

Soil Remediation Techniques for Improved Plant Health

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Abstract

Soil plays a vital role in supporting plant growth and maintaining ecological balance by supplying essential nutrients, moisture or proper aeration. However, due to human activities like rapid urbanization and erratic farming methods, soil quality, plant health, agricultural productivity or ecological stability have all drastically decreased. Therefore, the importance of soil remediation is restoring polluted soil to a safe and healthy state is growing. This chapter examines several soil remediation techniques such as bioremediation, phytoremediation, soil washing, thermal remediation and chemical remediation to reduce the negative impact of pollutants (fertilizer, heavy metals or pesticides). Bioremediation is sustainable, environmentally acceptable or economical method that may be used either in-situ or ex-situ and break down or detoxifies pollutants using plants and microorganisms. For the treatment of organic or heavy metal pollution, phytoremediation is very beneficial. It employs a number of methods such as rhizofiltration, phytoextraction or phytostabilization. Physical techniques, heat treatments or soil cleansing are employed to get rid of pollutants and enhance soil health. Manure and compost are two examples of organic amendments that are crucial for improving the soil structure and fertility. The relationship between plant growth, soil health or ecosystem health highlights the need of various soil remediation methods to prevent further soil deterioration and for long term sustainability in environmental management and agriculture.

Keywords: Soil Remediation, Techniques, Plant Health, Bioremediation, Phytoremediation

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Introduction

Soil, which supplies essential nutrients, water, and support for plant growth, is one of an ecosystem's most important elements (Gavrilescu, 2021). Soil equality has been severely deteriorated by human activities including pollution, industry, agriculture and urbanization. Plant health may suffer when soil deteriorates as a result of pollution, compaction, erosion or mental loss. Restoring plant health, guaranteeing agricultural output or maintaining ecological stability in forests all depend on resolving problems with soil quality (Bhaduri et al., 2022). The process of eliminating pollutants from soil to restore it to a safe and healthy condition is known as soil remediation. This might contain number of techniques such as Soil washing, phytoremediation, chemical treatment, thermal treatment removal or excavation of contaminated soil and bioremediation using microorganisms (Aparicio et al., 2022). Nitrogen, phosphorus or potassium are just a few of the vibrant minerals that healthy soil offers to plant. It assures that plants have access to water without getting the risk of waterlogging by maintaining moisture while allowing appropriate drainage. By providing suitable aeration or structure, healthy soil encourages strong root system by enabling roots to dig deeper and access more resources (Balliu et al., 2021). Since pH balance affects general plant nutrient or vigor availability, maintaining an ideal pH balance. Maintaining an ideal pH balance is particularly crucial. Nutrient accessibility is increased in healthy soil by thriving colony of beneficial microorganisms that break down organic materials or improve soil fertility. Both plant development and disease resistance may be enhanced by this mutually beneficial interaction that is promoted by the microbial activity (Yu et al., 2022). Strong root system enables plants to absorb more nutrients or moisture from the soil, which is made possible by well-aerated soil. As result these plants are more resilient to environmental challenges. This direct effect of soil health on strength of the plant, plant production and the overall health of ecosystem, serves as the primary indicator of the interconnectedness of soil condition and plant well-being (Friedrichsen et al., 2021).

Agricultural practices include herbicides or pesticides have the potential to contaminate soil, impacting microbial ecosystem or threatening non-target creatures (Bamal et al., 2024). Pesticides and herbicides are frequently used to manage weeds and pests. However direct application of runoff can pollute soil. Hydrocarbons breakdown can also produce hazardous chemicals that worsen the ecology. The use of solvents or industrial operation can release volatile organic compounds (VOC's) into the soil, which may contaminate ground water and have an adverse effect on air quality (Singh et al., 2021). These substances may have number of harmful health impacts such as an increased risk of cancer and respiratory issues. Nutrient pollution can result from fertilizer runoff, especially from nitrogen or phosphorus rich fertilizer. Even though these nutrients are necessary for plant growth. Excessive quantities of them can upset aquatic ecosystem by degrading the soil, raising salinity or causing toxic algal blooms in adjacent bodies of water (Lan et al., 2024). Personal hygiene and pharmaceutical items are examples of emerging

pollutants that are being found in the soil more frequently. These chemicals can interfere with human and wildlife hormone systems, which raises questions about their long-term ecological consequences. They enter the environment through wastewater and these pollutants negatively impact the condition of soil, reduce agriculture productivity, Damage the local environment, prevention or demonstrating the significance of monitoring (Singh, 2021).

Soil Remediation Techniques

Bioremediation

"Bioremediation" is a word used to characterize how organic wastes are organically broken down under controlled conditions (Patel et al., 2022). In broad terms, bioremediation involves using living organisms, such as microorganisms, microbial enzymes, and plants, to remove, detoxify, or convert to less toxic pollutants in the environment. Compared to conventional approaches like physical and chemical methods to reclaim soils, this method is a safer alternative, which is eco-friendly, sustainable, and economical. This method can efficiently clean, control, and restore polluted environments through microbial activity (Hussain and Dhanker, 2021). However, the degradation rate of pollutants depends on factors such as microbial competitiveness, nutrient availability, environmental conditions (e.g., temperature, aeration, pH, and moisture), and pollutant bioavailability (Alori et al., 2022). Bioremediation is a method that uses the nutrients and other chemicals that organisms require to grow to break down or detoxify hazardous pollutants (Malik and Kumar, 2022). Microbes in the soil perform the role of active engineers, modifying the soil to be conducive to plant development. Additionally, they contribute to the transformation of organic matter, produce important growth regulators, and promote access to nutrients. The primary principle of bioremediation is the conversion and degradation of contaminants to less toxic forms. Microorganisms play a key role in breaking down, eliminating, immobilizing, or detoxifying a wide variety of chemical waste and physically harmful elements from the environment (Maqsood et al., 2023).

Bioremediation is a microbe-mediated technique, which is environmentally friendly and economical for decontaminating the soil and environment. Because microorganisms can live in different environmental conditions, they use pollutants as their food and generate metabolites that break down pollutants, which help to clean up polluted areas organically (Aslonov et al., 2024). Due to its benefits over expensive physical and chemical procedures, this technique is commonly used. Both *In-situ* and *Ex-situ* bioremediation techniques, microbes can be utilized, are approved by the US Environmental Protection Agency. With the increase in soil depth, bacteria dominate soil microbial communities, while actinomycetes and fungi populations decrease along the soil profile. The main techniques of bioremediation include bioaugmentation, biostimulation, composting, bioventing, bioleaching, bioreactors, farming, phytoremediation, and rhizofiltration are important bioremediation techniques (Ganguly et al., 2024). The bioremediation technique is further divided into two broad categories, i.e., (1) *In-situ* bioremediation and (2) *Ex-situ* bioremediation.

In-situ bioremediation could be of two types, i.e., intrinsic or engineered bioremediation. Both techniques are applied at contaminated sites. In intrinsic bioremediation, the strategy is to use indigenous microbes to decontaminate pollutant sites (Sanjana et al., 2024). The process entirely relies on the natural ability of microbes without human interference. In contrast, the process of engineered bioremediation is an advanced and accelerated remediation in which the capacity of microbes to detoxify pollutants is enhanced. Bioventing, bioaugmentation, and phytoremediation are some examples of engineered bioremediation. This type of bioremediation involves human interference. Favorable conditions are created for microbes to grow and facilitate the process of detoxifying contaminants further. Physicochemical conditions of the soil are altered, and growth stimulants and nutrients are provided to increase the microbial activity at pollutant sites (Alori et al., 2025). Among different types of engineered bioremediation, phytoremediation is widely used, and plants are used to remediate contaminated sites. This strategy, however, relies on the quantity and nature of the pollutant. Different plants (i.e., alfalfa and willow) showed efficiency in contaminant removal through phytoremediation. It follows various approaches (extraction, transformation, and sequestration) to remediate soils by removing contaminants like radionuclides and heavy metals (Sharma et al., 2023).

In this *Ex-situ* bioremediation method, the contaminated sample is removed from the site and transferred to another site for the purpose of remediation. Compared to *In-situ* bioremediation, this method has more demerits than merits. For instance, the pollutants have to be excavated and transported to another place for treatment purposes. The excavation and transport costs depend on the nature and quantity of pollutants and the characteristics of the respective pollutants site. These factors also decide the success of this type of bioremediation (Baskaran and Byun, 2024). This method treats two types of pollutants, such as solid-phase and semi-solid phase (slurry-containing). Examples of this technique are composting, biopiles, land farming and windrows.

Phytoremediation

Phytoremediation is an innovative and environmentally friendly technique that uses plants and related soil microbes to decrease the toxicity or concentration or toxic effect of contaminants in soil, air and water (Oubohssaine and Dahmani, 2024). This method is particularly effective for addressing various pollutants including heavy metals, nutrients or organic compounds. Plants can go through several mechanisms i.e., phytoextraction, phytostabilization, phytovolatilization and rhizofiltration.

Mechanisms of Phytoremediation

Heavy metal contaminated soil can be Phyto-remediated using a single mechanism or a combination of two or more phytoremediation techniques. The primary methods of phytoremediation are rhizofiltration, phytoextraction, phytostabilization and phytovolatilization Shown in Figure 1 (VanCleave, 2024).

Phytoextraction is the process in which plants absorb heavy metals from the soil and stored in their stems, leaves or other tissues (Santoyo-Martinez et al., 2024). The pollutants are taken up by the plant and moved to the above-ground areas, where maybe they harvested to eliminate the pollutants. It is the most economically feasible choice. Numerous factors such as heavy metal bioavailability, soil properties, heavy metal speciation and the plants ability to absorb metals and accumulates aboveground contaminants (Yan et al., 2020). Plants like sunflower (*Helianthus annuus*) or Indian mustard (*Brassica juncea*) are frequently used to remove heavy metals from the soil such as lead, arsenic or cadmium.

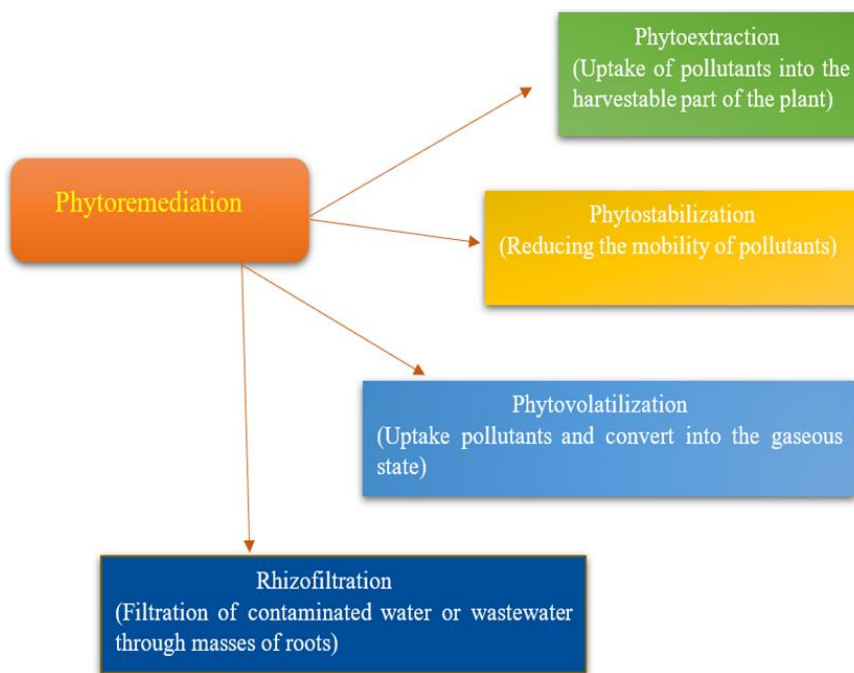


Figure 1: Various mechanisms involved in the phytoremediation of heavy metals

Phytostabilization uses plants to immobilize contaminants in the soil, preventing their migration or reducing bioavailability for heavy metals (Ren et al., 2024). Through root system erosion or absorption inhibition plants lessening the mobility of pollutants in the environment. This is cooperative for pollutants that are dangerous in water or easily carried by rain or wind. Organic matter, alkalizing agent, biosolids or phosphates are examples of soil amendments that can reduce metal solubility in soil and limit leaching to groundwater. Some plants like poplar (*Populus* spp.) or willow (*Salix* spp.) have been used to stabilize heavy metals in polluted soil (Wani et al., 2020).

Phytovolatilization permits certain plants to uptake water containing volatile organic compounds (VOC's) or release them into the atmosphere as less harmful gases (Meena et al., 2021). Some of the pollutants that plants receive from the soil are transformed into volatile forms (such as vapor) and then discharged into the atmosphere through the plant's stomata or other openings. By establishing a plant cover on the surface of the polluted sites, phytostabilization aims to decrease off-site contamination by limiting the movement of pollutants within the vadose zone by immobilization inside the rhizosphere or accumulation by roots. It has been demonstrated that plants like poplar or willow may release selenium or mercury into the atmosphere.

Rhizofiltration is a type of phytoremediation in which pollutants, mostly from water and wastewater, are filtered and eliminated using plant roots (Kristanti et al., 2021). This process successfully cleans the surrounding water by allowing plant roots to absorb, concentrate and occasionally change contamination. It is employed to eliminate organic compounds, pollutants or heavy metals found in water. Pollutants that are absorbed may build up in the roots of the plant or in other plant tissues (i.e., stems or leaves). This causes the facility to have a high concentration of contamination.

Soil Washing

A method of environmental remediation called "soil washing" (Zheng et al., 2022). Use water or chemical agents to remove pollutants from soil. This technique starts with a site assessment to determine the types and concentration of contamination or characteristics of the soil. After that contaminated soil is removed and brought to a treatment plant where it is cleaned with water and often treated with surfactants or other chemicals that aid in the solubilization and separation of pollutants from soil particles. Through procedures like sedimentation, filtration or centrifugation, the pollutants are either dissolved, absorbed or suspended into the washing solution before being extracted the clean soil (Rommel et al., 2021).

Soil Excavation is the process when polluted soil is extracted and transported to a treatment capacity for washing. This is important when contamination is widespread or if site conditions do not allow for in-situ (on-site) washing. In some situations, the procedure could involve the use of chemicals that increase the pollutant's solubility or facilitate their removal, such as surfactants, chelating agents or other chemicals. Depending on the degree of pollution or legal requirements, the treated soil is either disposed of or utilized again for its original purpose. Soil washing has several benefits, it is cost-effective and relatively fast compared to other methods like burning or excavation (Rahman et al., 2023). It might not be appropriate for all kinds of contaminants especially when contaminants are firmly ingrained or bonded to soil particles in a way that makes removal challenging. Since the contaminated wash water includes concentrated toxins that must be handled carefully to prevent environmental release, appropriate management or treatment are crucial. Depending on the present impurities, filtration, sedimentation or sophisticated techniques like reverse osmosis are available treatment options.

Thermal Remediation

A technique called thermal remediation uses heat to volatilize or eliminate contaminants in polluted soil (Wang et al., 2022). Usually, techniques like thermal desorption are used to apply the heat, which involves heating soil to high degree in specialized equipment to cause

pollutants to evaporate. This approach is useful for addressing a variety of contaminants including heavy metals, volatile organic compounds (VOCs) or other hazardous substances. Chemical remediation employs various chemical agents including soil amendments to effectively treat contaminated soil and groundwater. These agents can either enhance the degradation of pollutants or immobilize them or make them less hazardous. One common type of chemical agent used in remediation is oxidizing agent, for example potassium permanganate (Piezer et al., 2021). These agents are introduced into the contaminated site to break down organic pollutants through oxidation reactions and converting them into less toxins or more easily manageable substances. It can be costly or energy-intensive especially when working with large soil volumes or deep contamination. Significant amounts of heat are also produced by this procedure which can be difficult to control in urban and environmentally sensitive areas. Thermal remediation is not effective for all contaminants, those that are non-volatile or tightly bound in the soil matrix, limiting its application in some situations. This approach can be effective in promoting the growth of microorganisms that degrade pollutants (Bhatt et al., 2021).

Chemical Remediation

Chemical remediation is a process of treating or neutralizing pollutants in the soil by using chemical agents. Soil containing organic contaminants, heavy metals or dangerous substances that are challenging to eliminate through biological or physical methods (Rajendran et al., 2022). Chemical oxidation is a popular method that involves introducing oxidizing chemicals like hydrogen peroxide or potassium permanganate to polluted soil. These substances break down contaminants including petroleum hydrocarbons, insecticides or chlorinated solvents into less harmful or non-toxic byproducts. This procedure may be used for both *In-situ* or *Ex-situ* treatment. *In-situ* treatment takes place directly in the ground minimizing site disturbance or requiring less soil removal than *Ex-situ* treatment, which involves excavating soil (Perez-Vazquez et al., 2024).

Chemical reduction is the method of chemical remediation in which pollutants are changed into less dangerous forms by applying reducing agents. Heavy metals like chromium or arsenic can be reduced into less hazardous forms using zero-valent iron (ZVI). By adding chemicals (lime and phosphate) that bind to the metals or create insoluble molecules that stop them from leaking into groundwater. Chemical precipitation is also used to immobilize pollutants like heavy metals. Stabilization/solidification is the process of adding chemical agents to the soil to bind contaminants consequently decreasing their mobility and bioavailability. While chemical remediation techniques are very effective at rapidly eliminating or neutralizing pollutants (Saravanan et al., 2021).

Aeration of the Soil and Bioventing

Soil aeration is a crucial process for preserving soil health and promoting plant growth. Aeration enhances the interchange of gases such as oxygen or carbon dioxide, which are necessary for plant roots or soil bacteria (Sharma and Kumar, 2023). Well-aerated soil supports beneficial microbial processes like organic matter decomposition, nutrient absorption or root respiration. Techniques like mechanical aeration which creates holes in the soil with tools or biological aeration, which uses earthworms and other soil organisms improve soil structure or prevent issues like waterlogging. These procedures ensure that plants have the conditions necessary for optimal growth and are essential for both plant development and efficient nutrient cycling.

In order to encourage the organic pollutants' natural biodegradation, bioventing is a technique for soil aeration that regulates air volumes entering the soil (Stanciu, 2023). Aerobic bacteria that produce innocuous metabolites from pollutants like solvents or petroleum hydrocarbons. Air is introduced into the soil through perforated pipes to increase oxygen levels and encourage microbial metabolism. Bioventing is particularly useful for treating low to moderate amounts of pollutants without disturbing the soil and it is also cost-effective or environmentally friendly. This approach is commonly employed in petroleum contaminated sites and other places with volatile organic compounds because it reduces dangerous emissions. It aids in improving soil health and plant development

Composting and Organic Amendments

Manure, food scraps and plant residues are examples of organic waste items that naturally compost and turn into nutrient-rich humus that may be used as a beneficial soil additive. During composting beneficial elements such as potassium, nitrogen or phosphorus are released as microorganisms that break down the organic debris. These nutrients are crucial for plant growth (Gao et al., 20024). Composting enhances the soil's structure by boosting aeration, encouraging healthy microbial activity and enhancing the soil's ability to retain moisture. This organic matter promotes the development of earthworms and other soil organisms, improving soil fertility and plant health in general. Examples of organic amendments that are important in replenishing depleted or damaged soils with nutrients include compost, charcoal, manure, and cover crops. These supplements enhance the soil's organic matter and restore vital minerals, both of which are essential for robust root systems and increased soil water retention. Organic amendments are essential for soil carbon sequestration, which helps to slow down global warming by storing carbon in the soil. Long-term plant health and production are supported by sustainable soil management techniques that include organic amendments, which improve soil structure, increase microbial diversity or provide slow-release nutrients (Futa et al., 2024).

Conclusion

Plant growth, agricultural output or ecological stability all depends on healthy soil. The health of plants and the operation of ecosystems are seriously threatened by the deterioration of soil quality brought on by human activities including pollution, urbanization and sustainable farming method. Restoring soil quality and reducing the negative impact of pollutants like heavy metals, fertilizers or herbicides that interfere with normal processes of soil depend on efficient soil remediation. Promising method for eliminating or neutralizing contaminants and reestablishing soil health including bioremediation, phytoremediation soil washing, thermal and chemical remediation. Although these techniques differ, they all stress how crucial it is to use plants microbes and natural process to clean and restore contaminated soil. By adding organic amendments like compost and manual, soil fertility or structure are further improved. Creating a favorable environment for

planning development and promoting microbial activity. By increasing the soil ability to retain water or fostering long-term plant health, techniques, like composting not only supply vital nutrients but also sports sustainable soil management. These remediation methods or organic amendments offer a comprehensive strategy to address the problem of soil degradation as the relationship between soil, plant health and overall ecosystem stability becomes more evident. We can guarantee a more sustainable and healthier further for the soil and the plants that depend on it by incorporating these methods agriculture and environmental management.

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