**Bioremediation: A sustainable approach towards environmental detoxification**

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**ABSTRACT**

Environmental pollution reached to alarming level in past few decades due to various anthropogenic and industrialization. Pollution caused by xenobiotic and other refractory substances are now recognized as a severe threat to both human health and the natural environment. A variety of pollutants, such as heavy metals, polychlorinated biphenyls, plastics, and other chemicals, are prevalent in the environment due to their toxicity and non-biodegradability. Bioremediation is a rapidly growing remediation method for eliminating toxicants from contaminated sites. In order to detoxify harmful pollutants, bioremediation uses a variety of bacteria that can act simultaneously or sequentially.  Bioremediation also referred as an  acceleration of the normal degradation process, in which microorganisms (such as bacteria and fungi), green plants (a process known as phytoremediation), or their enzymes break down or transform toxic contaminants into CO2, H2O, microbial biomass, inorganic salts, and other by-products (metabolites) that are less toxic than the parent compounds**.**It is a process that eliminates, degrades, detoxifies, and immobilizes potentially hazardous contaminants and pollutants. The basic purpose of bioremediation is to breakdown pollutants and transform them to less harmful forms. Depending on criteria such as cost, pollutant type, and concentration, ex situ or in situ bioremediation can be used.This article gives a comprehensive glance at the bioremediation process, different forms of bioremediation and its principles, and the merits and drawbacks of bioremediation.

**Keywords**—Bioremediation, toxicants, pollutants,environment,detoxification, pollution

1. **INTRODUCTION**

Global industrialization has led to environmental pollution. Due to anthropogenic activities, such as mining, removal of toxic metal effluents from steel mills, battery manufacturers, energy generation, causing serious environmental issues.As a result of this vast quantities of inorganic and organic pollutants are added into the environment every year. In some cases, these releases are intentional and well regulated (e.g., industrial emissions) where as in other cases they are accidental (e.g., chemical or oil spills).These compounds often toxic, and more persistent in environment which results in accumulation and biomagnification. Many of these contaminants can cause mutations in the humans and harm environment. The brain, liver, and kidney accumulate heavy metals via absorption. Animals may also experience cancer, nervous system damage, stunted growth, other negative effects and even death. Heavy metals in soils reduce food quality and quantity by inhibiting nutrient absorption, plant growth, and physiological metabolic processes. Removal of such environmental contaminants using bioremediation techniques is a practical and affordable solution.The word remediate" means to solve a problem, and "bio-remediate" means to solve an environmental problem such as contaminated soil or groundwater using biological organisms. Toxicants or Metal-contaminated soils are being remedied using chemical, biological, and physical methods. However, physicochemical methods produce a lot of waste and pollution, so they are not effective. Bioremediation is aenvironmentally responsible method that uses natural biological methods to entirely remove hazardous or toxic pollutants. Any method that restores the natural environment damaged by contaminants to its original state using microorganisms, fungus, green plants, or their enzymes.In general, there are two types of bioremediation technologies: in situ and ex situ. Ex situ bioremediation entails removing the contaminated material from the site to be treated elsewhere, whereas in situ bioremediation treats the polluted material on the spot. Bioventing, landfarming, bioreactor, compositing, bioaugmentation, rhizofiltration, and bio-stimulation are a few examples of bioremediation technology. Bioremediators are microorganisms that carry out the bioremediation process. For bioremediation to be effective, microorganisms must enzymatically attack the pollutants and convert them to harmless products. As bioremediation can be effective only where environmental conditions permit microbial growth and activity, its application often involves the manipulation of environmental parameters to allow microbial growth and degradation to proceed at a faster rate.Because bioremediation can be effective only where environmental conditions permit microbial growth and activity, its application frequently involves the manipulation of environmental parameters to allow microbial growth and degradation to proceed at a faster rate.Bioremediation procedures are often less expensive than traditional methods such as incineration, and certain contaminants can be treated on-site, lowering exposure risks for clean-up personnel or potentially wider exposure due to transportation mishaps. Bioremediation is more acceptable to the public than other technologies because it is based on natural attenuation.

**II. PRINCIPLE OF BIOREMEDIATION**

"Bioremediation" means the biological degradation of organic wastes under regulated conditions. By giving the organisms the nutrients and other chemicals they require to function efficiently. The hazardous compounds can be destroyed or detoxified through bioremediation. Every stage of the metabolic process requires the use of enzymes like hydrolases, lyases, transferases, and oxidoreductases. Many enzymes may break down a variety of substrates due to their non-specific and specific substrate affinities. For bioremediation to be effective, the contaminants must be subjected to enzymatic activity. Environmental factors frequently need to be changed during bioremediation in order to hasten microbial growth and breakdown .This is due to the fact that bioremediation only functions when the conditions are favourable for bacteria to grow and disperse. The natural and encouraged process of bioremediation can be aided by organisms and fertilizers. A crucial aspect of bioremediation technology is biodegradation. It is the process of biotransformation of toxic substances or pollutants in to non-toxic compounds or naturally-occurring inorganic compounds that are safe for use.

**III. TYPES OF BIOREMEDIATION**

Bioremediation through microorganisms can be classified into 2 types: In-situ bioremediation and ex-situ bioremediation (Marykensa, 2011). The process of treating contaminated soil and water where it originated is known as in-situ bioremediation. This method is less expensive and very efficient.The fundamental benefit of this technology is the absence of soil excavation. In order to perform bioremediation, it entails the use of nonpathogenic microorganisms (Gomes et al., 2013).The primary application of in-situ bioremediation is the remediation of petroleum-contaminated environments. Because microbes can enter the contaminated region via their chemotactic capacity, chemotaxis is important (Jorgensen, 2007). In order to boost the proliferation of microorganisms, in-situ bioremediation requires an aerobic technique that involves introducing oxygen into the soil through bioventing and injecting hydrogen peroxide (Brown et al., 2017).One of the main limitations of in-situ bioremediation is the slow rate of decomposition and survival of microorganisms on the waste material existing in the soil. (Hao Chang et al., 2013).Because it is less disruptive and does not require excavation and transportation of contaminated soils, in situ remediation is more appealing and cost effective. Natural attenuation, bio-stimulation, bioventing, and bioaugmentation are some of the most often employed **in situ** techniques.

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**Fig.1. Various Bioremediation approaches**

1. **Natural attenuation:** Natural attenuation refers to natural processes to achieve pollutant remediation. Consideration of this method for remediation of contaminated sites typically requires modelling and evaluation of contaminant degradation rates, exposure pathways, effects on sensitive receptors, and prediction of contaminant concentrations downgradient to the contaminant plume if the plume migrates. The applicability of this strategy is usually determined on a case-by-case basis. This strategy's is not a straightforward process, it requires multidisciplinary skills in microbiology, chemistry, hydrogeology, and geochemistry**.**
2. **Biostimulation:** Biostimulation offers favorable nutrition and physiological conditions for the growth of naturally occurring microbial communities. This stimulates metabolic activity, which degrades the contaminants.
3. **Bioventing:** Bioventing is a type of engineered in situ bioremediation that boosts the natural biodegradation of some aerobically degradable pollutants, such as non-chlorinated volatile organic compounds (VOCs) and semivolatile organic compounds (SVOCs) such as hydrocarbons from petroleum, that are located in the vadose (unsaturated) zone, by supplying air/oxygen to pre-existing native aerobic microbes (USEPA 2006). Bioventing uses low air flow rates and offers a limited amount of oxygen essential for biodegradation while minimizing volatilization and pollutant discharge into the ecosystem.This approach is more effective when the contaminated sites are hot and the water level is lower than the surface.

Figure : Bioventing

1. **Bioaugmentation:** The incorporation of strains or cultures to contaminated sites to accelerate contaminant degradation is known as bioaugmentation. This approach can target specific chemicals, such as refractory organics. Microorganisms that are already present in the environment can break down contaminants, but only at a very slow rate. This technique is utilized to overcome the problem of a slower rate.
2. **Bioslurping:** It is a multiphase separation approach, an efficient in In-situ remediation method that combines vacuum-augmented free product recovery by bioventing of subsurface soil to simultaneously restores PAH-polluted soil, sediment, and groundwater. Bioventing encourages the aerobic decomposition of pollutants that remain in contaminated soil, whereas vacuum-enhanced recovery employs negative pressure to create a partial vacuum that extracts free product and water from the subsurface.

**Ex situ** techniques entail excavating and removing contaminated soil for treatment on-site or transportation to a suitable location before treatment. Ex situ bioremediation methods that are regularly utilized include land farming, biopiles, and bioslurries.Ex-situ bioremediation involves treatment of pollutants, contaminated soil or water once excavated from its initial site.

1. **Land farming:** Land farming, is an ex situ treatment method in which contaminated soil, sediment, or sludge is dug and spread on a prepared bed and cyclically turned over (tilled) to aerate the mixture until contaminants are degraded by means of stimulated aerobic microbial activities in the soils resulting from aeration and/or the supplementation of moisture, minerals, and nutrients. This method is only suitable for treating the top 10-35 cm of soil.
2. **Biopiles:** It is an ex situ bioremediation procedure in which burrowed soil, sludge, or sediment are combined with soil amendments, deposited on a treatment area, and remediated using forced aeration. The technique entails layering contaminated soil, sludge, or dry sediments into piles and boosting aerobic microbial community biodegradation activity by generating optimum proliferating conditions within the pile (Germaine et al. 2012). Biopiles are typically 2-3 meters tall, with polluted soil, sludge, or sediment typically deposited on top of the treated soil.
3. **Composting:** Composting (windrows) is a controlled biological process in which excavated contaminated soil is mixed with bulking agents and organic amendments (wood chips, hay, manure, green waste, etc.) in appropriate quantities to provide the carbon and nitrogen balance required for thermophilic microbial activity maintenance. Organic pollutants (e.g., polycyclic aromatic hydrocarbons (PAHs), 1,1,1-trichloro-2,2-bis(p-chlorophenyl) ethane (DDT)) are transformed to non-toxic or less toxic stable products by microbial activity under aerobic and anaerobic conditions throughout the composting process. The heat created by indigenous bacteria during organic material degradation will result in a thermophilic phase (55°-65° C) throughout the composting process, which is critical for proper transformation of hazardous pollutants.
4. **Biofilter:** This technique is an oldest and mostly usedto remove gaseouscontamination. Columns embedded with microorganisms are employed in this technology to eliminate gaseous contaminants (Boopathy, 2000).It is an important isolation technique for removing organic pollutants from air and water.The efficacy of biofilters is determined by the residence duration of effluent within the system as well as the distribution of particle sizes in the filler material (Van Os et al., 1998).
5. **Bioslurries:** This remediation is a combination of different bioremediation processes. As compared to composting, where contaminated soil contains only a trace amount of water, bio-slurry method artificially mixes affected soil with water to form a slurry in which the water volume is generally higher than that of the soil, which merely reduces the initial concentration of contaminants to reduce microbial pressure but also improves the diffusion of organic contaminants to increase the chances of microbial contact with the contaminants.The bio-slurry remediation is done in a reactor, which prevents the emission of volatile organic chemicals and thereby preserves the environment.

**IV. MERITS & DEMERITS OF BIOREMEDIATION**

Environmental pollution is a severe public health issue since it negatively affects both humans and other living things including environment. Available Chemical and physical remediation procedures are expensive to completely remove contaminants. Both strategies may also cause more pollution and site disruption, which could have a negative impact on local people and other biota. Therefore, remediation techniques that rely on chemicals and physical force are not thought of as environmentally sustainable.

In contrast to these methods, bioremediation relies on biological processes (mediated by various kinds of living organisms) to eliminate various persistent pollutants. All bioremediation techniques have their own advantages and disadvantages as they have their own specific applications. Like other technologies; bioremediation has its limitations.Some contaminants, such as chlorinated organic or high aromatic hydrocarbons, are resistant to microbial attack. They are degraded either slowly or not at all, hence it is not easy to predict the rates of clean-up for a bioremediation exercise; there are no rules to predict if a contaminant can be degraded.

Figure 3: Advantages & disadvantages of bioremediation

Table : Case studies on bioremediation of various contaminants

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| **CONTAMINATED SITE / SAMPLE** | **POLLUTANT** | **METHOD OF CLEAN UP** | **INFERENCE** | **REFERENCE** |
| Soil (Borhola oil fields) | Petrolium hydrocarbon | microslurry reactor | By applying nutrient and microbial enriched solution, the crude oil components were decreased by 75% under aerated conditions within a year.  | B.K. Gogoi et. al (2001) |
| River Water (Mutha RIVER, Pune) | heavy metals (Mercury, Lead, arsenic and Zinc), chlorides, phosphates and nitrates | bioaugmentation > biostimulation | Bioaugmentation was more effective than biostimulation with aeration and nutrient in eliminating a variety of organic pollutants from lake sediments. | G S Anaokar et.al (2012) |
| Liquid waste oil | Aliphatic & aromatic hydrocan compounds | Bioreactor | With adequate oxygen supply, the speed and acceleration of microbial growth rates increase.It increases rate of bioremediation. | Hasmway (2013) |
| Synthetic wastewater | Selenium | Jar fermenter (biovolatilization from the aqueous phase.) | 82% of the selenium volatilized by strain NT-I was recovered with minor contaminants in a simple gas trap with nitric acid, indicating that strain NT-I as a potential biocatalyst for Selenium recovery  |  Kagami et.al (2013) |
| Soil | Pentachorophenol (PCP) Pesticide | Microorganism mediated | Flavobacterium sp. cultures degraded PCP more efficiently in Columbia soil than Arthrobacter sp. cultures. The mixed culture proved the most effective at degrading PCP. | Sujata Ray (2014) |
| Aqueous stock solution of 10ppm for methyl orange (MO), chromium (Cr) and lead (Pb)  | methyl orange (MO), chromium (Cr) and lead (Pb) | Biosorption by dead fungal biomass of *Aspergillus flavus*. | After 5 cycles of desorption processes, biosorption capacity towards Pb, Cr, and MO at 76%, 72%, and 53% respectively was observed by dead fungal biomass of *Aspergillus flavus*. | Mahmooda Takey et.al (2014) |
| Kulv river water | Total nitrogen (TN), total phosphorus (TP), suspended solid (SS), ammonia nitrogen (NH3-N) | mussel/microalgae/bacteria system | After several months of treatment, the mussel/microalgae/bacteria system improved the water environment and had a low operating cost. | Bing Geng et.al (2021) |

**V. CONCLUSION**

 Pollutant deposition in the environment has reached a critical point in recent years as a result of urbanization, population growth, and industrial expansion. The only environmentally benign answer to this problem is bioremediation, which can be done in two ways: in situ and ex situ. The first step towards effective bioremediation is site characterization, which aids in determining the best and most feasible bioremediation technique (ex situ or in situ). Under controlled condition this technique can be utilized to treat wide spectrum of contaminants. Compared to other technologies that are frequently used for clearing hazardous waste or toxic compounds. Bioremediation is one of the less expensive, safe and more acceptable technique of remediation which has a number of economic or efficiency benefits.Hence, in order to effectively treat polluted sites, geological characteristics of the polluted site(s), such as soil type, pollutant depth and type, site location relative to human habitation, and performance characteristics of each bioremediation technique, should be considered.

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