THE ROLE OF BIOREMEDIATION IN ACHIEVING ENVIRONMENTAL SUSTAINABILITY

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ABSTRACT
Research on biological solutions for sustainable environmental health has grown significantly over the years, highlighting the urgent need for innovative and effective remediation strategies. Bioremediation, an ecologically significant practice, uses biological agents to address despoiled habitats by harnessing the metabolic potential of microorganisms or cells to degrade, remove, or dispose of contaminants from soil, water, or air. Bioremediation pathways are part of general life processes, like energy production, and do not result in the breaking down of one pollutant into a harmful substance. A broad spectrum of pollutants can be bioremediated through a specific selection of biological agents such as bacteria, microalgae, aquatic pulmonated, fungi, and plants. The ecological health of any ecosystem and human health are emphasized, as chemical spills into environmental components can influence sustainable management hydraulics and ecosystem results due to the intricate food chain. Bioremediation stands as a potential development and low-cost methodology for removing pollutants heavily from affected parts, and several cases of microorganisms and their enzymes and processes are used in the removal of industrially produced hazardous substances. The following sections are dedicated to a detailed understanding of microorganisms and exploration of the potential of biodegradation processes useful for the removal of environmental pollutants, as well as the reduction in human health hazards. Bioremediation stands as one of the potential developments and low-cost methodologies for removing pollutants heavily from the affected parts. Furthermore, several cases of microorganisms and their enzymes and processes involved are used in the removal of industrially produced hazardous substances.

Key Words : *bioremediation, living organisms, sustainable, eco-friendly environmental challenges*

I. INTRODUCTION

Bioremediation is an innovative and effective process that employs natural biological systems to clean up and restore contaminated environments effectively. This method stands out as a low-cost and environmentally friendly solution that holds significant potential for promoting sustainable development across various regions. The remarkable ability to clean up and rehabilitate contaminated environments helps restore natural ecosystems, effectively transforming an area that was once considered a liability into a valuable asset. Bioremediation represents a progressive technology that harnesses the process of contaminant degradation, utilizing living organisms to convert harmful metal contaminants into less toxic, less soluble, and/or immobile forms that pose minimal risk to the ecosystem. While the bioremediation of inorganic contaminants is still not widely embraced or accepted, some regions have begun to adopt it on a trial and experimental basis, reflecting a growing interest in this viable solution. In general, it is essential to regard bioremediation not merely as a treatment technology but also as a vital journey toward comprehensive ecosystem restoration and alignment with the principles of green chemistry, which emphasize sustainability and environmental stewardship. Through careful implementation and ongoing research, bioremediation can play a crucial role in healing our damaged landscapes and promoting environmental health. Bioremediation makes use of living organisms to remove or neutralize contaminants. Bioremediation technologies use naturally occurring bacteria, fungi, plants, and other organisms to degrade or assimilate toxic substances into non-toxic substances. Fungi have been used to clean up a variety of environmental contaminants from chlorinated solvents to hydrocarbons. Early bioremediation efforts, many of which were quite successful, focused on biostimulation strategies. These can vary considerably, from simple strategies to complex, elaborate ones. While it is not necessary to dig up large amounts of soil for solid-phase treatments, it is important to keep in mind the geographical and geological context and to conduct appropriate feasibility studies. Although people have used bioremediation techniques at least since Roman times, the modern bioremediation industry is a product of the last 50 years as well as new concepts in environmental chemistry and toxicology. This growth is in part a response to the vast increase in the number of contaminated sites caused by industrial growth. The import stems are increasing faster than clean systems [1, 2].

II. LITERATURE REVIEW

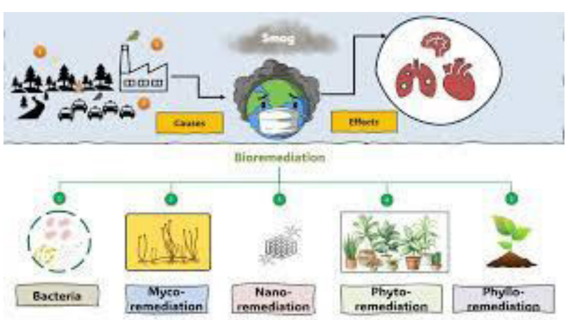
The term bioremediation is also often used as a synonym for the process of using biological organisms to detoxify polluted environments. There are also various definitions available for bioremediation. However, the following description is a practical and working definition: bioremediation is the process of using biological processes to harness the capacity of biological systems to degrade, sequester, or immobilize environmental contaminants to protect human health, animal health, or whole ecosystems. To perform the process assessment, the main factors that can affect remedial capabilities and toxic levels in a sample are taken into consideration, which include environmental and biological factors. The effectiveness of microbial processes is firmly established through preceding research. When microorganisms break down compounds, they use metabolic pathways to form a variety of intermediate compounds and ultimately generate carbon dioxide, water, inorganic salts, and additional microorganisms. These ultimate advantages of microbial metabolism form the esthetic appeal of bioremediation. Microorganisms also have a greater metabolic capability than higher organisms because they are capable of degrading and/or detoxifying lipophilic organic compounds. Microorganisms can metabolize these compounds through the degradative or catabolic pathways. Though metabolism primarily results in the biotransformation of the original pollutant into another organic form, it is also possible that microorganisms can degrade to inorganic products by mineralization or restoration of the original compound structure. Although it is not certain, and also depends on the level of metabolism, soil and environmental conditions can cause the converted compounds to accumulate and, in turn, increase toxicity [3].

Historical development

The emergence of industrial microbiology known as the fermentation industry in which microbial processes are used to obtain chemicals, pharmaceuticals, and fuels in addition to the manufacture of food products, resulted in development of bioprocesses for the treatment of wastewater, industrial emissions, and solid waste from multiple sources including Abattoirs, Dairy, Pulp and paper, Pharmaceuticals, Petro-chemicals, Energy and Textiles have undergone judicious intervention with bacteria, fungi, yeasts, and algae. Although biotechnological processes were developed to control, optimize and mitigate large scale fermentation procedures to break down and detoxify the environment of sugar, amino acid, and alcohol fortified effluents, the organic compounds such as lignin and humic substances were only structurally unaltered and hence multifaceted in toxicity. This led to the development of technology for secondary wastewater treatments based on physico-chemical processes, which employed acclimatized bacteria from polluted environments, giving rise to "activated sludge technology." Facultative aerobic bacteria within activated sludge, aerobic activated sludge for the consumption of external organic substrates that occur within the same cells constituting a "contained microenvironment." This ended the era of sterile bacteriology, starting modern biological methods for controlling bioprocesses and addressing environmental issues [4]. Bioremediation is not a new concept. Historically, this process had been observed among primitive agricultural societies, which tweaked the microbial communities present in the soil to treat pollution. Industrial Revolution marked the beginning of a new era of exploitation of natural resources via anthropogenic activities such as mining and the use of petroleum, which resulted in an unprecedented number of pollutants being released into the environment [5]. There are numerous examples that illustrate the destruction caused by anthropogenic pollution. One such example is the contamination of the Minimata Bay in the former industrial city of Minimata in Japan. It was noted that the wastewater discharged from the Chisso chemical factory contained high levels of methylmercury as a byproduct. The levels increased when electrical production due to hydroelectric dams led to $Hg2+$ that was being deposited in the Minimata Bay being converted to $CH3Hg+$ through biotic interaction, and got assimilated by the marine biota which became toxic to humans and the cats that were higher up in the marine trophic levels [6].

Types of bioremediation techniques

Bioremediation can be categorized into four primary methodologies. These are in situ bioremediation, ex situ bioremediation, biostimulation, and bioaugmentation. In situ bioremediation is the unobtrusive treatment of a contaminated site; the contaminants are treated within the site without being removed or drawn to the surface. In certain usages, this term represents both in situ and on-site bioremediation. In this instance, biological, chemical, or other treatment systems are set up on-site to treat contaminated soil, water, or air. The general idea is to bring the treatment to the contamination to maximize efficiency and minimize disturbance. Conversely, ex situ bioremediation is microbially stimulated in the straightforward treatment of contaminated material that is physically removed from the initial site. It is then treated repeatedly and, once clean, returned to the site en masse. Ex situ bioremediation is often used at steeply contaminated sites where on-site cleanup is not obvious [2, 7, 8, 9]. Biostimulation aims to encourage extant populations of microorganisms to degrade contaminants more quickly. This works by providing them with all of the necessary nutrients. If the right nutrients are supplied, the native strains of microorganisms can break down organic contaminants (up to their capacity) with biostimulation. Alternatively, bioaugmentation involves the addition of microorganisms to the ecosystem to increase the numbers of organisms able to degrade the contaminants. In the proper circumstances, bioaugmentation can focus the activity of specialized microorganisms to clean up the contamination. Bioremediation can be geared to aquatic or terrestrial systems, and it can differ in the source or mode of introduction of organisms. In land farming, now a relatively common technique, contaminated soil is overturned for periods of time and moisture is checked periodically; this creates an environment where biodegradative bacteria can propagate and metabolize the contaminants. In soil vapor extraction, petroleum hydrocarbons are volatilized by the extraction of volatile interferents into the air stream to facilitate uptake by microorganisms for biodegradation. The removal of aromatics by bacteria, which are reconnected to at least 50% of the oil from the ground, is another form of ex situ remediation. The resilience of biodegradable microorganisms to competition from aerosolized microbes generated through steam cleaning or chemical dispersion has been established in a variety of trials. However, ex situ cultures did not survive when reintroduced. Bioaugmentation, usually used with composting, is a type of bioremediation in which the concentration of microorganisms in the soil is enhanced to treat contaminated soils. Bioaugmentation, on the other hand, is typically considered to be a relatively unsustainable way to treat environmental legacies because the newly introduced species cannot always survive under the often-harsh environmental conditions. In contrast, in regions with elevated concentrations of polychlorinated biphenyls, in situ indigenous forces have achieved greater success [10, 11, 12].



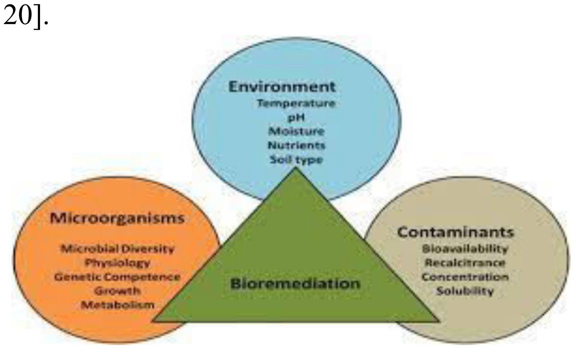
Microorganisms in bioremediation

The bioremediation field has seen significant numbers of new bacteria discovered that can break down oil and use its aromatic hydrocarbons as an energy source. There is substantial commercial interest in these microorganisms, which can be used to treat soils contaminated with crude oil. Their production can be used to ascertain the environmental fate and half-life of such compounds. Their activity can be used in both the bioremediation of benzene-mediated pollution in soils and in the refining and provision of additional natural resources such as biofuels and recombinant microbial bioremediation. There is also interest in assessing whether methods used to biologically produce fine chemicals and pharmaceutical products can be adapted for bioremediation purposes where there is modular employment of engineered bacterial enzymes. So, for example, DDT was added to culture of Pseudomonas putida JMP134; subsequently, its catabolic processes were used to purify the compound. These organisms can also shrink and discharge antibodies that can detect harmful waste, which could be used as biosensors for on-site rapid discovery of microorganisms that are central to the bioremediation process. They are known to have great potential in the field of biodegradation, which is the degradation of various types of environmental pollution by natural means. According to this definition, biodegradation could be an advantage to clean up the polluted areas. The geographic location of the polluted area will determine the type of microbial community responsible.

Microorganisms can be classified into bacteria, fungi, actinomycetes, and algae groups and are widely distributed throughout the soil or wastewater, exhibiting a unique role in a single enzyme. For example, bacteria play a role in different metabolic activities. These groups have strains that are distinguished by a type of enzyme that will degrade a given pollutant. Another possibility of these microorganisms is that the microbial community responsible has the ability to interact with each other during pollutant degradation; one bacterial strain can supply a given substance for the growth of the related strain of bacteria. There is a diverse assem [13, 14, 15] blage of microorganisms capable of biodegradation. Numerous microorganisms, like bacteria, fungi, yeast, and other single-celled eukaryotes, have been identified for rapid growth and degrading various toxins present in the polluted soil or liquid medium. Consequently, a number of well-characterized microorganisms have attracted much attention in laboratories for their greater ability to bio-utilize and provide energy to the associated cells, if any, for biodegradation. These microbes will become fully active when they are provided with a high content of nutrients such as carbon and energy sources. When conditions are suitable, chemicals are converted to the intermediate, cell biomass, and gaseous and energy compounds in accordance with the typical bacterial metabolic pathway. The microbe-mediated biodegradation of the PAHs will occur at the required pH range. Typically, a pH of 5 to 10 is suitable for the growth of various bacteria.

Key microbial species

Bioremediation is the ability of microorganisms to degrade, alter, and metabolize pollutants found in environments. Key microbial players used in bioremediation projects include many species of bacteria, fungi, yeast, and, recently, archaeal species. Members of all three domains of life possess the ability to biodegrade various compounds; fungi and bacteria are the most frequently used for the degradation of xenobiotics such as polycyclic hydrocarbons, polychlorinated biphenyls, polychlorinated dibenzo-p-dioxins, ethidium bromide, reactive dyes, and some herbicides and pesticides. Bacterial species are usually employed for the biodegradation of hydrocarbons, heavy metals, organic, and inorganic pollutants, whereas fungi are mainly used to degrade lignins, polycyclic hydrocarbons, cellulose, hemicellulose, and toxic aromatic compounds [15, 16, 17]. Bacterial species offer several advantages, such as producing various extracellular enzymes responsible for the bioremediation of a vast range of oligotrophic environments; interacting with available nutrient sources as well as being amenable to culturing under laboratory conditions; being genetically manipulatable with respect to isolation, cloning, and transferring of genes of interest; exhibiting their presence even if targets are found in the groundwater; and conferring protective protein parts for the further generation of recombinant products of bacteria. The first bacterial species was isolated from the soil, while the fungal species live mostly on decaying organic matter and can be found in the soil, in the colon of certain animals, and in association with plants in the form of mycorrhizal species. Archaea are prokaryotic microorganisms closely related to bacteria and are found in the most extreme environments, like the gut of living beings and in geothermal habitats as the most heat-resistant species. Genomic studies of uncultivable microorganisms are necessary to verify their capabilities for their natural application in bioremediation. Bioaugmentation is done after the isolation, culturing, and augmentation of the organism. Bioaugmentation is advantageous when a lake ecosystem is to be cleaned in less time with fewer operational strategies [18, 19, 20].



Microbial community dynamics

Biodegradation as a microbial utilization of pollutants led to the two cooperatively acting components, substrates and enzymes. Substrates are very specific in their mode of interactions with the biological macromolecules and thus act as a driving force to select an enzyme for a particular reaction. As enzymes are proteins or their macromolecular complexes, their catalytic properties can be modulated in response to structural and conformational modifications to the interaction with pollutants. The structure of the microbial community dynamics can be predicted from the given environmental conditions and functional potential derived from the functional structure. Ecosystem functions are often not determined by the abundance of the individual species, but by species interaction. Interaction between the organisms is influenced by biotic and abiotic factors. In natural environments, the structures of the microbial communities can change actively through secondary metabolites, biofilms, and MDRs or passively through random genetic drift, founder events, bottlenecks, and population sizes due to evolution. Different consortia can have a significant effect on pollutant degradation and therefore, BAS processes. The implication, however, is that environmental conditions may affect the structure of the community and, consequently the biodegrader's structure. The number and rate of metabolism, multiplication, copies of MDRs and toxins, and formation of exoenzymes by the microbes are increased or decreased by the addition of nutrients. Likewise, environmental factors can affect the diversity and dynamics of microbial activities, which is the subject of ecophysiology. Therefore, there is a need to study the dynamics of microbial communities, which are involved in pollutant cold assimilation and its interaction [21, 22, 23, 24].

Enzymes in bioremediation

Enzymes are the most effective and selective biocatalysts in bioremediation. Enzymes accelerate the breakdown of complex and scientifically recalcitrant pollutants into simpler and less toxic metabolites. By affecting cell membrane permeability, the enzymes improve the cell's ability to degrade organic pollutants and assist in solubilizing hydrophobic contaminants. Enzymes catalyze every conceivable biological hydrolytic, reductive, oxidative, and conjugative reaction. There are different types of enzymes involved in catalysis, including hydrolases, involved in hydrolysis; oxidoreductases, involved in oxidation-reduction activities; isomerases, involved in isomerization; and transferases, involved in transferring chemical units from one molecule to another. Microbial enzymes act on the hydrophobic molecules to form hydrophilic products. When microorganisms reach the boundary of the hydrophobic pollutants in the contaminated zone, an enzyme is secreted, serving as a partial reaction in the process, splitting the contaminated sites into hydrophilic products that can be assimilated into the cell. Then the products can be used as carbon, carrier, and electron donor to transform to CO_2 and H_2O [25, 26, 27]. Different types of bacterial strains have their own associated enzymatic activities that assist in carrying out the process of bioremediation efficiently. This is an association between the bacteria and the enzymes, where the bacteria secrete enzymes that are active against a majority of the pollutants present in the particular area. Based on the characteristics of the microorganisms and the enzymes present, several types of bioremediation can be carried out efficiently. Important enzymes involved in the degradation of complex hydrocarbons to simple hydrocarbons include dehalogenases, alcohol dehydrogenases, catechol dioxygenase, catechol 1,2-dioxygenase, aromatic ring cleavage, protocatechuate meta-cleavage, salicylate hydroxylase, 1-hydroxyl-2-naphthoate dioxygenase, and others. Crop root exudates can act as a natural magnetic field for the microbes, while the hyperaccumulators act as a magnet for the remediators. Most of the paddy crops have a rhizosphere that sludge sticks to the surface of the roots, whereas the area above the roots is waterlogged. Many of the steps in the bioremediation process are catalyzed by enzymes. The efficiency and stability of enzymes used in practical remediation applications have always been a problem, but we can comfort ourselves that many improvements can be made using a variety of novel approaches, including protein engineering. Many natural biological processes are governed by the constraints of specific enzymes produced and degraded or secreted by the particular microbial species that live in a particular environmental condition. The specificity of these enzymes and the conditions requiring their production contribute to the overall selectivity and strategies microbial species use to coexist and produce functional proteins [28, 29, 30].

III. RESULTS AND SIGNIFICANCE OF RESEARCH

Applications of bioremediation

Bioremediation has the potential to remediate a wide variety of environmental pollution in various ecosystems, including soils, water, and air. For example, bioremediation can be used to restore soil or water contaminated with mining or military activities, or to restore or rehabilitate oil spills in oceans or seas. For this topic, bioremediation serves all ecosystems. Some successful case studies of bioremediation applications in different ecosystems are described next. In the most unconventional environments, like the Arctic ice, bioremediation techniques are not commonly applied. However, a bioremediation process was able to counteract hydrocarbon pollution in North-West Spitsbergen. In the desert, a consortium of bacteria able to degrade PAHs and phenols has been selected with favorable applications in bioremediation. More conventional applications of bioremediation are described, for instance, for cleaning oil-polluted water or groundwater, using, in some cases, immobilized bacteria or simple equipment to help the process. The same applies to the oxic treatment of groundwater using bacteria or the rehabilitation of mercury-polluted sites with one strain of bacteria. As in the case studies, bioremediation is mainly applied in the restoration of contaminated sites since it contributes to the ecological resiliency of these sites and, in addition, improves the local inhabitants' public health. This approach not only facilitates the removal of toxic substances but also mitigates the adverse effects on the surrounding ecosystem. Additionally, the use of specific microbial strains can enhance the efficiency of degradation processes, making bioremediation a viable solution in various environmental contexts. Recent advancements in genetic engineering further allow for the development of engineered bacteria that can target and break down complex pollutants more effectively highlight the importance of microbial processes in degrading pollutants, such as hydrocarbons and heavy metals, which are crucial for restoring contaminated environments [44]. Bioremediation techniques are highly versatile since they can be applied for the removal of a large variety of materials, including organic and inorganic compounds, such as heavy metals, emerging pollutants like perfluorooctanoic acids, and nanoparticles, among others. Furthermore, it can be applied to a wide variety of environmental conditions, from the cleaning of contaminated aquifers to the restoration of soils or the polluted atmosphere in urban areas. Indeed, bioremediation can take several forms depending on the environmental conditions and the matrix where the pollutants are found. When the bioremediation technique is applied to remove contaminants from a liquid medium, whether it is water or soil extracted with the appropriate solvents, the technique is called biosorption and bioaccumulation, respectively. An example of a successful application of these techniques is the removal of heavy metals from industrial wastewater. In the case of sites contaminated with organic pollutants, the bioremediation technique can be applied to the rehabilitation of the soil, and it is used to stimulate the degradation of the different contaminants by the endogenous microbial population. This group is represented by several other possibilities, such as in situ, on site, surface, bioaugmentation, biostimulation, constructed wetlands, or hotspots, among others. Additionally, the bioremediation technique can be applicable at all stages of the pollution; for example, when a decontamination procedure is required, it can be applied at the time the contamination is produced or after. The simultaneous application is known as phytoremediative bacterio-phytostabilization, while the residual application is known as a biostabilization mechanism [45, 46, 47].

Soil remediation

Bioremediation has enormous potential for soil remediation. Heavy metals, pesticides, and petroleum products represent the main contaminants found in soils. Several strategies can allow contaminant degradation by both autochthonous and allochthonous organisms. Among them, phytoremediation, when assisted by plant-associated microorganisms, and microbially-assisted remediation have proven to be effective in decontaminating polluted areas. Crops are grown in soils, with preference given to those that produce biomass with high energy density. Remediated areas are often left degraded and polluted, and the interest in restoring soil health has recently increased. Bioremediation often takes place in grasslands and forests. Soil fatty acids have been revised, and different applications have been presented in the emerging world of soil. Many examples of successful soil remediation with both bacterial and fungal amendments or in situ stimulation have been demonstrated. The use of local microorganisms is considered a valid alternative to the use of allochthonous bacteria to exert biostimulation and bioaugmentation. Consistently with this, bioremediation of contaminated soil is depicting bioremediation strategies based on local microflora exploiting several in situ technologies. After each bioremediation application, both the residual pollutant content and any potential negative impacts require the use of sophisticated analytical and assessment strategies to determine and evaluate the effectiveness of monitored technologies [48, 49, 50, 51].

Water treatment

Bioremediation strategies have been of great interest for the treatment of waters contaminated by a wide array of biodegradable organic and inorganic compounds. In such cases, the main processes that occur are degradation of the pollutants through chemical and biological reactions. Microorganisms, particularly bacteria, are the key players in such remediation projects. In subsurface environments with anoxic conditions, microorganisms degrade pollutants in the absence of oxygen. This process, known as anaerobic bioremediation, can also be stimulated using a number of different approaches [52].

The concentration of pollutants in contaminated water may be quite low, such as nutrients, making bioremediation by microorganisms problematic. In such a case, a strategy called biostimulation is typically used to increase the numbers of indigenous microorganisms. Alternatively, in some cases, the contamination may be so severe that the indigenous microorganisms are unable to degrade the pollutants under normal conditions. In such cases, bioaugmentation may also be utilized. In the case of solid or hazardous waste landfills, bioaugmentation may involve the artificial introduction of either chosen or engineered microorganisms that could potentially degrade the contaminants. Contaminants in water are typically of two types: either organic compounds like chlorinated organic solvents, coal derivatives, and chlorophenols, or inorganic compounds such as heavy metals, nitrogen, phosphorus, dieldrin, and other non-specific organic compounds. Based on the biodegradability of the pollutants, different strategies have been developed for remediating contaminated water [53, 54, 55, 56]. The large surface of rivers, lakes, estuarine systems, and seas is in sustained contact with soil or sediments at various degrees. Microorganisms are present in large numbers together with invertebrates and vertebrates. Microbial populations are able to remove carbon, phosphorus, and human pathogens, as organic materials from leaves, bark, fowl, and human waste are included in the trophic chains supported by microbial consumption. Indigenous and natural microbial populations break down and detoxify most hazardous wastes. Nevertheless, it may become necessary to boost and stimulate them to augment biodecomposing rates and abilities toward pollutants. In addition, in some specific conditions, environmental factors have made it impossible for microorganisms to degrade and detoxify simultaneously large amounts of specific compounds. In water, almost any kind of pollutant can be entirely removed, thanks to the activities of microbial communities. Several case studies demonstrate the feasibility and effectiveness of bioremediation. After a dike break flooded a large part of the Rhine River in 1995, 2500 ha of forest, 1600 ha of swamp, and 1000 ha of grasslands were flooded. The water was diverted to the Rhine River without additional problems. Regulators in many countries have established water quality regulations with maximum levels of certain pollutants. The presence of pollutants at a higher level than that established by law must be a signal to water treatment utilities, which must intervene to remove pollutants or to obtain water from a less polluted river. The natural depuration capacity of water in rivers and wetlands is remarkable. For example, the Parklands were flooded without any significant drought impact. Several guidelines and acts have been developed for the application of bioremediation to the treatment of polluted waters. In our laboratories, continuous and discontinuous systems, including alginate beads, have been created to assess the potential and biological stability of constructed cultures suitable for bioremediation of large amounts of water. An array of important pollutants can be sensibly and completely eliminated from water by such systems [57, 58, 59].

Air pollution control

Since air pollution has detrimental effects on economies and human health, there is a growing demand for controlling atmospheric pollutants. Various waste air cleaning techniques have been innovated and patented in the last few years. Many of the conventional approaches for dealing with airborne pollution are based on physical and chemical processes. Nowadays, bioremediation strategies are becoming more attractive and environmentally sound. A significant amount of potentially toxic and recalcitrant compounds can be degraded in air treatment systems by microbial cells or enzymes. Up to date, many well-documented studies have addressed developments in the biodegradation of low-volatile organic pollutants and greenhouse gases, which are extensively encountered, including microbial and enzymatic blooms and the biochemistry and microbiology of pollutant degradation. Moreover, advances achieved in studying a multitude of enzyme properties as well as their fundamental applications have been highlighted [37, 60, 61, 62]. In nature, airborne volatile organic compounds are oxidatively degraded by a diverse range of organisms, including plants, fungi, and bacteria, as part of their carbon cycling mechanisms. These organisms can be cultivated and used in various biofiltration and biotrickling filtration systems for the removal of air from diverse sources such as paint exhausts, cleaning processes, facilities, car garages, gasoline tankers, or assemblages that release organic solvents; emissions from dry cleaners, refineries, and fuel-propelled automobiles; meat production; purification of liquid, slurry, and solid waste from processing paper and raw rubber; protection from fumigation and herbicides; drinking water treatment to eliminate an undesirable mold aroma; agencies for the treatment of polluted lands, army storage, biofilm release, and shared sewage bacteria for their defense. It should be underlined that the utility of microbial cultures in air pollution control does not mean that different microbial properties must be analyzed. Atmospheric circumstances may adversely affect and have negative consequences on microbial activity in the emergency department. It is important to understand the relationship between functional use and thermodynamic and biological principles. Some studies have investigated the efficiency of the system with specific case presentations. Considering that other pollution control devices may be used as a study conifer model, regulatory measures and security standards must also be complied with. Despite their industrial application to air treatment, new technology papers highlight the importance of sampling microbiological matter from the procedure. Other treatment strategies may be coupled with the policies and technologies to achieve integrated air pollution control [63, 64].

Emerging technologies-

Molecular biology and biotechnology tools are being used to develop microbial strains showing superior degradation capabilities to promote the remediation process, such as gene cloning, genetic screening, and recombination techniques. Biofilms and methods to enhance their attachment and initiate bacterial growth are being further developed. Adhesion strategies will foster the creation of highly complex and effective bacterial communities that interact with the support and optimize the potential for removing and degrading pollutants. These techniques can be highly effective in multispecies biofilm systems, for example, in cleaning up main columns contaminated with toxic chemicals. Molecular biology tools can be used to determine whether bacteria with added degradation capabilities are functioning within the biofilm, and thus can be used to monitor the success of the immobilized biofilm reactor [38, 77, 78]. Nanotechnology detection methods are expected to improve at a rapid pace with the employment of new advances in chemical systems and electronic plasma technologies. Remediation of pollutants in real time often capitalizes on in situ sensor systems, which offer a rapid and versatile technique for monitoring or controlling certain key aspects of bioremediation. Bioinformatics is used to manage, integrate, visualize, and analyze the complex interactions among humans, other organisms, and the environment. Important tools relevant to bioremediation include the metagenomics approach, which uses a new sequencing strategy and a set of bioinformatics tools to understand which organisms are present in an environmental sample. An automated bioremediation system is needed to monitor and control the processes of bioremediation to ensure that appropriate nutrients are added at the appropriate time and safe conditions are maintained. Automated real-time systems in bioremediation are now in the final stages of development and testing. These systems are intended as a feature of in situ bioremediation for contaminated groundwater that includes toxicity reduction and biodegradation. The toxicity levels can be monitored from the well under treatment on a real-time basis. These systems could also be used in conjunction with reactive zone treatment. Reactive zone treatment is based on the establishment of reaction zones for the biodegradation of contaminants as they are transferred through the groundwater system [7, 44]. Microorganisms and enzymes play a crucial role in bioremediation processes, facilitating the breakdown of pollutants and contributing to environmental restoration.

When introducing emerging technologies, an integrated system approach could also be considered as single processes may not prove to be the best system. Currently, no commercial biological systems are available for adjusting heavy metal concentration in groundwater. Although they were beyond the scope of the current report, it is noted that identified emerging technologies for bioremediation showed some promise for treating in situ groundwater. The use of bioremediation in gas-propelled pump and treat systems would also be an area where future research and development is warranted. Processing potential for bioremediation and the interception of low levels of contaminants in situ that exist with this technology option may provide greater water processing capabilities. Moreover, these systems are operated continuously to manage the concentration of discharge. Flow-based systems degrade the feed with a constant hydraulic retention time, irrespective of the nature of the feed. In contrast, contact-based systems degrade the feed with a constant feed concentration, which corresponds to a varying hydraulic retention time. Flow-based bioreactors, or mixed and suspended-growth systems, are commonly used in ex situ bioremediation applications, although attention is moving toward the use of immobilized-cell contact bioreactors [79, 80, 81, 82].

IV. CONCLUSION

Bioremediation proves to be a sustainable and efficient method for removing toxic compounds from nature, offering an eco-friendly alternative to traditional physical and chemical remediation approaches. By harnessing the metabolic activities of bacteria, fungi, yeast, and plants, bioremediation can effectively degrade and transform a variety of pollutants into harmless products, thereby cleaning the environment from hazardous substances. This method can be carried out in situ or ex situ, utilizing specific microorganisms tailored to individual pollutants to achieve successful remediation of soils and aquatic systems. Bioremediation plays a crucial role in addressing environmental sustainability and managing a wide range of environmental pollutants, offering a safe and effective solution to combat the challenges posed by pollution. By promoting the use of biological agents for remediation, such as microbes and plants, bioremediation not only enhances human health but also contributes to improving global air quality and enriching soil and water resources. As a rapidly expanding discipline, bioremediation aims to address environmental issues in a responsible manner and aligns with multiple sustainable development goals. This chapter has provided an overview of the importance of bioremediation and its potential to make significant contributions toward achieving a more sustainable and healthier environment.

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