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BIOREMEDIATION AND BIODEGRADATION: SUSTAINABLE SOLUTIONS FOR ENVIRONMENTAL POLLUTION CONTROL

Diepiriye C. Okujagu[1], Victor Lucky[2]

[1,2]Department of Geology, University of Port Harcourt, Rivers State, Nigeria

ABSTRACT

Bioremediation and biodegradation serve as harm-free practice for mitigating the rising cases of pollution. Such processes are mainly the continuing use of the natural biological occurrence of microbial and plant life whereby the toxic pollutants are changed into less hazardous forms. This review seeks to evaluate the application and the restriction of bioremediation and biodegradation. In situ, ex situ, below surface, biostimulation, bioaugmentation, composting, and biopiles of which have been successful in treating various types of pollutions including: oil, heavy metals, industrial wastes, plastics, and agrochemicals. In particular, wetlands have been confirmed to play a very crucial role in water filtration including elimination of dangerous compounds. While bioremediation has many advantages at the same time bioremediation has such issues as, for instance, low biodegradation rates, and environmental needs. However, advancements in biotechnology, including synthetic biology, genetically engineered microorganisms, and nanotechnology, present opportunities for improving efficiency and scalability. Successful case studies demonstrate the effectiveness of bioremediation in addressing large-scale pollution issues. To fully realize its potential, continued research, interdisciplinary collaboration, and policy development are essential. By integrating bioremediation into broader environmental management strategies, we can contribute to a cleaner and healthier planet.

Keywords: Microorganisms, Bioremediation, Biodegradation, Biosparging, Organic contaminants, Inorganic contaminants, environmental pollution, wetlands, heavy metals

1. INTRODUCTION

Bioremediation is a process used to treat contaminated sites, including the cleanup of hazardous substances, primarily through the activities of plants and microorganisms (Atuchin et al., 2023). Green plants and their associated rhizospheric microorganisms contribute to the removal or degradation of various soil contaminants by supporting diverse, beneficial plant-microbe interactions. Studies on arbuscular mycorrhizas and their effects on soil phytoremediation have potential applications for sustainable and reforested bioremediation. Metal and metalloid phytoremediation, specifically, involves important soil microbe-plant associations and interactions. Understanding plant-microbe associations is crucial for the success of bioremediation treatments, requiring examination at structural, physiological, biochemical, molecular, and ecotoxicological levels (Patel et al., 2022). Effective bioremediation relies on the complex relationships between plants and microorganisms, highlighting the need for continued research into these interactions to develop innovative, sustainable solutions for contaminated site remediation. Bioremediation can be carried out in air, water and land.

Biodegradation is a detoxification process where microbial, plant, or animal catalysts break down compounds through acidolysis, hydrolysis, and redox reactions, eliminating them from contaminated environments (Maqsood et al., 2023). If correctly interpreted and performed under environmentally friendly conditions, biodegradation offers economically efficient and environmentally friendly methods of cleaning up soil, water, wastewater, and the atmosphere. This process has particularly important relevance to environment since it leads to conversion of organic pollutants to carbon dioxide, methane and other greenhouse gases. Consequently, biodegradation is widely used technique in waste management, design of bioreactor systems, and evaluation of microbial consortia in environmental biotechnology. Nevertheless, biodegradation processes underwent limitations and possible limitation impacts, especially based on soil pollutant fate (Fouad et al., 2022). These factors should therefore be well managed when applying the technique of biodegradation in order to realize the maximum advantage.

Bioremediation and biodegradation are two green means of microbial pollutant degradation and transformation of soils or environment by using metabolic capabilities of microbes that transform various materials for instance oils, toxic metals, pesticides, explosives and other wastes. Bioremediation technologies typically employ two approaches: through a process of nutrient enhancement or by addition of certain pollutant- consuming strains of indigenous bacteria obtained from the other contaminated fields through bio-augmentation. This targeted approach makes it possible to degrade and transform pollutants as and when they are found. Bioremediation holds a burdensome utility for environmental restoration because microbes can perform several activities beyond what man-made equipment is capable of; research is ongoing to continually enhance the possibilities (Bala et al., 2022). Proper bioremediation measures could turn polluted sites into clean and health promoting environment.

Biodegradation and bioremediation are two related but distinct processes. Biodegradation is the breakdown of organic pollutants into simpler compounds by microorganisms, which can occur in various environments, including soil, water, and air. In contrast, bioremediation is the deliberate use of microorganisms or their enzymes to remove pollutants from the environment. While biodegradation can occur naturally in air, bioremediation in air is more challenging due to the lack of moisture and nutrients necessary for microbial growth.

Bioremediation is a practical implement of sustainable development, and its effectiveness recovers the environment by enhancing indigenous processes at a decreased cost to enhance the living of all creatures. However, bioremediation has remained low in its implementation and application, and where used it has been abused. In some projects, goals for the reduction of pollution have not been realized notwithstanding the assimilation of substantial resources. Bioremediation is not always possible with all the contaminated sites, that is, bioremediation is not a panacea. But where used there are positive early interventions that could cause its adoption as an important ingredient in efficient solutions to environmental pollution and resource degradation on costs (Samarasekere, 2024).

Effective implementation requires careful consideration of site-specific factors to maximize bioremediation's benefits. Over the last four decades, the petroleum industry and the U.S. government have developed and validated effective bioremediation processes for treating petroleum-contaminated soils in situ, achieving significant success (Trejo and Quintero, 2023). One successful application is bioventing, which simulates natural in situ biodegradation of oil vapors and volatile chemicals in permeable soils. Through bioventing, essential plant nutrients are added, and microbes break down pollutants, which are then aerated out of the soil via air pipes. This process results in rapid soil remediation, meeting environmental air pollution standards. Bioventing's effectiveness demonstrates the potential of bioremediation technologies for environmental cleanup (Trejo and Quintero, 2023). By leveraging these innovations, the petroleum industry and government agencies can continue to improve remediation outcomes.

The environment plays a vital role in the survival and evolution of living organisms, but since the Industrial Revolution, increased use of harmful substances has severely impacted natural and synthetic environments, deteriorating water, air, and soil quality and affecting agricultural productivity and human health (Saravanan et al., 2023). However, microorganisms can utilize pollutants as energy sources, forming the basis of technologies like extraction, bioremediation, and biodegradation. Bioremediation leverages living organisms - including plants, algae, bacteria, fungi, and aromatic rings - to degrade or transform organic pollutants without harmful byproducts. Bioremediation offers a low-cost and efficient solution for environmental cleanup. Research has explored fungal bioremediation potential for radioactive elements, metals, drugs, and organic pollutants in various matrices (Haripriyan et al., 2022). This review highlights fungal bioremediation's potential as an attractive technique for cleaning up pollutants and contaminated wastes, emphasizing its future directions and current state of knowledge.

2. MECHANISMS OF BIOREMEDIATION AND BIODEGRADATION

Microbial Biodegradation:

Bioremediation relies on microorganisms and biological processes to transform and degrade hazardous substances into less toxic forms (Alabssawy & Hashem, 2024). Bacteria, fungi, and other microorganisms can metabolize organic and inorganic pollutants in ideal environments, utilizing these pollutants as growth substrates. Due to the variability of the conditions in the environment and the specified physicochemical factors, bioremediation can be adjusted to different functional environments through the introduction of suitable microorganisms. But, some bioremediation efficiencies have challenges on the basis of multiple pollutant mixtures, elemental pollutants' concentration, and probable adverse effects of some pollutants (Ayilara & Babalola, 2023). However, bioremediation also causes second pollution that should be controlled in order to achieve a clean environment. It is important to note that these factors need to be well understood to fully realize the advantage of effective bioremediation.

In biodegradation, microorganisms form anaerobic or aerobic conditions to transform organic as well as inorganic pollutants by enzyme reactions, or conversion into less toxic elements (Xu et al., 2023). Independent of being aerobic or anaerobic, fundamental pollutants in contaminants containing hydrocarbons, nitroaromatics, and polynitroaromatics are fully mineralized to carbon dioxide and water. Anaerobic conditions, or microbial processes, can also be used for biodegradation, as demonstrated by recovering heavy metals by forming a complex with reduced iron sulfide (FeS), for example copper. Secondly, bacterial decomposes play an important role in nitrate degradation process. Heavy-metal-resistant bacteria can be enriched and isolated during bioremediation, effectively removing heavy metals from sewage through mechanisms like bioaccumulation, biomineralization, and metal ion complexation or reduction (Basumatary et al., 2023). These microbial processes highlight the potential of bioremediation for environmental cleanup.

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In biotransformation of a substrate, the compound or the xenobiotic should pass through a number of modified stages to give carbon dioxide, water, nitrate, and energy. They are

1) Biotransferation i.e. Co-metabolism: Activated molecules are produced but not incorporated or undergo further modification. Ex: Hydroxylation, oxidation

2) Mineralization: It is the complete destruction of the molecule into water, carbon dioxide, and nitrogen.

The enzymatic pathways and metabolic processes involved in microbial biodegradation are:

1. Desulfonation: In this process, desulfonation results in the removal of inorganic or single organic sulfonate groups from the alkyl or aromatic compounds.

2. Nitrification and denitrification: Microorganisms incorporated in the soil are capable of nitrification and denitrification, endowing the soil with the ability to oxidize or reduce nitrogenous organic compounds or to reduce them to ammonia.

3. Nitrification: Oxidation of nitrate by nitrate non-oxidation to nitrate by the nitrifying organisms with the resulting liberation of energy. Nitrate is typically used as some devices for its reclamation.

4. Denitrification: In denitrification, a wide variety of bacteria carry on respiration with the nitrogen oxides in place of oxygen. This process is adjustable in the anaerobic condition.

5. Other pathways: Besides nitrate reduction, other energy-generating reactions help the microorganism acquire atomic sulfur and nitrogen, including sulfate reduction, sulfate combustion, sulfide oxidation, and anaerobic sabatical in metabolism.

Phytoremediation:

Phytoremediation, the use of plants to absorb, degrade, or sequester pollutants from soil, water, and air, has gained significant attention due to its perceived low cost and non-invasive nature (Ogundola et al., 2022). Additionally, it is the only known cost-effective solution for commercial extraction of heavy metals. While most research has focused on soil remediation, efforts are also underway to utilize high-biomass plants for water and air treatment. Phytoremediation holds promise in addressing aesthetic concerns, such as sight, sound, and smell, near environmental cleanup installations (Kafle et al., 2022). However, the technology's maturation still requires development. Organisms may using genetic manipulations may also help to move the world forward towards this vision.

Microorganisms and soil sciences, green plants and bioremediation are trending in recent years as they provide cost effective and sustainable remedial technologies when compared to the conventional ones (Hidangmayum et al., 2023). Some important component of our ecosystem, green plants are being used to cleanse the environment that is contaminated through phytoremediation. One such process of phytoremediation of heavy metals is hyperaccumulation of heavy metals in the above-ground plant organs that can be harvested without downstream processing. Phytoremediation depends fundamentally on the Rhizosphere interactions and microorganisms that make the process efficient; cost effective; and eco-friendly (Tak et al., 2022). This newly trending strategy can help to remediate contaminated sites that were earlier off limits to other strategies. Principal stakeholders in phytoremediation are hyperaccumulators, inoculants, siderophores, organic acids, bacterins, arbuscular mycorrhizal fungi (AMF), biosurfactants, and degradative enzymes.

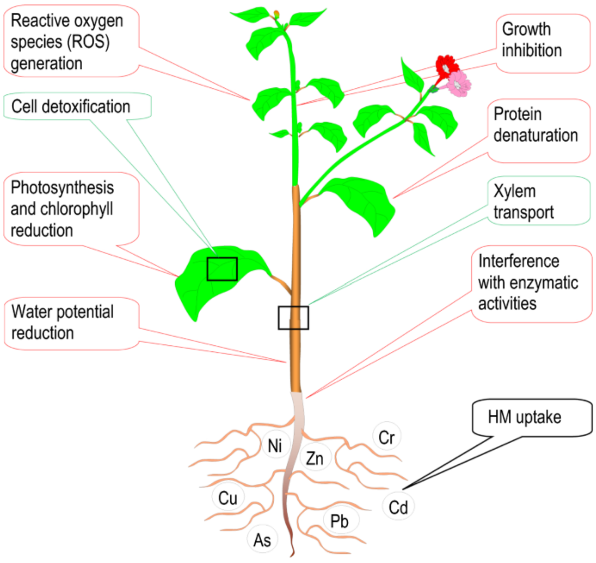

Figure 1: image showing uptake/translocation and detoxification (Nedjimi, b. 2021)

As illustrated in Figure 1, the process of phytoremediation involves complex mechanisms of uptake, translocation, and detoxification of pollutants (Nedjimi, 2021). The figure demonstrates the critical steps by which plants can effectively remove and process contaminants from the environment. It means most plants can phytoremediate most efficiently with the backing from associated microorganisms that catapults phytoremediation technology into the modern phase (Nong et al., 2023). Steady research in this area is turning green amendments into emerging remediation technologies eradicating drawbacks of conventional techniques. Contaminated sites can be successfully reclaimed provided there is enhancement of its physical, chemical and biological status. Phytoremediation and its newer trends are likely to be very effective reclamation techniques in the future years (Rabani et al., 2022). Hyperaccumulators, alongside local soil amendments can enable the direct reclamation of contaminated sites. Ideal amendments should be environmentally friendly, inexpensive, and derived from within the locale in an effort to cut energy consumption, financial costs, and increase the probabilities of successful remediation.

Hyperaccumulators and root-boundary relationships significantly contribute to phytoremediation processes, including pollutant acquisition, degradation, and plant resistance. Knowledge of these mechanisms may be applied to the creation of better strategies on the use of plants in cleaning up contaminated sites.

Biotransformation and Bioaccumulation:

Biotransformation

Biological means employed by organisms to minimize the toxic effects of the compounds that are being discharged in to the environment.

How microorganisms transform pollutants:

Metabolic Processes: Pollutants act as carbon energy or nutrients for carrying out several metabolic processes among the microorganisms (Hossain et al., 2022). This is the process of breaking large, difficult to strain pollutants into smaller manageable ones by application of enzyme.

Enzyme Activity: Our Microbial ore longer contaminants, since it is recognized that these do not promote biodegradation of pollutants; On the contrary microorganisms immobilize pollutants since they disrupt chemical bonds of contaminants, making them biodegradable by other microorganisms (Mukherjee et al., 2022).

Biotransformation: Chemoautotrophic microorganisms degrade pollutants through an electrode position mechanism that results in the formation of carbon dioxide, water, and simple organic acids most of the time (Xiang et al., 2022).

Bioaccumulation

The buildup of substances in an organism's body, possibly causing toxicosis.

How bioaccumulation works:

Absorption: Living beings take up the pollutants from their surroundings in many ways including; ingestion, inhalation or dermal sorption (Priyadarshanee et al., 2022).

Bioconcentration: The concentration of the pollutant in the organismic tissues increases considerably beyond the concentration of the surrounding environment (Saravanan et al., 2022).

Biomagnification: When a predator consumes a prey organism containing pollutants, the pollutant concentration can be further magnified in the predator's body, leading to higher levels of contamination at higher trophic levels (Okoye et al., 2022).

3. TYPES OF BIOREMEDIATION

In Situ vs. Ex Situ Bioremediation:

In Situ:

In situ bioremediation techniques often involve disrupting the subsurface to allow for the required environmental factors to be introduced to enhance biodegradation. However, many in situ procedures incorporate a method in which the pollutants are treated directly at the contaminated site without excavation by either introducing key environmental factors or biodegrading cultures directly into the subsurface (Hussain et al., 2022). There are three in situ bioremediation techniques that involve the direct treatment of contaminated sites: bioventing, biosparging, and natural attenuation (Bala et al., 2022). However, the in situ application of existing technologies may still involve some excavation or the extraction of soil or groundwater to treat conditions off-site.

Bioventing: the use of oxygen to enhance the rate of natural bioremediation at a polluted environment. Bioventing is mostly applied to biodgrade petroleum hydrocarbons that exist within a zone known as unsaturated zone below the water table (Anekwe & Isa, 2024). Surface or subsurface air distributors bring oxygen to the unsaturated zone enhancing microbial action and hence quick in-situ bioremediation. Current research validates that the bioventing system can raise the rate of biodegradation (Triozzi et al., 2023; Khodabakhshi and Zytner, 2023). This technique is therefore a viable solution to environmental challenges towards pollution control.

Biosparging: the use of pressurized air with a water table below the injection area to enhance biodegradation of the organic constituents (Bell et al., 2022). At a particular site, air or pure oxygen is injected into the saturated zone rather than treating the groundwater extracted from subsurface to achieve greater volatile removal from the zone and improved biodegradation.

Biosparging is a ground water remediation technique that involves the gentle injection of air into the saturated zone (aquifer), to enhance microbial aerobic process. For biosparging to be effective hydrocarbon contaminant will have to be in a dissolved phase, Tier 1 & 2 Environmental Assessment has to be carried out to know the extent of spread of contaminants, these process aid in knowing the vertical depth of contamination and soil profile of the area. The formation found in a particular area influences the radius of influence and flowrate.

As illustrated in Figure 2, a typical biosparging system consists of several key components. For Biosparging to occur the following will be in place:

a. Neatly arranged and properly drilled injection well.
b. Air source (air compressor)
c. Biosparging system

- Air tanks
- Spools
- Check valves
- Flow meter
- Totalizers
- Pressure gauges
- Pressure horses

Figure 2: Image showing a typical Biosparging system

Natural attenuation: is a technique that uses native microorganisms to transform and manage deleterious substances in the subsurface (Divine et al., 2024). As one of the natural optimization methods, it is founded on observing natural signals in order to confirm efficacy of contaminant removal and cleanup goals. It can be easily influenced by modifying physical and chemical characteristics, including pH levels, or the levels of oxygen within the soil, and therefore this approach is normally less disruptive and cheaper compared to the former (Skinner et al., 2024). In its simplest form, natural attenuation is an aggressive strategy that employs native microbial communities to disarm pollutants in both saturated and unsaturated media (Sun et al., 2023). At times, the inherent variables, including DO and OPPM, foster biodegradation resulting in lower operating costs and minimized risk. Nonetheless, natural attenuation proves useful, but its extent may be slowed down by the presence of oxygen or lack of nutrients (Xu et al., 2024). As a result of these research and observations we are able to appreciate how natural attenuation occurs in some media, for instance petroleum hydrocarbons and chlorinated solvents but not in other media. Thus, if the influence of the natural conditions decreases the extent of biodegradation, then there is the need to perform other methods like bioaugmentation or biostimulation.

Ex Situ:

Another form of on site bioremediation is inactivation process, whereby contaminated material can be removed for further treatment. Conventionally, this practice is referred to as ex-situ bioremediation which is the removal of contaminated material for treatment (Perez-Vazquez et al., 2024). Different approaches can be used Solids phase methods can be employed and techniques borrowed from waste treatment and industrial fermentations (Naseem et al., 2023). However, ex-situ bioremediation is characterised by the following challenges. Small-scale bioreactors, which require fine nutrients, cleaning of hazardous chemicals from contaminated soil, and treatment of toxic culture support systems, are the main concerns (Naseem et al., 2023). Later works have focused on the solutions that can be provided to these problems, and the feasibility of the ex-situ bioremediation towards combating the environment pollution has been investigated (Hussain et al., 2022).

Composting as a process of recycling and reuse is an age old technique in which organic wastes are converted into soil conditioners for land application (Li et al., 2024). This oxidative process involves gases, separating the cellulose proteins and lignin, a carbon structure large enough to reduce to carbon dioxide, water, ammonia simple forms of carbons, heat.. Composting has been successfully applied to carbonization oil-refinery tailings as suggested in Castro et al., (2022). The through-feed composting consists on the mixing of municipal solid waste with refinery tailings, shredding and windrow composting at a specified moisture level. Small windrows' turning ensures that thermophilic microbial temperature requirements are met during the waste treatment process.

As composting progresses, selected thermophilic microorganisms biodegrade volatile aromatic hydrocarbons in the tailings (Allam et al., 2023). After several days, the biodegraded product is aerated in a bioreactor to volatilize remaining volatile organic compounds. The final dry product boasts low hydrocarbon concentrations and is a free-flowable powder suitable for land application.

Integrate the citations within the paragraphs, provided and where more than one citation exists use only the most recent or appropriate "In a bioreactor, you are able to control and optimize environmental conditions for the microbes to treat soil, water, or air (Bhattacharyya et al., 2022). This helps increase the rate and efficiency of biodegradation. There are a number of factors to take into account when looking at whether a bioreactor is a good clean-up tool, such as finding a balance between the costs and benefits of a reactor. Small-scale bioreactors can be used for testing different bacterial cultures under various environmental conditions, such as pH, contaminant level, and available nutrients. Nutrient levels are an example of an environmental condition that can undergo continuous monitoring and supplementation in a bioreactor (Masojídek et al., 2022). In nature, there is only a certain amount of a limiting nutrient, such as nitrogen or phosphorus. The addition and use of these nutrients can help increase the rate of biodegradation.

Currently, researchers are exploring in situ bioremediation, which involves injecting water, nutrients, and bacteria directly into contamination sites (Patel et al., 2022). However, complexities in contaminant and soil composition, as well as geographical factors, often hinder effective biodegradation. Bioreactors offer a controlled environment, optimizing bacterial performance and making off-site bioremediation a viable solution (King et al., 2023). Bioremediation is rapidly gaining attention from environmental engineers and scientists, despite being considered a relatively new technology (Karimi et al.2022). While costs remain prohibitive for many pollution cleanups, advancements in bacterial and genetic research are driving down bioreactor costs, making bioremediation more accessible (Saeed et al., 2022). Ongoing research aims to enhance bioremediation efficiency by identifying optimal conditions for biodegradation. This study contributes to these efforts by examining fundamental modeling techniques for optimizing biodegradation conditions (King et al., 2023). By refining these processes, bioremediation can become a more cost-effective and efficient solution for environmental cleanup.

Landfarming, first developed in the 1930s, is a field treatment option for petroleum-contaminated soil, historically limited to petroleum-contaminated properties (Gan, 2023). This process is most effective in environments with minimal precipitation and high sunlight levels. Compared to other treatment processes, landfarming is considered a cost-effective option for petroleum-contaminated soils (Varga, 2022). Although its effectiveness is lower than other processes, landfarming is often selected for its relatively lower cost, provided there is ample time for treatment. Treated soils must still meet regulatory standards for contaminant concentration prior to disposal.

Landfarming involves spreading contaminated soil across specially prepared, biologically active areas, typically 12-25 cm thick, designed to promote microbial populations for contaminant degradation (Waoo and Pandey, 2023). To maintain aeration, the landfarming procedure often involves frequent, shallow tilling of the soil, as high oxygen levels are necessary for microbial degradation. Adding fertilizers and water can also enhance biodegradation (Usman, 2024). Nutrients are carefully analyzed and added at optimal levels to benefit soil inhabitants, while the water supply promotes healthy microbial layers. Soil analysis informs fertilizer application to ensure effective treatment.

Biostimulation and Bioaugmentation:

Biostimulation:

Biostimulation is a treatment process used to simulate the growth and activity of microorganisms. In biostimulation, the addition of nutrients and the control of environmental conditions, such as the addition of oxygen, are required to make the conditions more favorable for the indigenous microorganisms to carry out the biodegradation process.

Sometimes, the indigenous soil or ground water microorganisms are always available to perform the biodegradation. In the course of biostimulation process, there is no need to introduce certain microorganisms, for the process is meant to revitalize native microorganisms. An example of biostimulation is use of oxygen and nutrients to stimulate the expanse of microbial population inherent in the aquifer with the aim of breaking down the contaminants in the groundwater. Indirect ways of ultimate monitor of biostimulation, can be put into practice once biostimulation has been achieved and the process of biodegradation is under way, including respiration and other metabolic parameters of these microorganisms. What one sees or detects is that the higher the amount of biological activity, for instance high oxygen demand, is evidence that biodegradation is underway. For instance, where methods to determine the aerobic or cometabolic microbial biodegradation of contaminants are employed, oxygen related consumption rates possibly indicate the existence of these microorganisms.

Bioaugmentation:

Bioaugmentation is therefore the integration of specific microbial species which will have the ability to degrade the contaminants into the system. One technique is to use hydrocarbon-degrading bacteria whose strains are obtained from petroleum-infested environments (Chettri et al., 2024). This method addresses different concerns such as treatment of oil ballast water, management of contaminated intertidal zones, wastewater and bioremediation of contaminated bioreactors (Wang et al., 2024). Thus, while bioaugmentation strategies work in laboratory and microcosm studies as well as in limited scale field studies, they fail in various environmental conditions in the field sites. Constraints include high conductivity or temperature, biotic competition with native microorganisms, availability of the substrate and nutrients, and the inability to fully mineralize all the contaminants (Zhao et al., 2024). These challenges have thrown the light on the necessity to pay attention to the environments as well as the microbial stains to be used. Farrell et al (2004) opined that, successful bioaugmentation involves factors like the environmental conditions, competition by autochthonous organisms, degradation pathways and functionary microbes as well as the appropriate microbial strain. The top challenges realised put bioaugmentation in a position where it can be described as a good and effective remediation strategy.

Bioaugmentation is not something newly invented. Even as early as 1945, it has been proposed that different hydrocarbon degrading pseudomonads could be employed for increasing crude oil degradation in soil (Hartman, et al., 2023). Hydrocarbon degrading bacteria were looked at, in the 60's, as a means of tackling fouling of oil fired ship boiler and biodegradation of oil in service tanks. In the last two decade, bioremediation has set the standard of using bioaugmentation to clean up oil-contaminated site. The development of new techniques has enriched bioaugmentation by using genetically engineered strains; bioimmobilization approaches; and microorganisms other than bacteria (Hassan et al., 2023). Some of these are genetically modified cyanobacteria and pollution sensing and degrading bacteria (Patowary et al., 2023). These strategies improve the efficiency of bioaugmentation in dealing with the oil spillage challenge. Small-scale studies presented concern the ability of bioaugmentation to remain workable throughout environmental change, confirming its biomedical nature. Because of the technique and microorganisms used for the bioaugmentation, the process remains relevant in the rehabilitation of contaminated ecosystems due to oil spillage.

Composting and Biopiles:

Composting refers to the fundamental bio-oxidative process involving controlled aerobic decomposition of organic material including green wastes, food waste and animal manure (Xie et al., 2023). This process prepares environmental bioresources scientifically to recycle them as composts having immense horticultural, agricultural, and landscaping values. Within compost matrix, organic matter and oxygen enhance multiplication of microbes which mineralize organic pollutants and other volatile organic compounds (Angeles-de, et al., 2023). It solves the problem of managing the contaminated soils, which include: heavy metals and chlorinated hydrocarbons. Because composting relies on microbial breakdown, the use of compost as a method for dealing with waste products and cleaning up contaminated land is a green technology. Composting is a topic which is applicable to many fields and industries because of the potential for solving the problems in the field of waste management and ecological restoration. Composting means the amount of oxygen available, type and amounts of organic materials, microbial activities that exist and results in beneficial products for farming, gardening and landscaping for agriculture.

Biopiles resemble composts but are meant for the treatment of soils that contain polycyclic aromatic hydrocarbons or wood preservative and petroleum product wastes (Lusk et al., 2023). The main strategic intent of biopile design is to construct a conducive matrix that will allow for the practice of low-rate biodegradation under aerobic conditions. This poses the need to accord the water retention coefficient of the soil the much needed attention as both moist and less moisture conditions are detrimental to this process. Agitation of biopile, moisture control, and aeration should also be catered for in biopile design for bioremediation pollutions to be stripped effectively (Henriksen, 2023). Biopiles are designed to maintain optimal conditions for aeration and, if the organic material cannot be treated by just aeration, bioaugmentation of the indigenous population may be required. In such circumstances, the biodegradation in the form of water and nutrients that is required may be applied where necessary. However, concentrations of nutrient influxes can aggravate the problem markedly; thus, it is essential to develop site- and soil-type-specific biopile configurations (Barathi et al., 2023). Thus, the right combination of some factors determines the efficiency of biopiles as technologies for soil remediation and encourage the sustainable development. It becomes possible therefore to obtain the general higher rate of biodegradation and at the same time minimize on the adverse impacts of such processes.

4. APPLICATIONS OF BIOREMEDIATION AND BIODEGRADATION

Oil Spill Cleanup:

Bioremediation stands as the strongest tool for the Management of Marine oil spill which entails the use of naturally occurring compounds for the improvement of pollutant retrieval (King et al., 2023). Generally the enhancement process requires the use of nitrogen containing compounds like urea or ammonia water which creates microbial growth. The most typical application chemical is nitrogen and the most used nutrient is urea or ammonia water. These added nutrients in relation to algae use in aquatic ecosystems to tap on available C sources. For example, in New England (specifically, Mass Bay), cyanophyte blooms are constrained by access to nitrogen; nonetheless, nitrogen compounds can spur their expansion (King et al., 2023). Yet in the recent oil spill in Mass Bay, carbon piled into the ecosystem and whereas nitrogen balance existed before, this displaced it. Unlike the ecological theories, the algae perish, while the environment also perishes as well. According to the ecological theory, algae growth would be favored because the N/C ratio essential for their growth was high, while carbon was available to the bacteria that grew with a latent period of 2 to 21 days by King et al., 2023. The objective of bioremediation measures is to bring back order, this by adding nitrogen which fuels the growth of microorganisms in the degradation of pollutants. Based on such dynamics, bioremediation it is possible to manage the effects of marine oil spills and support ecological rehabilitation.

When nitrogen was added to the estuary of Mass Bay the results were phenomenal with fish larvae returning soon after (King et al., 2023). These results are consistent with other research on green and brown algae, where nitrogen addition enhances cell numbers as well as algal biomass accrual at an earlier stage. For example, studies have shown that I can increase growth in these species as compared to a setting where nitrogen was not essential. However, it was observed that biostimulation success is different in different studies and confirmed that complexity is an encompassing criterion in bioremediation (Saeed et al., 2022). Some papers have elaborated on causes of bioremediation failure and pointed out that such concerns should take into consideration certain aspects of ecosystems. Another point is that biotechniques themselves are inconclusive even in case if they worked in other experiments. Consequently, bioremediation ideas are not standard and may need fine-tuning every so often, unlike commercial products, as noted by King et al., (2023). That is because ecosystems are extremely complex systems that interact with thousands of species some of which are poorly understood. Thus, it’s necessary to understand that even though the certain technique was effective before, it won’t be effective again. But in order to optimize strategies for bioremediation of the environment, these factors play an important role in establishing appropriate approaches in this field.

Exxon Valdez

The largest oil spill in North America to date was the Exxon Valdez oil tanker disaster in March 1989 (Bacosa et al., 2022). In just a few minutes about 240000 barrels of petroleum spilled over 17900 square kilometers when the ship grounded on Alaskas Bligh Reef. Within six years more than 60% of the oil that had spilled naturally biodegraded despite numerous physical chemical and biological remediation efforts (Bacosa et al., 2022. This demonstrates that microbial biodegradation is a viable and affordable substitute for the extraction of crude oil. Nevertheless the severe weather at the location had a major effect on microbial metabolic processes which limited the generalizability of these results. When environmental variables like air and sea temperatures were recorded during the spill correlations between these chemical signals and ecosystem shifts were found (Zhu et al., 2022). Developing successful bioremediation techniques suited to particular locations and circumstances requires an understanding of these dynamics. The Exxon Valdez accident highlights the significance of taking the environment into account when conducting bioremediation procedures and the potential of microbial biodegradation as a workable oil spill cleanup method. The density of native bacteria in areas where oil had accumulated significantly increased after the oil spill according to research (Bacosa et al., 2022. The main remediation method was the removal of contaminated soil since oil pools developed in the intertidal zone killing off a large amount of vegetation. Scientists isolated and described a bacterium from these saline sandy soils that can grow on alkanes from C1 to C15 at concentrations of 10-500 $\mu l\ l^{-1}$. Notably the genomes of local bacteria in contaminated areas were responsible for an exceptionally high oil-degradation rate that was recorded in the first week following the accident (Liu et al., 2022).Identifying these oil-degrading genes could significantly enhance bioremediation efforts for similar oil spills. However, attempts to cultivate these organisms on a large scale revealed challenges, including low growth yield, induction of non-commercially available metabolites, and disruption of the complex biological web between introduced microbial communities and indigenous biodegrading bacteria. Elucidating the interactions between introduced microorganisms and native bacterial populations is crucial for optimizing bioremediation strategies (Zhou et al., 2022). Further research on these dynamics will inform the development of more effective and sustainable solutions for mitigating oil spill impacts.

Deepwater Horizon

The Deepwater Horizon spill, considered the largest oil spill in history, began on April 20, 2010, following an explosion and fire on the deep-sea oil-drilling rig (Chuah et al., 2022). The disaster released approximately 780,000 m^3 of crude oil into the Gulf of Mexico. After the rig sank on May 8, a coral at 1,500 meters is the final cap to the Macondo well. The oil spill formed a huge slick that flowed towards the shore, of which 40% of the surface oil is dissipated by sunlight and by biodegradation of the naturally occurring oil-degrading bacteria (Muthukumar et al., 2022). These bacteria were also used to process the oil to allow it to be separated into its simplest constituent parts. This natural process was of great importance especially in the management of oily slick impacts on the environment. Deepwater Horizon Macondo blowout points to the need of the involvement of microorganisms in the degradation of oils and bioremediation techniques (Chuah et al., 2022). Additional studies of metabolic capacity of the oil degrading bacteria can help in developing good strategies in tackling oil spills and hence save the marine environment.

The Deepwater Horizon oil spill influenced bacterial diversity on the deep seafloor and the abilities of indigenous and introduced bacteria to remanufacture the Gulf of Mexico’s oil (Saeed et al., 2022). Molecular and microbiological techniques used in research studies from 2010 to 2019 by independent researchers confirmed this fact. Interestingly, the response to the spill was natural; the affected marine environment recovered within months according to Saeed et al., 2022. It was also followed by large regeneration of plants and the marine animals that inhabit the island. This was important because previous studies pointed to the efficiency of indigenous bacteria in biodegradation of oil and the need to appreciate microbial processes in the management of oil spill incidents. The previously catastrophic event that occurred in the Gulf of Mexico shows that natural bioremediation processes occur at a fairly quick rate (Thomas et al., 2021). Future qualitative studies on the roles of microorganisms in breaking down oil can help in deployment of functional, constructive solutions in case of future oil slick events.

Heavy Metal Remediation:

Pollution of soil and water with toxic heavy metals is an emerging environmental concern all over the world (Sharma et al., 2023). This problem has led to continuing investigation of microbial and plant-based bioremediation. However, it is surprising that phytodegradation has been considered to be more useful than microbial degradation. Phytoremediation which is one of the plant based technique abates, transforms, encapsulates, disinfects and/or immobilise metal pollutants in the soil and water (Sharma et al., 2023). It involves the following processes: transpiration, solubilization and lastly transformation. It is the complexing agents and the plant root exudates where such chemical and biological transformations take place. The feasibility of phytoremediation is greatly determined by plant-induced transformations and detoxification mechanisms (Priya et al., 2023). In relasing complexing agents and root exudates, contamination through heavy metals can be addressed. Further studies focus on improvement of the efficiency of phytoremediation processes since various types of plants and approaches are being investigated. By using phytoremediation, there are several advantages ustilization of plants for remediation, which comprises of clean and cheaper ways of eradicating and immobilization of heavy metals (Priya et al., 2023). It is with promise for sustainable environmental remediation they remain viable as phytoremediation technologies develop with future research.

The application of rhizobacteria along with plants constitutes a rather perspective strategy for the remediation of the soil contaminated by metals (Sharma et al., 2023). What is more, by using this mutually dependent cooperation scheme, bacteria can assist in solving the issue of soil pollution. For instances, bacteria where $Fe2+$ was replaced by cadmium have been used to detoxify water and act as high specificity bio- detectors of cadmium ions. Thermophilic microorganisms have also been used in bioleaching to line the inside of lead-contaminated pipes to minimize pipe lead contamination (Priya et al., 2023). Also, the effects of bacteria like Pseudomonas fluorescens have also proved to be able to tolerate zinc, then mean for heavy metal removal. The bio-absorption process also has the potential for removing heavy metals as a technique. Some have proposed that specific metal ions should be removed from water or solutions by introducing fine powders or granules from bacteria (Priya et al., 2023). For a start, Candida has been recognized in studies as a candidate for this approach. It also opens for highly efficient and selective metal removal as a metalworking method – which is the main idea of this article.

Effective bacterial-based remediation strategies can provide numerous benefits, including:

- Synergistic plant-bacteria relationships
- Effective metal ion absorption
- Bioleaching for pipe decontamination
- High-affinity biosensors for metal detection

By exploring the capabilities of rhizobacteria and other microorganisms, scientists can develop novel solutions for mitigating heavy metal contamination.

Industrial Waste and Sewage Treatment:

Bioremediation is an important technology for the treatment of industrial and domestic sewage and has possible uses for enhancement of potable water (Padhan et al., 2021). This green approach exploits several processes to remove or minimize toxic heavy metal pollutants such as biotransformation, precipitation, bioreduction, biosorption, bioaccumulation and genetically engineered microorganisms. For example with reference to bioremediation, biotrasformation aids the microorganisms in converting toxic metals to forms that can not harm living beings. Velues have been established for wastewater management quantities that include vegetated drip irrigation systems, constructed wetlands, rotating biological contactors and inverse fluidization beds (Singh et al., 2021). Similarly, the immobilized plant cell technology has also potential for remediation of wide range of toxic compounds in the environment both in the bioreactor and in situ.

Biodegradation is the natural process, which is catalyzed by indigenous microorganisms, can be augmented by biostimulation and bioaugmentation (Zhou et al., 2023). Moreover, the advancing techniques of recombinant DNA and genetically manipulated microorganisms possess a rich prospect for the enhanced remediation. Modern bioremediation technology focuses on addressing new pollution challenges that result from the utilization of chemicals and other dangerous substances, without causing new problems (Nag et al., 2024). Such an approach finds favor with customers because more and more people start realizing the problem of environmental pollution and the government tightens control over emissions. The push for bioremediation is as a result of its being cost effective and environmentally friendly, its success in the removal of heavy metals and its ability to address multiple pollution issues (Alabssawy & Hashem, 2024). Thus, the idea as research develops moving forward, bioremediation remains a viable solution to the current environmental problems.

Plastic Biodegradation:

Today's society heavily uses plastics in many commodities that formed a real problem in the past years because they do not decompose easily and remain pollutants (Okal et al., 2023). Compared with many consumers, plastics production also takes up large proportions of fossil oil and gas and consequently yields fewer products. This has made itdirely call for new approaches in addressing plastic waste problem. Another prospect of applying biodegradation to degrade plastics is the idea of reducing plastics usage to low molecular weight products attributable to the capability of living organisms (Li et al., 2023). Microbes play their part on this and use a variety of enzymes to enhance degradation of poorly utilizable foods. This microbial approach used for plant cell wall solubilisation also opens new angles for the improvement of plastic biodegradation. Improvement of the current biodegradation technologies to be used in combination with the current biodegradation technologies can also improve their functionality (Choi et al., 2023). Enhancing recycling capability, providing for biodegradability, and generally reducing the requirement and disposal of plastics can be complemented by biodegradation. Thus, using these biological processes academics are able to design unique strategies that will help minimize the use of plastics. The prospects of biodegradation technologies are vast, these include: breakdown of stubborn plastic enemies, use of microbial enzymes, and potential for the creation of biodegradability specifications (Okal et al., 2023). With the emissions of new technologies on its effective disposal increasing, biodegradable plastics present the best way of eliminating the negative effects of plastic in the environment.

Recent studies have identified a highly efficient cutinase enzyme released by brewer's yeast which create all new approaches to decomposing plastics (Oliveira et al., 2022). Subsequently, several companies have been founded for marketing the yeast, optimizing it, and for genetically engineering the crop plants to make plastics which can be eaten. This discovery shows that synergistic collaboration between chemistry and biology could help combat the scourge of plastic pollution. In the prior work concerning biodegradable plastics, the focus has been made on the features which cause vulnerability of the material to microbial action (Łukaszewicz et al., 2024). However, these studies have often been conducted under artificial conditions, neglecting the critical final step in biodegradation: the fact that in natural environment the microorganisms have the capacity to reach, utilize and metabolize the degradation products. It is here that a broader view is required – a fusion of plant and microbial genetics, polymer, botany, and engineering (as cited more fully in Gumienna et al., 2024). This will approach can facilitate the transition from the laboratory into the market since it will ensure that biodegradable plastics developed do not harm the environment. In this way, keeping a wider perspective, the researchers harness the strategies of nature and come up with the best solutions of right disposal of plastics in order to enable them to biodegrade fully (Bitew and Andualem, 2024). Applying knowledge from chemistry, biology and physics may assist in the improvement of current biodegradable plastics, and in developing better alternatives.

Effective biodegradation strategies require:

- Interdisciplinary research collaborations
- Natural setting simulations
- Focus on complete biodegradation
- Development of digestible plastic substitutes

By addressing the problem in this way, scientists have the best chance to tap into creative ways of addressing the plastic problem.

Agricultural Waste and Pesticides:

Such activities are rife in agriculture; it is shocking to find out that it causes environmental pollution in terms of quantity of nitrate and phosphate from the used fertilizers (Rashid et al.2023). These nutrients make water vedicted to contribute to eutrophication of surface water, a factor which reduces the ability of aquatic life. Excessive nitrate concentrations are also toxic to human health, as well as to animals: methemoglobinemia or Blue baby syndrome in young children can be fatal. Chemicals such as pesticides and herbicides use in farming also pollute the surface water in a nonpoint source manner (Morin-Crini et al., 2022). Excessive level of phosphate and nitrogen can be toxic to fish and thus cause death to other water organisms. Among the pesticides, there is high tendency for the herbicides to remain in water bodies thus posing a danger to the water inhabitants. The effects of contamination in agriculture reaches everyone in the environment in one way or the other. Use of fertilizers has detrimental effects because the extra nutrients thrown in the ecosystems tamper with balances while use of pesticides and herbicides can be stored in the food chain." crimes (Fei et al., 2022). Some of these effects need reasonable sustainable management practices as highlighted by the use of appropriate farming methods; sufficient measures of risk management. Concerning the contamination of agriculture: eutrophication, human health hazard resulting from nitrate ingestion, effect on aquatic organisms as a result of pesticide and herbicide admixture, and nonpoint source pollution via herbicides. Solving all these problems requires environmental conservation in order to avoid a depletion of the earth's resources.

Agricultural sites can be effectively treated via Bioremediation because bioengineering techniques deliver affordable ways of reversing the nutrient laden croplands (Kumar et al., 2022). These technologies enhance the ability of point sources materials in the immediate surroundings to sorb phosphate, apply constructed wetlands to filter nutrients and contaminants from field drainage, and alter the microbial population in the soil to transform ammonia gas through plant modification by genetic engineering. Bioremediation activity through the green method utilizing plant species which encompass a procedure with a historical background of over three decades (Khan et al., 2022). This approach utilises the bioremediation characteristic of some plant species such as wetland plants in that they absorb, concentrate and immobilise such heavy metals to forms that are less toxic or bioavailable. Besides, plants can exclude macronutrients, organic and inorganic origin, volatile organic compounds, and radioactive elements from the surroundings. Optimum strategies to apply phytoremediation include selecting some plant varieties that have high removal rate of the contaminants as investigated by Babu et al., (2021). Through insight of the causes and process of phytoremediation, the scientists can plan and provide proper solutions to the affected areas. This reduces pollution beneficent for the environment as it is accompanied with an approach to the ecological reconstruction. Phytoremediation of soils as a remediation technology have the prospect of eliminating cost-effective contamination and plant-based heavy metal transmutation together with nonmetal contaminants (Khan et al., 2022). While the researchers are still working hard to expand this research area, phytoremediation can be regarded as the environmentally friendly way to solve pollution issues in the agricultural sector.

5. CHALLENGES IN BIOREMEDIATION AND BIODEGRADATION

Limited Degradation Rates:

Technological limitations of terrestrial soil bioremediation are many, starting with slow degradation rates of some pollutants like polycyclic aromatic hydrocarbons and chlorinated aliphatics (Alori et al., 2022). These contaminants are persistent in the environment, thus calling for more structure-activity analysis on the degradation patterns. Dung et al., 2021; Hasanzadeh et al., 2021; Karimi et al., 2022 Some authors have paid much attention to studying the low biodegradation rates of these pollutants. Research work has been directed to offer more light to the various interactions that exist between the structure of pollutants and their biodegradability, to enhance the efficiency of cleanup techniques. The emergence of new patterns for bioremediation of soil suggests further differentiation of strategies according to the type of pollutant (Li et al., 2022). The combination of utilising structure-activity analysis with the study of biodegradation enables the society to boost the effectiveness of remediation strategies and thus, improve the process of disinfection of the soil. Any bioremediation scheme is critical for pollutant patterns and degradation processes (Aparicio et al., 2022). As mentioned by Kebede et al., (2021), current research initiatives help in expanding the current understanding of bioremediation of soil and eradication of environmental pollution for enhanced processes for remediation.

For instance, chlorinated ethenes including chlorocarbons, present remarkable bioremediation problems because of their slow biodegradation by bacteria (Chen et al., 2024). In particular, organic hydrohalic compounds are utilized under amino acid fermentation, not for bacterial growth, thereby accounting for slow cell mass formation.Deimos Because of this slow degradation rate, chlorinated ethenes cannot be easily removed or bioremediated in environments influenced by sources such as dry cleaning stations.Chlorocarbons effect problems worsened by the slow degradation time of the substance in the environment, with anaerobic activity increasing gradually (Krett et al., 2024). Chlorinated ethenes have been found to possess bioavailability – in some cases, for years – namely making the cleanup process cumbersome. Literature reviews and experiments published on chlorocarbons have focused on the metabolic processes that take place during chlorocarbon degradation to understand its mechanisms (Wang et al., 2024). For example some bacteria, use chlorocarbons in fermentation to derive their energy requirements but it does not allow for the rapid reproduction. Understanding of these aspects is imperative in formulating bioremediation approaches on chlorocarbons whereby; slow degradation of chlorocarbons compounds and few bacterial metabolisms could be potential ways to disinfect chlorocarbons (Chen et al., 2024). More studies have to be conducted in order to devise specific strategies to reduce the effects of these hazardous and long-lived contaminants.

PAHs are very refractory compounds and their mineralization involves a sequence/series of steps: (Kaur et al., 2023). Among them are oxygenases that are active at different stages of the redox cycle, as well as at stages 3 and 4. However, the expression of these enzymes tends to be regulated under natural repressive control as conditions that promote PAH degradation are often lethal to the cell.In addition, studies have also reported that the expression of genes that facilitates naphthalene degradation was repressed by reducing conditions as well as when adequate terminal electron acceptors are available (Ansari et al., 2023). In natural environment, availability of readily biodegradable energy sources like carbohydrate in the form of dead plant matters can also reduce the requirements for degradation of PAH. Literature reviews have revealed some of the difficulties that surround the biodegradation of PAHs, for instance the necessity of having probes that would in turn activate the oxygenases (Vijayanand et al., 2023). However, recent development has been a lead in revealing the control and mechanisms of biodegradation of PAH containing environments leading to enhanced bioremediation technology. Thus, it became important to examine these factors, including the activation of enzyme and repressive controls, to facilitate efficient methanotrophic biodegradation for PAHs (Schwab, 2024). Various studies being conducted today are focused on eradicating these challenges and therefore coming up with appropriate measures that can cup with the aim of reducing the effects of Pollution by PAHs on environment.

Environmental Factors:

Environmental bioremediation offers various techniques to remove pollutants that have infiltrated different sites as well as rehabilitate them (Narayanan et al., 2023). Bioremediation is actually a subspecies of the slightly more general field of biodegradation which itself depends on some specific factors such as temperature, acidity/alkalinity (Ph), oxygen availability, and nutrient status. By using microorganisms or enzymes biodegradation transforms toxic substances into less toxic forms that other living things can eat. Scholars have discovered that microorganisms are vital in bioremediation aiming at reducing air pollution, groundwater pollutions, and metallic pollution (Bala et al., 2022). For example, thermal P has been identified to improve the catalytic b of nitrophenol with lignosulfonate using thermally P microbial cells. However, some pollutants such as the benthic harmful dinoflagellates remain a challenge since they have toxicity characteristics and it is unsure what the content is made of (Doukani et al., 2022). Such microorganisms retain high toxin levels in aquatic habitats around the globe and therefore there is still need to understand more about them and methods to effectively mitigate them. Thus, bioremediation and such treatment processes should consider a variety of factors such as microbial action, nutrient presence, or pretreatment processes Naryana et al., 2023. Further exploration is still pursued in order to unveil new possibilities of bioremediation applications to enhance the impact of global pollutions.

Large scale high productivity and safe bio reactor operations are a complex matter due to the fact that exothermic reactions in prokaryotic cultures pose significant challenges (Datta et al., 2024). More recently, a number of authors have outlined a method for determining temperature and heat generation rate distributions within spinning drop shaped bioreactors, identifying a new stationary heat source within the culture (Finore et al., 2023). Experiments using red fluorescent protein overexpression have put more insight into the non-monomial evolution of this heat source spatial distribution warring the exponential growing phase (Zhao et al., 2024). By incorporating these discoveries and previous heat sources at cardiomycytes cell membranes, researchers predict that the novel heat source is associated with elongating protein aggregates synthesised during exponential growth. In order to solve the extended exothermic crisis problem, details of heat production processes in bioreactors (Francisco et al., 2024) must be examined at a microscopic level. This approach will provide more reliable information on heat production at the cellular level for various bioreactor types and with regard to various bacterial strains. Exploring the phenomena of exothermic processes further will allow the researchers to improve bioreactor management and increase the safe scale-up of bacterial fermentation processes (Pakostova et al., 2024). Further research is being conducted to reveal the intricate relationship which dictate heat generation in bioreactors to enhance large scale bioprocessing.

pH is an important factor controlling biodegradation because microorganisms are sensitive to the pH of environments when degrading substrates with variation in pH ranging from 4 to 11 (Li & Meng, 2023). For the purpose of empirical analysis the pH should be measured at various instances throughout the test and then averaged. But, small organisms regulate their activity regarding the pH of the surroundings that they obtain themselves. In the case of static tests, usually, the pH is only measured at the start and at the end of the test, making it possible to guess the average value for the entire experiment (Kapoor et al., 2021). It also became clear that oxygen partial pressure plays an important role in microbial degradability, according to the studies done by researchers. High as well as low oxygen partial pressure can slow down the biodegradation rate of contaminants within the soil matrix. The present study also suggested that the synergistic effect of pH and oxygen partial pressure could greatly affect biodegradation (Naz et al., 2022). For example, the highest microbial activity is observed under optimal pH, whereas the least degradation rates occur under suboptimal oxygen conditions. Knowledge of these factors is critical for the formulation of strategies of bioremediation. According to Li and Meng (2023) biodegradation phenomena depend on the value of pH and oxygen partial pressure. By fine tuning these conditions, then the researchers are able to foster increased metabolic activities among the microbes with a positive impact on the bioremediation and environmentally based improvements.

In alkaline soils of Alberta, solubility is also only one side of the pictures concerning the availability of oxygen to microorganisms. It is used up in numerous biological and chemical processes such as with carbonates, oxides especially under the conditions that are poorly wetland (Dai et al., 2023). Mesophilic aerobic microorganisms needs an oxygen partial pressure of about 0.15 KPa so as to enhance the growth rates. These soils contain high amounts of carbonates which tend to reduce the oxygen in environment very quickly. Nonetheless, bacteria affiliated to carbonate solution synthesize carbonic anhydrase which increases the transformation of bicarbonate ions into carbon dioxide (Tran et al., 2022). This process also assists to maintain favourable aerobic conditions through precipitation of carbonates in the lower soil solution. Bicarbonate build-up can cause reversible changes in the pH while the carbonate will cause irreversible changes leading to harm bacteria, Cockell, 2022. This implies that there exists a general metabolic pathway for bacterial tolerance in the solutions that are characteristic for their buffering capacity in the soil. The studies suggests that suppression of oxygen and increase in carbonate activity and microbial amelioration augments the high alkalinity of the soil (Rosso et al., 2023). Appreciation of these dynamics is important for enhancing bioremediation efforts, and improving the health of the microbial consortia under difficult conditions.

The mineral of saturated zones on a soil is primarily in the non-oxidized state, which leads to the occurrence of reducing environment on unsaturated pores in the initial stage of drainage (Zhang et al., 2022). Whenever oxygen is used up, the overlying saturated zones in the soil quickly tend to become anaerobic in nature because of low permeability of gases.

This change takes place a little while after oxygen has been consumed. Fluid dynamic properties of odic materials affect oxygen delivery to the saturated zone relative to density of drained soil particles (Murphy et al., 2022). The outcome of the preceding has in research studies been established that after five months of the water table drawdown, the formation of anaerobic conditions indicates that the oxygen partial pressure is declining as nitrogen and methane levels are rising. Oxygen consumption rises beyond the oxygen diffusion rates hence producing anaerobic conditions (Zhang et al., 2022). Oxygen removal in natural systems depends on four key factors: are also input characteristics, population size of suitable biomass, and output characteristics of the volume of the soil. It is important for life, fertility and muscle matters especially in drain and aerating activities; understanding these dynamics will help in estimating the oxygen in the soil (Murphy et al., 2022). It is now possible for researchers and practitioners to find the best conditions for microbial activity, plant health and function in the ecosystem.

Toxic By-products:

Organic pollutants in soil and groundwater may be treated with bioremediation a technique that uses naturally occurring organisms to convert dangerous substances into less toxic or non-toxic compounds (Bala et al., 2022. When compared to traditional treatment methods this technology may have benefits such as lower costs and a smaller environmental impact. Bioremediation does however have drawbacks because certain biological treatment methods produce hazardous byproducts that need further processing (Ghosh et al., 2021). These adverse effects may impede bioremediation efforts if they are not adequately managed. For bioremediation to be effective these factors must be carefully taken into account in order to maximize effectiveness and minimize negative outcomes (Bala et al., 2022). In order to maximize the advantages of this technology while minimizing any potential disadvantages researchers are constantly improving bioremediation techniques. Scientists and practitioners can create long-term solutions for environmental remediation by utilizing bioremediations potential which will lower pollution and improve ecosystem health (Bala et al., 2022). Research is still being conducted to enhance bioremediation methods guaranteeing their efficacy and suitability for the environment.

Bioremediations biological processes can produce toxic byproducts that need further processing. Vinyl chloride a known human carcinogen is first produced when trichloroethylene is biologically treated with methane-oxidizing bacteria. Afterward it is transformed into non-toxic products (Chen et al., 2024. Ethene is a byproduct of another bacterium that breaks down trichloroethylene. Ethene is an undesirable intermediate as is vinyl chloride. Techniques such as wall-to-wall mixing through air sparging can address these problems by raising oxygen concentrations and eliminating dangerous gases as they arise (Lee et al., 2024). As an alternative trichloroethylene can be converted by cometabolic conversion processes into primarily non-toxic byproducts though they may also result in the production of the odorous gas bisulfide. Studies have demonstrated that preserving comparatively low oxygen concentrations can prevent the formation of bisulfides while permitting the continuation of advantageous trichloroethylene transformations (Chen et al., (2024). According to these results its critical to maximize bioremediation conditions in order to reduce hazardous byproducts. To guarantee the safe and effective degradation of pollutants these factors must be carefully taken into account in bioremediation strategies (Lee et al., (2024). Scientists can reduce pollution and improve ecosystem health by improving bioremediation techniques and creating more sustainable environmental remediation solutions.

Economic and Logistical Barriers:

Although bioremediation processes have the potential to be cost-effective and environmentally beneficial, a number of disadvantages prevent them from being widely used as in situ treatment solutions (Fernández-i-Marín et al., 2024). Regulatory bodies in charge of site assessment and cleanup are frequently wary of high implementation costs which leads to the continued use of traditional technologies like excavation, transportation, and disposal for significant amounts of impacted materials. Due to the industry's lack of experience with bioremediation technologies and subpar results from certain pilot projects, regulatory support has been weakened (Younis et al., 2022). Project costs are also raised by strict monitoring requirements. Uncertainty and risk aversion are major factors contributing to the slow adoption of bioremediation technologies (Fernández-i-Marín et al., 2024). To allay these worries, improve performance, and prove the effectiveness of bioremediation, however, more research and developments are being conducted. To effectively implement bioremediation, these obstacles must be overcome and cooperation between researchers, industry stakeholders, and regulatory bodies must be encouraged (Fernández-i-Marín et al., 2024). In this way, bioremediation can be a useful substitute for conventional cleanup techniques and develop into a sustainable, workable solution for environmental remediation.

Site accessibility and monitoring are examples of logistical issues that call for project-specific solutions (Romantschuk et al., 2023). Taking into account variables like site selection transportation logistics land use requirements and regulatory considerations ex situ treatment of contaminated material is still the recommended method for overcoming potential obstacles. Because bioremediation technologies are seen as riskier by financial institutions interest rates may rise (Hussain et al., 2022). Even if technological limitations werent the main reason public skepticism can be increased by well-publicized bioremediation failures. For example after recovering from a spill slowly and insufficiently a petroleum company experienced severe public relations backlash. Concerns about off-site or long-term off-gas migration may also be attributed to bioremediation technologies (Romantschuk et al., 2023. This places the onus of proof on site remediation teams contrasting their guarantees with the conjectures of local residents and regulatory bodies. In order to implement bioremediation effectively these logistical financial and reputational issues must be resolved (Romantschuk et al., 2023). By doing this stakeholders can mitigate risks and build public trust while utilizing bioremediations potential for effective long-term environmental remediation.

Regulatory and Policy Challenges:

Many factors introduce uncertainties and potential risks making the implementation of bioremediation technologies complex (Madison et al., 2023). Random occurrences like human exposure and site-specific environmental variations add to these uncertainties. It can be difficult to comprehend the type and scope of these factors effects. Making educated decisions requires an understanding of the underlying variability in bioremediation outcomes and the uncertainties that go along with them (Baskaran and Byun 2024). Long-term performance completion conditions water-bearing stone efficacy possible secondary effects regulatory compliance and short-term monitoring performance are among the main unknowns. Designing and carrying out bioremediation projects effectively requires taking these uncertainties and the information at hand into account (Madison et al., 2023). Determining the prerequisites for timely endpoint achievement is also crucial. Stakeholders can maximize bioremediation tactics by recognizing and resolving these uncertainties. According to Baskaran and Byun (2024) a thorough assessment of these variables and uncertainties is necessary for the successful application of bioremediation. By doing this practitioners can guarantee regulatory compliance reduce risks and produce effective and long-lasting environmental remediation results.

Consistent rules and policies are required to control approval and implementation even though the results of bioremediation projects are unpredictable (King et al., 2023. These regulations ought to give regulatory staff a framework for making decisions specific to a project while taking into account the special qualities of bioremediation and prior experiences. The framework for making decisions should take into account the information that is currently available and distinguish bioremediation from other technologies (Kuppan et al., 2024). Instead of concluding that bioremediation is inherently better or worse for particular contaminants or site conditions this chapter compares the risks of bioremediation to those of alternative technologies. The effectiveness of bioremediation for different contaminants and site conditions has been thoroughly compared in previous reviews (Jain et al., 2022). These reviews can be used by practitioners to optimize decision frameworks tailored to a given project maximizing advantages and reducing expenses. Clearly defined rules and guidelines will help people make well-informed decisions and encourage the ethical application of bioremediation technologies (King et al., 2023. Through comprehension of the hazards and advantages of bioremediation interested parties can capitalize on its potential for efficient and long-lasting environmental restoration.

6. OPPORTUNITIES AND FUTURE DIRECTIONS IN BIOREMEDIATION AND BIODEGRADATION

Genetically Engineered Microorganisms (GEMs):

Genetic engineering can improve biodegradation, the process by which microorganisms break down organic materials using enzymes (Zhang et al., 2022). Researchers have inserted an esterase gene into E. coli to break down resistant materials, making the development of a metabolic pathway possible. GEMs are frequently utilized in metabolic engineering, and the E. coli GEM model has been used to optimize a number of metabolic processes. Synthetic GEMs have the ability to salvage energy and redirect it towards the production of products, promoting fungal efflux growth without the need for delicate metabolic machinery (Zhang et al., 2022). These GEMs could be activated during one-phase flow operations. Currently, superimposing mutations on engineered strains is the best approach to produce effective GEMs. Developing networks that utilize diverse effluxed carbon sources, with fungal growth and viability as outputs, will facilitate the creation of mutant libraries (Jadaun et al., 2022). Sharing results from GEM-manufacturing facilities and leveraging high-throughput technologies will accelerate biodegradation research. Effective GEM manufacturing requires large datasets of tested reactions and exploitation of bio-similar efflux mixtures and biodegradation products (Zhang et al., 2022). Disposable synthetic products and advanced technologies will enhance biodegradation efficiency, driving innovation in environmental remediation and sustainable bioprocessing.

Synthetic Biology and CRISPR:

Environmental pollutants pose significant threats to human life, making their degradation and removal crucial (Chunyan et al., 2023). Bioremediation, using biological agents to remove pollutants, has gained attention due to its cost-effectiveness. Biodegradation relies heavily on microorganisms and bioremediation performance is improved by recombinant techniques such as metabolic and genetic engineering. But according to Chunyan et al., 2023, microbial degradation of pollutants still does not meet environmental safety standards. Immediate action is required due to growing public concerns about pollution. By allowing precise microbial engineering to degrade resistant pollutants synthetic biology and gene editing transform bioremediation. According to Wu et al., 2023 these technologies enable controlled gene expression extensive genome editing and precise gene modification. Nowadays microbes can effectively work eliminate complex contaminants and target particular pollutants. Microbes exhibit degradative activities as they grow which improves the removal of pollutants and creates non-toxic products. Gene editing and synthetic biology can get around the drawbacks of conventional bioremediation techniques (Chunyan et al., 2023. Applications in the future have enormous potential to manage pollution effectively and make the world a greener place. The performance of bioremediation can be maximized through feedback control and real-time monitoring. Innovation will be fueled by the incorporation of gene editing and synthetic biology in bioremediation which will tackle the challenges of environmental sustainability and pollutant degradation (Wu et al., 2023). A more effective and efficient way to reduce environmental pollution is promised by this synergy.

Nanotechnology in Bioremediation:

Since they can break down a variety of organic and inorganic substances, microorganisms—especially bacteria and fungi—have exceptional metabolic versatility which makes them essential for bioremediation (Madhavan et al., 2023). In situ bioremediation can be accelerated and ecological systems can be modulated with the help of nanomaterials. Engineered nanomaterials with specific characteristics can improve biodegradation, address constraints in contaminated environments, and alter the activity of microbial communities (Mutanda et al., 2022). In contrast to commercial products, ecological nanocomposites can be engineered to combine material properties with particular impacts on microbial communities. Using eco-friendly materials and techniques, these composites ought to be non-toxic, effective, and adaptable (Madhavan et al., 2023). Since nanomaterials speed up procedures that would otherwise take years, they can have a big impact on bioremediation. Collaboration between interdisciplinary teams of scientists, engineers, and businesses is necessary for the site-specific performance and application of ecological nanocomposites (Blombach et al., 2022). Diverse stakeholders should have access to research findings. Integration of engineered nanomaterials and microorganisms will enhance the efficacy of bioremediation techniques, offering novel approaches to environmental remediation (Madhavan et al., 2023). The efficiency and effectiveness of bioremediation procedures could be revolutionized by this synergy.

Integrated Bioremediation Approaches:

Certain site conditions can make it difficult to remediate both organic and inorganic pollutants through biodegradation (Kapoor and Shah 2023). Consequently bioremediation is being combined more and more with other strategies such as microbial and plant-based techniques physicochemical and engineered methods and others. To increase the pollutants accessibility for bioremediation at locations where organic pollutants have decreased in bioavailability chemical solvents surfactants or biological sequestration agents are employed (Nagda et al., 2022). Flexible management regimes are used by less-coupled remediation systems to maximize site conditions for improved natural attenuation. In order to support bioremediation fully integrated systems actively engineer site conditions (Kapoor & Shah 2023). The strengths of different remediation techniques are combined in this all-encompassing approach to achieve more effective and efficient pollution mitigation. According to Kapoor and Shah (2023) integrated bioremediation techniques have demonstrated potential in handling intricate pollution situations. Environmental remediation can be improved by researchers and practitioners by utilizing the synergies between biodegradation and other remediation techniques. For many synthetic and resistant pollutants bioremediation provides a complete natural response system (Sharma and Dahiya 2022). It includes a variety of remediation instruments that function at various scales enabling the combination of technologies to enhance effects or offer feedback for the best results. Although bioremediation was first used as a stand-alone strategy more recent studies have concentrated on integrating bioremediation measures and combining them with other remediation techniques (Nagda et al., 2022). No engineered system can be optimized in isolation as acknowledged by this integrated approach. Choosing remediation methods according to the conditions and features of the system is essential to effective site management (Sharma & Dahiya 2022). By taking these things into account professionals can determine the best remediation plan utilizing the advantages of bioremediation as well as other methods. The development of bioremediation emphasizes how crucial interdisciplinary study and cooperation are (Srivastava et al., 2022. Researchers can create environmentally friendly more sustainable remediation methods by deepening our understanding of the potential and constraints of bioremediation. In order to improve the effectiveness of pollution mitigation initiatives optimized bioremediation strategies will increasingly integrate integrated approaches (Sharma & Dahiya 2022). The field of environmental remediation is expected to undergo a transformation thanks to this integrated viewpoint.

Circular Economy and Waste Valorization:

A circular economy improved environmental sustainability lower energy use and less pollution all depend on turning waste materials into useful resources (Nazareth et al., 2022). The value of waste has increased significantly and biodegradation presents an alluring sustainable option especially when it comes to phase-out of single-use plastics. As inexpensive remediators of contaminated waters and polluted bodies beneficial organisms can extract value from waste (Molina-Besch 2022). Water treatment facilities can also recover energy through biodegradation demonstrating the potential of this process. Combining waste valorization and biodegradation techniques can greatly reduce environmental effects (Nazareth et al., 2022). Through the utilization of natural processes and beneficial organisms industries can shift to more sustainable practices. Biodegradation and efficient waste management can propel the circular economy and create a more sustainable future (Nazareth et al.2022. Biodegradations potential will be further unlocked by ongoing research and innovations promoting both economic growth and environmental stewardship.

This collection highlights biotech solutions that use beneficial microbes and invertebrates for environmental remediation and it features projects that have a substantial social and environmental impact (Alsafran et al., 2023. The potential of biotechnology in sustainable construction is exemplified by the use of mushroom bricks for building restoration. In order to make living spaces cleaner environmental remediation techniques concentrate on eliminating and recovering pollutants restoring ecological environments soil water and air (Alsafran et al., (2023). These ideas will be further developed by research which will look into creative approaches to effective pollution control. There have been encouraging outcomes from the application of beneficial organisms in environmental remediation (Bhatt et al., 2022). The potential of these microbes and invertebrates to contribute to a more sustainable environment will be further explored in ongoing research. These discoveries will be expanded upon in future studies spurring advancements in environmental remediation and biotechnology (Alsafran et al., 2023. We can create better solutions for a healthier cleaner environment by utilizing the power of helpful microorganisms and invertebrates.

Climate Change and Bioremediation:

Bioremediation applications and other engineered biological systems are at serious risk from changing climates and warming environments (Rafeeq et al., 2023). Experts discuss new data on the effects of shifting environmental conditions current bioremediation challenges and risk-reduction adaptation techniques. For a sustainable future using microbes for environmental applications is essential but care must be taken to make sure these systems work in a variety of environments (Rafeeq et al., 2023). Efforts to bioremediate must take into account how climate change may affect the resilience and efficacy of microbes. Researchers stress how crucial it is to create bioremediation techniques that are climate resilient (Saravanan et al., 2022). Enhancing environmental conditions investigating new microbial strains and combining bioremediation with other remediation methods are all part of this. Adaptive strategies will be necessary for bioremediation to be effective in addressing the problems caused by climate change (Rafeeq et al., (2023). Through recognition of these hazards and the creation of robust remedies the field can keep making contributions to a more sustainable environment. Addressing these climate-related issues is essential to the future of bioremediation (Rafeeq et al., 2023). The long-term viability and effectiveness of bioremediation technologies will depend heavily on ongoing research and development. The creation of organisms and consortia that can degrade and or immobilize different pollutants toxins and contaminants has advanced significantly in the field of environmental biotechnology (Younis et al., 2022. The transfer of these artificially created biological systems from lab to natural environments is still very difficult though. The effectiveness of bioremediation is seriously threatened by climate change especially due to warming and algal bloom events (Willard et al., 2022. The efficiency of cleanup techniques may be limited by the stress that these shifting environmental conditions can place on organisms at bioremediation sites. Climate change may result in stressful conditions for organisms in bioremediation systems such as higher temperatures and changed nutrient availability (Younis et al., 2022). This emphasizes the necessity of bioremediation techniques that are climate-resilient and flexible enough to adjust to changing environmental conditions. These elements must be taken into account for bioremediation to be effective in the face of climate change (Willard et al., 2022. Developing microbial strains that can withstand climate change and adapting bioremediation systems to changing conditions are two examples of creative solutions being investigated by researchers. Environmental biotechnology can continue to create sustainable solutions for pollution mitigation by tackling the issues brought on by climate change (Younis et al., 2022. The long-term effectiveness of bioremediation technologies will depend heavily on ongoing research.

7. EXAMPLES OF LARGE-SCALE BIOREMEDIATION PROJECTS

Exxon Valdez Oil Spill, Prince William Sound, Alaska (1989)

- **Overview**: In 1989, the Exxon Valdez oil tanker spilled approximately 11 million gallons of crude oil into Prince William Sound, Alaska. This was one of the largest oil spills in U.S. history, affecting over 1,000 miles of coastline.
- **Bioremediation Efforts**: In response, bioremediation techniques were employed, particularly **biostimulation**, where fertilizers (nitrogen and phosphorus) were added to stimulate the growth of indigenous oil-degrading bacteria.
- **Results**: Over time, the oil was degraded significantly by microbial action, contributing to the long-term recovery of the ecosystem. However, full recovery has taken decades.

- **Deepwater Horizon Oil Spill, Gulf of Mexico (2010)**
- **Overview**: The Deepwater Horizon spill, caused by the explosion of the BP-operated drilling rig, released over 200 million gallons of crude oil into the Gulf of Mexico.
- **Bioremediation Efforts**: A combination of **natural attenuation** and **bioremediation** was employed. Indigenous oil-degrading bacteria in the Gulf's warm waters played a key role in breaking down hydrocarbons. Dispersants were also used to break the oil into smaller droplets, which made it more accessible to microbes.
- **Results**: While bioremediation significantly reduced the impact of the spill, the scale of contamination meant that recovery continues, and residual oil remains in some areas.
- **Niger Delta Oil Spill Bioremediation, Nigeria (2004–ongoing)**
- **Overview**: The Niger Delta has experienced chronic oil pollution from pipeline leaks, operational discharges, and sabotage, resulting in severe environmental degradation.
- **Bioremediation Efforts**: Projects in the Niger Delta have focused on both **in situ** and **ex situ** bioremediation techniques. These include **Biosparging, biostimulation** and **bioaugmentation** using native microbial strains and engineered bacteria to degrade hydrocarbons in the soil and water.
- **Results**: While bioremediation has shown some success, challenges persist due to ongoing pollution, lack of infrastructure, and environmental conditions that slow the degradation process. The Ogoni Land Cleanup Project initiated in 2016 aims to restore the region.

TNT Bioremediation at the Umatilla Army Depot, Oregon, USA (1993)

- **Overview**: The Umatilla Army Depot stored and disposed of munitions, leading to the contamination of soil and groundwater with toxic compounds like TNT (trinitrotoluene).
- **Bioremediation Efforts**: A bioremediation strategy was implemented using **bioaugmentation**, where specific strains of bacteria capable of breaking down TNT were introduced into contaminated areas. In combination with **biostimulation**, the process accelerated degradation.
- **Results**: This project successfully reduced TNT concentrations in the soil and groundwater, demonstrating the potential for microbial bioremediation in military sites.
- **Amoco Cadiz Oil Spill, Brittany, France (1978)**
- **Overview**: One of the world's worst oil spills happened in the early part of this year when the Amoco Cadiz tanker was wrecked off the coast of Brittany coast, and let an estimate of 68 million gallons of oil to the sea.
- **Bioremediation Efforts**: Subsequently, biostimulation was applied in the impacted zones, where nutrients were introduced in order to enhance the rate of oil degrading bacteria in the messy shores.
- **Results**: The process of the bioremediation was proved to be effective for overcoming the long-term negative outcome but the environmental restoration required some years because of the large area which was influenced by the pollution.

Zinc Mine Tailings Remediation, Sudbury, Ontario, Canada (2003–2005)

- **Overview**: An area of interest in this case study is the Sudbury region where mining activity led to soil and water pollution by heavy metals such as zinc and nickel.
- **Bioremediation Efforts**: Remediation process included phytoremediation of willow and poplar to remove the heavy metals from the site and stabilize them on the plant body. Such plants referred to as hyperaccumulators are plants that are able to endure and bio concentrate metals.
- **Results**: Indeed, with time the levels of metals in the soil reduced considerably indicating that phytoremediation can effectively redial mining environment.

Puchuncaví Mining Site Remediation (2010, Chile)

- **Project Overview**: The Puchuncaví region in Chile has been held contaminated with heavy metals due to copper smelting for years. This led to increase erosion of the soils, poor yields on the fields, pollution of the surrounding environment.
- **Bioremediation Approach**: Techniques on phytoremediation involving the use of metal-tolerant plants were implemented to remediate and immobilize heavy metals such as arsenic, lead and cadmium. To restore the affected areas, some specific types of grasses and shrub species were introduced on the land.

- **Outcome**: In the past, this strategy has proven useful to minimize the concentration of heavy metals in the ground and at the same time, reinculate some of the lost fertility. Phytoremediation has therefore been accepted to be affordable and eco-friendly approach towards remediating mining waste pollution.

Doverspike Mine Acid Mine Drainage Remediation (2001, Pennsylvania, USA)

- **Project Overview**: The Doverspike mine in Pennsylvania was a known source of AMD, untreated and previously posed threat to the surrounding streams and groundwater through release of heavy metals and acidic water.
- **Bioremediation Approach**: Constructed wetlands were given a try as a solution to AMD. Wetland plants together with SRB were used to mitigate the acidic water and to coagulate the heavy metals. The bacteria that was incriminated was capable of converting sulfate to sulfide which innovates with metals and de-salts them and thereby making it nonpoisonous.
- **Outcome**: This passive bioremediation system enhanced the water quality of the environment over time as recorded by the free water DO levels. The wetlands are however still functional and its efficiency in treating AMD as remained high and therefore making the project a long one.

Sydney Tar Ponds Cleanup (2004–2013, Nova Scotia, Canada)

- **Project Overview**: Cleaning up Sydney Tar Ponds contaminated by the steel processing for over a hundred years, was one of the biggest environmental remediation projects in Canada. The hazardous risks associated with this site included Polycyclic Aromatic Hydrocarbon (PAH), Poly Chlorinated biphenyl (PCB), and metal.
- **Bioremediation Approach**: Bioremediation was done jointly with other remediation methods. For the bioremediation aspect, the soil was assessed as to its ability for biostimulents and amendments to be added in order to break down organic constituents.
- **Outcome**: The project was able to perform a general remediation of the site, making it safe and conducive for people to be on. It has since then been turned into parklands this show that the area has been remediated and restored to normal use.

Chernobyl Radioactive Contamination Bioremediation (1986-present, Ukraine)

- **Project Overview**: The April 25 Chernobyl nuclear reactor leak in USSR give out extensive quantities of radioactive particles into the biosphere. Biodegradation using microorganisms for the removal of radioactive substances has been occasioned as a solution to radioactive pollution.
- **Bioremediation Approach**: Some fungi and bacteria that are able to take up and store cesium-137 and strontium-90 have been tested on the bioremediation experiment in the Chernobyl polluted zone.
- **Outcome**: The efficiency on large scale is yet to be tested, yet initial studies suggest that microbial and fungal species can be used to limit the movement of radionuclides in soils, which would imply reduction in rates of radiation exposure.

8. CONCLUSION

Bioremediation and biodegradation are modern, eco-friendly technologies removing pollutants from the environment by using biology. These sinks utilize metabolic reactions of microorganisms in the degradation of organic substances that are pollutants with harmlessness products as effects. The main benefits of bioremediation include specificity, relative cost and positive environmental impact; but the main difficulties are low degradation rates, variability in the environment and cost considerations. The up-to-date developments in biotechnology such as synthetic biology, genetically engineered microorganisms and the nanotechnology give much potential for improving the performance of bioremediation. These examples especially show that the use of knowledge management concepts can also be applied on an extent larger scale. However, much hope and forward movement will depend on continued research, development of the new technologies and favourable policies in the legal framework. Even the indigenous microorganisms have the potential to degrade pollutants still the processes are hindered by toxicity or inadequacy of correct pathways. Genetic manipulation may enhance microbial degradation ability but the use of produced engineered strains on site and consideration of some risks is a challenge. To overcome these challenges biostimulation, and bioaugmentation bring enhancement to the existing natural biodegradation process. These trials suggest that microbial populations are not simple, and large scale biostimulation trials have varied success. Nevertheless, bioremediation and biodegradation, apart from facing these challenges offers an opportunity in trying to find interventions or solutions to pollution issues currently affecting the world and assist in the enhancement of circular economy systems. Linking bioremediation to large environmental management systems as well as interdisciplinary research and policy together with enhanced investment is going to be key to developing such green technologies.

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