**BIOREMEDIATION: An Ecofriendly approach for Waste Management**

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**Introduction**

In present time, environment issues are of utmost concern due to increased pollution by human interference in natural environment. Rapid growth of population and race for economic growth has put huge pressure on biotic and abiotic resources. Besides creating high demand for renewable and non-renewable resources, industrialization is also releasing harmful and toxic pollutants as insecticides, weedicides, fungicides, heavy metals, nuclear wastes, synthetic dyes, detergents, greenhouse gases, oil spills etc. in the environment and destroying its natural composition. Some of these substances are carcinogenic in nature. As the pollution level in increasing at alarming rate and posing threat to existence of living beings and exposing human being to lead unhealthy living conditions; so, to combat these pollutants has become necessary. An economic and effective method to treat pollutants in a deteriorated environment is bioremediation.

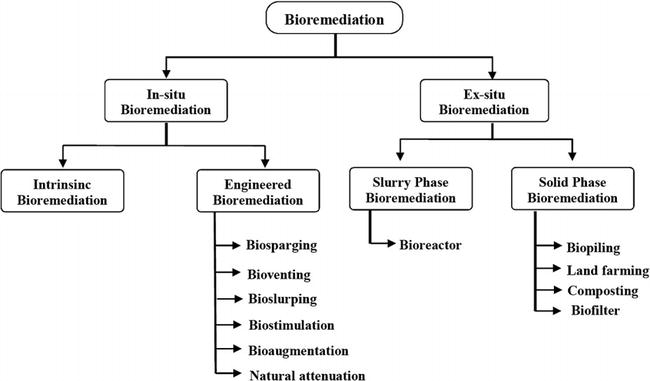
**Definition of bioremediation**

Biological organisms are used in the bioremediation method to eliminate or neutralise an environmental pollution through a metabolic reaction. The term "biological" refers to both the "remediation"—the process of fixing the problem—and microscopic organisms like fungi, algae, and bacteria. So, bioremediation may be defined as-

*“A waste management strategy called "bioremediation" employs living organisms to remove or neutralise contaminants from contaminated sites”.*

Bioremediation is a method of pollution treatment that is safe, economical, and sustainable [1,2]. Utilising microorganisms and plants as examples of creatures is part of the technology. The kind, location, and intensity of the pollution determine the viability of this strategy. It has been demonstrated that microbes are effective at cleaning up environmental pollutants. They are preferred to plants in remediation because they grow easily, have a quick growth cycle, and are simple to manipulate. To support a sustainable ecosystem, it is vital to improve the utilisation of microorganisms as a bioremediation agent. Bioremediation is extensively involved in the destruction, eradication, immobilisation, or detoxification of numerous chemical wastes and physically harmful substances from the environment through the microbial activity. The main concept is to degrade and change contaminants into less dangerous forms. Bioremediation can be carried out *in-situ* or *ex-situ*, depending on a variety of factors, such as cost, site circumstances, type, and pollutant concentration. As a result, a suitable bioremediation technique is picked. Additionally, the primary methods for creating bioremediation are bio-stimulation, bio-augmentation, bioventing, biopiles, and bio-attenuation, provided that the environmental factors that indicate whether bioremediation is complete are met. Each bioremediation technology has benefits and drawbacks because of its many applications.

If the environment is conducive to their growth and metabolism, autochthonous microorganisms found in polluted environments have the potential to address the majority of problems related to the biodegradation and bioremediation of polluting substances [3]. The goal of bioremediation is to lessen the toxicity of contaminants by detoxifying, degrading, mineralizing, or other means. Most challenging pollutants are pesticides, agrochemicals, heavy metals, xenobiotic compounds, hydrocarbons, nuclear waste, dyes, plastics etc. To remove harmful waste from a polluted environment, cleaning techniques are used. (Fig.-1).



**The following categories of microorganisms are employed in bioremediation:**

1.Aerobic: *Actinobacter*, *Nocardia*, *Flavobacterium*, *Rhodococcus*, and *Mycobacterium* are examples of aerobic bacteria which can break down polyaromatic chemicals, hydrocarbons, alkanes, pyrene and pesticides. A large number of these bacteria utilise the pollutants as a source of carbon and energy.

2.Anaerobic: anaerobic bacteria as *Clostridium, Paracoccus* and *Pseudomonas* are utilised in bioremediation to break down pyrene.

**Factors affecting microbial bioremediation**

The composition and concentration of the contaminants, the environment's physicochemical properties and present microorganisms are responsible for efficiency of bioremediation [4]. The key contributing components include the microbial population's capacity to degrade pollutants, the ease with which toxins may be accessed by the microbial population, and environmental variables such soil type, pH, temperature, oxygen content, and nutrition levels. The factors are as follows:

**A. Biological or biotic factors**

The concentration of decomposing microbes with insufficient carbon sources, microbial antagonistic, competition, succession, and predation interactions are all included in biotic factors. Enzymatic activity, mutation, horizontal gene transfer, growth rate for biomass production, population size, and composition are among the key biological determinants [5, 6].

**B. Environmental or inorganic factors**

The environmental conditions temperature, pH, moisture, soil structure, water solubility, nutrients, site conditions, oxygen content and redox potential, resource depletion and physico-chemical bioavailability of pollutants, concentration, chemical structure, type, solubility, and toxicity are all factors that affect microbial growth and activity. The aforementioned variables regulate the kinetics of deterioration [5, 7].

The pH range of (6.5-8.5) is generally ideal for contaminant biodegradation in all ecosystems. Besides pH, the osmotic pressure and moisture of systems have an impact on the metabolism of contaminants [8].

**Using bioremediation**

The selection criteria that are taken into account while choosing any bioremediation technique include the type of pollutant, the depth and volume of contamination, the type of environment, the location, the cost, and environmental policies.

**A. Ex-situ bioremediation:** These methods entail removing pollutants from contaminated areas and transferring them one at a time to another location for remediation. The depth of pollution, kind of pollutant, degree of pollution, cost of treatment, and location of the contaminated site are frequently taken into consideration when ex-situ bioremediation strategies are being evaluated. Ex-situ bioremediation technology selection is governed by performance standards as well. Ex-situ bioremediation methods are:

**1.Solid-phase processing**

In solid-phase bioremediation, the contaminated soil is removed from its natural environment and piled up. It also comprises home, industrial, and municipal trash, as well as organic wastes like leaves, animal dung, and agricultural wastes. Pipes positioned all over the piles are used to transport bacterial growth. In order for the pipes to ventilate and allow for microbial respiration, air must be drawn through them. Biopiles, windrows, land farming, composting, and other techniques for solid-phase treatment are available [9].

**2.Bioremediation in the slurry phase**

This is a somewhat quicker process than the other types of treatment. In the bioreactor, contaminated soil is blended with water, nutrients, and oxygen to provide the microorganisms with the best possible environment in which to break down the pollutants that are present in the soil. Stones and rubble are separated from the contaminated soil during this operation. After this procedure is finished, the soil is extracted and dried using centrifuges, vacuum filters, and pressure filters. The next step is to dispose of the soil and treat the resulting fluids in advance.

**Ex situ bioremediation types**

The following are the most typical applications for bioremediation.

**1. Biopile**

Aeration and fertiliser enrichment are used in conjunction with above-ground piling of dug-up polluted soil to enhance bioremediation by microbial metabolic processes. This method includes leachate collection, bed systems for treating leachate, nutrients, irrigation, and aeration. Due to its advantageous qualities and economic effectiveness, this particular ex-situ technology is increasingly being evaluated since it enables effective control of operational biodegradation conditions, including pH, nutrient, temperature, and aeration. The biopile can be employed to remediate polluted very cold harsh settings as well as volatile low molecular weight contaminants [10, 11, 12]. Because heating systems can be incorporated into biopile designs to boost microbial activity and pollutant availability, which in turn increases the rate of biodegradation, remediation times can be decreased [13]. In order to promote better bioremediation, warm air can also be injected into biopile designs to give air and heat simultaneously. To improve the remediation process in a biopile construct, bulking agents such as straw sawdust, bark or wood chips, and other organic materials have been included. Although biopile systems were connected to other ex-situ bioremediation methods in the field, such as land farming, bioventing etc., they were expensive to maintain due to remote power supply required for constant air circulation in contaminated piles of soil through air pumps. Extremely high air temperatures might cause soil to dry out during bioremediation, which will impede microbial activity and promote volatilization rather than biodegradation [14].

**2. Windrows**

In order to improve bioremediation, windrows rotate the piled polluted soil on regularly. This increases the microbial activity that break down the native and transient hydrocarbon clastic present in the polluted soil. The uniform distribution of nutrients, pollutants, and microbial activities, along with periodic turning of polluted soil, increase aeration with the addition of water, as well as the rate of bioremediation, which is accomplished through acclimatisation, biotransformation, and mineralization. Although the efficacy of the windrow for removing hydrocarbons from the soil was lower than that of the biopile treatment, windrow treatment demonstrated a faster rate of hydrocarbon removal [15]. Due to the development of an anaerobic zone inside the heaped dirty soil, which frequently restricted aeration, windrow treatment has been linked to the emission of greenhouse gases (CH4) [16].

**3. Farming on land**

Due to its low operating costs and little equipment requirements, land farming is one of the most straightforward and effective bioremediation approaches. It is primarily seen in ex-situ bioremediation, while it can also occur in some instances of in-situ bioremediation. The treatment site is a factor in this decision. Here pollutant depth is crucial. In land farming, toxic soils are frequently dug up and tilled, and the type of bioremediation is strictly controlled by the treatment site. In order to enable aerobic biodegradation of the pollutant by autochthonous microorganisms, polluted soils are often carefully deposited on a fixed layer support above the ground surface [17]. Overall, the land farming bioremediation technology is very easy to develop and apply, necessitates little investment to remediate huge toxified soil with little negative impact on the environment [18].

**4. Bioreactor**

A bioreactor is a container where raw materials are transformed into certain products as a result of a chain of biological reactions. Bioreactors can be operated in a variety of ways, including batch, fed-batch, sequencing batch, continuous, and multistage. The ideal growing environment for bioremediation is provided by the bioreactor. Polluted samples for the cleanup procedure are in the bioreactor. The time required for bioremediation is significantly decreased by bioremediation methods based on bioreactors that have great control over pH, temperature, aeration, substrate and inoculum concentrations. Maximum biological degradation is possible while abiotic losses are kept to a minimum thanks to the adaptable nature of bioreactor designs [19].

**1.Ex-situ bioremediation benefits**

* Appropriate for a variety of pollutants.
* Site investigation data can be used to assess suitability in a straightforward manner.
* Because the polluted environment in a bioreactor system is easier to handle, control, and anticipate, biodegradation is more rapid than in solid-phase systems.

**2. Disadvantages**

* Not applicable to chlorinated hydrocarbons like trichloroethylene or contamination with heavy metals.
* Non-permeable soil needs to be processed further.
* Before being added to the bioreactor, the contaminant might be physically or chemically removed from the soil.

B. **In-situ bioremediation methods**

These methods involve treating contaminated materials at the source of the pollution. Chlorinated solvents, heavy metals, dyes, and hydrocarbon-polluted sites have all been successfully treated with in-situ bioremediation approaches [20, 21, 22].

There are two types of in-situ bioremediation: intrinsic and engineered bioremediation.

1.Intrinsic bioremediation

This is an in-situ bioremediation process that involves passive cleanup of polluted places without the need of outside force. The stimulation of the local or is the focus of this approach. The method for degrading resistant contaminating elements that uses activities of both aerobic and anaerobic naturally occurring microbial population.

2.In-situ bioremediation that is engineered

This strategy entails introducing certain microorganisms to the contaminated site. By improving the physicochemical conditions to promote microorganism development, genetically engineered microorganisms utilised in in-situ bioremediation speed up the degradation process. This uses the following methods:

(i) bioventing

In order to improve the activity of local bacteria for bioremediation, bioventing techniques require regulated stimulation of airflow by supplying oxygen to the unsaturated (vadose) zone. In bioventing, modifications are performed by adding moisture and nutrients to boost bioremediation. By doing so, contaminants will be microbially converted to a harmless state. Comparatively to other in-situ bioremediation approaches, this is popular [23].

(ii) Bioslurping

By indirectly supplying oxygen and encouraging pollutant biodegradation, this technology combines vacuum-enhanced pumping, soil vapour extraction, and bioventing to achieve soil and ground water remediation [24]. The recovery of products from capillary, light non-aqueous phase liquid (LNAPL), unsaturated, and saturated zones is the intended use of this technology. This method is used to clean up soil that has been contaminated with organic volatile and semi-volatile substances. The procedure employs a "slurp" that spreads into the free product layer and draws liquids up from it. LNAPLs are lifted to the surface by the pumping device, where they are separated from air and water. According to this method, soil moisture restricts air permeability and slows oxygen transport, which lowers microbial activity. Although this method is not appropriate for remediating low permeable soil, it is a cost-effective operation method due to less groundwater utilization, lower storage, treatment, and disposal expenses.

(iii) Biosparging

Similar to bioventing, this technique involves injecting air beneath the surface of the soil to enhance microbial activity for better bioremediation. In contrast, air is introduced into the saturated zone during bioventing, which may aid in the upward migration of volatile organic molecules to the unsaturated zone and promote the biodegradation process. Two key elements, specifically soil permeability and pollutant biodegradability, determine how effective biosparging is. In the context of bioventing and soil vapour extraction (SVE), in-situ air sparging (IAS), which depends on high air-flow rates for pollutant volatilization, and biosparging, which promotes biodegradation, are closely related operations. Diesel and kerosene-contaminated aquifers have often been treated with biosparging.

(iv) Phytoremediation

The contaminated soils are cleaned up using phytoremediation. This method uses plant interactions, such as physical, chemical, biological, and biochemical ones in contaminated areas to lessen the toxicity of contaminants. There are a number of mechanisms involved in phytoremediation, depending on the type and quantity of the pollutant. These include extraction, degradation, filtering, accumulation, stabilisation, and volatilization. Extraction, transformation, and sequestration are frequently used to remove pollutants including radionuclides and heavy metals. Hydrocarbon and chlorinated organic pollutants are mostly eliminated through degradation, rhizoremediation, stabilisation, and volatilization, with the possibility of mineralization when certain plants, like willow and lucerne, are utilised [25, 26].

A plant's ability to act as a phytoremediator depends on a number of important factors, including its root system, which can be either fibrous or tap-like depending on the depth of the pollutant, above-ground biomass, the toxicity of the pollutant to plants, its existence and ability to adapt to the local environment, its growth rate, site monitoring, and most importantly, the amount of time required to reach the desired level of cleanliness. The plant also needs to be immune to pests and illnesses [27]. Phytoremediation comprises uptake and transfer from roots to shoots. Additionally, transpiration and partitioning are necessary for translocation and accumulation [28]. However, other factors, such as the type of pollutant and plant, may cause the procedure to change. Most of the plants that are present in any contaminated environment are effective phytoremediators. Therefore, enhancing the remediation capabilities of native plants growing in polluted locations through bioaugmentation with endogenous or exogenous plants is crucial to the success of any phytoremediation strategy. The fact that some precious metals can bioaccumulate in specific plants and be retrieved after remediation, a process known as phytomining, is one of the main benefits of employing plants to clean up polluted sites.

v) A reactive barrier that is permeable

This procedure is frequently used as a physical way to clean up contaminated groundwater. Bio-enhanced PRB and passive bioreactive barrier have been also proposed for bioremediation. Generally speaking, PRB is an in-situ method for removing heavy metals and chlorinated compounds from contaminated groundwater [ 29,30].

**In-situ bioremediation benefits**

• Excavation of the polluted soil is not needed using in-situ bioremediation techniques.

• Volumetric treatment is provided by this technique, which can handle both dissolved and solid pollutants.

Why Accelerated in-situ bioremediation can often treat sub-surface contamination more quickly than pump and treat procedures.

• Complete conversion of organic pollutants to harmless elements like carbon dioxide, water, and ethane may be achieved.

• Due to the little site disruption, it is a cost-effective solution.

In-situ bioremediation has limitations.

1.Some toxins might not completely be converted into safe compounds depending on the site.

2.If a compound undergoes transformation and stops at an intermediate, the intermediate may be more hazardous and/or mobile than the parent component; also, some stubborn pollutants are incapable of degrading.

3.When improperly administered, the addition of nutrients, electron donors, and electron acceptor may cause injection wells to become plugged by voluminous microbial growth.

4.Local microorganism activity is inhibited by the concentration of heavy metals and organic substances.

5. Acclimatisation of the microorganisms was typically necessary for in-situ bioremediation, which may not occur for spills and stubborn substances.

**Prospects for bioremediation**

There are several different bioremediation strategies, and many have proven successful in repairing polluted environments. The variety, abundance, and community structure of microorganisms in polluted settings provide insight into the likelihood that any bioremediation strategy will include other environmental elements that can limit microbial activity. Microorganisms play a crucial role in bioremediation. Advanced molecular approaches as genomics, proteomics, metabolomics, and transcriptomics, have aided in the identification of microorganisms and the understanding of their roles in metabolic and catabolic pathways. The availability of nutrients, a lack of or low population of microorganisms with the ability to degrade materials, and the bioavailability of pollutants can all cause a delay in the completion of bioremediation. Biostimulation and bioaugmentation techniques speed up microbial activities in polluted sites since bioremediation rely on microbial processes. A contaminated sample is stimulated by adding nutrients to boost microbial activity. The growth and metabolic activities of naturally present pollutant-degrading microbes in contaminated sites may depend on the type and concentration of pollutants; later, we can use agro-industrial was tes, which contain nitrogen, phosphorus, and potassium as a nutrient source for most polluted sites. Pollutants are reportedly degraded more effectively by microbial consortiums than by isolated isolates [31].

Bioaugmentation has been proven to be an efficient strategy, but it has also been demonstrated to speed up the breakdown of several chemicals. Specific microorganisms can be added as "introduced organisms" to improve the current populations if proper biodegrading microorganisms are not present in the soil or if microbial populations decreased due to contaminant toxicity. However, this method is very uncertain because there is a chance that the inoculated microorganisms may not survive in the new environment. The practise is referred to as bioaugmentation. Using the bioremediation process, sewage or contaminated water or soil is treated using naturally occurring or genetically modified microorganisms with specific metabolic profiles. Some of the issues with bioaugmentation are resolved by the use of alginate, agar, agarose, gelatin, gellan gum, and polyurethane as carrier materials [32].

Chemically speaking, biosurfactants are comparable substances with green and biodegradable characteristics. However, using biosurfactants to a polluted site would be economically unviable due to their high building costs and limited scalability. Combining agricultural and industrial wastes provides nutrients for the growth of biosurfactant producers throughout the fermentation process. The use of various bioremediation strategies will aid in improving remediation effectiveness [33].

A beneficial strategy is to increase bioremediation capacity through systematic use of genetically engineered microorganisms (GEM). This is because it is possible to create a designer biocatalyst that can break down pollutants including resistant substances by combining a new, efficient metabolic pathway with an expanded range of substrates for current pathways and more stable catabolic activity [34].

**Benefits of bioremediation**

• It is a natural process that takes some time but is adequate for treating waste from polluted soil. Reduced biodegradative populations are caused by microbes that can break down the pollutant. Commonly safe treatment byproducts include carbon dioxide, water, and cell biomass.

• It requires very little work and is frequently done on-site, frequently, and without interfering with typical microbial activities. Additionally, this eliminates the need to transfer garbage off-site and any potential risks to the environment and human health.

• It performs in a cost-effective manner when compared to other traditional procedures that are commonly used to treat oil-contaminated locations and clean up toxic hazardous waste. Additionally, it aids in the total breakdown of pollutants; many toxic dangerous substances can be converted into less harmful products and contaminated material can be disposed of.

• No hazardous chemicals are used. Fertilisers, in particular, are provided as nutrients to promote active and quick microbial development. The dangerous compounds are entirely removed as a result of bioremediation, which transforms toxic chemicals into water and innocuous gases.

• Due to their inherent place in the ecosystem, they are easy, less labour-intensive, and inexpensive.

• It functions as an eco-friendly sustainable opportunity and is an efficient method of cleaning up the environment from significant impurities.

**Drawback of bioremediation**

The use of biodegradable substances is prohibited. Not all chemicals undergo an immediate and thorough breakdown process.

• Some of the novel biodegradation products may be more harmful than the original chemicals and remain in the environment.

• The presence of metabolically active microbial populations, optimal environmental growth conditions, and accessibility to nutrients and pollutants are all characteristics of highly particular, environmentally friendly biological processes.

• Promoting the process from bench and pilot-scale to large-scale field operations is difficult. Contaminants can exist in the form of solids, liquids, or gases. It frequently requires more time than other treatment options including excavation, soil removal, or cremation.

• Bioremediation systems that are acceptable for locations with complex combinations of pollutants that are not evenly diffused in the environment must be developed and engineered through research.

**Bioremediation's limitations**

The use of bioremediation is restricted to biodegradable substances. This process is prone to quick and total deterioration. Products of biodegradation may be more harmful or persistent in the environment than the parent chemical.

1. Specificity

The availability of metabolically competent microbial populations, optimal environmental growth conditions and appropriate nutrients and pollutants are key site elements.

2.Technological progress

The diverse pollutants with uneven distribution at site require advance technologies to treat them.

3. Lengthy process

In comparison to alternative treatment options like excavation and soil removal from contaminated sites, bioremediation requires more time.

4. Regulatory ambiguity

Since there isn't a universally agreed-upon definition of clean, we can't state with certainty that remediation is 100% finished. There is no acceptable endpoint for bioremediation treatments as a result, making it impossible to evaluate their effectiveness.

**Conclusion**

When it comes to remediating, cleaning, maintaining, and recovering methods for resolving a polluted environment through microbial activity, biodegradation is a very profitable and alluring alternative. The rivalry between biological agents like fungi, bacteria, and algae as well as unfavourable external abiotic factors (aeration, moisture, pH, and temperature) and limited bioavailability dictate how quickly undesired waste materials degrade. The effectiveness of bioremediation depends on a number of variables, including but not limited to cost, site features, and the kind and quantity of pollutants. Site description is the first step in a successful bioremediation since it aids in the creation of the most effective and promising bioremediation technique (ex-situ or in-situ). Because ex-situ bioremediation methods require excavation and shipment from the archaeological site, they are typically more expensive. They can, however, be utilised to cure a variety of contaminants. Contrarily, in-situ techniques do not incur additional costs for excavation; yet, some inefficient in-situ bioremediation approaches can be reduced by the on-site installation cost of equipment, attached with successfully, and controlling the subsurface of a polluted site. When choosing the most effective bioremediation method to successfully treat polluted sites, geological properties of the polluted site, including soil, pollutant kind and depth, human habitation site, and performance of each bioremediation approach, should be taken into consideration.

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