Role of Bioremediation in Environmental Sustainable Development

Muhammad Nasir Sulaiman[1*], Ma'aruf Abdulmumin Muhammad[2*], Abubakar Abdullahi Tijjani[3*], Ramgopal Dhakar[4*].

[1]Department of Life Sciences, Mewar University,
NH 48 Gangrar, Chittorgarh, Rajasthan-312901

[2]Department of Chemistry, Faculty of Science and Engineering,
Mewar University, NH 48 Gangrar, Chittorgarh, Rajasthan.

[3]Department of Life Sciences, Mewar University, NH 48 Gangrar,
Chittorgarh, Rajasthan-312901.

[4]Department of Life Sciences, Mewar University, NH 48 Gangrar,
Chittorgarh, Rajasthan-312901

E-mail: nasirmuhammadnms@gmail.com, maarufabdulmumin@gmail.com,
tijjaniabdallah84@gmail.com, dhakarramgopal35@gmail.com.

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Abstract

The Earth is currently experiencing a growing pollution crisis that is endangering both ecosystems and human health. Conventional approaches to remediation, frequently severe and not environmentally friendly, find it difficult to keep up. Conventional approaches to remediation frequently fall short, resulting in a lasting impact of damage. Bioremediation is an eco-friendly and economical process that utilizes microorganisms to remediate polluted surroundings in a more advanced manner. The importance of sustainable development has become crucial. Quick industrial growth and careless disposal of waste have led to pollution of soil, water, and air with various harmful substances such as heavy metals, pesticides, and hydrocarbons. These impurities present significant risks to human well-being, ecological balance, the safety of food, and the ability to continue progressing in a sustainable manner. Previous studies have looked into different physicochemical methods for pollution control such as incineration, chemical use, thermal remediation, and landfilling, but these methods usually have downsides like being expensive, having limited usage, and causing additional environmental harm. Furthermore, they do not tackle the main source of pollution. Bioremediation makes use of naturally existing microorganisms like Pseudomonas, Sphingomonas, Rhodococcus, Alcaligenes, and Mycobacterium. This paper aims to evaluate the possibilities of bioremediation and its integration into sustainable development strategies, which can help restore ecosystems, improve soil quality, and reduce the impacts of climate change. Assess the efficiency of different in-situ and ex-situ bioremediation methods, analyzing their benefits and drawbacks. This article ends with a powerful plea for action, encouraging policymakers, researchers, and the public to fully realize the potential of bioremediation and work together towards a more sustainable future.

Keywords: *Bioremediation, Pollution, Microorganisms, Sustainable development, Environment.*

1. INTRODUCTION

Bioremediation, the use of microorganisms to degrade and remove environmental pollutants, is a cornerstone of environmental sustainable development. This natural and eco-friendly process leverages the metabolic capabilities of bacteria, fungi, and plants to detoxify contaminated soil, water, and air, thereby restoring ecosystems without the adverse effects associated with chemical remediation methods. By addressing a wide range of pollutants—from heavy metals and hydrocarbons to pesticides and industrial wastes—bioremediation not only cleans up polluted sites but also enhances biodiversity and promotes the health of natural habitats. Furthermore, bioremediation aligns with the principles of a circular economy, converting waste into harmless byproducts and enabling the recycling of natural resources. This sustainable approach reduces the ecological footprint of human activities, supports the United Nations Sustainable Development Goals (SDGs), and fosters a healthier planet for future generations. [1]

The contamination from harmful heavy metals is seen as a significant environmental problem that has rapidly increased because of shifting industrial practices. More advanced techniques for treating heavy metal contamination include both physicochemical and biological methods, with the biological methods further divided into in situ and ex situ bioremediation. The in situ process comprises bioventing, biosparging, biostimulation, bioaugmentation, and phytoremediation. Ex situ bioremediation methods consist of land farming, composting, biopiles, and bioreactors. Bioremediation makes use of naturally existing microorganisms like *Pseudomonas, Sphingomonas, Rhodococcus, Alcaligenes, and Mycobacterium.* In general, bioremediation is a process that requires minimal effort, is not labor-intensive, cost-effective, environmentally friendly, sustainable, and relatively simple to carry out. The majority of bioremediation drawbacks are linked to its slow pace and time-consuming nature; in addition, the byproducts of biodegradation can occasionally be more harmful than the initial substance. Assessing the effectiveness of bioremediation can pose challenges due to the lack of a definitive endpoint [2]

Irregularity and uncertainty of completeness could constrain bioremediation efforts. Additionally, evaluating the effectiveness of bioremediation is difficult because there is no clear endpoint. More studies are needed to improve bioremediation techniques and find new biological solutions for heavy metal pollution in different environmental environments [2] Different types of microorganisms can be utilized for bioremediation, as they are nature's natural recyclers. They can also convert chemicals into energy and materials for their growth, creating a cost-effective and eco-friendly biological process. Heavy metals have turned into a global environmental issue due to their widespread industrial usage. Industrial activities and fuel consumption result in the accumulation of toxic heavy metals in the food chain, causing environmental and health issues. These toxic effects are caused by heavy metals such as mercury, silver, lead, cadmium, and arsenic on living cells. Various bacteria have genes resistant to various cations and oxyanions of heavy metals within their DNA. Bacteria employ various mechanisms to confront the absorption of heavy metal ions in order to survive. These mechanisms consist of biosorption, entrapment, efflux, reduction, precipitation, and complexation. Microorganisms have the potential to be a promising and boundless resource for developing new environmental biotechnologies. Bioremediation, the process of using microorganisms to degrade and remove pollutants from the environment, plays a pivotal role in promoting sustainable development. By harnessing the natural metabolic processes of bacteria, fungi, and plants, bioremediation offers an eco-friendly and cost-effective alternative to traditional methods of pollution control. This approach not only helps in cleaning up contaminated soil, water, and air but also contributes to the restoration of natural habitats, thereby enhancing biodiversity. As environmental challenges escalate with industrial growth and urbanization, bioremediation emerges as a crucial tool in achieving ecological balance and fostering a sustainable future [4]

The effectiveness of bioremediation lies in its versatility and adaptability to various pollutants, including heavy metals, hydrocarbons, pesticides, and other hazardous chemicals. Different techniques such as bioventing, bioaugmentation, and phytoremediation are tailored to specific contaminants and environmental conditions, making bioremediation a highly flexible solution. For instance, oil spills in marine environments can be treated using oil-degrading bacteria, while contaminated soils can be rejuvenated through the introduction of specific plants that absorb and accumulate toxic substances. This natural and biological approach minimizes the need for harsh chemical treatments, thereby reducing secondary pollution and preserving the integrity of ecosystems [3].

This review discusses the typical techniques, tactics, and biological methods used in heavy metal bioremediation. It also offers a broad summary of how microorganisms play a role in detoxifying heavy metals in contaminated environments.

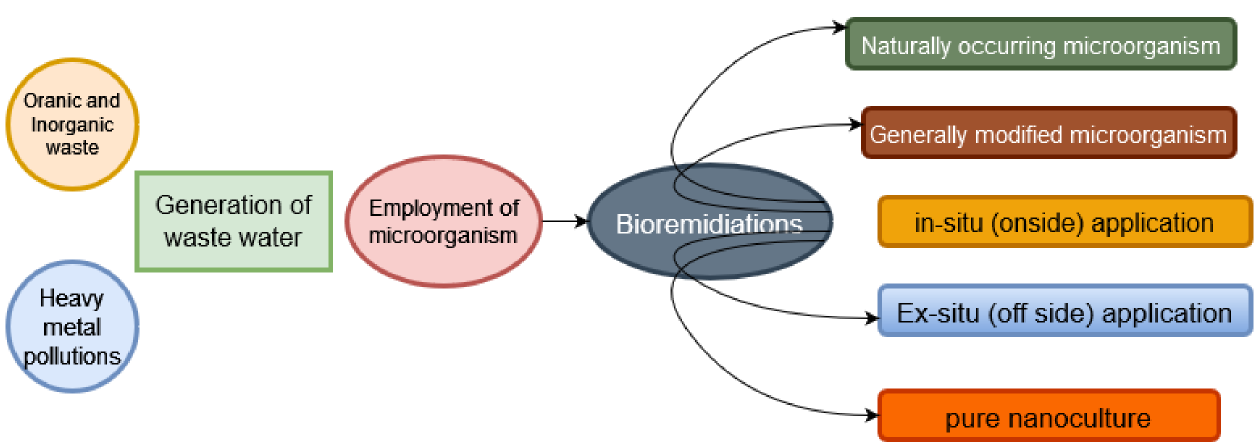

Fig. 1: Bioremediation of pollutants by different applications

2. IMPORTANCE OF INTEGRATING BIOREMEDIATION INTO SUSTAINABLE DEVELOPMENT STRATEGIES

Because of their extensive use in industry, heavy metals have emerged as a significant global environmental issue. Industrial processes and fuel usage result in the accumulation of toxic heavy metals in the food chain, causing environmental and health issues. These toxic effects on living cells are caused by heavy metals such as mercury, silver, lead, cadmium, and arsenic. Numerous bacteria contain genes that provide resistance to various cations and oxyanions of heavy metals in their DNA. In order to survive, bacteria utilize various mechanisms to combat the absorption of heavy metal ions. Some of these mechanisms are biosorption, entrapment, efflux, reduction, precipitation, and complexation. Microorganisms have the potential to be a valuable, limitless source for novel environmental biotechnologies. Bioremediation harnesses natural microorganisms to break down or neutralize harmful substances in order to protect human health and the environment. The microorganisms at the contaminated site can be either native or obtained from other sources [3], [4].

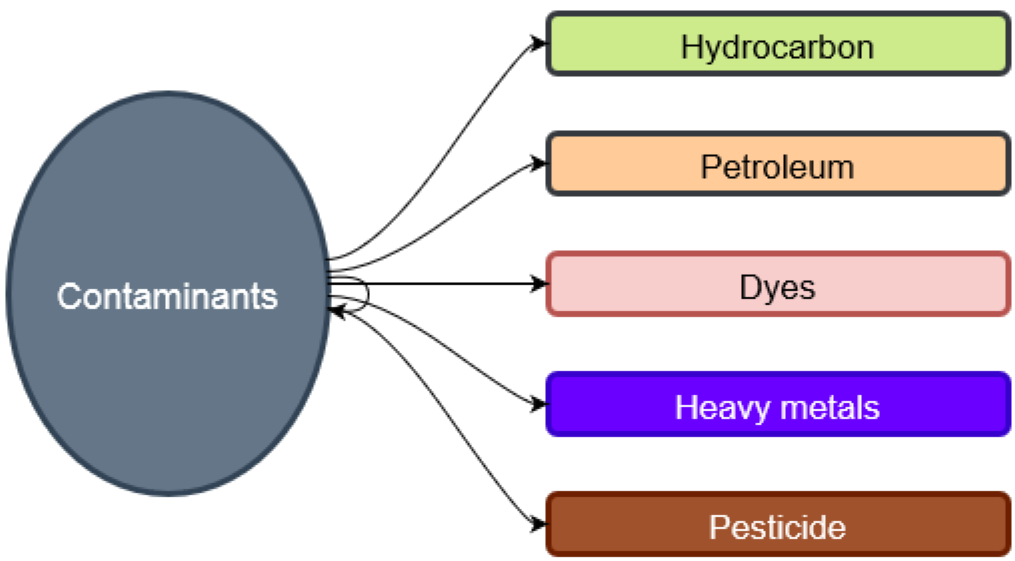

Fig 2: Contaminants that can be remove by Bioremidiations

Bioremediation remains a valuable, eco-friendly method where biological agents break down pollutants in the environment. Microbes have a vital part in eliminating heavy metals contaminants. Toxic effects on living cells are caused by heavy metals such as mercury, silver, lead, cadmium, and arsenic. *Pseudomonas, Alcaligenes, Sphingomonas, Rhodococcus, and Mycobacterium* are all types of aerobic bacteria that break down substances. Anaerobic bacteria have been utilized in the bioremediation of biphenyls, dechlorination, and chloroform as well. In addition, fungi microorganisms are capable of efficiently breaking down numerous harmful environmental contaminants. Phytoremediation is a developing method that employs plants to eliminate contamination from soil, water, and other surroundings. Bioremediation is a cost-effective, environmentally friendly, sustainable solution that requires minimal effort and labor to implement. The majority of drawbacks of bioremediation are associated with the slow pace and time-consuming nature; additionally, the byproducts of biodegradation can occasionally become even more harmful than the initial substance [2]

Table 1 – Contaminants and bioremediating microorganisms

Compounds	Microorganisms
Hydrocarbon	*Penicillium chrysogenum, P. alcaligenes P. mendocina, P. veronii, Achromobacter, Flavobacterium, Acinetobacter, Pseudomonas putida, Phanerochaete chrysosporium, A. niger, A. fumigatus, F. solani e P. funiculosum, Coprinellus radians, Alkaligenes odorans, Bacillus subtilis, Corynebacterium propincum, Pseudomonas aeruginosa, Tyromyces palustris, Gloeophyllum trabeum, Trametes versicolor, Candida viswanathii, cianobactérias, algas verdes e diatomáceas e Bacillus licheniformis, Ralstonia sp. e Microbacterium sp,, Gleophyllum striatum, Pseudomonas sp.*
Petroleum	*Fusarium sp., Alkaligenes odorans, Bacillus subtilis, Corynebacterium propincum, Bacillus cereus A, Aspergillus niger, Candida glabrata, Candida krusei e Saccharomyces cerevisiae, B. brevis, P. aeruginosa KH6, B. licheniformis e B. sphaericus, P. putida, Arthobacter sp e Bacillus sp, Pseudomonas cepacia, Bacillus coagulans, Citrobacter koseri e Serratia ficaria*
Dyes	*B. subtilis estirpe NAP1, NAP2, NAP4, Myrothecium roridum IM 6482, Pycnoporus sanguinous, Phanerochaete chrysosporium e trametes trogii, Penicillium ochrochloron, Micrococcus luteus, Listeria denitrificans e Nocardia atlântica, Bacillus spp. ETL-2012, Pseudomonas aeruginosa, Bacillus pumilus HKG212, Exiguobacterium indicum, Exiguobacterium aurantiacums, Bacillus cereus e Acinetobacter baumanii, Bacillus firmus, Bacillus macerans, Staphylococcus aureus e Klebsiella oxytoca*

Heavy metals	*Saccharomyces cerevisiae, Cunninghamella elegans, Pseudomonas fluorescens e Pseudomonas aeruginosa, Lysinibacillus sphaericus CBAM5, Microbacterium profundus cepa Shh49T, Aspergillus versicolor, A. fumigatus, Paecilomyces sp., Terichoderma sp., Microsporum sp., Cladosporium sp., Geobacter spp., Bacillus safensis (JX126862) cepa (PB-5 e RSA- 4), Aeromonas sp., Aerococcus sp., Rhodopseudomonas palustris*
Pesticide	*Bacillus, Staphylococcus, Enterobacter, Pseudomonas putida, Acinetobacter sp., Arthrobacter sp., Acenetobactor sp., Pseudomonas sp., Enterobacter sp. e Photobacterium sp.*

Sources: [5-9]

POTENTIAL OF BIOREMEDIATION IN DIFFERENT SECTORS

Bioremediation holds significant potential across various sectors, particularly in agriculture, water management, and land pollution remediation. In agriculture, bioremediation can detoxify soils contaminated with pesticides, herbicides, and heavy metals, enhancing soil health and productivity while reducing the reliance on chemical fertilizers. For water management, bioremediation techniques can purify wastewater and treat industrial effluents, thereby protecting aquatic ecosystems and ensuring safe drinking water supplies. When addressing land pollution, bioremediation is effective in cleaning up hazardous waste sites, oil spills, and mining areas, restoring these lands for safe use and contributing to land conservation. The implementation of bioremediation across these sectors not only mitigates environmental damage but also promotes sustainable practices and long-term ecological balance.

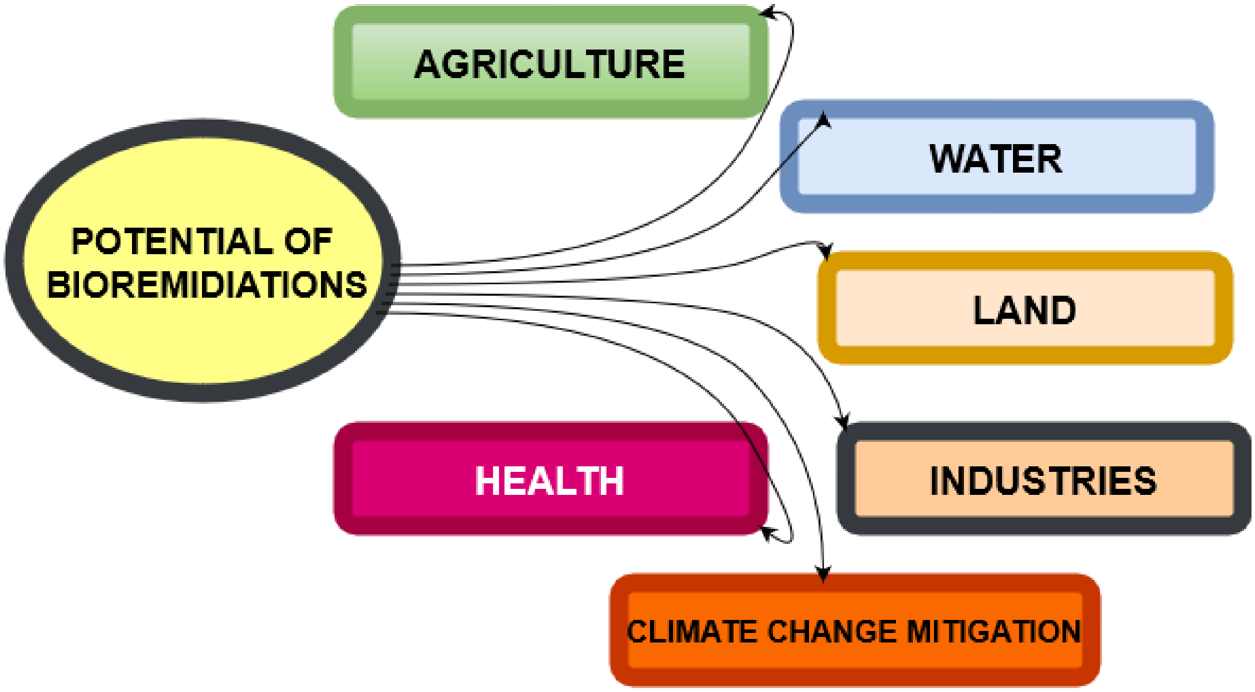

Fig: 3 Potential of Bioremediation

2.1 Agriculture

By employing techniques of bioremediation soil fertility can be improved and at the same time promote safe agricultural production. This has been demonstrated by a study on biostimulation where crude fungal extract and green manure significantly reduced waste motor oil (WMO) contamination in soil, decreasing the concentration to a level that allows the restoration of soil fertility for agricultural use [10]. Another study that focused on grass-based phytoremediation system coupled with organic amendment and biostimulants concluded a positive impact of increasing soil fertility and plant growth while reducing the bioaccessibility of potentially toxic elements in industrially contaminated soils [11]. By removing environmental contaminants from the soil, bioremediation techniques help in improving soil quality and increasing crop yield by using biological agents derived from plants or microorganisms [12]. Microbial augmentation in phytoremediation helps in enhancing soil quality which in turn improves crop growth, yield and ecosystem services. [13]. Pollution caused by the application of pesticides on farms to tackle the issue of pests has a long term implication on human health and also the genetics of the crop itself. Microorganisms can be used to treat environmental pollution caused by pesticides which are widely used in agriculture [14]. To increase the efficiency of bioremediation in phytoremediation, biostimulants (PBs) are used especially when dealing with heavy metals. PBs such as humic substances, protein and amino acid hydrolysate, inorganic salts, microbes, seaweed, plant extracts, and fungi have produced fantastic results in counteracting the deleterious effects of pollutants on plants [15].

2.2 Water

Heavy metals such as As, Cd, Pb, Cr, Zn, Cu, and Hg are generally unsafe to both fish and humans, as they cause various health issues and genetic abnormalities. Heavy metal contamination of aquatic environments significantly impacts the aquatic creatures' physiology, altering hemato-biochemical parameters, and impairing the fish reproductive performance [13]

2.2.1 In-situ and ex-situ bioremediation approaches for water bodies

Scientist worldwide are studying different approaches of in-situ and ex-situ bioremediation to find efficient methods for the treatment of water bodies contaminated with pollutants. In-situ bioremediation is the term used for explaining the treatment of polluted water in the same location without transferring it to a different location [16]. This approach strongly relies on the availability of nutrients, electron donors, and acceptors to support microbial activities for pollutant degradation [17]. Ex-situ bioremediation on the other hand involves treating the contaminated water bodies away from their natural location. Artificially constructed chambers made particularly for these applications such as natural wetlands, constructed wetlands, and floating wetlands are commonly used for ex-situ treatment [18]. These systems utilize the capabilities of microbes to continuously treat the water bodies and ensure their conservation and revival ([19]). Application of phytoremediation in the treatment of water bodies to remove contaminants is also considered by scientist for possible utilization in both in-situ and ex-situ bioremediation approaches [20].

2.2.2 Ecological restoration of aquatic ecosystems

Aquatic ecosystems contaminated by recalcitrant contaminants posing serious risk to the ecological balance can be mitigated by bioremediation through the use of biological methods such as constructed wetlands, sand filters, and microbial communities [21], [22]. Diverse plant species including water hyacinth, duckweed, and pond weed, have been studied and confirmed to have a role in handling wastewater and removing contaminants [23]. Microbes such as bacteria and microalgae are also among the biological agents employed in bio-remediating aquaculture effluents [24]. The Bioremediation techniques used in eliminating pollution in fresh water ecosystems include phyco-remediation and phytoremediation [25]. These techniques can be improved for effectiveness and result by physical-chemical and microbial activity stimulation techniques, as well as electro-bioremediation.

2.3 Land

Bioremediation is an effective and cost-efficient method for addressing land pollution caused by various contaminants such as heavy metals, hydrocarbons, pesticides, and plastics [26],[27]. It involves the use of living organisms, including bacteria, fungi, plants, and microorganisms, to degrade or transform these pollutants into less harmful substances ([28],[29]. Bioremediation can be applied directly to the contaminated site, reducing the need for extensive soil removal and transportation, resulting in lower environmental impact and cost. It also contributes to the recovery of soil fertility and water quality by integrating degraded contaminants into biogeochemical cycles. Metagenomic approaches have further enhanced the identification and degradation of soil pollutants, allowing for the exploration of the vast bioremediation potential for different contaminants. Mycoremediation, a specific form of bioremediation using fungi, has shown promise in reducing and biodegrading toxic compounds in agricultural land. Overall, bioremediation offers a sustainable and environmentally friendly solution for addressing land pollution.

Promoting sustainable land use practices integrating bioremediation involves the use of plants and microorganisms to restore soil fertility and remediate contaminated land [30]. Phytoremediation, which includes processes like phytodegradation, phytoextraction, and phytostabilization, is a low-cost and long-term solution for enhancing soil quality in marginal land [31]. Plant growth-promoting bacteria (PGPB) play a crucial role in promoting plant development and soil bioremediation by secreting metabolites and hormones, fixing nitrogen, and increasing nutrient bioavailability [32]. Additionally, the use of biosurfactants as remediation agents can enhance the sustainability of the remediation process by utilizing renewable or waste substrates and employing greener production and recovery processes [33]. Bioremediation technologies, such as plant and microbe-based soil remediation, can help address issues related to high salinity, heavy metal contamination, and oil contamination in soils, ensuring soil health and sustainable development [34]. The success of bioremediation technologies relies on the conservation of microbiota and biodiversity, as well as the ecological reconstruction of degraded or polluted areas.

2.4 Health

Water and land pollution have significant impacts on human health. Water pollution can lead to contamination of drinking water sources, resulting in various health risks such as diarrhea and other waterborne diseases [35],[36]. It can also affect the quality of food crops and contribute to food crop contamination and disease [37]. Land pollution, particularly soil pollution, can have detrimental effects on human health through exposure to potentially toxic elements (PTEs) present in polluted soil. PTEs can enter the human body through soil ingestion, consumption of contaminated food crops, inhalation of dust and fumes, and direct contact with contaminated soil [38]. The toxicity of PTEs can lead to various disorders, including neurotoxicity, nephrotoxicity, hepatotoxicity, skin toxicity, and cardiovascular toxicity. Therefore, addressing water and land pollution is crucial for protecting human health and reducing the risks associated with exposure to pollutants.

Bioremediation plays a crucial role in mitigating health risks associated with environmental contamination. It offers several advantages, such as the ability to remove or transform contaminants into less harmful substances, including hydrocarbons, heavy metals, pesticides, and toxic organic compounds [27]. Bioremediation can be applied directly to the contaminated site, reducing the need for the removal and transportation of large amounts of contaminated soil, resulting in lower environmental impact and cost [39]. Additionally, bioremediation integrates degraded contaminants into biogeochemical cycles, contributing to the recovery of soil fertility and water quality [40]. It also preserves biodiversity and ecosystem services, which can be affected by other decontamination techniques [41]. However, there are challenges and limitations, such as the possibility of partial degradation and the formation of more toxic or persistent by-products [42]. Despite these limitations, bioremediation is a promising tool for promoting the health and quality of life of populations affected by environmental contamination.

2.5 Industries

Microbial biotechnology plays a crucial role in bioremediation, as microorganisms are capable of breaking down contaminants and restoring ecosystems. Indigenous microorganisms or specific strains of microorganisms can be used for bioremediation, depending on the contamination site and environmental conditions [43]. In addition, the application of microbial surfactants, derived from microbial sources, has shown promise in bioremediation due to their versatility, biodegradability, and environmental safety ([44]). Overall, bioremediation offers a sustainable and cost-effective solution for the removal of industrial pollutants and the restoration of contaminated sites [45], [46].

In-situ bioremediation is an effective and sustainable approach for treating contaminated sites. It involves the use of microorganisms to degrade or transform pollutants in soil and groundwater. By directly measuring contaminant-degrading microorganisms and associated bioremediation processes, additional insights can be gained to inform remedial decision-making [47]. In the case of perchlorate contamination, a large-scale in-situ treatment using a cyclic process was successful in removing co-contaminants and reducing perchlorate levels in the unsaturated zone and groundwater [48]. In-situ bioremediation is preferred over ex-situ methods as it allows for the treatment of contaminated areas without the need for transfer and deposition of polluted soil and water [49]. Overall, in-situ bioremediation has shown promise in effectively treating contaminated sites and reducing environmental risk [18].

Successful applications of in-situ bioremediation have been demonstrated in several studies. Madison et al. applied a standardized framework combining Molecular Biological Tools (MBTs) with traditional contaminant and geochemical analyses to inform the design and implementation of enhanced bioremediation approaches at contaminated sites [47]. Another study highlighted the use of bioremediation techniques, such as in situ microbial bioreactors, to remove pollutants from the environment effectively [50]. Additionally, a large-scale in-situ treatment of heavily contaminated unsaturated zones and groundwater systems using a cyclic process was successful in removing perchlorate and other co-contaminants [51]. These studies showcase the cost-effectiveness, environmental friendliness, and sustainability of in-situ bioremediation as a remedial approach for various contaminants.

In-situ bioremediation is a cost-effective and environmentally friendly technique for removing pollutants from contaminated sites. It utilizes microorganisms to degrade or transform pollutants in soil and groundwater. The advantages of in-situ bioremediation include its natural remedial approach, the ability to directly measure contaminant-degrading microorganisms and associated bioremediation processes using Molecular Biological Tools (MBTs), and the potential for more consistent remedy effectiveness when combined with traditional contaminant and geochemical data analyses (51]. In-situ bioremediation can be used to remove a variety of contaminants, including heavy metals, poly-aromatic hydrocarbons, chlorinated solvents, and petroleum hydrocarbons [47], [52], [49]. However, there are limitations to in-situ bioremediation, such as the need for favorable conditions for microbial growth and metabolism, the potential for limited activities due to electron donor availability, and the absence of understanding of the processes and control [48].

Ex-situ bioremediation is a promising approach for the removal of pollutants from contaminated environments. Various studies have demonstrated the effectiveness of ex-situ bioremediation methods in different contexts. For example, Cenčič Predikaka et al. found that an on-site land farming unit (LU) showed potential for bioremediation of diesel fuel-contaminated soil. Ambaye et al. developed an experimental mesocosm using bio-slurry enhancement and external stimulants to degrade petroleum hydrocarbons (PHs) in contaminated soil. Kugler et al (2022) investigated the bioremediation potential of *Cupriavidus basilensis* SRS for copper-contaminated sediments in a constructed wetland [53]. Kumar et al. demonstrated the ability of biofilms to remove heavy metals from industrial wastewater, using *Escherichia coli* and petroleum soil isolated microorganisms (PSIM). Jasme et al. isolated *Aspergillus flavus* USM-AR1 and showed its effectiveness in removing waste cooking oil. These studies highlight the potential of ex-situ bioremediation methods for the remediation of various types of pollutants in different environmental settings.

In-situ bioremediation is a cost-effective and environmentally friendly method for treating contaminated sites without the need for transferring polluted soil and water to another location. It relies on the capabilities of microorganisms to degrade or transform pollutants in the same location. This approach requires the availability of nutrients, electron donors, and acceptors for microbial activity. Monitoring techniques such as gas chromatography, high-performance liquid chromatography, and spectroscopy are used to assess the effectiveness of in-situ bioremediation. The success of in-situ bioremediation depends on factors such as climate, plant species, and the presence of contaminant-degrading microorganisms. Comparative analysis with ex-situ bioremediation methods shows that in-situ bioremediation can be more sustainable and efficient in treating contaminants in soil and groundwater. [48], [54]

Table two: A comparative analysis of in-situ and ex-situ bioremediation

Aspect	In-Situ Bioremediation	Ex-Situ Bioremediation
Definition	A method for treating contaminated sites in their original location.	A method involving the removal of contaminated soil and water for treatment at another location.
Mechanism	Utilizes microorganisms to degrade or transform pollutants on-site.	Contaminated material is excavated and treated either on-site (but removed) or off-site.

Aspect	In-Situ Bioremediation	Ex-Situ Bioremediation
Cost	Generally more cost-effective due to the lack of need for transportation of contaminants.	Often more expensive due to excavation, transportation, and off-site treatment costs.
Environmental Impact	Minimizes disturbance to the site, preserving the natural habitat.	Can cause significant site disturbance and habitat destruction during excavation and transportation.
Treatment Time	May require longer timeframes for complete remediation.	Potentially faster remediation times as conditions can be more easily controlled and optimized.
Monitoring Techniques	- Gas Chromatography (GC) ,High-Performance Liquid Chromatography (HPLC) - Spectroscopy	Similar techniques as in-situ, plus additional lab-based assessments due to off-site treatment.
Success Factors	- Climate , Plant species Presence of contaminant-degrading microorganisms	- Controlled environment - Technology and equipment availability - Expertise in handling and treatment
Site Accessibility	Ideal for sites with limited access, where excavation is impractical.	Suitable for sites where contaminated material can be easily removed and transported.
Sustainability	More sustainable, with a lower carbon footprint due to no need for transport and reduced site disturbance.	Less sustainable due to higher energy use and carbon emissions from transportation and treatment processes.
Examples	- Phytoremediation - Bioventing - Biosparging	- Landfarming - Biopiles - Composting

2.6 Climate Change Mitigation

Bioremediation plays a significant role in carbon sequestration by utilizing living organisms to absorb carbon dioxide from the atmosphere and store it in various forms such as vegetation, soils, and woody products [55]. One method of bioremediation is the application of biochar into the soil, which has been shown to effectively remove greenhouse gases from the atmosphere and store them in the soil for long periods of time [56]. Biochar application not only helps in carbon sequestration but also provides additional benefits such as increased crop yield, nutrient and water use efficiency, and reduced emissions of methane and nitrous oxide [57], [58]. Additionally, the presence of soil microorganisms can enhance the carbon sequestration capacity and efficiency of biochar. Therefore, the combination of bioremediation techniques, such as biochar application, with the involvement of soil microorganisms can significantly contribute to carbon sequestration efforts and mitigate the greenhouse effect.

Bioremediation is a technology that uses living organisms to remove or transform contaminants in soil, water, or air into less harmful substances. It offers several advantages, including the ability to degrade a wide variety of contaminants, the potential for direct application to contaminated sites, lower environmental impact and cost compared to other techniques, integration of degraded contaminants into biogeochemical cycles, and preservation of biodiversity and ecosystem services [54]. Various approaches have been employed to enhance bioremediation, including in situ and ex situ techniques, biostimulation, bioaugmentation, and genetic engineering [59],[60]. It can degrade a wide range of contaminants, including hydrocarbons, heavy metals, pesticides, and toxic organic compounds [54]. Bioremediation can be applied directly to the contaminated site, reducing the need for soil removal and transportation, resulting in lower environmental impact and cost [39]. It also integrates degraded contaminants into biogeochemical cycles, contributing to the recovery of soil fertility and water quality [51]. It relies on favorable environmental conditions and may result in partial degradation or the formation of more toxic by-products [47]. Factors such as nutrients, oxygen, pH, and bioavailability of contaminants can affect the effectiveness of bioremediation. In addition, in-situ bioremediation treats contamination in place, while ex-situ bioremediation involves excavation and treatment in bioreactors. Both approaches have their own advantages and limitations, and the choice depends on site-specific factors. The possibility of partial degradation or the formation of more toxic by-products, dependence on favorable environmental conditions, and the need for in-depth knowledge and careful risk assessment [39]. Further research is needed to improve the effectiveness of bioremediation, considering factors such as climate, location, and types of pollutants [47]. Bioremediation approaches, both in-situ and ex-situ, offer several advantages and limitations. In terms of advantages, bioremediation is a cost-effective and environmentally friendly method for removing contaminants from the environment [27].

Recent developments in nanotechnology and bioremediation have increased the potential for efficient and sustainable decontamination methods [61]. Molecular Biological Tools (MBTs) can provide additional insights into contaminant-degrading microorganisms and bioremediation processes [47]. Omics approaches, such as meta-genomics, meta-transcriptomics, meta-proteomics, and metabolomics, have provided critical insights into microbial communities and mechanisms in bioremediation [62]. Biostimulation has been shown to be an effective method for bioremediation of soils contaminated with petroleum products in high-mountainous landscapes [63]. Genetic engineering is a worthy process that will benefit the environment and ultimately the health of our people, when many genes for pollutant degradation were discovered, it was possible to create new engineering strains with improved adapt- ability to heavy metals and other recalcitrant environmental contaminants by introducing genes for pollutant degradation into recipients with high adaptability and fecundity [1]. These findings highlight the importance of using genetically modified microbes, nanotechnology, MBTs, and omics approaches in bioremediation to achieve successful outcomes.

SUMMARY

Bioremediation is a crucial technique for environmental sustainable development, utilizing microorganisms to degrade and remove pollutants from soil, water, and air. This eco-friendly process harnesses the natural metabolic abilities of bacteria, fungi, and plants to detoxify contaminated environments, offering an alternative to traditional chemical remediation methods. Its versatility allows for the treatment of various pollutants, including heavy metals, hydrocarbons, and pesticides, across different sectors such as agriculture, water management, and land pollution remediation. By restoring natural habitats, enhancing biodiversity, and converting waste into non-toxic byproducts, bioremediation aligns with circular economy principles and reduces secondary pollution. Additionally, it contributes to achieving the United Nations Sustainable Development Goals (SDGs) by supporting clean water, land conservation, and climate action. Bioremediation not only mitigates environmental damage but also promotes sustainable practices, long-term ecological balance, and socio-economic benefits, fostering a healthier planet for future generations.

CONCLUSION

Bioremediation processes, such as biostimulation and bioaugmentation, can efficiently remove toxic petroleum hydrocarbons and their derivatives. Nevertheless, bioremediation alone has limitations in addressing the variety of environmental contaminants and the levels to which it can effectively remediate. To overcome these limitations, nanobioremediation has been developed by integrating nanotechnologies and nanomaterials with bioremediation approaches. Nanobioremediation has shown enhanced remediation efficacies and solutions for the removal/sequestration of a wide variety of environmental contaminants. It offers a sustainable, eco-friendly, and economically viable approach to environmental restoration and clean-up. The integration of biomolecules, microbes, and enzymatic processes with nanotechnology has the potential to address the present challenges in environmental remediation and restoration. Future research should focus on optimizing the wider applicability and compatibility of nanobioremediation, genetic engineering, and omics approaches in bioremediation to achieve successful outcomes.

CHALLENGES AND FUTURE DIRECTIONS

Bioremediation is a promising approach for the sustainable development of contaminated environments. However, there are several challenges in integrating bioremediation into sustainable development. One challenge is the increasing population density and industrialization, which leads to a higher burden of pollutants such as petroleum hydrocarbons and other organic and inorganic contaminants in the environment. Another challenge is the need for low-cost and eco-sustainable technologies for efficient bioremediation. Additionally, the complexity of biodegradation mechanisms and the need for a better understanding of biodegradation pathways hinder the development of efficient bioremediation technologies. Furthermore, factors such as the vulnerability and dynamic nature of the environment, toxicity of pollutants, and the survival of microbe degraders pose challenges to the degradation process. Overall, integrating bioremediation into sustainable development requires addressing these challenges through research and the development of innovative strategies. There is a need for further studies to develop bioremediation technologies and approaches suitable for the bioremediation of pollutants from various environmental systems.

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COMPETING INTEREST

The authors declare that they have no known competing interests including but not limited to financial and personal relationships with other people or organizations that could inappropriately influence the review of this paper.

AUTHOR'S CONTRIBUTIONS

Corresponding Author: Led the construction of the initial manuscript, thorough analysis and rigorously monitored the editing process, ensuring consistency and clarity throughout.

Co-Author 1: Conducted a thorough analysis and detailed comparison investigation, which increased the depth and breadth of the article's content.

Co-Author 2: Provided crucial supervision throughout the process, offering advice and expertise that greatly improved the article's quality and trustworthiness.

Co-Author 3: Methodically polishing the writing style and structure to ensure readability and interest.

Co-Author 4: Played an important role in the editing process, methodically evaluating and revising the content.

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