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# Advances in Environmental Risk Assessment and Remediation Technologies for Heavy Metal Pollution in Agricultural Soils

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Managing heavy metal pollution in agricultural soils remains a major environmental and public health concern. These contaminants pose serious risks to ecosystems and human well-being. Effective evaluation and remediation of heavy metals in farmland soils are both essential and interdependent, forming a comprehensive decision-making framework. This review provides a systematic overview of the distribution patterns of heavy metals in soils, the relationships between heavy metal concentrations in soils and crops, and the occurrence, migration, and transformation mechanisms of these metals within the soil–crop system. It also examines the strengths and limitations of various risk assessment tools and models used to evaluate heavy metal contamination in farmland, offering valuable insights for better understanding and managing such pollution. Additionally, the paper reviews current soil remediation approaches—encompassing physical, chemical, biological, and integrated methods—comparing their effectiveness and potential for treating contaminated agricultural soils. Lastly, the review discusses existing challenges and suggests future research directions for improving the assessment and remediation of heavy metal pollution in agricultural environments. It aims to support the development of more effective strategies for evaluating risks and selecting appropriate remediation technologies based on detailed soil heavy metal characterization.

## Introduction

Soil is an essential natural resource with an inherent ability to self-purify. However, the introduction of external pollutants significantly intensifies soil contamination, adversely affecting both agricultural productivity and environmental quality. Heavy metals are particularly problematic because they persist in the soil, resisting degradation. Over time, their accumulation alters soil functions, reduces crop quality, and poses risks to human health through the food chain. Consequently, heavy metal pollution in agricultural soil has emerged as a critical global issue that threatens sustainable development and demands urgent attention. In regions like China, the challenge of managing heavy metal pollution in farmland is especially severe. This is due to several factors, including the uneven spatial distribution of heavy metals, problems like soil acidification and imbalanced soil nutrient composition, weak correlations between heavy metal levels in soil and crop uptake, limited long-term effectiveness of current remediation methods, and the absence of robust regulatory systems to manage long-term risks. These challenges highlight the need for location-specific risk assessment tools and cost-effective remediation strategies to effectively manage heavy metal contamination, enhance soil quality, and improve agricultural and living environments.

In recent years, significant progress has been made in the research of heavy metal risk assessment and remediation in agricultural soils. Studies have evaluated long-term contamination trends and examined the effectiveness of amendments like titanium gypsum in reducing the bioavailability of harmful metals and supporting crop growth. This review discusses the sources of heavy metal pollution in farmland, their spatial distribution across regions, the link between metal concentrations in soil and crops, and how heavy metals behave and transform within the soil–crop system. It also covers risk evaluation methods for heavy metal pollution and recent developments in remediation technologies, highlighting their strengths, limitations, and appropriate use cases.

Ultimately, risk assessment plays a crucial role in determining the urgency of remediation and selecting appropriate treatment technologies. It also helps evaluate the outcomes of remediation efforts, ensuring the health of the soil–crop system and protecting human health. Together, risk assessment and remediation form an integrated decision-making framework that promotes the scientific and sustainable management of contaminated soils.

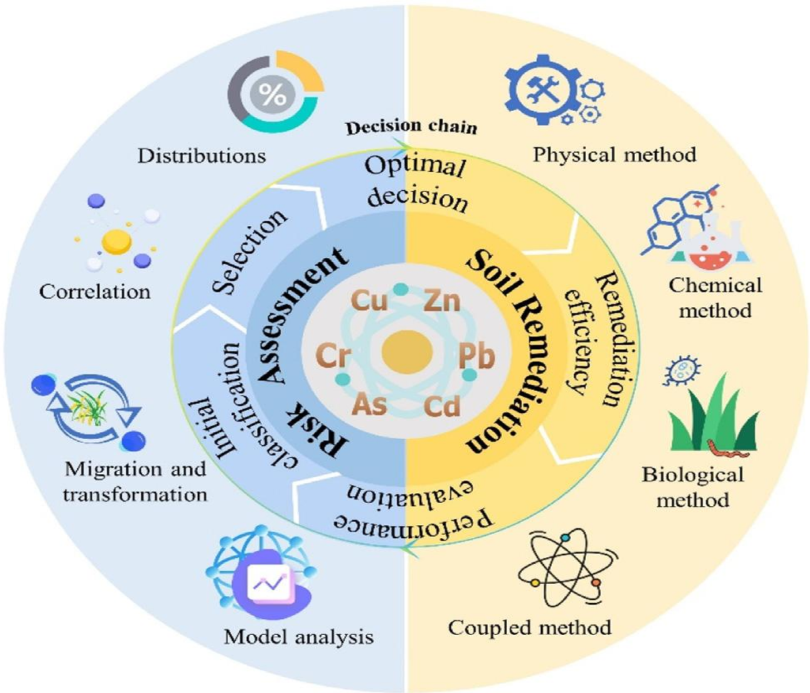


**Fig. – The relationship between the risk assessment and remediation technologies for heavy metal-polluted agriculture soil.**

## Distribution characteristics of heavy metal pollution in agricultural soil

Due to the complex origins of heavy metals, the characteristics of contaminated agricultural soils can vary significantly. Soil acts as the final recipient of pollutants from both the atmosphere and water sources. Heavy metals released into the environment eventually accumulate in soil through processes such as atmospheric deposition, adsorption by waterborne particles, and various geochemical cycles. The sources of heavy metal pollution in agricultural soils are generally classified into natural and human-induced categories. While natural sources are relatively stable, anthropogenic sources are more diverse and unpredictable. These include the extensive use of fertilizers and pesticides, irrigation with polluted water, accumulation of industrial waste, air pollution from industrial activities, metal smelting, and vehicle emissions.

Recent studies have extensively mapped the distribution of heavy metals in China's agricultural soils. Among the most commonly detected elements are chromium (Cr), lead (Pb), and arsenic (As). A comprehensive database was created based on research from multiple platforms covering the years 2002 to 2022. It was found that the levels of most heavy metals increased from 2005 to 2014, with the exception of lead. After 2014, a stabilization or decline in accumulation was observed, likely due to the implementation of effective soil pollution control measures in several provinces such as Jiangsu, Zhejiang, and Shandong. Overall, the distribution of heavy metal contamination in Chinese farmland soils exhibits marked regional variability and a complex pattern of change over time.

## Risk evaluation of heavy metals in agricultural soils

Given the growing environmental and health concerns associated with heavy metal pollution in agricultural soils, it is essential to investigate how these metals transform and where they ultimately accumulate. Understanding their behavior within the soil–crop–human system is key to identifying potential risks. Risk assessment of heavy metals in agricultural soils involves examining the relationships between different metals, their migration and transformation processes under varying environmental conditions, and evaluating the potential threats they pose to both ecosystems and human health.

## Correlation between soil and crop heavy metal contents

Studying the correlation between heavy metal content in soil and crops is a key step in assessing soil ecological health and crop quality. Two main methods are used for this purpose: pot experiments and field sampling. Pot experiments offer controlled conditions and consistent results, while field sampling, though more affected by environmental variables, better reflects real-world agricultural conditions.

Field studies have shown varying degrees of correlation between heavy metals in soil and their accumulation in crops. For instance, cadmium (Cd) often shows a strong transfer potential to wheat and rice, indicating a higher risk to the food chain. In contrast, lead (Pb) typically has a lower transfer risk. Some crops, like vegetables, also show significant correlations between metal uptake and both total and active heavy metal content in the soil.

However, these correlations are influenced by many factors beyond total metal content. Soil properties such as pH, organic matter, and planting patterns can affect metal mobility and crop uptake. For example, lower soil pH and organic matter can increase Cd absorption in tobacco. Interactions between different metal elements can also influence uptake—some may enhance while others inhibit the absorption of certain metals in specific crop parts.

## The migration and transformation of heavy metals in soil-crop system

The migration behavior of heavy metals in a soil–rice system varies by metal type. For example, rice grains tend to accumulate cadmium (Cd) the most, followed by arsenic (As), chromium (Cr), mercury (Hg), and lead (Pb). Each metal also exhibits different migration patterns among rice organs. In the case of Cd, it enters the rice root system through specific transporters and moves upward via the vascular tissues, eventually accumulating in stems, leaves, and grains—a process that intensifies with increased plant transpiration. Soil properties, such as pH and ion exchange capacity, also play a significant role; for instance, a lower pH accelerates the migration of heavy metals into rice plants. Interactions with other elements, such as zinc, can either inhibit or promote Cd's movement depending on its concentration.

The bioavailability of heavy metals is closely related to their chemical forms: a higher proportion of non-residual (active) states means greater mobility and risk, whereas increasing the residual fraction can lower bioavailability, though it might also raise overall soil pollution. Adjustments to soil pH and the addition of organic matter can help simultaneously reduce bioavailability and residual content, thereby controlling pollution while improving crop yields.

Moreover, heavy metals in the soil interact in complex ways, often competing for adsorption on soil particles. Some elements, like selenium or compounds formed from iron–manganese reactions on root surfaces, can transform and precipitate with metals such as Cd or Hg, effectively curbing their uptake by the plant. Overall, understanding the transformation of heavy metal forms throughout their migration in soil–crop systems—especially at regional scales—is crucial for accurately assessing the risk and developing effective mitigation strategies.

## Risk evaluation of soil heavy metal pollution

A thorough analysis of heavy metal characteristics and distribution in soil is crucial for effective risk assessment. Common evaluation methods include the single factor index, Nemerow index, potential ecological hazard index, and geo-accumulation index. These tools help identify pollution levels and key contaminants. For instance, a study in Shandong Province found that most soil samples posed moderate ecological risks, but a small percentage showed strong to extreme risks—mainly due to high levels of mercury (Hg) and cadmium (Cd), often linked to urbanization and sewage irrigation. In another case, farmland in the Yellow River Delta was assessed using pollution indices, revealing that copper (Cu), chromium (Cr), and lead (Pb) were the main pollutants, though overall contamination remained low. Based on heavy metal accumulation in crops, wheat was recommended as the preferred crop. Similarly, other assessments using the geo-accumulation index found that Cd, Pb, and Zn pollution was notable, with Hg being the most severe in some areas.

## Remediation technologies for heavy metal pollution of farmland soil

Risk assessment plays a key role in guiding the selection of appropriate soil remediation technologies. For example, after evaluating contamination in Lianhua Mountain, specific methods like cadmium stabilization using modified lime or fly ash were recommended. Risk assessment is also crucial in evaluating the effectiveness of remediation efforts, considering factors such as changes in heavy metal content, their chemical forms, and crop growth. In a wheat test area, physical remediation showed the highest risk reduction, while phytoextraction offered the greatest environmental benefits. This continuous loop of assessment and validation ensures both the scientific reliability and long-term sustainability of remediation strategies.

Remediation of heavy metal pollution in farmland generally follows three approaches: removing metals completely, reducing their bioavailability, or limiting their transfer to organisms. The main types of remediation methods include physical, chemical, biological, and combined approaches. When evaluating these technologies, both direct costs (e.g., equipment, labor, materials) and indirect costs (e.g., monitoring, potential secondary pollution) must be considered, along with time investment. Other important factors include the technology's maturity, effectiveness, and suitability for specific conditions. Each method has its strengths and weaknesses, but recently, combined remediation techniques have gained popularity for their improved efficiency in removing heavy metals from soil.

## Physical remediation technologies

### 1. Engineering measures

Engineering remediation methods mainly include soil blending, soil replacement, and soil turning. Soil blending involves mixing clean soil with contaminated soil to dilute pollutant concentrations. Soil replacement removes polluted soil and replaces it with clean soil, while soil turning brings less contaminated soil to the surface and mixes it with more polluted layers to reduce surface contamination. These methods are straightforward and effective in lowering heavy metal levels. However, they can disrupt soil structure, reduce nutrient content, and negatively affect crop yields. Additionally, they are costly and generally suitable only for small, localized areas of contamination.

### 2. Electrokinetic remediation

Electrokinetic (EK) remediation uses an electric field to drive heavy metal ions toward the electrodes through electrodialysis and electromigration, allowing pollutants to concentrate near the electrodes for easier removal. This method is efficient, cost-effective, and relatively simple to operate. However, its effectiveness depends on several factors, including soil type, voltage, pH, electrode material, and the type of electrolyte used. For example, graphite electrodes have shown better cadmium removal than stainless steel or titanium due to their higher activity in promoting ion migration. Higher voltage levels also improve removal rates by accelerating metal ion movement. EK remediation works best in low-permeability soils like clay and silt. To boost its efficiency, chemical agents—such as inorganic or organic acids and chelators—can be added to help dissolve and mobilize heavy metals, improving their removal during the EK process.

### 3. Thermal desorption technology

Thermal desorption removes volatile heavy metals like mercury, arsenic, and selenium from soil by heating, causing them to evaporate. Its efficiency improves with optimal temperature, treatment time, and additives like $FeCl_3$. While effective—removing up to 96% of mercury—it requires high energy and may not suit large-scale use. Additionally, it can alter other metal forms and cause secondary pollution through the release of vaporized metals into the atmosphere.

## Chemical remediation technologies

### 1. In-situ chemical stabilization method

In-situ chemical stabilization involves adding passivating agents directly to contaminated soil to reduce the mobility of heavy metals by altering their chemical form. Materials like biochar, industrial wastes, natural minerals, and nanomaterials are commonly used. For example, lime and phosphate fertilizers have shown high stabilization efficiency for metals like Pb, Cu, Cd, and Zn. However, this method does not remove the metals but only reduces their activity, requiring long-term monitoring to ensure stability, which increases energy use and overall remediation costs.

### 2. Chemical leaching method

Chemical leaching removes heavy metals from soil by applying a leaching agent that reacts with contaminants, transferring them into a liquid phase for collection and treatment. Common agents include $FeCl_3$, EDTA, citric acid, nitric acid, and acetic acid, with citric acid and $FeCl_3$ causing the least soil damage. Leaching efficiency depends on the agent's concentration—up to an optimal point. For instance, 0.1 mol/L EDTA achieved a maximum Cd removal of 83.6%, but higher concentrations reduced efficiency. This method is relatively simple and cost-effective (around 826 CNY/ton), but it can harm soil health by stripping nutrients and introducing secondary pollution from the leaching agents.

## Bioremediation technologies

### 1. Phytoremediation

Phytoremediation is an eco-friendly, sustainable technology that uses plants to remove, stabilize, or detoxify heavy metals in soil without disturbing its structure. It mainly works through three mechanisms: phytoextraction, phytofixation, and phytovolatilization. Phytoextraction involves plants absorbing heavy metals through their roots and accumulating them in aboveground parts, which are then harvested for safe disposal. Hyperaccumulator plants like *Solanum nigrum L.* and *Pteris vittata L.* are commonly used due to their high tolerance and uptake capacity. Phytofixation reduces metal toxicity by altering their chemical forms through root activity without removing them from the soil. Plants like willows are effective in immobilizing metals. Phytovolatilization involves the uptake of volatile metals, such as mercury or selenium, which are then converted into less toxic forms and released into the atmosphere—though this may cause secondary pollution through redeposition. Phytoremediation is low-cost, environmentally friendly, and helps retain soil moisture and structure, with methods like drill seeding costing as little as $754 per hectare. However, it requires long treatment periods and is affected by environmental conditions, highlighting the need for selecting efficient plant species suited for specific contaminants.

**2. Microbial remediation**

Microbial remediation uses microorganisms to reduce heavy metal toxicity in soil by processes like adsorption and transformation. Microbes such as bacteria, fungi, yeast, and algae can bind heavy metals or convert them into less toxic forms through mechanisms like reduction, oxidation, and methylation. For example, *Aspergillus niger* has shown high removal rates of metals like Cr, Cd, Pb, Cu, and Zn under optimal conditions. Other microbes, such as *Bacillus sphaericus* and *Citrobacter*, also demonstrate strong metal-removal capabilities. This method is cost-effective, environmentally friendly, and preserves soil structure, making it a popular research focus. However, it requires a longer treatment time, and the potential impact of microbes on crop growth still needs further investigation.

**3. Animal remediation**

Animal remediation involves using soil-dwelling animals to absorb heavy metals into their bodies, helping to reduce soil contamination. Earthworms are commonly used due to their widespread presence and ability to consume large amounts of soil daily—up to 5–30 times their body weight. They also have a high tolerance to heavy metals, aided by special tissues that allow them to accumulate these pollutants. However, this method is still limited in application and research, with relatively few studies conducted so far.

## Combined remediation technologies

**1. Electrokinetic-permeable reaction barrier (EK-PRB) technology**

Electrokinetic-permeable reactive barrier (EK-PRB) technology has attracted attention for its effective in-situ removal of heavy metals. It works by placing a reactive barrier in the path of water flow, where pollutants are captured or degraded through processes like adsorption, redox reactions, and biodegradation. Under an electric field, contaminants are driven into the PRB material and treated. Performance depends on factors like soil and barrier moisture, voltage, pH, electrode type, and electrolyte composition. Cost-effective materials such as activated carbon, fly ash, and nano-iron composites are commonly used. Studies show that increasing voltage can enhance removal rates—for instance, using fly ash-yeast pellets at 2.5 V/cm achieved a 53.7% Cd removal rate. EK-PRB offers better practical application potential than traditional EK methods due to its improved efficiency and in-situ treatment capabilities.

**2. Electric-microbial combined remediation technology**

Traditional electrokinetic (EK) remediation often faces reduced efficiency due to heavy metal precipitation near the cathode, which limits metal migration. To address this, electric-microbial combined remediation has been developed, enhancing removal efficiency while lowering energy use. This method uses electromigration, electroosmosis, and electrophoresis to move contaminants, which are then removed through cathodic reduction. In experiments using Cd-tolerant bacteria like *Escherichia coli*, *Bacillus sp.*, and *Bacillus cereus* with a 1 V/cm voltage for 10 days, Cd removal rates improved by 7.63%, 17.2%, and 19.5%, respectively, compared to traditional EK. Energy consumption also dropped significantly—by up to 116.5 kW/min/mg.

## Conclusion

In conclusion, the effective management of heavy metal pollution in agricultural soils is vital for safeguarding environmental and human health. This review highlights the critical interdependence of risk assessment and remediation strategies in forming a robust decision-making system for addressing soil contamination. By analyzing the distribution, behavior, and transformation of heavy metals in the soil–crop continuum, and evaluating the applicability of various assessment models, the review provides a deeper understanding of contamination dynamics. It also presents a comparative analysis of current remediation technologies, outlining their respective strengths and limitations. Despite advancements, significant challenges remain, such as improving long-term remediation efficacy, minimizing secondary pollution, and enhancing the precision of risk assessment tools. Future research should focus on developing site-specific, cost-effective, and sustainable remediation approaches. Overall, this review serves as a guide for informed decision-making in risk evaluation and technology selection, aiming to enhance the effectiveness and sustainability of heavy metal pollution control in agricultural settings.

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