Biology, Agriculture, SciTech and Environment
Vol 4 [12] December 2024; 01-07
ISSN 2321-8746

Full Text: https://www.basecongress.com/ebase.html

Bioremediation as a Tool to Reduce Soil-Based Biomagnification

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ABSTRACT

An efficient and sustainable method for reducing soil contamination and the possibility due to biomagnification - the buildup and magnifying of toxic compounds through food chains—is bioremediation. This method offers a sustainable way to fight contamination by dangerous compounds like pesticides and heavy metals by using living creatures like bacteria, plants, or enzymes to break down or remove contaminants from the soil. One of the most extensively researched types of bioremediation is microbial remediation uses bacteria, fungus, and other microorganisms that have the innate capacity to break down contaminants into less dangerous forms. Complex organic contaminants, like pesticides, are broken down by these microbes into harmless byproducts which have no pesticidal property. In contrast, phytoremediation employs plants to absorb, concentrate, or change pollutants in the soil. Some plants, referred to as hyperaccumulators, have the ability to absorb pesticides and heavy metals, thereby reducing soil contamination. A less invasive method of decontaminating soil is to use enzymatic techniques, which make use of plant or microbial enzymes to help break down toxins like metals and organic pollutants. Bioremediation has a number of obstacles in spite of its potential. The kind of pollutant, the characteristics of the soil, and the surrounding environment can overall affect how effective these methods are. The efficacy of bioremediation procedures in circumstances of severe contamination may also be limited by their slowness. However, a viable long-term strategy for avoiding the buildup of toxic materials in soil, maintaining healthier ecosystems, and lowering the possibility of biomagnification in food chains is bioremediation.

Keywords: Bioremediation, Soil contamination, Biomagnification, Microbial remediation, Phytoremediation, Hyperaccumulators

Received 23.11.2024 Revised 28.11.2024 Accepted 30.11.2024

CITATION
Riya D and Sitesh C. Bioremediation as a Tool to Reduce Soil-Based Biomagnification. Biol. Agricul. SciTech and Environ. Vol 4 [12] December 2024; 01-10

INTRODUCTION

Heavy metal, herbicide, and other persistent organic pollutants (POP)-induced soil pollution is a serious environmental issue that endangers ecosystems and public health. When these contaminants build up in soil, they have the potential to infiltrate the food chain and trigger biomagnification, a process whereby the concentration of harmful compounds rises as trophic levels are reached. Higher-level creatures are negatively impacted by this, including people who eat tainted food. For example, persistent environmental heavy metals like lead and mercury can build up in plant and animal tissues, causing long-term health concerns like kidney failure, neurological impairment, and reproductive disorders (Glick, 2010).

Conventional soil restoration techniques, like chemical treatments and excavation, are frequently expensive, energy-intensive, and occasionally worsen environmental damage. Additionally, these approaches might not be able to effectively address the underlying pollution. This has led to the demand for more economical and environmentally friendly substitutes. Bioremediation, which uses biological agents like bacteria, plants, or enzymes to eliminate, break down, or neutralize pollutants in soil, is one potential approach. For instance, certain plants can absorb and store toxins in their tissues, a process known as phytoremediation; microorganisms can also break down toxic substances into less damaging compounds (Pilon-Smits, 2005).

What is Biomagnification:

The process by which harmful compounds, such as pesticides, heavy metals, and other contaminants, concentrate more as they go up the food chain is known as biomagnification. It happens because organisms find it difficult to break down or get rid of these chemicals. Therefore, more of the poisonous material is accumulated by creatures at higher trophic levels (predators) than by those at lower trophic levels (primary producers or herbivores).

The problem is made worse by pesticide runoff from agricultural fields into adjacent water bodies, which promotes toxicant biomagnification and bioaccumulation. As water quality metrics deteriorate, the balance of aquatic plants and animals is upset, harming aquatic ecosystems. Aquatic organism mortality cases increase in frequency, highlighting the magnitude of the ecological cost. Concurrently, pesticide drift exacerbates the problem by negatively affecting populations of pollinators, natural enemies, beneficial pests, and non-target pests. Urgent action is required to lessen the effects of this complex influence on soil and water ecosystems, highlighting the significance of sustainable farming methods and strong regulatory frameworks to protect ecosystems and advance environmental health (Dey et al, 2024).

Despite their immediate advantages, pesticides can eventually be fatal and seriously harmful to human health. Many bug genera become resistant to and resurgent in response to the regular application of certain pesticides. However, because of their environmentally favourable qualities, farmers should be urged to switch to botanical pesticides (Roy et al, 2024).

What is Bioremediation:

Bioremediation is the practice of cleaning up the environment through the use of living organisms, including but not limited to, bacteria, fungi, plants, or enzymes. This process specifically targets, soil, water, and air. This is an eco-friendly approach to pollution control as compared to the traditional methods and is effective in terms of cost. Bioremediation outcomes are achieved through the interaction of plants and other microorganisms, which employ their metabolic processes to transform and or break down toxic substances into less or non-toxic compounds.

Bioremediation can broadly be classified into two types:

a) In situ bioremediation: This is bioremediation where the contaminants are treated where they are found without taking the pollution away from the site. This method focusses on the biodegradation and neutralization of pollutants by seeking active boring microbes found within the area. This involves addition of nutrients and oxygen or any other agents that increase microbial activity to hasten the degradation of the pollutants.

b) Ex situ bioremediation: Contaminated areas such as soil or water is being taken to some other area for management and it is done through process of a bioreactor or other treatment plant, which is safe for contaminants. Such materials are only returned once pollutants have been broken down or taken out or appropriate waste disposal has been administered.

Biomagnification of pesticides:

Biomagnification of pesticides is the increase in concentration of pesticide chemicals that occurs with each step in the food chain. Although they are intended to be used for particular organisms, they tend to be scattered throughout the environment and are certain to be found in soils, water and plants. These pesticides enter the food web and become concentrated as one progresses up the trophic level, which can be detrimental to both animals and man.

This is how pesticides magnify between trophic levels:

- **Pesticides in the environment:** Pesticides can be introduced into the environment through agricultural runoffs, leaching through the soils or through direct applications. These compounds tend to adhere to soil particles or get taken up by plants and may remain with them for a long duration especially persistent DDT or organochlorines.
- **Absorption by primary producers (plants and algae):** Pesticides tend to be absorbed from either the water or the soil by plants and crops, which includes grasses and aquatic plants. Owing to the fact that pesticides are known not to degrade easily, they can become deposited in plant bodies over time.
- **Consumption by herbivores:** Small herbivores, such as insects, rodents, or small fish, eat these contaminated plants. The pesticide concentration in their bodies is now higher than in the plants they consume because they accumulate the chemicals in their tissues as they feed.
- **Transfer through higher trophic levels:** As predators eat contaminated herbivores, the concentration of pesticides increases in the predator's body. For example, larger fish eating smaller fish, or birds of prey eating contaminated rodents, accumulate even more pesticides. This process continues as predators higher up the food chain consume contaminated organisms, leading to increasingly higher concentrations of pesticides in their tissues.
- **Impact on top predators (including humans):** Organisms at the top of the food chain, such as apex predators (e.g., eagles, large fish, and humans), can accumulate dangerous levels of pesticides. These substances can cause a wide range of health issues, including reproductive disorders, immune suppression, and neurological damage. In some cases, pesticides like DDT have been shown to thin

eggshells in birds, causing reproductive failure. In humans, long-term exposure to pesticide biomagnification has been linked to cancer, developmental disorders, and endocrine disruption.

A classical example of biological magnification or bio-magnification is given below:

Assume that irrigation or rainfall causes pesticides or pesticidal residues to be rinsed off of crops. Through leaching or surface runoff, these leftovers have the potential to penetrate the soil and eventually reach water bodies. The chemical characteristics of the pesticide, the type of soil, the flow of water, and the surrounding environment can all affect the concentration of pesticides in the soil and water throughout this process. The balance of the ecosystem, water quality, and soil health may all be significantly impacted by this movement.

Suppose a pesticide present in soil washes into water bodies (ponds, rivers, ditches, lakes, sea etc.) and suppose the concentration of pesticide remains in water bodies as 0.00000000001%.

Suppose, through water bodies, the pesticide enters into micro flora and fauna **(primary consumer)** into 100 times, then,

Each micro flora or fauna contains,

0.00000000001% x 100

= 0.000000001% concentration of pesticide

If an insect **(secondary consumer)** feeds 100 numbers of flora and fauna each day, then,

Each insect contains,

0.000000001% x 100

= 0.0000001% concentration of pesticide

If one small fish **(tertiary consumer)** feeds 100 numbers of insects each day, then,

Each small fish contains,

0.0000001% x 100

= 0.00001% concentration of pesticide

In the same way, if one large fish **(top level consumers/ quaternary consumer)** consumes 100 numbers of small fish each day, then,

Each large fish contains,

0.00001% x 100

= 0.001% concentration of pesticide

In this way the concentration of pesticide is being increased from the lower level of consumers to the higher level of consumers in the trophic level.

A. Food chain:

An arrangement of organisms that each provide food for the one after it is known as a food chain. It symbolizes how nutrients and energy move through an environment within a food chain:

The producers are eaten by the primary consumers, or herbivores

↓

The primary consumers are eaten by secondary consumers, or carnivores

↓

Secondary consumers are consumed by tertiary consumers, or apex predators

↓

Dead organisms are broken down by decomposers, such as bacteria and fungi, which recycle nutrients back into the environment

The term **"trophic level"** refers to each level of the food chain. There are fewer apex predators than producers since energy diminishes as it goes up the hierarchy.

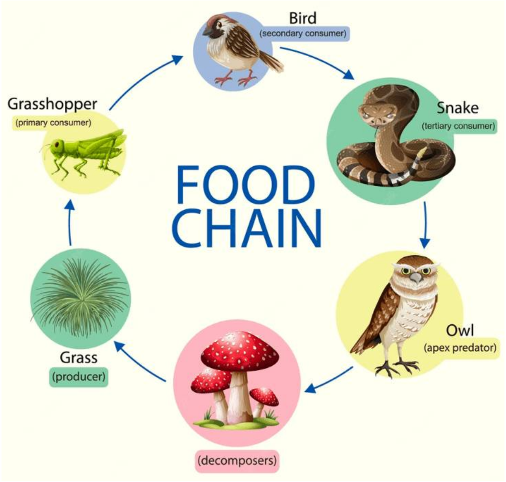

Fig. 1. Flowchart of Food chain

B. Food web:

A food web, which consists of several overlapping food chains, is a highly intricate and linked system of feeding connections within an ecosystem. It illustrates how different creatures are connected in numerous ways, displaying diverse feeding relationships, in contrast to a food chain, which depicts a single linear channel of energy and nutrients. The intricacy of actual ecosystems, where the majority of organisms consume and are consumed by many species, is better depicted by the food web than by a food chain. Because energy and nutrients move through multiple pathways due to this interconnectedness, the ecosystem is more resilient to shocks like the extinction of a single species.

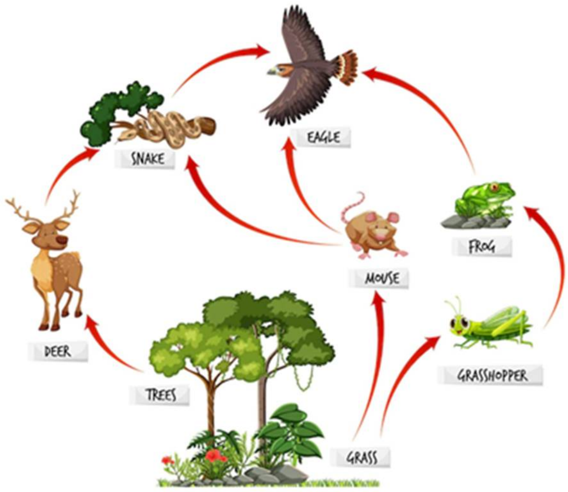

Fig. 2. Flowchart of Food web

METHODS

Microbial Bioremediation

Utilising bacteria, fungus, and other microorganisms to break down or immobilise contaminants is known as microbial remediation. Bacillus, mycorrhizal fungi, and pseudomonas are often employed species (Ahemad & Khan, 2011).

Mechanism:

Microbial bioremediation breaks down or immobilizes pollutants by using bacteria, fungus, and other microorganisms. The procedure entails:

- **Contaminant Metabolism:** Through enzymatic mechanisms, microbes convert harmful chemicals (such as pesticides and heavy metals) into less complex, non-toxic molecules.
- **Enzymatic Breakdown:** Microbes generate oxidative or reductive enzymes that break down or change contaminants into innocuous forms. For example, they can change heavy metals into less harmful states or hydrocarbons into carbon dioxide and water.
- **Immobilization:** Toxic compounds are bound by some microbes, such as mycorrhizal fungus, which reduces their mobility and lessens environmental damage.

Phytoremediation

Plants are used in phytoremediation to absorb, stabilise, or change contaminants. *Vetiveria zizanioides* for organic pollutants and *Brassica juncea* for heavy metals are common species (Pilon-Smits, 2005).

Types include phytodegradation, phytoextraction, and phytostabilization.

- **Phytodegradation:** Pollutants are broken down into less dangerous forms by plants through absorption and metabolic activities. For instance, organic contaminants such as pesticides can be broken down by plants into less dangerous, simpler forms.
- **Phytoextraction** is the process by which pollutants, such heavy metals, are taken up by plants from the soil and concentrated in their tissues, usually the leaves or stems. When the plants are harvested, this procedure enables the pollutants to be eliminated from the environment.
- **Phytostabilization:** By immobilizing pollutants in the soil, plants stop them from spreading through erosion or leaching. This lessens the possibility that pollutants will enter groundwater or be absorbed by other living things.

Enzymatic bioremediation

Enzymatic approaches involve the use of purified enzymes, such as laccases and peroxidases, to degrade complex organic pollutants (Chen & Wong, 2008).

Integrated approaches

Combining multiple bioremediation methods often results in synergistic effects, enhancing efficiency and applicability (Singh & Singh, 2020).

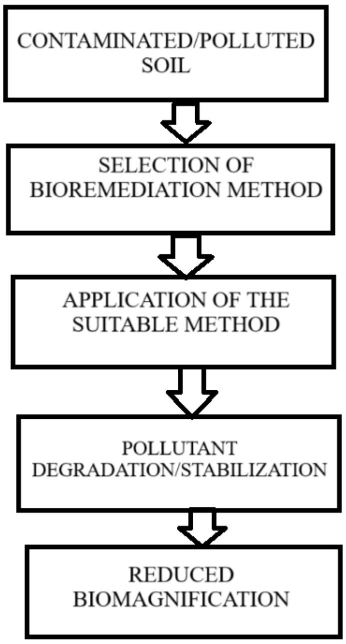

Fig. 3. Flowchart of Bioremediation Process

RESULTS AND DISCUSSIONS

Harmful effects of pesticides through biomagnification:

- The following are some negative consequences of pesticides through biomagnification: **Increased Toxicity:** Pesticide concentrations rise as they build up in the bodies of higher trophic level species (predators, for example), producing more potent toxic effects. Large fish and birds of prey are examples of top predators that can become poisoned.
- **Ecosystem Disruption:** By endangering important species that are essential to preserving the equilibrium of an ecosystem, such pollinators or aquatic life, the accumulation of pesticides in the food chain has the potential to upset entire ecosystems.
- **Reproductive Harm:** Since many pesticides are endocrine disruptors, they may affect wildlife's ability to reproduce. Birth problems, decreased fertility, or a fall in a species' population can result from this.
- **Decline in Biodiversity:** Ecosystems lose biodiversity as a result of sensitive species dying off or failing to reproduce as a result of significant pesticide accumulation.

- **Risks to Human Health:** Pesticide buildup in food can potentially affect humans, particularly those at the top of the food chain. Health problems include cancer, neurological diseases, and hormone abnormalities can result from prolonged exposure.

The risks of pesticide use are brought to light by biomagnification, especially when the chemicals linger in the environment and gradually build up in living things.

Efficiency of microbial remediation

Microbial remediation has proven to be highly effective in degrading hydrocarbons and immobilizing heavy metals. This can be proved by studies that show a reduction of oil contamination by 70–90% after six months of microbial application (Ahemad & Khan, 2011).

Performance efficiency of phytoremediation

Plants such as *Populus deltoides* and *Helianthus annuus* have demonstrated very high efficiency in phytoextraction, with up to 40% reduction of cadmium concentrations in contaminated soils in the course of one year (Pilon-Smits, 2005).

Problems of bioremediation

Soil-specific variations of pH, temperature, and availability of nutrients tend to affect microbial activity and plant growth. Treatment periods become somewhat lengthy for phytoremediation. Very few highly contaminated soils can be applied (Chen & Wong, 2008).

FUTURE PROSPECTS

Advances in genetic engineering and nanotechnology are likely to boost the efficiency of bioremediation technologies. Engineered microbes and hyperaccumulator plants are likely to revolutionize the field (Singh & Singh, 2020).

How to overcome biomagnification:

Several tactics, such as the use of bio-based and green insecticides, cultural control, and integrated pest management (IPM), can be used to combat biomagnification and lessen the negative impacts of pesticides. These methods operate as follows:

Utilizing Green and Bio-based Insecticides:

Bio-insecticides: These are less damaging to the environment and non-target species because they come from natural sources like fungi, bacteria, or plants. Examples include neem oil, which is extracted from the neem tree and acts as a natural insecticide, and *Bacillus thuringiensis* (*Bt*), a bacterium used to control pests like caterpillars.

Green pesticides are safer for beneficial insects, people, and wildlife than synthetic chemicals. Examples of these include diatomaceous earth, insecticidal soaps, and essential oils (such as citronella and eucalyptus).

Cultural Management of Insects: By altering farming methods, this strategy lowers pest populations without using chemical pesticides. Among the examples are:

Crop rotation is the process of switching up crops to interfere with the life cycles of pests.

Planting various crops together to confound pests and slow the spread of disease is known as intercropping.

Breeding plants that are resistant to pests is known as selective breeding. Physical barriers: To keep pests away from plants, use row coverings or nets.

Agro-Ecosystem Analysis (AESA): This entails routinely observing the agricultural ecosystem to evaluate weather patterns, pest numbers, and the efficacy of management measures. By decreasing the needless use of pesticides, AESA assists in determining when and how to apply treatments based on pest dynamics rather than preset schedules (Dhar et al,2023).

IPM, or Integrated Pest Management: IPM is a comprehensive strategy that uses a variety of techniques to control pests with little harm to the environment (DPPQS):

Biological control involves the introduction of natural parasites or predators, such as ladybugs for aphids.

Physical and mechanical controls include barriers, traps, and hand pest removal.

Chemical control: When required, apply targeted, low-risk pesticides (bio-insecticides or environmentally friendly alternatives) at the best periods to minimize damage.

Monitoring: Consistent data gathering and pest surveillance to assess pest populations and identify the best course of action.

Alternative Techniques:

- **Use of Resistant types:** Chemical interventions are less necessary when genetically resistant or improved crop types that are less vulnerable to pests and diseases are planted.
- **Natural Predators and Enemies:** Promoting beneficial creatures like birds and predatory insects (like beetles and spiders) aids in the natural management of pest populations.

When it comes to lowering risk, there are three key areas to consider:

- appropriate handling and storage;
- appropriate storage and disposal; and

- appropriate use of Plant Protection Equipment (PPE), such as chemical-resistant gloves, aprons, goggles, hats, and covering shoes.

The field must be inspected to ensure that there are no humans or animals present, and the area where pesticides are mixed must be away from ponds, streams, ditches, and wells. Pesticide cans, packages, etc. shouldn't be disposed of in fields, ponds, rivers, etc. It can be burned or buried deep in the ground. Pesticides should be kept locked up in secure locations out of the reach of domestic animals, children, and other family members (Chatterjee, 2021).

CONCLUSION

Bioremediation is thus a promising, environmental-friendly solution to alleviate soil pollution, thereby minimizing the harmful impacts of biomagnification in food chains. With this approach, sustainable remediation of soil is provided through the use of living resources and enzymes, utilizing their natural properties to degrade contaminants. In terms of remediation through microorganisms, plants, and enzymes, each process has its benefits, and together they may exhibit increased efficiency and wider applicability. However, the process of bioremediation has certain limitations in treating highly contaminated sites. Remediation periods might be long, and variable soil conditions can also challenge bioremediation processes.

Future breakthroughs in genetic engineering, nanotechnology, and bioreactor designs would help to cross these barriers and improve the efficiency of bioremediation. Bioremediation can then continue to transform soil health, protect ecosystems, and embrace sustainable agriculture. The present study emphasizes the adoption of bioremediation technologies in dealing with the increasing threats posed by soil pollution and biomagnification.

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