**Chapter**

**Bioremediation: Harnessing Nature's Power for Environmental Cleanup**

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The explosive rise of global population has led to the increased exploitation of natural resources and sources to respond to the high demands of the population for food, energy, and all other requirements. Industrial revolution was a response to these requirements; however, it has resulted in the production of huge number of various organic and inorganic chemicals that have directly and indirectly led to the prolonged pollution of the habitats. The duration of the contamination is regarded to be because of their difficult biodegradability. The trend of environmental pollution is so fast and vast that the detectable rates of contamination are even encountered in the farthest ocean waters. Based on the estimations made by the environmental protection agency (EPA) only around 10 % of all wastes were safely disposed off (Chaudhry 1994; Reddy and Mathew 2001).

Today, we want to shed light on an innovative and eco-friendly approach to environmental cleanup called bioremediation. This fascinating process utilizes the power of nature to restore contaminated sites and mitigate pollution.

**What is Bioremediation?**

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The term of bioremediation has been made of two parts: “bios” means life and refers to living organisms and “to remediate” that means to solve a problem. Bioremediation is a branch of biotechnology that employs the use of living organisms, like microbes and bacteria, in the removal of contaminants, pollutants, and toxins from soil, water, and other environments. Toxic chemicals are detoxified, reduced, degraded, or transformed into less toxic substances as part of this process. It is a type of waste management technique which involves the use of organisms to remove or utilize the pollutants from a polluted area.

There are several remedies where contaminated water or solid is purified by chemical treatment, incineration, and burial in a landfill. There are other types of waste management technique which include solid waste management, nuclear waste management, etc. Bioremediation is different as it uses no toxic chemicals. Bioremediation involves the use of living organisms, such as bacteria, fungi, and plants, to break down or neutralize hazardous substances in the environment. These organisms have unique abilities to metabolize or transform pollutants into less harmful forms. By harnessing their natural processes, we can effectively clean up polluted areas without causing further harm.

Microorganisms like Bacteria and Fungi are the main role player when it comes to executing the process of Bioremediation. Bacteria are the most crucial microbes in this process as they break down the waste into nutrients and organic matter. Even though this is an efficient process of waste management but bioremediation cannot destroy 100% contaminants. Bacteria can easily digest contaminants like chlorinated pesticides or clean oil spills but microorganisms fail to destroy heavy metals like lead and cadmium.

Theoretically, there are enough bioremediants in nature that can be applied against a broad range of pollutants and bioremediation can be considered as a useful technique for the complete destruction of a wide variety of contaminants. Many compounds that are legally regarded as detrimental and dangerous can be biotransformed to harmless products. This eliminates the chance of future liability associated with treatment and disposal of contaminated material. Instead of transferring contaminants from one environmental medium to another, for example, from land to water or air, the complete destruction of target pollutants is possible. (Vidali 2001).

**Concept of Bioremediation**

Bioremediation has been defined as “Use of living organisms to clean up or remove pollutants from soil, water, or wastewater; use of organisms such as non-harmful insects to remove agricultural pests or counteract diseases of trees, plants, and garden soil,” as reported by US EPA, United States Environmental Protection Agency (Cristaldi et al., 2017). This activity can be carried out by green plants that are able to remove pollutants from the soil or water by absorption through the roots and next accumulation into the leaves. It also can make use of microorganisms to detoxify or remove inorganic pollutants from the environments (Khalid et al., 2017). Bioremediation also offers a permanent in situ remediation rather than simply translocating the problem. This technique can be used for remediation of heavy metals, metalloids, or other inorganic pollutants from soil or water (Ali et al., 2013; Ashraf et al., 2019). It is proved cost-effective, efficient, novel, eco-friendly, and solar-driven technology with good public acceptance as compared with engineering techniques like excavation, soil incineration, soil washing, flushing, and solidification (Ali et al., 2013; Sarwar et al., 2017). The efficiency of bioremediation on removing inorganic pollutants usually depends on numerous plant, microbes, and soil/water factors such as the physicochemical properties of the soil/water, microbial, and plant exudates and the capacity of living organisms to uptake, accumulate, sequester, translocate, and detoxify pollutants (Khalid et al., 2017).

**How Does Bioremediation Work?**

There are two main types of bioremediation: In situ and ex situ.

**1. In Situ Bioremediation:**

In this method, biodegradable materials or microorganisms are applied directly to the contaminated site. The microorganisms then utilize the pollutants as a source of energy or nutrients, effectively degrading them in place. This approach is particularly useful for soil and groundwater remediation.

**2. Ex Situ Bioremediation:**

Ex situ bioremediation involves excavating contaminated material and treating it outside its original location. This allows for more controlled conditions during the remediation process. Contaminated soil or water is typically treated in specially designed bioreactors that provide optimal conditions for microorganisms to thrive and break down pollutants.

**How Does Bioremediation Work?**

1. Microbial Bioremediation:

Microorganisms such as bacteria, fungi, and algae are employed to degrade organic contaminants like petroleum hydrocarbons or industrial chemicals. These microorganisms feed on the pollutants as an energy source, effectively breaking them down into harmless byproducts.

2. Phytoremediation:

Plants play a crucial role in phytoremediation by absorbing contaminants through their roots and accumulating them in their tissues. They can remove heavy metals, pesticides, and other pollutants from soil or water. Additionally, some plants have the ability to break down complex organic compounds through metabolic processes.

**Types of Bioremediation**

Bioremediation is of three types –

1) Biostimulation

As the name suggests, the bacteria is stimulated to initiate the process. The contaminated soil is first mixed with special nutrients substances including other vital components either in the form of liquid or gas. It stimulates the growth of microbes thus resulting in efficient and quick removal of contaminants by microbes and other bacterias.

2) Bioaugmentation

At times, there are certain sites where microorganisms are required to extract the contaminants. For example – municipal wastewater. In these special cases, the process of bioaugmentation is used. There’s only one major drawback in this process. It almost becomes impossible to control the growth of microorganisms in the process of removing the particular contaminant.

3) Intrinsic Bioremediation

The process of intrinsic bioremediation is most effective in the soil and water because of these two biomes which always have a high probability of being full of contaminants and toxins. The process of intrinsic bioremediation is mostly used in underground places like underground petroleum tanks. In such place, it is difficult to detect a leakage and contaminants and toxins can find their way to enter through these leaks and contaminate the petrol. Thus, only microorganisms can remove the toxins and clean the tanks.

4) Bioreactors

The use of biological processes in a contained area or reactor for biological treatment of relatively small amounts of waste. This method is used to treat slurries or liquids. Slurry reactors or aqueous reactors are used for ex situ treatment of contaminated soil and water pumped up from a contaminated plume. Bioremediation in reactors involves the processing of contaminated solid material (soil, sediment, sludge) or water through an engineered containment system. Bioreactors have been used to treat soil and other materials contaminated with petroleum residues (McFarland et al. 1992; De´ziel et al. 1999).

5) Bioventing

The process of drawing oxygen through the contaminated medium to stimulate microbial growth and activity. Bioventing is the most common in situ treatment and involves supplying air and nutrients through wells to contaminated soil to stimulate the indigenous bacteria. Bioventing employs low air flow rates and provides only the amount of oxygen necessary for the biodegradation while minimizing volatilization and release of contaminants to the atmosphere. It works for simple hydrocarbons and can be used where the contamination is deep under the surface (Vidali 2001). In many soils effective oxygen diffusion for desirable rates of bioremediation extend to a range of only a few centimeters to about 30 cm into the soil, although depths of 60 cm and greater have been effectively treated in some cases (Vidali 2001).

6) Biopiling

Biopiles are a hybrid of landfarming and composting. Essentially, engineered cells are constructed as aerated composted piles. Adding compost to contaminated soil enhances bioremediation because of the structure of the organic compost matrix (Kastner and Mahro 1996). Compost enhances the oxidation of aromatic contaminants in soil to ketones and quinones, which eventually disappear (Wischmann and Steinhart 1997). Typically used for treatment of surface contamination with petroleum hydrocarbons they are a refined version of landfarming that tend to control physical losses of the contaminants by leaching and volatilization. Biopiles provide a favorable environment for indigenous aerobic and anaerobic microorganisms (Vidali 2001).

Biopile treatment is a full-scale technology in which excavated soils are mixed with soil amendments, placed on a treatment area, and bioremediated using forced aeration.

**Organisms Involved in Bioremediation Process**

Organisms that are due to be applied in bioremediation shall fulfill the following requirements (Alexander 1994) : (a) The organisms will have the effective enzymes important in bio-remediation; (b) The organism shall be able to live and demonstrate its bioactivity under conditions of pollution; (c) The organism must be able to get access to the contaminant that may be not soluble in aqueous environments or severely adsorbed to solid surfaces; (d) the substrate site of the contaminant must be accessible for the active site of the enzyme of role in bioremediation; (e) contaminant and the enzymatic system must come in close contact somewhere in or out of the cell; and finally (f) appropriately favorable environmental conditions must exist or be provided to arise the population of the potential bioremediant.

various types of uni-/ multicellular organisms have the required potentials to be applied in bioremediation processes. Indeed species of plants, bacteria, and fungi may be used to eliminate pollutants. However, microorganisms are of the highest bioremediation potentials as they are natural decomposers in different ecosystems and can easily proliferate. Microorganisms as fungi and bacteria degrade and break down the molecules of natural and or synthetic origins.

Phytoremediation is referred to the type of bioremediation that is relied on plants and algae as bioremediants. Mycoremediation is a type of bioremediation where fungi serve as bioremediants. (Levin et al. 2003).

**Advantages of Bioremediation:**

1. Environmentally Friendly: Bioremediation offers a sustainable solution that minimizes environmental impact compared to traditional cleanup methods that rely on chemicals or excavation. The most significant advantage of adopting bioremediation technologies is the positive impact on the environment. Nature is used to fix nature in bioremediation.

2. Cost-Effective: In many cases, bioremediation can be a more cost-effective option compared to other cleanup techniques since it requires fewer resources and infrastructure.

3. Versatile Applications: Bioremediation has proven successful in treating various types of contaminants, including petroleum hydrocarbons, heavy metals, pesticides, and even radioactive materials.

4. Long-Term Solution: Bioremediation not only removes pollutants but also promotes the natural restoration of ecosystems. It allows for the regeneration of habitats and the return of biodiversity to previously contaminated areas.

5. Safest And Least Invasive: This is the safest and least invasive soil and groundwater treatment available when properly done by skilled workers using specialised bioremediation equipment.

6. Highly Treatable: Organic pathogens, arsenic, fluoride, nitrate, volatile organic compounds, metals, and a variety of other pollutants such as ammonia and phosphates can all be treated by bioremediation.

7. Removal of Pesticides And Herbicides: It works well to remove pesticides and herbicides from aquifers, as well as seawater intrusion.

8. No Risk of Transportation: For the most part, work is done on-site, avoiding the risks of transportation.

9. Less Requirement Of Equipment: Except for specific parts, very little equipment is required.

10. Low Maintenance Cost: Maintenance costs are low, and input costs are low.

11. Reduction Of Liability: Liability is reduced since toxins are less likely to escape.

12. Low Energy Consumption: In comparison to incineration and landfilling, there is very little energy consumed.

**Bioremediation - Disadvantages**

1. Treats Only Biodegradable Substances: The major shortcoming of bioremediation technology is that it can only deal with biodegradable substances.

2. Hazardous New Product: Researchers have also discovered that the new product created following biodegradation is sometimes more harmful to the environment than the original component.

3. Time Consumption: Finally, the procedure takes time, particularly ex-situ bioremediation, which necessitates excavation and pumping.

**Conclusion and Perspective**

In conclusion, bioremediation represents a promising approach to environmental cleanup, harnessing the power of nature to restore contaminated sites. By leveraging the incredible abilities of microorganisms and plants, we can work towards a cleaner and healthier world for future generations. World is moving towards promoting sustainable practices and providing innovative solutions for environmental challenges. Bioremediation is just one of the many ways we are working towards a cleaner future.

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