmosphere, especially under sunlight, where they can be further degraded.

These natural processes collectively contribute to the mitigation and eventual removal of contaminants from the environment, illustrating the effectiveness of bioattenuation in environmental remediation.

Biostimulation

Biostimulation, a technique in bioremediation, enhances the biotransformation of soil pollutants by supplementing trace minerals, soil nutrients, electron donors, or electron acceptors (Wong et al., 2010). Native microorganisms can be effectively stimulated to biodegrade contaminants under suitable conditions. For instance, the addition of lactate has been demonstrated to expedite the complete conversion of trichloroethene and perchloroethene to ethane by microbial communities in a short period (Shan et al., 2010).

Humic substances (HS), acting as electron shuttles, significantly accelerate anaerobic biotransformation processes by enhancing the rate of electron transfer. Anthraquinone-2,6-disulfonate (AQDS), a specific HS compound, serves as an electron shuttle to aid in reducing iron oxides and transforming chlorinated organic contaminants (Bond et al., 2002).

Research by Chen et al. (2012) demonstrated that the addition of lactate and AQDS biostimulated native microbial communities, enhancing the activities of dechlorinating and iron-reducing bacteria in soils contaminated with pentachlorophenol (PCP). Additionally, glycerol was found to enhance the metabolic activities of native Rhizobium Ralstonia taiwanensis against phenol toxicity in various nutritional media, thereby improving the efficiency of hazardous pollutant breakdown (Chen et al., 2007).

Studies comparing biostimulation with other remediation approaches have shown varying results depending on the contaminants and environmental conditions. For instance, Liliane et al. (2012) found biostimulation to be more effective than natural attenuation alone in treating polluted soils contaminated with biodiesel. Conversely, Camargo et al. (2005) reported that bioaugmentation was more successful than biostimulation in diesel oil-polluted soils, while natural attenuation showed promising results.

In the biodegradation of polycyclic aromatic hydrocarbons (PAHs), autochthonous microbes in the environment can interact and compete with enriched microbial consortia introduced during biostimulation (Yu et al., 2005). Moreover, studies have highlighted that natural attenuation may be the preferred method for treating mangrove sediments contaminated with fluorene and phenanthrene, whereas biostimulation was more effective for sediments contaminated with pyrene (Wong et al., 2005).

These findings underscore the versatility of biostimulation in enhancing microbial activities for pollutant degradation across different environmental contexts and highlight its potential alongside other remediation strategies.

Bioaugmentation

Bioaugmentation involves the introduction of specific strains or consortia of microorganisms into a polluted environment, such as soil, to enhance its ability to degrade pollutants (Thierry et al., 2008). The concept behind bioaugmentation is that introducing genetically diverse microbes will augment the metabolic capabilities of the existing native microbial community, thereby expanding the range of effective biodegradation reactions (Fantroussi et al., 2005). There is also potential for using genetically modified microbes (GEMs) in soil bioaugmentation to enhance their ability to degrade various aromatic hydrocarbons (Mrozik et al., 2006).

When traditional methods like biostimulation or natural attenuation fail, bioaugmentation is often considered a viable strategy (Fantroussi et al., 2005). Numerous studies have highlighted the influence of both abiotic and biotic factors on the efficacy of bioaugmentation. Abiotic factors such as temperature, moisture, pH, and organic matter content play critical roles, along with soil type, aeration, and nutrient levels (Mrozik et al., 2006). Biotic factors including competition between native and introduced microbes for resources, antagonistic interactions, and predation by bacteriophages and protozoa also significantly affect outcomes.

Combining bioaugmentation with biostimulation is a promising approach to expedite bioremediation efforts. Biostimulation involves adding energy sources or electron acceptors to stimulate both native and introduced microbial communities, enhancing their degradation capabilities (Fantroussi et al., 2005). Moreover, bioaugmentation-assisted phytoextraction using plant growth-promoting rhizobacteria (PGPR) or arbuscular mycorrhizal fungi (AMF) presents a viable strategy for cleaning up metal-contaminated soils (Thierry et al., 2008).

In summary, bioaugmentation holds significant potential as a remediation strategy, particularly when tailored to address specific environmental conditions and microbial interactions, offering a versatile approach to enhance pollutant degradation in contaminated environments.

Factors affecting microbial degradation

Microorganisms possess robust metabolic capabilities that enable them to degrade a diverse array of organic contaminants, making them pivotal in environmental remediation efforts. However, their effectiveness in breaking down pollutants is influenced by several key variables. These include the type and concentration of pollutants present, their accessibility to microbial action, and the physicochemical characteristics of the surrounding environment (Fantroussi et al., 2005). Consequently, factors influencing the rate at which microorganisms degrade pollutants can be categorized into environmental factors, which relate to the surrounding conditions, and biological factors, which pertain to the nutritional requirements and activities of the bacteria involved.

Biological factors

Microbial metabolism is a crucial biotic factor influencing the degradation of organic substances. Two specific biotic factors that significantly impact this process include the direct inhibition of enzyme activities and the dynamics of microbial community development (Roberts et al., 1998). Enzyme inhibition can occur when microbes compete for limited carbon sources, engage in antagonistic interactions, or fall prey to bacteriophages and protozoa (ERD, 1998).

The rate of contaminant degradation is often influenced by the quantity of enzymes, which correlates with both the enzymatic capacity of individual cells and the abundance of microorganisms capable of metabolizing the contaminant. Additionally, the specific enzymes involved, their affinity for the contaminant, and the availability of the contaminant play critical roles in the extent of degradation. Moreover, optimal microbial growth requires sufficient oxygen and nutrients in appropriate quantities and forms (ERD, 1998).

Temperature, pH, and moisture are other crucial variables affecting the pace of biodegradation by modulating the rates of enzymatic reactions. Enzymes involved in degradation pathways have optimal temperature ranges, and their metabolic rates fluctuate accordingly. For every 10°C decrease in temperature, the biodegradation rate typically decreases by approximately half (Sayler et al., 2000). While a pH range of 6.5 to 8.5 generally supports optimal biodegradation in aquatic and terrestrial systems, a wide pH range can impact microbial activity. Moisture levels influence pollutant metabolism by altering the availability of soluble substances, as well as the pH and osmotic pressure within terrestrial and aquatic systems (Lorenzo et al., 2005).

Environmental factors

The potential for an organic compound to adhere to a solid surface is influenced by soil type and the amount of organic matter present. Similarly, absorption occurs when pollutants infiltrate into the bulk mass of the soil matrix. Both adsorption and absorption reduce the availability of contaminants to most bacteria, thereby slowing down their chemical degradation rates (ERD, 1998).

Variations in the porosity of saturated and unsaturated zones within an aquifer matrix can affect groundwater flow patterns and contaminant migration. Fine-grained sediments hinder the movement of gases such as carbon dioxide, methane, and oxygen, which can influence the type and rate of biodegradation processes (ERD, 1998).

The oxidation-reduction potential (Eh) of soil indicates its electron density and plays a crucial role in microbial activity. Oxidation involves the transfer of electrons to more oxidized molecules known as electron acceptors, releasing biological energy. Aerobic conditions, characterized by a low electron density (Eh greater than 50 mV), support oxidation, whereas anaerobic conditions, with a high electron density (Eh less than 50 mV), support reduction processes (ERD, 1998).

Challenges and Future Recommendation

Advancements and challenges in microbial biodegradation are shaping the future of environmental remediation, driving the development of innovative strategies and addressing significant hurdles in biotechnology. One of the foremost challenges is the immense diversity of microbial communities, which exhibit substantial variation in composition and function across different environments (Steffan et al., 2015). Effectively harnessing this diversity requires adaptable approaches capable of accommodating the dynamic microbial landscapes encountered in diverse settings.

Environmental variability presents another formidable challenge, influencing the efficacy of microbial biodegradation through factors such as temperature, pH, and nutrient availability (Eijsink et al., 2019). Designing strategies that optimize these conditions is crucial to fostering favorable environments for microbial communities to thrive. Complicating matters further are emerging contaminants like microplastics and pharmaceuticals, posing distinct challenges that necessitate ongoing research and adaptation of biodegradation methods (Seshan et al., 2017).

Bioavailability of contaminants remains a critical obstacle in biodegradation efforts, as pollutants are often sequestered or exist in forms resistant to microbial degradation (Zafra et al., 2016). Enhancing the accessibility of pollutants to microbial action is thus a paramount concern for researchers and practitioners alike.

Looking ahead, promising approaches are guiding the future application and study of microbial biodegradation. Metagenomics and metatranscriptomics, as highlighted by Delgado-Baquerizo et al. (2018), offer powerful tools to explore gene expression in diverse environmental contexts, providing invaluable insights into the genetic makeup and functional potential of microbial communities. Similarly, genetic engineering and synthetic biology present opportunities to tailor microbial populations for specific biodegradation objectives, as noted by Schlüter et al. (2018).

Real-time monitoring technologies are indispensable for in situ assessment of biodegradation processes, enabling adaptive management strategies and enhancing overall cleanup efficiency (Baelum et al., 2012). Concurrently, there is a growing recognition of the ecological implications of microbial biodegradation, urging researchers to investigate potential unforeseen consequences (Gan et al., 2018).

Ensuring that the benefits of microbial biodegradation do not compromise environmental integrity requires the development of sustainable and ecologically sound bioremediation techniques. Collaboration among scientists, policymakers, and industry stakeholders is essential to establish regulatory frameworks that promote responsible application of microbial biodegradation technologies. Public education initiatives, as emphasized by Mason et al. (2020), play a pivotal role in garnering support for sustainable biodegradation initiatives and fostering community engagement towards environmental stewardship.

Conclusion

The maintenance of the global carbon cycle and the restoration of our environment hinge significantly on microbial activities, encapsulated in the concept of biodegradation. Microbes play a crucial role in breaking down hydrocarbons, heavy metals, and various synthetic chemicals with ecological impacts. However, laboratory-based assessments often overestimate degradation rates compared to real-world conditions due to complexities like microbial competition, substrate limitations, unfavorable environmental factors (temperature, pH, moisture, aeration), and limited pollutant accessibility.

Environmental biotechnology aims to tackle these challenges by optimizing conditions for microbial action in biotopes contaminated with pollutants. Strategies such as bioaugmentation and biostimulation enhance the degradative capabilities of indigenous microorganisms, while genetic engineering offers potential for further boosting biodegradation efficiency. Nonetheless, deploying genetically engineered microorganisms (GEMs) in field applications carries inherent risks and requires careful consideration of ecological impacts.

The effectiveness of these bioremediation methods will ultimately influence our ability to reduce waste, mitigate industrial pollution, and foster a sustainable future. Continued research and technological advancements in environmental biotechnology are crucial to refining these approaches, ensuring they are both effective and environmentally responsible. By harnessing the power of microbial biodegradation responsibly, we can contribute to the preservation and restoration of our natural ecosystems for generations to come.

Author Contributions

M.A.M.A., F.S.A.S., M.A.A.S. drafted the manuscript and made substantial contributions to the design of the study. L.E.A.H., S.M. reviewed and drafted the paper.

Acknowledgment

The authors are thankful to their university to support this study.

Competing financial interests

The author has no conflict of interest.

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