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A Comparison of Different Remediation Technologies of Contaminated Agricultural Soils

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Abstract. Soil contamination is a major threat to the sustainability of agricultural fields and the safety of food production. This paper presented the remediation techniques, including surface covering, encapsulation, thermal restoration, stabilization, solidification, phytoremediation, bioremediation, and combined remediation. Bioremediation, which uses microorganisms to break down contaminants, has gained popularity due to its low cost and minimal secondary pollution. In conclusion, remediation techniques for soil contamination in agricultural fields are essential for maintaining the environmental quality of agricultural products. By utilizing a combination of techniques, we can effectively remediate the soil and ensure the safety of food production.

1. Introduction

Soil is an essential component of a sustainable ecosystem. However, it is also a significant storage site for pollutants, where contaminants such as heavy metals, pesticides, and organic pollutants can accumulate through agricultural activities or environmental transport. Pollution of agricultural soils poses a threat to human life because contaminated soil can lead to reduced crop yields and food safety problems. Various methods are currently available for soil remediation, including physical remediation, chemical remediation, bioremediation, and combined remediation. Combined remediation uses a combination of the above methods to enhance remediation efficiency[1].

2. Sources of Contaminants in Agricultural Fields

One of the main factors contributing to the production of contaminants in soil is atmospheric deposition. Human activity, such as industrial production, transportation, and fuel combustion, leads to increased emissions of organic pollutants and heavy metals, which can attach to atmospheric particulate matter and be deposited into the soil through atmospheric circulation. Studies have shown that atmospheric deposition is the main source of increased input of heavy metals, such as chromium, nickel, and zinc, in Chinese agricultural fields. Organic pollutants such as PCBs from transportation and fuel combustion can also accumulate in the soil through atmospheric deposition[2].

The scarcity of water resources and the increasing population has led many cities to use urban domestic sewage and industrial wastewater for irrigation, resulting in the presence of both inorganic and organic pollutants in the soil. Different regions in China, such as Shenyang, Xi'an, Zhengzhou, Lanzhou, Beijing, Harbin, and Shijiazhuang, have reported varying degrees of heavy metal contamination in farmland soil, and higher levels of polycyclic aromatic hydrocarbons and organochlorine pesticides in irrigation areas[3].

According to statistics, China only has 9% of the world's farmland, yet it is the world's largest consumer of pesticides, using over 30% of the world's fertilizers and pesticides. The excessive use of chemical fertilizers has led to the pollution of the environment and a decrease in soil quality. Recently, organic fertilizers have been touted as a solution to improving soil quality, but they also come with the risk of heavy metal and antibiotic pollution. Studies have shown that organochlorine pesticides and heavy metals such as Cd, Zn, Ni, As, and Cu in farmland soil are mainly attributed to historical pesticide and fertilizer applications[4].

3. Methods for the Remediation of Contaminations in Farmlands

3.1. Bioremediation of agricultural soils

Bioremediation is an effective method for cleaning up contaminated soil, which utilizes soil-specific

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microorganisms, plant root secretions, mycorrhizae, and super-enriched plants. The process involves the degradation, absorption, transformation, or fixation of pollutants in the soil without disturbing its structure at a lower cost. The principle is that soil organisms reduce the level of contaminants in the soil environment by combining with them, or by reacting to change the chemical form of the contaminants in the soil, thereby reducing their toxicity. Bioremediation techniques can be categorized into three types, namely, microbial remediation, phytoremediation, and animal remediation.

3.1.1. Microbial Remediation of agricultural soils. Soil microbial remediation technology refers to the use of indigenous or artificially domesticated microorganisms to reduce the activity of harmful pollutants in the soil by degrading them into harmless substances through metabolic processes. There are different modes of action for microbial remediation, including bioenrichment and biotransformation for heavy metal-contaminated soil and degradation and transformation by microorganisms for organically contaminated soil[5]. Fungi, actinomycetes, and bacteria are the main microorganisms utilized for microbial remediation techniques. This technology has been considered an efficient, economical, and environmentally friendly method for remediation of various contaminated soils. As shown in Table 1, research has shown that specific bacteria such as two urease-producing bacteria can mitigate the toxicity of heavy metals in contaminated soil while Streptomyces nucleus can degrade deltamethrin in soil[6, 7].

3.1.2. Phytoremediation of agricultural soils. Phytoremediation is a technique that uses plants and their associated microorganisms to remove, degrade, or immobilize environmental pollutants. It is a low-cost, environmentally friendly, and effective method that has been widely used in the remediation of contaminated soils. During phytoremediation, plants absorb pollutants through their roots and accumulate and transport them to different parts of the plant, where the pollutants are transformed into less toxic forms or stored.The effectiveness of phytoremediation depends on the type of contaminant, type of plant species, and environmental conditions Various plant species have been used for phytoremediation of agricultural soils contaminated by heavy metals, organic pollutants, and pesticides(as shown in Table 1). For example, Sunflower (*Helianthus annuus* L.) has been used to remediate soils contaminated with lead, arsenic, and other heavy metals. Indian Mustard (*Brassica juncea*) is a hyperaccumulator plant that can accumulate high levels of heavy metals such as zinc, nickel, cadmium, lead, and copper in its tissues[8]. Vetiver grass (*Chrysopogon zizanioides*) is another plant that has been used for the remediation of contaminated soils. It can accumulate and degrade organic pollutants such as hydrocarbons and pesticides[9].

3.1.3. Soil faunal remediation on agricultural land. Animal remediation is a technique that uses animals such as earthworms, insects, and microarthropods to improve soil quality and reduce the toxicity of pollutants. This technique is mostly used for the remediation of organic pollutants and pesticides. Animals can facilitate the degradation of pollutants by promoting soil aeration, nutrient cycling, and microbial activity.

As shown in Table 1, earthworms are commonly used for animal remediation due to their ability to improve soil structure and promote microbial activity. They burrow through the soil and create channels for air and water to circulate, thus promoting the breakdown of pollutants[10]. Insects such as beetles and crickets are also effective for the remediation of organic pollutants, as they feed on decaying organic matter and promote the growth of soil microorganisms.

Table 1. Bioremediation remediation technology

Remediation technology	Bio	Contaminants	Removal effects	Cites
Microbial Remediation	urease-producing bacteria	Cd, Pb	Two urease-producing bacteria reduced the Cd (25.6–68.9%) and Pb (48.7–78.8%)	[6]
	Streptomyces	Deltamethrin	Streptomyces rimosus reduced 200 mg/L deltamethrin	[7]
Phytoremediation	Brassica juncea	Cd, Pb	Accumulation range for Cd（2.49 to 2.02mg/kg）and Pb（3.78 to 3.04 mg/kg）	[8]
	Vetiver	Atrazine	The removal efciency of atrazine in Farmlands was 7.27% higher than that in vetiver-unplanted soil	[9]
Animal remediation	Earthworms	Chlorpyrifos	Chlorpyrifos dissipation was not accelerated, but soil enzyme activity was significantly increased	[10]

3.2. Physico-chemical remediation of agricultural soils

3.2.1. Physical Remediation of agricultural soils. There are various soil physical remediation methods available, including the guest soil, encapsulation[11], thermal restoration[12], and electric remediation techniques[13](as shown in Table 2). In heavily polluted areas, guest soil and soil exchange methods are commonly used. These engineering measures offer advantages such as thoroughness and stability but come with large engineering volumes, high investments, and a risk of damaging soil structures, which could result in reduced soil fertility. To avoid secondary pollution, polluted soil must be treated in a centralized manner. Therefore, these methods are only applicable to the remediation of small areas with severely contaminated soil.

3.2.2. Chemical Remediation of agricultural soils. Soil chemical remediation aims to improve the behavior of pollutants in soil by adding amendments or inhibitors that reduce the water solubility, diffusion, and bioavailability of pollutants in soil. This transforms them into less toxic or less mobile chemical forms to alleviate their harm to the environment and ecology. Soil chemical remediation mechanisms include precipitation, adsorption, redox reactions, hydrolysis, and pH regulation, soil solidification-stabilization, leaching, and redox technologies are commonly used for soil chemical remediation(as shown in Table 2). Inorganic stabilizers such as non-metallic mineral materials, biochar, lime, silicon fertilizers, and phosphorus-containing substances are widely used in agricultural soil remediation. Clay mineral materials such as zeolite with strong ion exchange and adsorption capabilities are commonly used in heavy metal pollution remediation[14] . Organic stabilizers such as animal manure, crop residues, sewage sludge, and industrial organic waste also can inert and remediate heavy metals. Red mud-based stabilizers and montmorillonite-biochar composite materials have been used to remediate pollutants effectively[15].

Table 2. Physico-chemical remediation technology

Remediation technology	Method	Contaminants	Results	Cites
Physical Remediation	Encapsulation	Pb	the risk of Pb contaminated soils can be effectively mitigated	[11]
	Thermal treatment	Hg	Soil quality should also be considered when mercury is removed from farmland	[12]
	Electric remediation	2,4-D	the main mechanism for the removal of 2,4-D was found to be volatilization (which totalizes up to 57% of removal of 2,4-D)	[13]
Chemical Remediation	Stabilization	Cu, Zn, Pb, Cd	Bone char effectively immobilized Cu, Zn, Pb and Cd in soil and reduced their mobility	[14]
		Cd	with the removal rate of 48.14% in early rice, 20.24 and 47.62% in late rice).	[15]

3.3. Combined remediation of agricultural soils.

Currently, there are several combined technologies available for remediating contaminated agricultural soils, including combined plant-microbial, combined physical-chemical, and combined chemical-biological technologies. The combined plant-microorganism remediation technology utilizes the coexistence relationship between plants and soil microorganisms to leverage each other's strengths and remediate contaminated soil. The key mechanisms employed in this approach are promoting plant growth, improving plant tolerance to pollutants, detoxifying soil, and promoting plant uptake and fixation of contamination. The combination of rice straw, lime, and engineered bacteria yielded the lowest Cd concentration in lettuce leaves and the highest plant yield among the five treatments[16]. Biochar-assisted vermicomposting is a suitable method for remediating organically contaminated agricultural soils[17].

A comparative analysis was conducted on farmland pollution remediation technologies (as shown in Table 3), comparing them in terms of applicability, cost, treatment efficiency, and environmental impact. This analysis can serve as a reference for the selection of farmland soil remediation technologies.

Table 3. Comparison and analysis of remediation techniques.

Remediation technology	Applicable conditions	Cost	Efficiency	Environmental impact
Microbial remediation	large agricultural soils, difficult to apply	Low	Long time , low efficiency	No secondary pollution to the environment
Phytoremediatio n	large agricultural soils, provided the level of contamination does not exceed that suitable for plant growth	Low	Long time , low efficiency	Environmentally friendly
Physical Remediation	large, deeply contaminated soils	Higher	Less time , more efficient	damage the soil structure and affect the soil quality

Chemical Remediation	remediation of hard-to-degrade hazardous substances, such as heavy metals	High	Convenient operation, high efficiency	Potential secondary contamination of soil and groundwater

4. Summary

Agricultural soils are polluted with contaminants from various sources such as atmospheric deposition, sewage irrigation, and agricultural activities. Remediation techniques can be categorized into bioremediation and physicochemical techniques. Remediating contaminated agricultural soil is a challenging and long-term process. Remediation technologies are evolving to combine advantages and minimize negative impacts, and low-cost environmentally friendly methods are being developed. Bioremediation using microorganisms and plants is a less harmful and effective method for treating metal-contaminated sites, although it has some limitations such as climate sensitivity, slow plant growth, and long remediation time. Selecting appropriate remediation strategies should consider environmental, time, and economic factors.

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