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Microbial Bioremediation for Environmental Sustainability: Recent Developments

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Abstract:

Microbial bioremediation has become an interesting and sustainable technique for dealing with pollution of the environment through microbial degradation, transformation, immobilization, and recovery of contaminants. This review looks into recent developments of microbial bioremediation with focus on pollutants such as wastewater, pharmaceuticals and antibiotics, heavy metals, petroleum hydrocarbons, plastics, microplastics and other emerging pollutants. Mechanisms employed by microbes include biodegradation, biosorption, bioaccumulation and biotransformation together with advancements in the use of bioaugmentation, microbial consortia, microbial electrochemical systems, omics technology, and genetically modified microbes. The reviewed research shows that microbial technologies have the potential of providing efficient pollutant management as well as resource recovery in the form of biogas, microbial biomass, biopolymers, nutrients and metals, thus making circular economy possible. However, some limitations like slow degradation rate, incomplete mineralization, formation of toxic metabolites, instability of the microbes, antibiotic resistance, lack of field studies, scalability issues and biosafety concerns are evident. Future studies should focus on long-term field investigations, realistic environmental matrix, understanding of microbial community dynamics, transformation product identification and use of advanced biotechnology, life cycle assessment and process engineering. In general, microbial bioremediation holds great promise towards sustainable future but development of efficient, safe, scalable, resource recovery and human relevant technologies is crucial.

Keywords: Microbial Bioremediation; Environmental Sustainability; Wastewater Treatment; Emerging Contaminants; Microbial Consortia; Circular Economy.

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1. INTRODUCTION

Chemicals have a great impact in environment, and it is very harmful for health not only human but also animals.[1] Microbial bioremediation is considered one of the most promising biological methods of environmental pollution due to its capability of degrading, transforming, immobilizing, or recovering many types of pollutants within relatively moderate environmental conditions. The process of rapid industrialization, urbanization, population growth, intensification of agriculture, increased consumption of pharmaceuticals, and intensified production of plastics have led to the constant emission of organic pollutants, heavy metals, petroleum hydrocarbons, pharmaceuticals, antibiotics, plastics, microplastics, and other novel pollutants in water, soil, and sediment environments[2]. Conventional remediation techniques, such as chemical oxidation, precipitation, adsorption, incineration, and filtration via membranes, offer effective treatment of pollutants, but they may be energy-intensive, require chemicals and infrastructural investments, and create secondary wastes. Thus, microbial bioremediation offers an alternative biological technology where microorganisms, bacteria, fungi, algae, and microbial consortia use a variety of metabolic and enzymatic pathways to decrease environmental pollution and promote sustainable resource recovery.

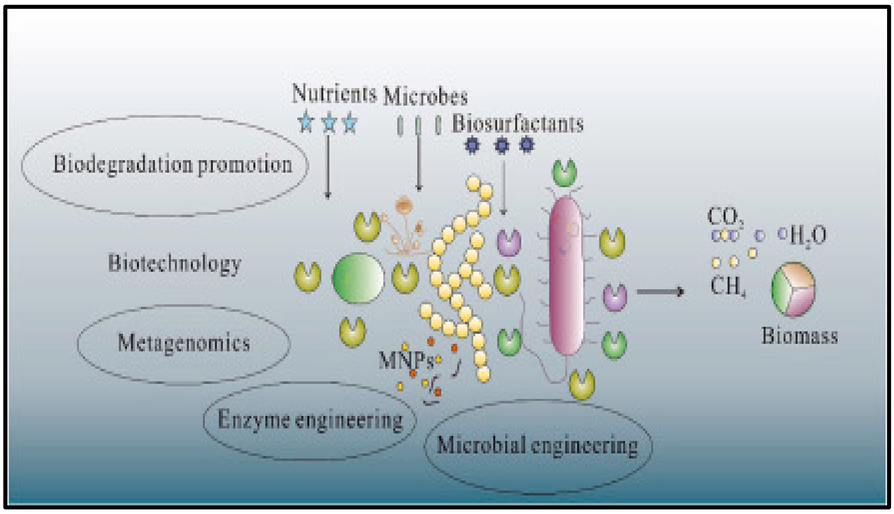

Figure 1: Microbial Bioremediation[3]

Bioremediation using microorganisms has been linked to the biological treatment of sewage and organic waste, but recently, the area has greatly broadened due to the advancements made. Microorganisms can be used in biodegradation, mineralization, biosorption, bioaccumulation, biotransformation, biomineralization, and oxidation-reduction reactions. All these have been explored in the removal of municipal and industrial wastewater, pharmaceuticals and antibiotics, heavy metals, oil hydrocarbons, pesticides, plastics, microplastics, and other novel contaminants[4]. The development of microbial consortia, bioaugmentation, biofilm technology, microbial electrochemical technologies, omics, enzyme engineering, and synthetic biology has further broadened the potential of the process of microbial remediation. However, there are several problems that include slow degradation rate, microbial instability, incomplete contaminant transformations, transformation product formation, scale-up problems, antimicrobial resistance, and environmental safety. Furthermore, natural methodologies utilizing microorganisms and plants or plant extracts for metal nanoparticle synthesis have been recommended as important options in contrast to chemical methods[5]. It is therefore essential to conduct a review of recent developments in the area to determine the contribution of microbial bioremediation towards environmental sustainability.

1.1 Background Information and Context

The problem of pollution of the environment is becoming more and more relevant and relates not only to the contamination by a certain pollutant but often consists of complex contamination by pollutants including organic substances, drugs, antibiotics, heavy metals, petroleum hydrocarbons, pesticides, plastics, and microplastics. Such pollutants can be introduced into the environment through municipal, industrial, agricultural, and pharmaceutical activities and can cause adverse effects on the quality of water, soil, ecosystems, and exposure pathways for humans[6]. Microorganisms including bacteria, fungi, algae, and microbial consortia have unique metabolic diversity and are able to degrade, transform, immobilize, and accumulate pollutants by means of biodegradation, biosorption, bioaccumulation, and enzymatic mechanisms. Due to recent advancements in the use of microbial consortia, bioaugmentation, microbial electrochemical systems, omics technologies, enzyme engineering, and synthetic biology, possibilities of microbial bioremediation have extended from pollutant degradation to sustainable resources utilization. Nevertheless, the effectiveness of treatment is affected by various factors including environmental conditions, microbial stability, pollutants' properties, and production of transformation products.

1.2 Objectives of the Review

The major aims of this review include the following:

- To give a brief background about the basic concepts and principles of microbial bioremediation for environmental sustainability.
- To review recent studies about microbial bioremediation of wastewater, pharmaceuticals and antibiotics, heavy metals, petroleum hydrocarbons, plastics, microplastics, and other emerging contaminants.
- To discuss recent trends in bioaugmentation, microbial consortia, microbial electrochemical techniques, omics and engineered microbes.
- To assess the effectiveness, merits, limitations, and application of the various microbial bioremediation approaches.
- To highlight significant areas of research for the development of safe, scalable and human-relevant microbial bioremediation technologies.

1.3 Importance of the Topic

The growing complexity of pollution makes the development of advanced and sustainable technologies for pollution remediation a necessity. Microbial bioremediation is crucial due to microorganisms' ability to break down organic substances, immobilize and recover inorganic compounds with reduced use of aggressive chemical reagents and energy in comparison with some traditional methods. Recent exploration survey uncovered that, medicinal plants are evaluated for biological activities for discovering likely new compounds for remedial use[7]. The application of microbial bioremediation in the management of wastewater, polluted soils, sediments, and industries helps in sustainable resources recovery as a source of biogas, microbial biomass, biopolymers, bio-fertilizers, and metals. Thus, microbial bioremediation can help to transition from the "treat and dispose" paradigm to the "recover, reuse, and recycle" strategy[8].

This technology can be applied in the area of human health because pharmaceuticals, antibiotics, heavy metals, and other contaminants can enter humans' exposure via polluted water and environment. Nevertheless, such limitations of this technology as slow degradation rate, incomplete mineralization, formation of transformation products, microbial stability, lack of field validations, and scaling up problems cannot be overlooked.

2. FUNDAMENTAL MECHANISMS OF MICROBIAL BIOREMEDIATION: BIODEGRADATION, BIOSORPTION, BIOACCUMULATION, AND ENZYMATIC TRANSFORMATION

Bioremediation through microorganisms is one of the most significant biological methods of removing, transforming, or immobilizing environmental contaminants. Bacteria, fungi, algae, and microbial consortia are the microorganisms that react with the pollutants through various biochemical mechanisms[9]. The efficacy of these reactions is based on the nature of the chemical compound, its concentration, type of microbial community, pH, temperature, availability of oxygen, nutrient conditions, and electron donors/acceptors. The current research trend is inclined towards gaining an insight into metabolic pathways of microorganisms to increase their efficiency of remediation through bioaugmentation, immobilization, microbial consortia, and enzymes. However, all the contaminants may not always get degraded entirely, and transformation products are always a major concern.

2.1 Microbial Biodegradation

The enormous heritage of vast natural resources is worth exploring the possibility of developing efficient, economically viable, and clinically acceptable antimicrobials for human application[10]. Biodegradation, defined as the decomposition of materials mainly by fungi or bacteria, is a natural process that acts on substances such as leaves, grass, and food scraps[11]. The biodegradation is one of the most significant pathways involved in microbial bioremediation that entails the enzyme-mediated decomposition of organic compounds to form simpler compounds[12]. In this process, microorganisms can utilize some pollutants as sources of carbon and energy, whereas other pollutants might undergo decomposition through metabolism reactions. Given suitable conditions, the process of biodegradation can lead to mineralization with formation of simple products like carbon dioxide and microbial biomass.

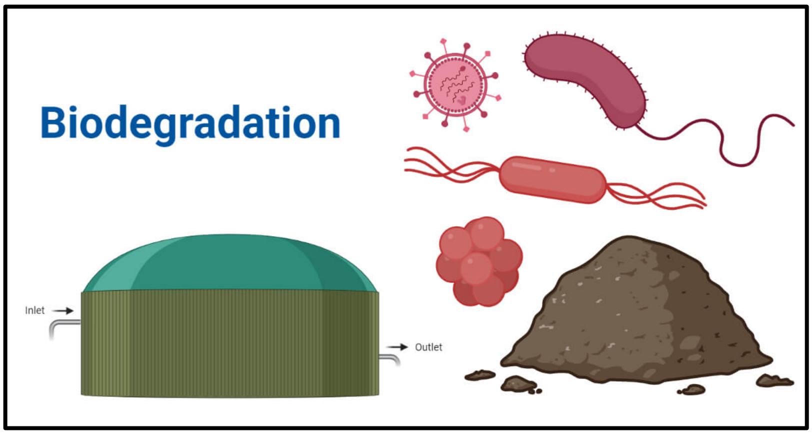

Figure 2: Microbial Biodegradation[13]

Aerobic microbes commonly depend on molecular oxygen in their oxidative degradative processes while anaerobic microbes have alternate electron acceptors like nitrate, sulfur, iron, or even carbon dioxide. Aerobic and anaerobic microbial processes play a significant role in the cleanup of polluted wastewaters, soils, and effluents from industries.

The efficiency of the biodegradation process will be a function of contaminant concentration, molecular structure, adaptation by the microbes, temperature, pH, nutrition, oxygenation, and presence of other pollutants. Environmental complex mixtures will also affect microbial activities compared to laboratory conditions[14].

Strengths

- Deals effectively with numerous types of organic pollutants
- Requires relatively few chemicals
- Possibility of converting pollutants to simpler substances
- Takes place under both aerobic and anaerobic circumstances
- Applicable for waste water and soil pollution treatment
- Has an environmentally sustainable character

Weaknesses

- Certain pollutants are recalcitrant to microbial biodegradation
- Biodegradation might be slow under environmental conditions
- Dependent on pH, temperature, availability of nutrients and oxygen
- Partial biodegradation is possible
- Formation of non-degradable intermediates
- Laboratory studies may not always reflect field conditions

Biodegradation is hence a vital process in microbial remediation; however, the success of such treatment needs to be measured not only through the elimination of the original pollutant but also the fate of its products[15].

2.2 Microbial Biosorption

In recent years, much progress has been made in improving the quality and quantity of agriculture[16]. Bio-sorption is one type of bioremediation technique where the contamination binds to the microbial cells surfaces. It is especially significant in removing heavy metals from the polluted water bodies. The cell wall of microbial cells contains some functional groups such as hydroxyl group, carboxyl group, amino group, phosphate group, and sulfhydryl group, which have the potential to bind to metal ions by means of electrostatic interaction.

Nature has been a source of medicinal agents for thousands of years and an impressive number of modern drugs have been isolated from natural sources[17]. Biomasses of bacteria, fungi, algae, and other microorganisms can serve as biological adsorbents. In contrast to biodegradation, biosorption does not always have to include the metabolism of the pollutant by the microbe. This is why the technique can be effective in decontaminating non-biodegradable substances[18].

Strengths

- Efficient in dealing with multiple heavy metals
- Quick uptake of contaminants
- The process works even in the absence of live microbial organisms
- Minimal chemicals needed
- Metal can be retrieved and recycled
- The process can be combined with wastewater treatment processes

Weaknesses

- Contaminants are mainly transported rather than being degraded
- Metal-bearing biomass has to undergo additional treatment
- Biosorption effectiveness can change depending on pH and environmental factors
- The competition among metal ions can lower effectiveness
- Microbial biomass regeneration can be problematic
- Scaling up needs further technical investigation

2.3 Microbial Bioaccumulation

Bioaccumulation involves the accumulation of contaminants by microbes. Some microbes have the ability to transport specific metals and contaminants within their cellular structures. These contaminants can become associated with proteins within the cell, incorporated into the cell structure itself, or even converted into an immobile form[19].

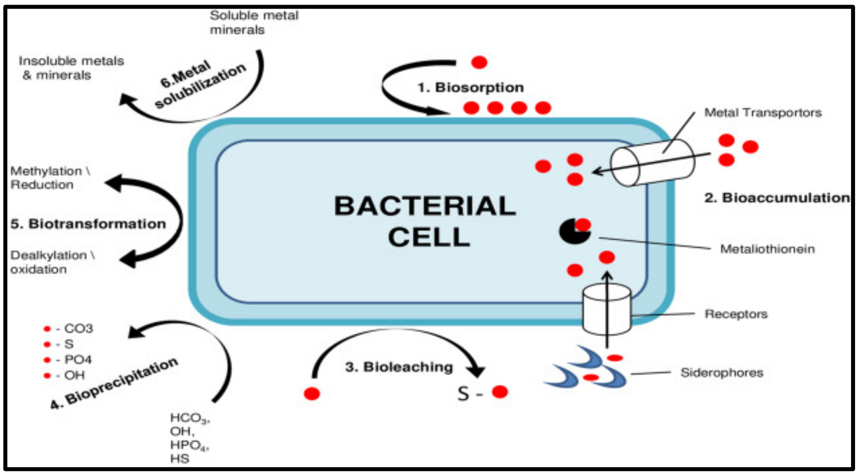

Figure 3: Bioaccumulation[20]

The accumulation of microbes is specifically pertinent in the removal of heavy metals because microorganisms have the ability to absorb metal ions from their surrounding water. Nevertheless, the process depends on the availability of live microorganism with proper physiology and metabolism.

Strengths

- It can decontaminate aquatic systems
- Offers intracellular containment of certain pollutants
- May decrease mobility and bioavailability of contaminants

- Can be used together with other microbial decontamination processes
- Aids in the study of microbial resistance to pollution

Weaknesses

- Necessitates viable and living micro-organisms
- High levels of contaminants may prevent microbial activity
- Build-up of contaminants may affect microbial activity
- Contaminated bio-materials must be handled safely
- Build-up of metals may not be easy to retrieve

Bioaccumulation may therefore lead to the removal of contaminants but the application of bioaccumulation must be done by considering a number of factors including viability of microorganisms and toxicity of contaminants among others.

2.4 Microbial Biotransformation

Sustainable agriculture is the most needed system in the contemporary context that is applicable to all kinds of crops including medicinal plants[21]. Biotransformation is a process where microorganisms undergo chemical changes in the chemical composition of the pollutant using enzymes[22]. In contrast to biodegradation, biotransformation does not necessarily result in the complete degradation of the pollutant; rather, the initial substance changes into another form.

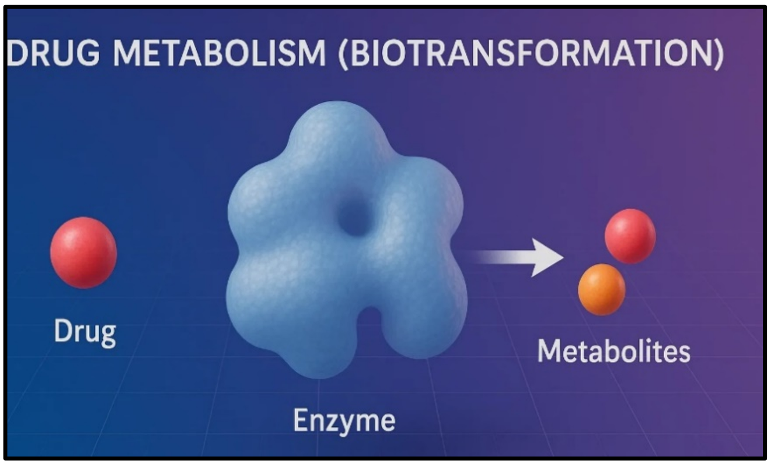

Figure 4: Drug Metabolism (Biotransformation)[23]

Biodegradation of emerging contaminants is very crucial in the case of pharmaceuticals, antibiotics, pesticides, and personal care products. Enzymes from microorganisms can add functional groups, eliminate certain groups, oxidize or reduce certain structures, and cleave chemical bonds.

Strengths

- Abilities to transform structurally complex compounds
- Possible application in pharmaceuticals and novel contaminants
- May be carried out at lower contaminant concentrations
- Based on metabolic capabilities of microbes present naturally

- Can be improved by microbial adaptation and bioaugmentation

Weaknesses

- May not result in total mineralization
- The formation of transformation products may persist
- The transformation products themselves may be more environmentally relevant than the initial chemical
- Fully understanding the process may be challenging
- Treatment efficiency may differ for microbial communities

Thus, microbial biotransformation cannot be assessed just through the disappearance of the parent pollutant. Transformation products need to be identified and characterized for the treatment to be considered environmentally beneficial.

3. THEMATIC APPLICATIONS OF MICROBIAL BIOREMEDIATION FOR ENVIRONMENTAL SUSTAINABILITY

There has been an increase in the application of microbial bioremediation that goes beyond traditional biological processes in cleaning up various types of environmental pollution. Various microorganisms like bacteria, fungi, algae, and microbial communities can be used to break down or remove various forms of pollution using a variety of physiological or biochemical techniques[24]. The recent advances in this area include treatment of wastewater, pharmaceutical and antibiotic pollution, heavy metals, petroleum hydrocarbons, plastic waste, and other microbial technologies. Furthermore, earthworm can act as a soil bioindicator, allowing for the measurement and monitoring of soil pollution, soil health, and ecosystem function under a wide range of land use regimes and management strategies[25].

3.1 Microbial Bioremediation of Wastewater

Wastewater management is one of the major areas where microbial bioremediation finds its application due to the presence of different contaminants that originate from household, municipal, hospitals, industrial and pharmaceutical sources. The traditional biological process of wastewater treatment is highly dependent on microbial communities for organic matter and nutrient breakdown[26]. Nonetheless, there might be no guarantee that micropollutants such as medicines, antibiotics, personal care products, among others, would be fully removed from wastewater through biological processes. Recent researches have been centered around increasing microbial diversity, biofilm formation, reactors designs and operating conditions to optimize the process.

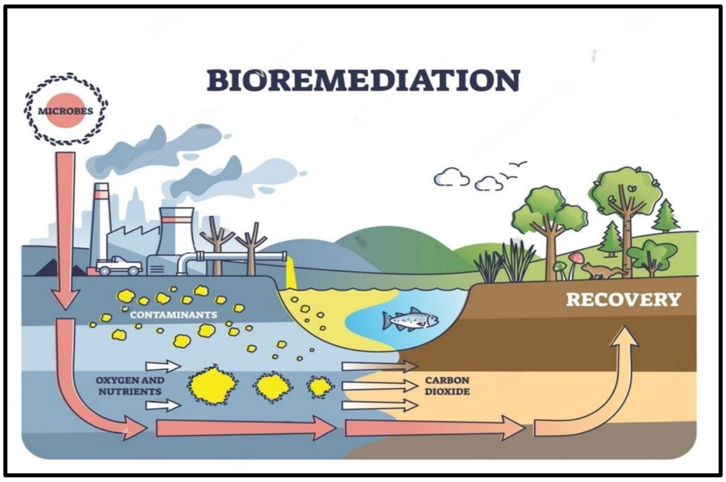

Figure 5: Bioremediation of Wastewater[27]

One critical issue with regard to wastewater bioremediation is the fact that microorganisms are exposed to a variety of pollutants when they exist in the environment. Some of these pollutants can compete with the enzymes of the microorganisms; inhibit growth of the microorganisms; or cause particular metabolic processes in the microorganisms. This makes it difficult to extrapolate the findings from studies that involve individual pollutants in laboratory settings. Future research should thus focus on real wastewater matrixes; realistic pollutant mixtures; long-term treatment studies; and microorganism community studies[28].

3.2 Microbial Treatment of Pharmaceutical and Antibiotic Contaminants

Residues of pharmaceuticals and antibiotics have become major environmental pollutants due to their constant addition to wastewater as a result of their use by humans. Residues of antibiotics, in particular, are very significant due to the possibility that their environmental resistance may contribute to the development of antimicrobial resistance. Antibiotic residues along with resistant microbes and antimicrobial resistance genes can be present in wastewater from hospitals and municipalities[29]. Microbial populations are capable of transforming several pharmaceutical products via enzymatic and metabolic pathways, although the effectiveness of this process depends on certain properties of individual products. Moreover, the growing expenses of prescription pharmaceuticals in the maintenance of human health and wellbeing, as well as the bioprospecting of novel plant-derived drugs, have fuelled interest in medicinal plants as a re-emerging health assistance[30].

The most significant drawback with using microbes in pharmaceutical remediation is that even the transformation of the parent molecule does not guarantee total detoxification. The process of microbial degradation can produce transformation products that are environmentally stable or biologically active. Consequently, future studies must address the issue of pharmaceutical concentrations, transformation products, microbial communities, antimicrobial resistance, and human health-related environmental assessments. Microbial remediation, therefore, needs to be assessed based on the ultimate fate of contaminants rather than their percentage removal[31].

3.3 Microbial Bioremediation of Heavy Metals

The struggle between man and microbes has been going on since times immemorial[32]. Metals like lead, cadmium, chromium, mercury, nickel, and arsenic are persistent pollutants because they cannot be broken down biologically. However, microorganisms can immobilize these metals via processes such as biosorption, bioaccumulation, biomineralization, precipitation, and oxidation-reduction. Functional groups present in microbial cells can help to adsorb metal ions, enabling the removal of these contaminants from polluted water and industry effluents. The process of microbial biosorption is very appealing due to its reduced need for chemicals compared to some other treatment techniques[33].

The primary disadvantage of microbial remediation of heavy metals is that the metals usually migrate from the polluted medium to the microbial biomass but are not degraded by the process. Thus, the metal-laden microbial biomass must be recovered, regenerated, stabilized, or disposed of safely. Future research work needs to take up something more than just removal of the metals. Incorporation of microbial biosorption with resource recovery technologies might make the process sustainable for both environment and economics.

3.4 Microbial Bioremediation of Petroleum Hydrocarbons and Organic Pollutants

Petroleum hydrocarbons serve as major environmental pollutants due to their occurrence in oil drilling, refining, transport, storage operations, and industries, among other activities. Microorganisms have the ability to break down some petroleum components by acting on them as a source of carbon and energy. While bacteria begin the breakdown process through oxygenase-catalysed processes, fungi are able to take part through the actions of extracellular oxidizing enzymes such as laccases and peroxidases.

The success of microbial petroleum remediation is affected by factors such as hydrocarbon composition, presence of oxygen, availability of nutrients, temperature, pH, moisture, microbial biomass, and concentration of pollutants. Even though a large amount of degradation can be accomplished under ideal conditions in a laboratory setup, the actual environment is much more complicated. The differences in soil type, pollution distribution, nutrient availability, competition between microbes, and environmental factors can lower the effectiveness of the process. Future research should focus on the actual implementation of the process in the environment[34].

3.5 Microbial Remediation of Plastics and Microplastics

The problem of plastic pollution is a serious environmental issue since most synthetic polymers are extremely difficult to degrade naturally. Plastic debris can stay intact for a long time before breaking up into micro- and nanoplastics. Some microorganisms can attach to the surface of plastic materials and create biofilms, whereas particular enzymes can degrade some polymer structures. The focus of many scientific studies has been on polyethylene terephthalate (PET) since it is possible to hydrolyze this polymer by microbial or enzymatic systems.

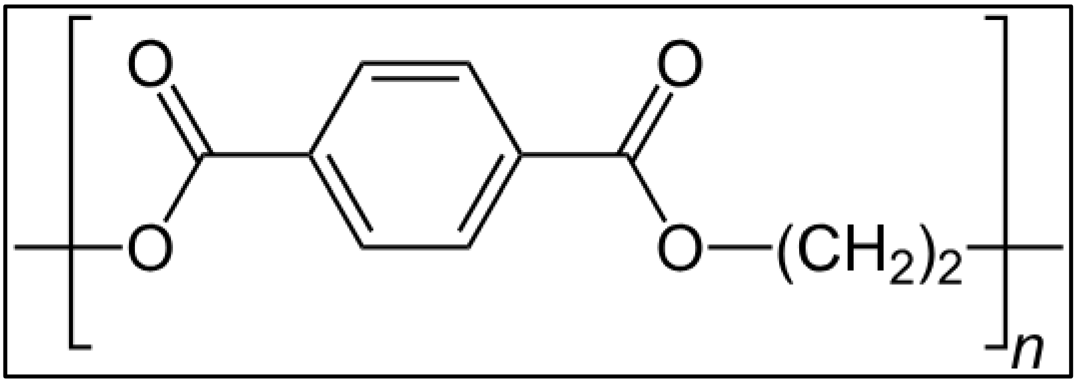

Figure 6: Polyethylene terephthalate (PET)[35]

However, despite all these advancements, microbial degradation of plastic is still at the emerging stage. Various polymers have various chemical structures, crystallinities, molecular weights, additives, and physical properties that could affect their microbial degradation. The environmental factors such as temperature, pH, moisture levels, and the presence of microorganisms would also affect the efficiency of the process. Therefore, future research needs to be carried out focusing on the degradation of mixed plastic waste, old plastics, environmental concentrations of plastic materials, transformation products, enzymes' engineering, and larger scale systems.

3.6 Advanced Microbial Technologies, Consortia, and Circular Bioeconomy

Latest trends have led to the development of microbial bioremediation from using microbial strains to using microbial consortia, bioaugmentation, omics techniques, synthetic biology, and microbial electrochemical technologies. Microbial consortia may be able to complement each other in their metabolic capabilities by involving various microorganisms in a process involving sequential degradation steps. Bioaugmentation involves adding specific microorganisms to the system for treatment purposes, while metagenomics, transcriptomics, proteomics, and metabolomics involve identifying genes and pathways involved in the breakdown of the pollutants.

A further development is the combination of microbial remediation with circular economy concepts. Microbial organisms have the capability of converting the organic carbon present in wastewater into microbial biomass, biogas, biopolymers, bio-fertilizer, and other forms of biomass. Microalgae and bacterial systems have the potential of being used not only in wastewater treatment but also in nutrient recovery and carbon recycling and even in biomass generation[36]. The idea here is to shift the purpose of environmental remediation from just “eliminating pollution” to “eliminating pollution while utilizing valuable materials.” There are several issues faced by advanced microbial systems that include microbial stability, reactor complexity, scaling up, biosafety, energy needs, and economic viability.

4. MICROBIAL BIOREMEDIATION FOR SUSTAINABLE RESOURCE RECOVERY AND CIRCULAR ECONOMY

Bioremediation involving microbes has slowly shifted away from the traditional aim of contaminant removal to resource recovery from polluted environments. In traditional treatment plants, wastewater, industrial effluent, and other forms of polluted substances are considered streams that need to be treated before being disposed of. Microbial-based treatment facilities, on the other hand, use microbes to convert organic substances, nutrients, and other substances into products. Bacteria, fungi, algae, and other microbial communities can convert biodegradable organic substances into microbial biomass, biogas, bio-fertilizer, and other value-added products[37].

However, wastewater is a good source of microbial resource recovery due to the presence of carbon, nitrogen, phosphorus, and other valuable compounds. Methane can be produced by microbes from organic carbon using anaerobic biological systems, while nitrogen and phosphorus can be absorbed by microalgae and bacteria[38]. This biomass may find application in bioenergy or biofertilizer production, etc. depending on the quality and content of contaminants in it. Thus, microbial systems can help in recycling nutrients and minimize dependence on non-renewable resources and energy-consuming traditional methods of treatment.

There is also great promise for microbial technology in the extraction of valuable materials from polluted sites. Microbes can absorb or immobilize metals through processes called biosorption, bioaccumulation, precipitation, and biomineralization. Instead of considering biomass containing metals as waste only, these can be recovered from the system for reutilization in some form or the other. Biodegradable polymers like polyhydroxyalkanoates (PHAs) which can be produced by microorganisms using organic compounds from sewage water can be used to make use of the wasted carbon[39].

Therefore, the combination of microbial bioremediation with the circular economy can be seen as a transition from the conventional "use-pollute-treat-dispose" paradigm to the sustainable one of "recover-reuse-recycle." Nevertheless, resource-recovery technologies need to be assessed in terms of their energy use, cost efficiency, product quality, contaminant accumulation, greenhouse gas emissions, and overall life cycle environmental impact[40]. Future studies will have to consider the development of microbial systems that would ensure not only contaminant degradation but resource recovery and value creation as well.

Table 1: Summary of Selected Literature on Microbial Bioremediation[41]

Author(s) & Year	Study Focus	Methodology/Model	Key Findings
Sharma & Kumar (2021)[42]	Heavy-metal bioremediation	Review of endophytic microorganisms	Endophytes showed potential for effective and sustainable heavy-metal removal.
Li et al. (2023)[43]	Algae–bacteria consortia	Review of aquatic remediation applications	Consortia supported pollutant removal, nutrient uptake, and resource recovery.
Ayilara & Babalola (2023)[44]	Microbial waste bioremediation	Review of microbial remediation mechanisms	Microorganisms showed potential for sustainable degradation and removal of environmental pollutants.

Wu et al. (2021)[45]	Engineered microbial remediation	Review of genetically engineered microorganisms	Genetic engineering improved remediation potential, but ecological risks required assessment.
Dey et al. (2024)[46]	Mining-waste bioremediation	Review of bioremediation and bioenergy approaches	Bioremediation supported waste management, resource recovery, and bioenergy generation.

5. DISCUSSION

Based on the reviewed literature, microbial bioremediation appears to be promising for sustainable management of wastewater, pharmaceuticals, antibiotics, heavy metals, petroleum hydrocarbons, plastic, micro-plastic, and many other emerging contaminants[47]. Biodegradation, biosorption, bioaccumulation, enzymatic degradation, bioaugmentation, and microbial consortia are some of the mechanisms by which microorganisms can remove pollutants. Recent technological developments in areas such as microbial electrochemical systems, omics, synthetic biology, and resource recovery have added more dimensions to the application of microbial bioremediation. But several limitations exist.

5.1 Interpretation and Analysis of Current Findings

The results reveal that microbial bioremediation has evolved from traditional biological degradation to more advanced microbiological or microbial communities' methods. Microbial organisms including bacteria, fungi, algae, and microbe communities may be used successfully in the biodegradation of some inorganic and organic contaminants[48]. But, biodegradation is highly influenced by the nature of the pollutant, the composition of the microbe community, pH value, temperature, oxygen level, nutrient level, and interaction between the contaminants.

5.2 Environmental Implications and Significance

Bioremediation using microbes is environmentally significant in that it can lead to less pollution but with reduced use of chemicals compared to some traditional treatment processes. Bioremediation processes such as those for wastewater, heavy metals, petroleum hydrocarbons, and plastics have the potential of improving environmental quality[49]. Additionally, microbial processes can aid resource recovery in the form of biogas, microbial biomass, bio-degradable plastics, nutrients, and metals, thus promoting circular economy practices in the environment.

5.3 Research Gaps and Limitations

There are several research issues that still exist, especially the inability to translate laboratory results to practical applications in the field. The majority of experiments use idealized conditions or single contaminants while in the real environment there is a mixture of different pollutants and dynamic environmental conditions[50]. Some other concerns are slow degradation rate, incomplete mineralization, formation of by-products, stability of microorganisms, antibiotic resistance, biomass control, and difficulty in scale up.

5.4 Future Research Directions

Future research will need to concentrate on long-term and field-based research utilizing actual environmental samples and real-life contaminant mixtures. More emphasis will need to be put on transformation products, microbial communities' stability, antimicrobial resistance, plastic decomposition, extraction of heavy metals, and highly persistent chemicals[51]. Incorporation of omics technologies, synthetic biology, artificial intelligence, microbial electrochemical technologies, life-cycle assessment, and techno-economic analysis could increase efficiency and sustainability of treatment. Future research should also consider human-relevant environmental evidence and refrain from unnecessary animal experiments.

6. CONCLUSION

This review has shown that microbial bioremediation is a promising and sustainable solution for the management of environmental contamination. Microbes can be efficiently utilized for the degradation, transformation, immobilization, and recovery of contaminants, which include wastewater pollutants, pharmaceutical and antibiotic wastes, heavy metals, petroleum hydrocarbons, plastics, and microplastics. Recent advancements in microbial consortia, bioaugmentation, microbial electrochemical systems, omics, synthetic biology, and resource recovery technologies have further widened the scope. This review has further demonstrated that microbial bioremediation can aid in the implementation of circular economy principles through the recovery of nutrients, metals, biogas, microbial biomass, and biodegradable products. Nevertheless, there are constraints like incomplete degradation, formation of transformation products, microbial instability, antimicrobial resistance, lack of field validation, scale-up problems, and biosafety issues associated with this technology. Consequently, this review has concluded that the incorporation of microbial biotechnology with environmental engineering and resource recovery and life cycle assessment and environmental monitoring is imperative.

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