**Biotechnological Breakthroughs: Paving the Path to Cleaner and More Productive Agriculture through Bioremediation**


## Abstract

In recent years, biotechnological advancements have played a pivotal role in transforming traditional agricultural practices into sustainable and environmentally conscious systems. This article explores the revolutionary concept of bioremediation and its potential to address soil pollution, enhance crop productivity, and mitigate the environmental impact of conventional farming methods. Bioremediation involves harnessing the power of microorganisms, plants, or enzymes to detoxify or remove pollutants from soil, presenting a promising solution to the challenges posed by agrochemicals and industrial waste. The first section of this abstract delves into the current state of agriculture, highlighting the widespread use of chemical fertilizers, pesticides, and herbicides, which has led to soil degradation, water contamination, and loss of biodiversity. These issues necessitate a paradigm shift towards sustainable agricultural practices that prioritize soil health and ecosystem balance. The second section explores the fundamental principles of bioremediation, emphasizing its versatility in addressing a wide range of pollutants, including heavy metals, pesticides, and organic contaminants. Through the use of genetically engineered microorganisms or naturally occurring plant-microbe partnerships, bioremediation offers a targeted and eco-friendly approach to soil restoration. Moving forward, the abstract examines specific biotechnological breakthroughs that have propelled the field of bioremediation. From the development of genetically modified crops with enhanced phytoremediation capabilities to the use of engineered microbes for efficient pollutant degradation, these innovations showcase the potential of biotechnology in revolutionizing agriculture. Furthermore, the abstract explores the economic and environmental benefits associated with the adoption of bioremediation techniques in agriculture. By reducing the reliance on synthetic chemicals, farmers can lower production costs, while simultaneously preserving soil fertility and safeguarding water resources. The potential for increased crop yields and improved food quality further underscores the positive impact of bioremediation on agricultural productivity.



Keywords: innovation, development, biotechnology, environment, synthetic


## Introduction

Environmental contamination of the soil is a worldwide problem that may be traced back to both natural and human-caused causes. As a result of urbanization, industrialization, and a growth in the need for food, a wide variety of chemicals, substances, and chemical agents have been utilized, which has resulted in the dispersion and build-up of pollutants in the environment [1]. Heavier metals, polycyclic aromatic hydrocarbons (PAHs), and pesticides are examples of common contaminants that may be found in terrestrial environments. To eradicate pests, weaken them, incapacitate them, and ultimately kill them, chemical substances known as pesticides are utilized. Insecticides, herbicides, rodenticides, bactericides, fungicides, and larvicides are some of the categories that might be taken into consideration while classifying these substances[2].

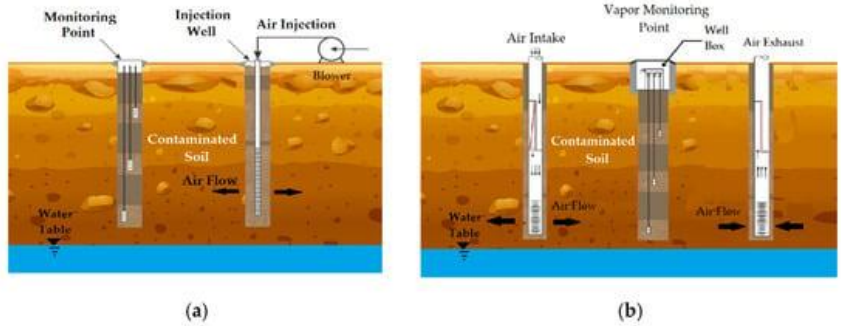


fig 1 Environmental contamination of the soil

Herbicides, insecticides, and fungicides were all examples of applications for plant extracts that were utilized during the 19th and 20th centuries. Inorganic chemicals like arsenic and sulfur compounds were used for crop protection throughout the 1930s, which coincided with the rise of synthetic chemistry, which led to an increase in the usage of pesticides[3]. Following World War II, a large number of pesticides, mostly organic compounds, were manufactured. These pesticides included dichlorodiphenyltrichloroethane



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(DDT), aldrin, and dieldrin, which were utilized for the purpose of controlling insects. On the other hand, 2-methyl-4-chlorophenoxyacetic acid (MCPA) and 2,4-dichlorophenoxyacetic acid (2,4-D) were utilized for the purpose of controlling herbicides[4].

There have been registered amounts of pesticides used by every country in the globe from 1990 to 2018, with the majority of these amounts being registered in Asia and the United States. In the year 2018, the global average quantity has grown from 1.55 kg·ha−1 in the year 1990 to 2.63 kg·ha−1 in the year 2018. The usage of fungicides and bactericides is far higher than that of the other types of pesticides, and several nations all over the world have placed directives in place to minimize the amount of pesticides that are used[5].

A reduction in the concentration of residual pesticides in the soil is required, and remediation strategies that are successful must be used. Bioremediation is a process that incorporates the microbiological activity of microorganisms to convert pesticides into less complex chemicals, carbon dioxide, water, oxides, or mineral salts[6]. These compounds may then be utilized as sources of carbon, minerals, and energy. Bioremediation is an environmentally benign, cost-effective, and cost-efficient method. Acting as catalysts, enzymes are an essential component in the processes that are taking place[7].

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The biodegradation of pesticides can take place in either aerobic or anaerobic circumstances, depending on the characteristics of the microorganisms involved. There are a number of different methods available for this process. In situ, ex situ, and on-site bioremediation are the three categories that may be used to classify the various bioremediation procedures[8]. In situ procedures entail the treatment of the contaminated zone itself, whereas ex situ methods require the removal of contaminated soil from polluted areas and its transportation to other locations for the purpose of it being treated. On-site techniques of treating contaminated soil on the surrounding site do not have any influence on the environment as a result of its transportation[9].

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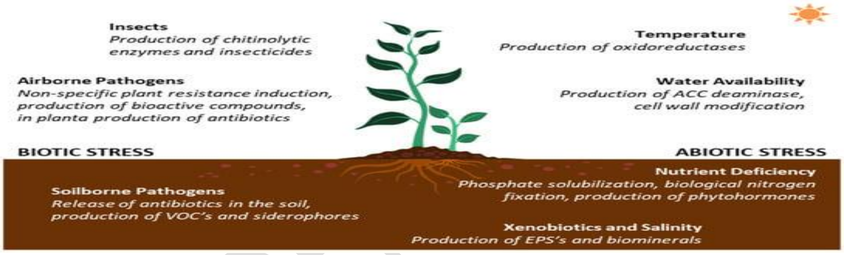

Fig 2 : Biotic stress

A number of parameters, including soil type, pH, moisture content, aeration, relative composition of soil elements, climatic circumstances, and interactions between microorganisms, all have a role in determining the composition of microbial communities in soils. Fungi, bacteria, and actinobacteria that have been sporulated are resistant to drought[10]. The aerial spores of the majority of actinobacteria genera are resistant to desiccation and exhibit a somewhat higher resilience to dry heat in comparison to Gram-negative bacteria. When it comes to the passive heat resistance of bacterial spores and osmotic stressors, the elevated osmotic pressure that occurs as a result of the low water activity (aw) of spores is of special significance. Bacterial cells are able to acquire osmotic signals and either absorb or manufacture suitable solutes when they are subjected to saline stress[11]. This allows them to keep their internal osmotic pressure equivalent to the external pressure, therefore preventing permanent damage. In addition to implying a rapid response to osmotic stress, these activities govern the degree of transcription of osmoprotective transport[12].

## Kind of Chemicals and pesticides disturbing soil ecosystems

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Depending on their origin, chemical composition, mechanism of action, and level of toxicity, pesticides can be categorized into several categories. In contrast to biopesticides, which are natural molecules that are used to control pests through benign methods, chemical pesticides are organic compounds that may be produced either naturally or through chemical synthesis[13].

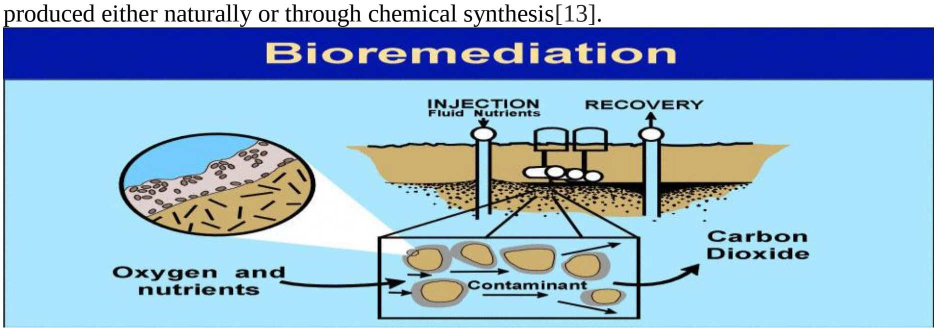


Fig 3 :Bioremediation process

Organochlorines, organophosphates, carbamates, and pyrethrins and pyrethroids are the four primary categories of pesticides. Organochlorines are the most common one. Organochlorines are organic compounds that are bonded with at least one atom of chlorine that is covalently attached[14]. Agriculture makes extensive use of organochlorines for the purpose of controlling insects. As a result of their lipophilic nature and the difficulty in breaking them down, they have a high level of persistence in the environment. They have the potential to cause harm to living organisms, including mutagenesis effects, histopathological effects, enzyme-inducing and/or enzyme-inhibiting effects, carcinogenicity, and teratogenicity[15].

Organophosphates, often known as OPs, are a kind of synthetic pesticide that can include phosphoric acid esters or thiophosphoric acid esters. Their ability to block acetylcholinesterase (AChE) in both the central and peripheral nerve systems makes them extremely hazardous to insects and other animals[16]. This is the reason for their acute toxicity. As a result of this inhibition, muscarinic and nicotinic effects are brought about. These effects include coughing, expectoration of frothy secretions, chest tightness, wheezing, pulmonary edema, hypersalivation, nausea, vomiting, abdominal cramps, diarrhea, tenesmus, eye, miosis, blurred vision, eye pain, profuse sweating, fasciculation, progressive flaccidity, and weakness of proximal muscle groups[17].

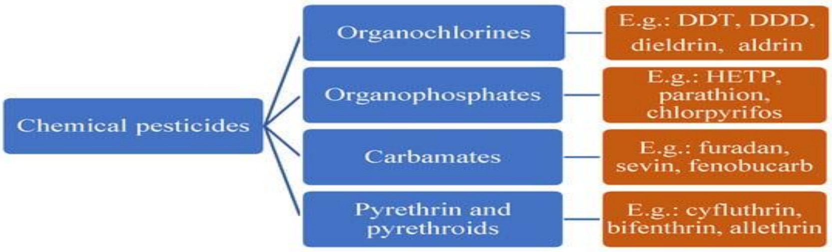


fig 4 : Chemical pesticides

Among the chemicals that are produced from carbamic acid, carbamates are those that have an amino group coupled with an ester group. They are utilized as biocides for the purpose of controlling pests in both industrial and domestic items. Aldicarb, carbofuran, fenoxycarb, carbaryl, ethienocarb, and fenobucarb are all examples of common pesticides that are classified as carbamates[18]. In humans, the chance of developing non-Hodgkin's lymphoma is increased when they are exposed to carbamate pesticides. This is because these pesticides suppress and induce apoptosis in human natural killer (NK) cells and cytotoxic T lymphocytes, which are cells that give defense against cancers[19].

Tanacetumcinerariaefoliumflowers are the source of the active ingredients that are used in the production of pyrethrins and pyrethroids, which are natural insecticides. Chrysanthemic acid, also known as 2,2-dimethyl-3-(2-methyl-l-propenyl)-l-cyclopropan acid, and pyrethric acid, also known as 3-(2-methoxycarbonyl-l-propenyl)-2,2-dimethyl-l-cy acid, are the two acids that are the esters of pyrethrins[20]. Changing the chrysanthemic acid moiety of pyrethrin I and esterifying the alcohols are the two steps that are required to produce pyrethroids, which are synthetic chemicals. First-generation pyrethroids and

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second-generation pyrethroids are the two categories that may be used to classify them[21].

As a result of their ability to disrupt sodium channels in the axons, pyrethrins and pyrethroids cause damage to the nervous system. While they are poisonous to insects, they pose a lower risk to human health. The inhalation of dust or aerosol droplets can cause respiratory symptoms such as coughing or irritation of the upper respiratory tract. Additionally, exposure to these pesticides can cause neurological effects such as headaches or dizziness, gastrointestinal effects such as nausea and vomiting, and irritation and/or skin effects. It is possible that pyrethroids will induce cardiovascular issues[22].

Pesticides that are obtained from natural sources, such as animals, plants, microbes, and minerals, are sometimes referred to as biopesticides. Microbiological pesticides, plant-incorporated protectants (PIPs), and biochemical pesticides are the three primary categories that may be used to classify them. Pesticides that are biochemicals are natural molecules that are used to control pests through methods that are not poisonous. Chemical molecules that are released by plants or animals are known as semiochemicals. Some examples of semiochemicals include pheromones, allomones, kairomones, and attractants. In the event that the pest consumes the plants, plant-incorporated protectants, also known as PIPs, can be created by the plants themselves. It is possible to genetically modify plants in order to compel their production by adding the gene that acts on a particular pesticidal protein into the genetic material of the plant itself[23].

Microbial pesticides are a type of pesticide that are composed of live organisms that suppress pests. These species include bacteria, fungus, algae, and viruses. They control pests by either creating poisonous metabolites that cause damage and infections or by blocking the development of other bacteria. Both of these methods help to eliminate pests. It is possible to categorize pesticides according to the functions they play and the kinds of bugs they kill[24].

There are a variety of chemical and biological substances that are classified as insecticides. One example of an insecticide is a larvicide, which is designed to destroy the larval stage of an insect's life cycle. Agriculture, horticulture, forestry, and gardening are among areas that make use of them. Additionally, they are utilized in the control of vectors such as mosquitoes and ticks, which are responsible for the transmission of illnesses such as dengue and malaria to both humans and animals. The categories of organophosphates, pyrethroids, and carbamates are the ones that are most commonly employed to control insect populations[25].

In order to enhance crop output, herbicides are typically administered to agricultural soils either before or during farming. Their primary purpose is to control and eradicate plants and weeds that are not desired. Rodenticides are substances that are used to eliminate rodents, which include rats, mice, squirrels, and nutria. These rodents are known to cause damage to crops, spread illness, and create ecological harm[26]. Fungicides are substances that are capable of eliminating parasitic fungus or their spores, thereby enabling the management of fungal infestations, particularly those that take place throughout the whole food supply. Enzymes and proteins that are involved in lipid metabolism, fungal respiration, and the synthesis of adenosine triphosphate (ATP) are inhibited by fungicides, which interfere with a variety of metabolic processes that occur inside the cytoplasm and mitochondria of the fungal cell[27].

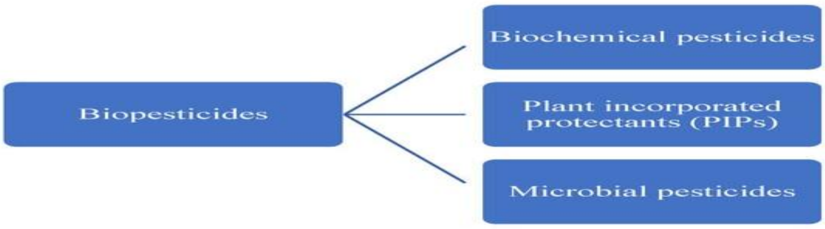


**Fig 5 :Biopesticides**

**Toxicology**

However, despite the fact that pesticides are indispensable instruments for avoiding, eliminating, and managing dangerous pests, they also have the potential to cause severe dangers to both human and environmental health. Pesticides have been categorized by the World Health Organization according to their level of toxicity and the harmful impact they have on human health[28]. Despite the fact that many pesticides have been prohibited in certain nations owing to the high level of toxicity they possess, their manufacturing and usage are nevertheless prevalent, particularly in developing nations. It is possible for pesticides to bioaccumulate and pollute the food chain, which can have negative effects on both human health and the ecosystem as a whole[29]. Pesticides are persistent in the environment. There are three categories that may be used to categorize them: nonpersistent pesticides (t1/2), moderately persistent pesticides (t1/2 between 30 and 100 days), and persistent pesticides (t1/2 greater than 100 days). Once they are present in the soil, pesticides have the potential to be absorbed by the particles of the soil, destroyed through processes that include photochemistry, chemistry, and microbiology, or transferred from the soil to the water[30].

Adsorption isotherms allow for the physical or chemical adsorption of pesticide molecules onto soil particles. The adsorption process is influenced by soil factors such as the amount of organic matter present, the amount of clay present, the mineralogy of clay, and the pH of the soil. Photographic deterioration, chemical and biological degradation, and leaching from soil to water are all processes that are involved in the degradation process[31].

For example, organochlorines, organophosphates, carbamates, pyrethroids, and pyrethrins are all examples of pesticides that are toxic and can cause damage both in the short term and over the long term. Organochlorines cause harm to the neurological systems by modifying ion channels, which results in hyperexcitability of the brain, convulsions, tremor, hyperreflexia, and ataxia. Organophosphates are acetylcholinesterase inhibitors that cause large quantities of acetylcholine to be produced[32]. This results in harm being caused to a variety of organs, including the brain, muscles, liver, pancreas, and peripheral and central nervous systems. Acute intoxication is brought on by high dosages of organophosphate, which ultimately results in pancreatitis. Pancreatitis is brought on by high levels of cholinergic overstimulation brought on by AChE inhibition. Seizure disorders are a potential consequence of organophosphate exposure over an extended period of time[33].

The LD50 values indicate that exposure to carbamates is moderate to slightly harmful. As a result, carbamates are moderately and mildly hazardous. Through their role as acetylcholinesterase inhibitors and endocrine disruptors, they are responsible for the development of respiratory disorders, as well as harm to the hippocampus and fetal and infant development[34]. Ethyl carbamate is a chemical that is known to cause cancer in a variety of animal species, although it is only rarely shown to cause cancer in humans. Pyrethrins and pyrethroids are less harmful to mammalian cells and less persistent in the environment than other pesticides; yet, they are still capable of causing harm to human health, particularly to the nervous system[35].

Pyrethrins and pyrethroids are less harmful to mammalian cells and less persistent in the environment than other pesticides; yet, they are still capable of causing harm to human health, particularly to the nervous system. These pesticides have the potential to induce a wide range of adverse effects, including those that are systemic, immunological, neurological, reproductive, developmental, genotoxic, and carcinogenic, as well as mortality[36]. Exposure to these pesticides causes harm to the neurobehavioral functioning of fetuses and children since their nervous systems and brains are still in the process of developing and growing and so cannot be fully developed. In the adult population, it has been discovered that there is a connection between the exposure to pyrethroids and an increased risk of developing diabetes[37].

**Pesticide removal from soil**

Through the use of biodegradation processes, which entail microorganisms employing pesticides as cosubstrates in their metabolic activities, bioremediation is a strategy that minimizes the amount of pesticide contamination that is present in agricultural soils. The features of pesticides, such as their dispersion, bioavailability, and persistence in soil, are important factors that determine the effectiveness of these treatments[38]. Because of the limited water solubility of pesticides and the fact that they adhere to soil particles, it is important to boost their availability in order to increase the availability of pesticides to microorganisms[39].

The breakdown of pesticides may be broken down into three distinct steps, which are as follows: The first phase involves the transformation of pesticides into products that are more water-soluble and less toxic through the use of oxidation, reduction, or hydrolysis reactions. The second phase involves the conversion of products from the first phase into sugars and amino acids that have a higher water solubility and a lower toxicity. The third phase involves the conversion of metabolites from the second phase into secondary conjugates that are less toxic[40].

One other essential component of bioremediation is microbial degradation, which involves the utilization of a number of bacterial strains that are capable of digesting pesticides that are present in soils. Because of the uniqueness that each bacteria possesses, it is particularly well-suited for a process that involves degradation. Furthermore, during the process of degradation, metabolites can be produced, which might result in further environmental issues. This is because it may be more challenging to remove metabolites than it was to remove the original component[41].

In many instances, the degrading process is simpler when a bacterial consortium is utilized as opposed to the utilization of a pure culture that has been isolated. Bacteria cohabit and are dependent on one another for their continued existence. Furthermore, each bacterium has the potential to produce metabolites that may be utilized by other bacteria as a substrate. When it comes to treating pesticide pollution in agricultural soils, bioremediation is an approach that is not only successful but also economical and considerate to the surrounding environment[42].

The biodegradation of pesticides in agricultural soils can be accomplished by the utilization of a process known as fungal degradation. By producing a large number of enzymes that are engaged in degradative processes, fungi are able to promote their own breakdown. These enzymes can also have an effect on the characteristics of the soil and its capacity to exchange ions[43]. By virtue of their unique bioactivity, growth morphology, and great resilience even when exposed to high concentrations of contaminants, fungi are superior than bacteria in terms of their ability to breakdown substances. It is standard practice to employ both fungus and bacteria in order to accelerate degradation. This is due to the fact that fungi have the ability to convert pesticides into a form that bacteria can more easily and readily consume[44].

It is the enzymes that are created during the metabolic processes of microbes or plants that are responsible for enzymatic biodegradation when it occurs. There are biological macromolecules known as enzymes that have the ability to catalyze biochemical events that are involved in the breakdown of pesticides. Oxidation, hydrolysis, reduction, and conjugation are the primary metabolic processes that take place[45]. Enzymes such as oxygenases and laccases are engaged in the process of oxidation, which includes the transfer of an electron from reductants to oxidants. The breaking of bonds in the substrate is made possible by hydrolysis, which involves the addition of hydrogen or hydroxyl groups from water molecules. This results in the division of pesticide molecules into smaller chain compounds[46].

Reduction makes it possible for reductive enzymes, also known as nitroreductases, to carry out the change. Fungal biodegradation is characterized by conjugation, which is carried out with the help of enzymes that are already present[47]. The process of mineralization makes it possible for pesticides to be broken down into inorganic substances, such as carbon dioxide, salts, minerals, and water. The pesticide chemicals serve as a source of nutrition for the microorganisms that consume them. The pace of mineralization is dependent on the concentration of the microbial community, and a reduction in the number of microorganisms does not enhance deterioration[48].

There is a relationship between the characteristics of the soil and the mineralization process in glyphosate mineralization. According to the criteria that have an effect on the mineralization of glyphosate include the cation exchange capacity, the exchangeable base cations, and the type of potassium that is readily accessible[49]. It is possible that the creation of strong chemical interactions with carboxylic or phosphoric acid groups of the glyphosate itself, a reduction in its bioavailability, or the toxic effects of exchangeable aluminium on soil microorganisms are the reasons for the low mineralization of glyphosate in soils that have a high exchangeable acidity[50].

Enzymes such as hydrolytic enzymes, transferases, oxidases, and reductases are engaged in the process of co-metabolism, which is the biotransformation of an organic substance through a sequence of processes. A co-metabolic transformation of imidacloprid (IMI), an insecticide. The researchers tested several substrates that were employed as sources of energy[51].

Techniques for microbial remediation can be implemented either on-site, in-situ, or beyond the site itself. It is possible to remediate the polluted zone using in situ procedures, which entail the use of aerobic processes that supply oxygen to the soil. Natural attenuation, bio stimulation, bio augmentation, bioventing, and biosparging are the primary strategies that are utilized directly in the environment. Due to the fact that they do not involve the movement of the polluted soil, these approaches are both efficient and economical[52].

The removal of contaminated soil from polluted locations and its subsequent transportation to the clean-up site is an example of an ex situ method implementation. The use of bioreactors, composting, land farming, and bioreactors are all examples of techniques. For example, land farming treatment is an example of an on-site approach that involves extracting and treating the soil that is located close to the contaminated location. When it comes to achieving optimum removal effectiveness, it is essential to maintain control over nutrients, oxygen, pH, water content, and temperature[53].

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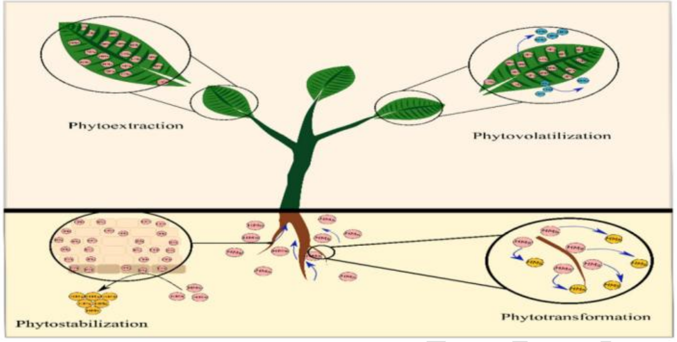

fig 6 : Phytoextraction and phytostabilization

The breakdown of contaminants by native microorganisms that are present in the soil is an example of natural attenuation. The biological degradation, volatilization, dispersion, dilution, radioactive decay, and sorption of pollutants onto organic matter and clay minerals are all components of this process[54]. The process of biostimulation involves the addition of nutrients (nitrogen, phosphorus, carbon, and oxygen) in order to encourage the development of microorganisms that are native to the area. In order to promote biodegradation and an increase in the variety of microbial species, nitrogen and phosphorus are introduced into the mixture[55].

Through the process of bioaugmentation, microbial consortia or single strains are introduced into the soil, which results in an increase in the variety of microorganisms. One of the parameters that determines the process is the concentration of pesticides in the soils. This is because large concentrations of pesticides impede the essential functions of the microorganisms that live in the soil[56]. The degradation of aldrin can be accomplished in a very short amount of time by bacteria strains that possess certain genes (cytochrome P450), according to studies. For the purpose of developing the subsequent experimental tests, the selection of certain bacteria and the optimization of soil conditions, including temperature, pH, and nutrients, are utilized[57].

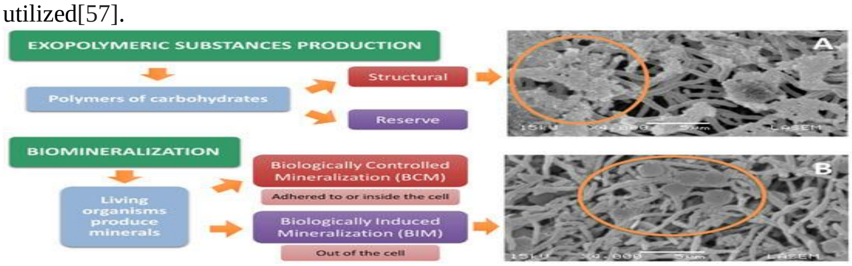

Fig 7 :Exopolymeric substances production

As a result of leaching into the subsurface of the soil and adsorbing on soil particles, pesticide concentrations can vary at different depths in contaminated soil. This is because both processes contribute to the pesticides being less bioavailable. A research conducted by Odukkathil and Vasudevan revealed that the concentrations of pesticides in the bottom soil were high[58]. This was attributed to the downward drift of pesticides that occurred during water seepage. On the other hand, the low concentrations in the centre soil might be attributed to increased microbial activity that favours breakdown. The conclusion is that bioremediation techniques may be implemented in a variety of ways, including on-site, ex-site, and in-situ procedures. For the purpose of achieving maximum removal efficiency, it is vital to exercise control over the nutrients, oxygen, pH, water content, and temperature[59].

The biodegradation of pesticides through natural attenuation, biostimulation, and bioaugmentation techniques has been the subject of a number of research that have been carried out in order to measure and compare their effectiveness. The biodegradation of atrazine using three distinct methods, and they discovered that the natural process was significantly slower[60]. On the other hand, after 35 days, the atrazine was entirely eliminated with the use of biostimulation and bioaugmentation therapy. When bioaugmentation and biostimulation treatments are combined, it is possible that the bioremediation of polluted soils will be more effective. For the purpose of proving that the removal of lindane can be increased and the half-life of pesticide may be shortened by concurrently utilizing bioaugmentation and biostimulation, Raimondo et al. [98] conducted a study in which they examined 1 kilogram of mesocosms that were polluted with lindane at a concentration equivalent to 2 milligrams per kilogram of soil[61].

In situ bioremediation, also known as bioventing, is a process that encourages the breakdown of organic contaminants that have been adsorbed to the soil. Microbial activity is increased when air or oxygen flow and nutrients are introduced into the unsaturated zone of soil through wells that have been deliberately built into polluted soils. This allows for the entry of nutrients and air into the soil. Remediation by bioventing can take anywhere from six months to five years to complete, depending on the kind and quantity of the pollutant, the pace of biodegradation, and the features of the soil, such as its permeability and the amount of water it contains[62].

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Biosparging is an additional method of biodegradation that involves the infusion of air into groundwater in order to raise the concentration of oxygen. This method is used to encourage the microorganisms that are native to the area. The process is comparable to bioventing, but instead of injecting air into the saturated zone, it injects air into the unsaturated zone to provoke the upward migration of volatile organic molecules, which in turn promotes biodegradation[63]. One of the characteristics that impacts the success of the process is the permeability of the soil, which is the factor that determines the bioavailability of pollutants to microorganisms. The other criterion is the biodegradability of the pollutants[64].

Composting is a method for the bioremediation of pesticides. This method involves combining the contaminated soil with organic amendments that are not hazardous in order to encourage the growth of a population of bacteria and/or fungus that are capable of decomposing the pesticides through a co-metabolic pathway. The microbial bioaccessibility to the pollutant is of the utmost importance in the process of composting. Additionally, it is essential to exercise control over the water content, soil composition, and qualities of the amendment that is being added[65].

The degradation processes in polluted soils can be accelerated by the addition of biochar, which can be utilized as an amendment. The thermal conversion of biomass under circumstances of low oxygen (gasification) or in the absence of oxygen (pyrolysis) results in the production of biochar, which is a form of black carbon[66]. The material is distinguished by its high porosity and broad surface area, both of which encourage the adsorption of pesticides and stimulate the activity of microorganisms, hence facilitating the process of biodegradation[67].

In order to create a slurry with aqueous suspensions ranging from 10% to 30% water-volume-to-volume ratio, slurry bioreactors consist of piles of contaminated soil that have been combined with wastewater. It is possible for the bioreactor to function in either anaerobic or aerobic conditions. The anaerobic biodegradation of organochlorine pesticides. They discovered that low temperatures lowered the removal rates of pesticides. This was due to the reduction in the desorption rates of slowly desorbing components of these pollutants[68].

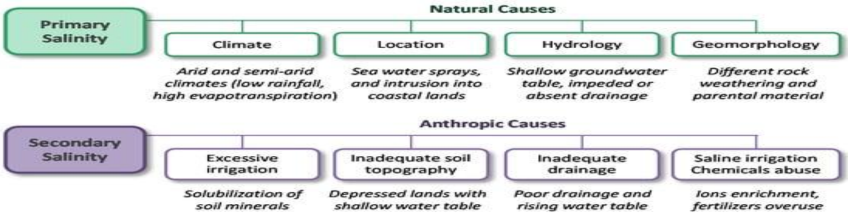


Chart 1 :Natural coauses of salinity

**Streptomyces in remediation**

Bioremediation is the process of removing, reducing, or transforming pollutants into species that are less detrimental to the environment through the utilization of organisms and the metabolic processes that they engage in. There are a multitude of benefits associated with microorganisms, such as their extensive distribution on the biosphere, their remarkable metabolic capacity, their nutritional flexibility, and their capacity to reproduce in a variety of environmental situations. They are also equipped with procedures that are commonly recognized, have a modest level of technology, and are reasonably inexpensive. These techniques may be carried out on-site[69].

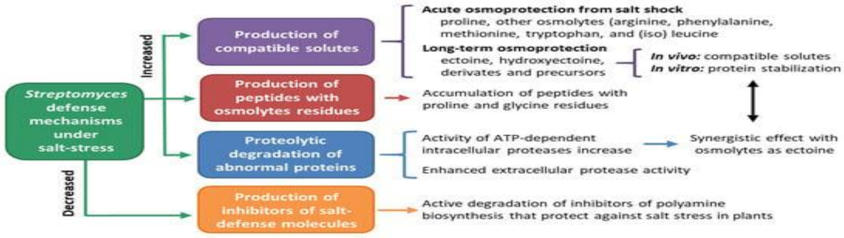


chart 2 : Streptomyces in remediation

Bioremediation that is mediated by Streptomyces has grown more essential over the course of the past 15 years (2004–2019), particularly in the case of hydrocarbons, organochlorine chemicals that are utilized in agriculture, heavy metals, and settings that include naturally high concentrations of salt or hazardous substances like as boron[70]. Excreting toxic components through intracellular and extracellular transport systems, generating sequestering compounds to bind and eliminate toxic agents, and excreting extracellular chelating compounds to immobilize or solubilize toxic substances are all examples of microbial mechanisms that are utilized in the process of bioremediation[71].

The process by which living creatures make minerals is referred to as biomineralization. Streptomyces is the second most significant group of organisms that produce a wide range of various minerals. The process of biomineralization can take place through two different methods: physiologically controlled mineralization (BCM) and biologically induced mineralization (BIM)[72]. Passive methods entail the contribution of crystallization nuclei that function as "seeds" for precipitation initiation, whereas active mechanisms involve the capture or excretion of certain metabolites. Active mechanisms are characterized by certain characteristics[73].

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In the field of bioremediation, one more technique that has a significant amount of relevance is the creation of exopolymeric substances (EPS) by bacteria. These chemicals are utilized by microorganisms in order to eliminate toxins from the environment. Exopolysaccharides are a kind of carbohydrate polymer that exhibits a wide range of structural variations in accordance with the many activities they provide[74]. The composition of structural extracellular polysaccharides (EPS), which include cellulose, is dependent on the microbe and the environmental circumstances that are favorable to its growth. These EPS are responsible for the interactions that occur between cells and their cells with the surface[75].

In the group of actinomycetes, Amycolatopsis sp. AB0 stands out due to its capacity to manufacture an EPS in the presence of copper. On the other hand, the actinomycetes known as "Salar del Hombre Muerto" have the ability to make an EPS when lithium is present. Recently, strains of Streptomyces spp. that were found in a natural environment that included a high concentration of boron have been shown to create an extracellular polymeric substance (EPS) that enables them to endure and thrive in these environmental circumstances[76].

In order to investigate the possibility of using salt-tolerant bacteria, such as halophilicStreptomyces, for the bioreclamation of salt-affected soils, research is now being conducted. It has been shown that these bacteria are capable of producing a wide variety of metabolites, such as enzymes, biosurfactants, and antibiotic proteins. Additionally, they are utilized in the process of biodegradation and bioremediation of hydrocarbons in settings saturated with salt[77].

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In order to withstand and survive saltwater stress, bacteria that are salt-tolerant employ a variety of strategies. These processes include the production or absorption of organic compatible solutes in order to maintain a balance in the osmotic potential. Ectoine, alanine, glutamine, and proline are some of the metabolites that are used for the purpose of providing acute osmoprotection as well as long-term protection against stress. Arginine, phenylalanine, methionine, tryprophan, and (iso) leucine are some of the other amino acids that have the potential to act as osmoprotectants[78].

An additional stress response is observed in relation to aberrant and denatured proteins that have accumulated as a result of harsh living situations. It is common for these proteins to be easily broken down by the process of ATP-dependent proteolytic degradation. Lon and Clp serine proteases are two families of ATP-dependent intracellular proteases that have been well studied compared to one another[79]. During the process of growth under salt stress, different strains of Streptomyces create a variety of PGP compounds. These chemicals include the formation of siderophores, the solubilization of tricalcium phosphate, and increased concentrations of nitrogen, phosphorus, iron, and manganese in plants. There is a correlation between these beneficial substances and considerable increases in the amount of chlorophyll content, the number of lateral roots, and the biomass of the plant[80].

**Comment [P14]:** what?

**Comment [P15]:** italics

**Comment [P16]:** write in full

Antimicrobial activity of soil-isolated actinomycetes have been evaluated under a variety of pH and salinity settings. The results of these tests have demonstrated the synthesis of antimicrobial compounds against a variety of bacteria, filamentous fungus, and yeasts. Secondary metabolites with antifungal and antibacterial activity are produced by Streptomyces that have been identified from saline soils[81]. These metabolites are effective against illnesses that cause root rot and have the potential to be used as a biocontrol agent for Fusarium wilt in chickpea populations. When it comes to the production of chemicals that have antibacterial or antifungal action, the species Streptomyces has the highest capable capability[82].

**Comment [P17]:** italics

**Comment [P18]:** italics

There is also the possibility of using Streptomyces as a biofertilizer in salty soils through the process of phytostimulation. The physiology of plants is altered as a result of the synthesis of phytohormones, which enables plants to deal with abiotic challenges such as salt and drought. Moreover, rhizobacteria are responsible for the production of volatile compounds, which control genes involved in sodium-ion homeostasis and shield plants from the effects of salt damage[83].

**Comment [P19]:** italics

All of these PGP features enhanced the germination rate, the number of roots, the uniformity, the shoot length, and the dry weight of the various crops. Additionally, they raised the concentration of nutrients in the various crops, demonstrating that Streptomyces has the potential to be used as a biofertilizer in soils composed of salt[84].

**Bioaugmentation**

Gasoline, which is often referred to as petrol, is a liquid that is formed from petroleum and is clear. Its primary function is to serve as fuel for internal combustion engines. With the addition of a number of different additives, it is made up of organic compounds that are produced by the fractional distillation of petroleum[85]. Small chain alkanes with carbon six to carbon ten and low boiling points of sixty to seventy degrees Celsius are the compounds that correspond to these chemicals. Iso-pentane, 2, 3-dimethyl butane, n-butane, and n-pentane are some of the volatile aromatic chemicals that fall into this category. Other examples include mono-aromatic hydrocarbons like benzene, toluene, ethylbenzene, and xylene[86].

A major influence on the environment is caused by gasoline, and this impact is seen both locally and worldwide. A number of different methods, including as liquid, vapors, leaks or inadvertent discharges during manufacture, transportation, distribution, and storage tanks, are the ways in which it enters the environment without experiencing combustion. In addition to the polynuclear aromatic hydrocarbons (PAHs), it has been discovered that gasoline is carcinogenic and has the potential to cause human ailments such as skin irritations and burns when it is exposed to the environment[87].

Because of the fact that soil pollution caused by hydrocarbons and their derivatives has become an inescapable occurrence on the environment, the effectiveness of conventional techniques of cleaning up and remediating the environment, such as incineration and land farming, has been called into severe question. Traditional techniques of cleaning are typically inefficient in terms of cost and harmful to the environment[88]. In addition, gasoline is extremely combustible, and technologies for cleaning up contaminated surroundings that include cremation or other conventional methods are typically not suggested in places that are close to residential neighborhoods[89].

When it comes to responding to oil and hydrocarbon spills, bioremediation has been seen as a more dependable choice. In order to cope with hydrocarbon pollutants, it makes advantage of the metabolic potentials associated with certain microbes. In the field of bioremediation, there are three primary approaches that have been utilized: bioaugmentation, which involves the use of allochthonous microbial strains or genetically engineered microbes; biostimulation, which involves the addition of nutrients or electron acceptors; and remediation through enhanced natural attenuation, which refers to the natural capacity of the soil's microorganisms. It has been demonstrated by a great number of researchers that bioaugmentation is the most effective method[90].

In this study, the effectiveness of bioremediation of gasoline-polluted soil is evaluated by employing a combined consortium consisting of Micrococcus luteus (AJ536198) and Rhizopusarrhizus (JN942919). Additionally, the study investigates the degradation performances of individual microbial species and models the TPH biodegradation through the use of linear kinetic modelling [91].

It was discovered that the population of total heterotrophic microorganisms was higher than the population of gasoline hydrocarbon utilizers. This finding suggests that in the event of a fresh hydrocarbon spill, a large number of microorganisms would be present in the polluted media, but only a small number of these microorganisms would have the metabolic ability to use the hydrocarbon as their sole source of carbon[92].

According to the findings of this study, bioaugmentation leads to the efficient elimination of contaminants and the efficient recovery of the biological activity of soil during a period of two months of incubation. In addition, the research suggests that bioaugmentation that involves fungal species is frequently accompanied by a low pH state throughout the course of the bioremediation investigations. The rate of biodegradation was high in the microbial consortia, and it was considerably different from the control in the location where the spill would be cleaned up[93].

**Case study on Mexico for using waste water through bioremediation**

On a worldwide and national scale, the demand for irrigation water and the quality of that water are key concerns that cause disputes. These conflicts are caused by the restricted supply of drinking water and the improper management of wastewater, which in turn leads to economic, social, and environmental challenges. The amount of wastewater that was discharged from industrial facilities in Mexico grew from 170 to 188.7 m3 s-1 between the years 1998 and 2007, while the amount of wastewater that was generated from urban areas went from 239 to 243 m3 s-1[94]. The amount of wastewater that was treated over those years was only 25.3% of the total volume that was produced. Seventy-seven percent of all water is utilized in agriculture; however, fifteen percent of all aquifers are already being overexploited, which indicates that the first-use water in this industry must be replaced by wastewater that has been treated[95].

The utilization of wastewater for crop irrigation can result in economic advantages. These benefits include the utilization of the nitrogen and phosphorus that are present in wastewater, the provision of a source of nutrients for plants, the reduction of the amount of fertilizers used, and the promotion of local food production[96]. An annual amount of wastewater utilized for irrigation in the Valle del Mezquital (Hidalgo) region of Mexico ranges between 10,000 and 20,000 cubic meters per hectare, with concentrations ranging from 20 to 40 milligrams of nitrogen per liter. This quantity is sufficient to meet the nitrogen requirements of some crops and represents an investment of between $335.00 and $11340.00 kg N ha-1 over the course of the year[97].

On the other hand, wastewater not only includes nutrients, but it also contains biological and chemical toxins, such as heavy metals, which may be harmful to human health. According to the official guidelines that were set by SEMARNAT, the utilization of wastewater is defined in accordance with the sector or infrastructure that benefits from it. For example, urban usage (irrigation of green spaces, golf courses) fall under this category. The sort of treatment that wastewater undergoes in order to be utilized for the irrigation of particular crops is contingent upon the type of treatment that is being utilized[98]. There are a number of procedures involved in the treatment of wastewater, which are aimed at recovering polluted water and reusing it. Because wastewater treatment eliminates certain pollutants, but not all of them, and many of them are hazardous, such as heavy metals, which may be absorbed into the food web, causing direct or indirect harms to human health, the discharge of treated water has consequences on soil and water bodies. These effects are caused by the fact that wastewater treatment removes harmful contaminants[99].

Comment [P20]: full meaning

Novel approaches to the treatment of wastewater have been developed, with the objective of enhancing the potential for reuse of the wastewater through the utilization of various remediation methods. The term "bioremediation" refers to the practice of optimizing naturally occurring remediation processes that are carried out by living organisms. These processes are responsible for the degradation, modification, or removal of harmful organic substance. The use of bioremediation techniques is an alternative method for the disposal of wastewater that has not been treated during crop irrigation[100]. However, the effectiveness of bioremediation techniques is contingent on a number of factors that should be taken into consideration when selecting a treatment that offers water quality that is suitable for the requirements of crops. Because of the rise in the urban population over the last several decades, wastewater discharge has grown. As a result, water has become an essential component of the environmental and economic policies that are now in place, as well as a significant influence in the development process[101].

The purification of effluents may be accomplished through the treatment of wastewater from urban and industrial sources. However, it is essential to have a thorough understanding of the harmful effects of certain compounds, as these substances have the potential to slow down the purification process and eliminate the action of microorganisms that are engaged in the purification of water[102]. In accordance with the biodegradability of the components of the wastewater, the purification process is broken down into three distinct stages: 1) the preliminary treatment eliminates large solid residues like cans, rags, bottles, and other similar items, as well as fatty contaminants; 2) the primary treatment eliminates suspended solids and organic matter through physical separation techniques like gravity or chemical sedimentation, or filtration; and 3) the secondary treatment eliminates ninety percent of the organic matter, transforming it into a sedimentable biological floc, which is an agglomeration of organic matter, bacteria, and minerals[103].

A number of anaerobic (for the decomposition of organic matter) and aerobic or facultative treatments are included in post-treatments, also known as tertiary treatments. These treatments are employed as a last supplement for the removal of organic material and suspended particles. The largest proportion of treated wastewater is found in Colombia, which is followed by stabilization ponds in 732 treatment facilities in Mexico[104]. The total amount of wastewater released into surface water sources in Latin America is around 400 m3 s-1. On the other hand, there is no information that is both comprehensive and trustworthy about the reuse of wastewater in Latin America, and only eight percent of the total wastewater that is created each day gets treated[105].

A number of economic benefits may be derived from the use of wastewater for crop irrigation. These benefits include the provision of nutrition and phosphorus content, the reduction of fertilizer consumption, and the promotion of local food production. The amount of wastewater that was discharged from industrial facilities in Mexico grew from 170 to 188.7 m3 s-1 between the years 1998 and 2007, while the amount of wastewater that was generated from urban areas went from 239 to 243 m3 s-1[106]. The amount of wastewater that was treated was only 25.3% of the total volume that was produced. However, fifteen percent of all aquifers are already at their maximum capacity, which means that first-use water must be replaced with treated wastewater. Agriculture accounts for seventy-seven percent of all water demand[107].

Since the year 2008, Mexico has been implementing programs for the treatment of wastewater, such as the PROTAR (wastewater treatment program), with the goal of increasing the volume of water that has been treated and improving the procedures that are used for wastewater treatment. The General Law of National Waters was followed by the construction of 2287 treatment facilities around the nation till December of 2013. These plants were working in accordance with the law[108]. Novel approaches to the treatment of wastewater have been developed, with the objective of enhancing the potential for reuse of the wastewater through the utilization of various remediation methods. During agricultural irrigation, bioremediation techniques offer an alternative method for disposing of wastewater that has not been treated; nevertheless, the effectiveness of these techniques is contingent on a number of criteria that should be taken into consideration when selecting a treatment that is tailored to the requirements of crops[109].

To summarize, the treatment of municipal wastewater is necessary in order to guarantee the quality of water resources and to provide opportunities for their reuse. On the other hand, the harmful effects of particular compounds might slow down the process of water purification and even prevent the microorganisms that are involved in the purification of water from making their contribution[110]. It is possible for Mexico to develop solutions that are more efficient and sustainable for its water resources if it has a better awareness of the potential and problems related with wastewater treatment techniques.

Since the beginning of the industrial revolution, issues concerning the treatment of wastewater have emerged as serious environmental and societal concerns. In contrast to industrial wastewaters, which might originate from any manufacturing, processing, or handling procedure, urban wastewaters are more consistent in their composition. These wastewaters are subjected to a series of physical, chemical, and biological processes throughout the treatment process in order to recover dirty water and transform it into clean water[111]. According to the biodegradability of the components of the wastewater, the purification process is separated into several stages. Large solid residues and fatty contaminants are eliminated during the preliminary treatment process, whilst suspended particles and organic materials are eliminated via the primary treatment process using physical separation techniques. Activated sludge, aerated lagoons, trickling filters, biodiscs, and stabilization ponds are some of the procedures that are utilized in secondary treatments. These treatments remove ninety percent of the organic content and transform it into a biological floc that may be sediment[112].

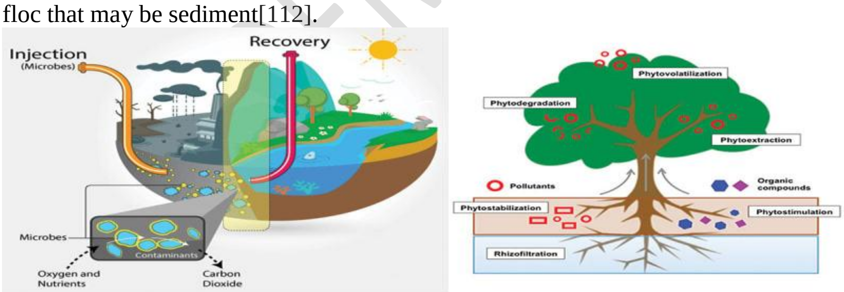


fig 8 : Tertiary treatments

Post-treatments, also known as tertiary treatments, are comprised of a number of anaerobic procedures that are used to degrade organic matter, as well as aerobic or facultative treatments that are utilized as a last supplement for the removal of organic material and suspended particles. Tertiary treatments can be either aerobic or anaerobic, and they involve bacteria and protozoa that are suspended in water or fastened to a surface. Anaerobic procedures are helpful in removing heavy metals, minerals, and pathogens[113].

Due to the fact that these purification methods may not entirely remove chemicals that may cause damage to ecosystems, such as heavy metals, it is not suggested that treated water be returned to these channels. At the Valle del Mezquital in Hidalgo, Mexico, which is the largest (100,000 hectares) and oldest agricultural zone in the world that is irrigated with wastewater, municipal effluent has been utilized in agriculture for more than a century. The organic matter that is present in wastewater not only improves the conditions of the soil and the productivity of plants, but it also adds to the contamination of the soil, which puts plants, the environment, and human health in dire danger[114].

The high concentration of salts, heavy metals, bacteria, and viruses that are found in wastewater has resulted in the establishment of rules in both developed and developing nations. As a result, the use of wastewater should be regulated. The reutilization of wastewater in desert regions has a number of benefits; nevertheless, it also highlights the necessity of employing suitable management and monitoring strategies in order to achieve more effective control over this resource[115].

All conceivable levels of epuration are included in wastewater that is used for irrigation, ranging from water that has not been treated to water that has undergone tertiary treatment. Several studies have been carried out in order to ascertain the quality of wastewater that is utilized for irrigation purposes and the impact that it has on the surrounding ecosystem. There is a substantial association between run duration, the levels of lead, cadmium, chromium, bromine, manganese oxide, organic carbon, and readily exchangeable fraction, according to the findings of several investigations[116].

## Conclusion

In conclusion, the realm of biotechnological breakthroughs offers a promising trajectory for revolutionizing agriculture through the innovative practice of bioremediation. This environmentally friendly approach harnesses the power of microorganisms and plants to detoxify soil, mitigate pollution, and enhance overall agricultural productivity. The potential impact of bioremediation on cleaner and more sustainable farming practices is profound, as it addresses pressing issues such as soil degradation, chemical contamination, and resource depletion. Through the application of cutting-edge biotechnological tools, researchers and farmers alike can collaborate to develop tailored solutions that optimize soil health, reduce reliance on synthetic chemicals, and bolster food security. As we navigate the challenges of the 21st century, embracing bioremediation in agriculture not only aligns with the imperative to safeguard our environment but also holds the key to a resilient and prosperous agricultural future. The integration of biotechnological breakthroughs into mainstream agricultural practices marks a pivotal moment in our quest for sustainable and productive food systems, where science and nature converge to cultivate a greener, more harmonious planet.

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