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Study on Soil Heavy Metal Pollution and Microbial Remediation Technology

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Abstract

With the rapid development of social economy and industrialization, the soil has been seriously polluted and damaged. As far as the environmental pollution situation in China is concerned, heavy metal pollution accounts for a relatively high proportion and causes great harm to the soil environment. The quality of soil profoundly affects the quality of life for humans and the state of human development. Therefore, it is urgent to control heavy metal pollution in soil. Among a series of soil remediation technologies, microbial remediation is an economical and sustainable remediation technology for soil heavy metal pollution. This review starts with the hazards of soil heavy metal pollution, analyzes the current soil heavy metal pollution situation in China, elaborates on the connection of microbial remediation technology, studies the role of microbial remediation technology in soil heavy metal pollution remediation, and explores practical applications of this technology. Lastly, reasonable remediation measures based on microbial remediation technology for soil heavy metal pollution were proposed and discussed.

Keywords: Soil heavy metal pollution; Pollution hazard; Microbial remediation

1. Introduction

Under the influence of human production and life, once the content of trace metal elements in the soil exceeds the background value, heavy metal pollution will be triggered, which will not only cause certain damage to the surrounding soil environment, crop yield reduction, ecological pollution, but also adversely affect human health. At present, China's agricultural land is contaminated by heavy metals in the area of about 25 million hm^2, accounting for 16.1% of the total area of arable land. The annual food production contaminated by heavy metals is about 12 million tons, accounting for more than 80% of the total amount of contaminated agricultural products, mainly Cd, Hg, Pb, Cu-based (Wei et al., 2016). The severity of soil heavy metal pollution cannot be found in time and attention due to its hidden, lagging, complexity, accumulation, and other characteristics (He & Chen, 2014). Under natural conditions, heavy metals in soil are difficult to degrade and will pose a severe threat to human health through the accumulation of the biological chain. Therefore, remediation of soil heavy metal pollution has become urgent.

In recent years, the technology of remediation of heavy metal-contaminated soil has been constantly updated, and the common methods for remediation of heavy metal contamination in soil include physical remediation, chemical remediation, and biological remediation. Among the physical methods, there are mainly guest soil method, electric remediation, electromagnetic remediation, drenching method, vitrification technology, engineering physics technology and other. Chemical methods mainly include the chemical passivation method, photocatalytic degradation method, and modifier method. Biological methods involve phytoremediation, animal remediation, and microbial remediation (Zhou et al., 2014). Physical and chemical remediation methods have high input costs and introduce new chemical components. Animal remediation methods have high requirements on the soil environment and animals will migrate. Phytoremediation methods are not ideal for the remediation of heavy metal contamination in soil because of it is long time consuming and the high requirements for cultivation techniques. Microorganisms with small individuals, large numbers, large surface area, easy to cultivate, and fast growth rate characteristics are considered to be the ideal method for soil pollution remediation. It can effectively reduce the content of heavy metals in the contaminated soil to repair contaminated soil. The advantages of this method include stable effect, minimum secondary pollution and low cost. Based on this, the technology has been widely used in the remediation of heavy metal-contaminated soil. Hence, the technology has been widely applied in heavy metal contaminated soil remediation as shown in table 1.

Table 1. A brief table of common remediation methods for soil heavy metal contamination

Technologies	Methods	Strengths and weaknesses
Physical rehabilitation	Guest soil method Electric restoration Electromagnetic repair Gonorrhea Vitrification technology Engineering Physics Technology	High input costs
Chemical remediation	Chemical passivation Photocatalytic degradation Modified-agent approach	New chemicals will be introduced
Bioremediation	Phytoremediation	Longer time period, higher requirements for cultivation technology
	Animal remediation	High demands of environment, animals migrate
	Microbial remediation	Stable effect, small secondary pollution and low remediation cost

This review introduces the hazards of soil heavy metal pollution in detail and summarizes the hazards to the human body and their impact on society through the study of strong toxic heavy metal elements in soil pollution. At the same time, the article analyzes the role of microbial remediation of soil heavy metal pollution mechanism, influence factors and optimization of the conditions of the cutting-edge results, limitations and mitigation measures. The purpose is to provide references and new ideas for the remediation of soil heavy metal pollution.

2. Hazards of Soil Heavy Metal Pollution

heavy metals are not easy to be degraded naturally and can only be transformed into different forms, therefore, the remediation of heavy metal pollution is extremely difficult. Heavy metals from various sources contaminate the soil, and cause serious harm to the soil environment, animals, plants, microorganisms, etc., especially to human health. 1) Impacts on the soil environment and plants. Soil provides basic nutrients such as nitrogen, phosphorus, and potassium for plant growth. When heavy metals in soil exceed the standard, it will affect the absorption of nitrogen and phosphorus by plants and change the form of potassium, thus affecting the growth of plants (Zhu et al., 2024). In addition, the effective state of heavy metals in soil can be directly absorbed by plants and produce toxic effects on plants. Heavy metals in soil can be adsorbed on the surface of colloids or produce precipitation with certain compounds in soil, which in turn affects the uptake of nutrients by plants. 2) Effects on animals, microorganisms, and soil enzymes. When the content of heavy metals in the soil exceeds the standard, it will inhibit or poison the animals and microorganisms in the soil, reduce the enzyme activity, and affect the quality of the soil. 3) Harmful to the human body as shown in Table 2: Cd can damage the kidney, liver, lung, bone, nerve, blood, and immune system of a human body (Nordberg, 2004). Pb and Cu can cause reproductive disorders by destroying the function of the reproductive organs, Pb and Hg can affect human pregnancy, and trigger the fetus. Pb and Cu can damage the central nervous system of children, causing intellectual and behavioral disorders, as well as the nervous, digestive, and cardiovascular systems of adults, etc. Cu can cause hepatosplenomegaly, ascites, and inhibit the intellectual development of children (Chowdhury et al., 2000), and also can cause backfoot, diabetes, nephropathy, cerebrovascular diseases (Wasserman et al., 2006; Chen et al., 1996).

Table 2. Table of hazards of several major soil heavy metals to humans

Heavy metal	Specificities	Jeopardize
Cadmium (Cd)	Heavy metal pollution tops the list and is highly migratory	Inhibition of phagocytosis by macrophages Causes kidney damage from urinary stones Interferes with vitamin D metabolism Cerebral metabolic disorder Causes bronchopneumonia, pulmonary edema Inhibits hemoglobin synthesis May exhibit teratogenic and mutagenic effects
Lead (Pb)	Into the body through food, drinking water and air	Decreased renal tubular reabsorption Peripheral neuritis, hypertensive encephalopathy Reproductive dysfunction leading to infertility Harms the liver, causing the body to develop hepatomegaly
Arsenic (As)	Non-metallic elements widely distributed in nature; compounds are toxic	Neurologic lesions with neuritis at the ends of the extremities Paralyze the vasomotor center
Mercury (Hg)	The only liquid metallic element that evaporates at room temperature	Corrosion, bleeding and necrosis of the digestive tract Death by consumption of 0.1 g of mercury Causes lesions in the lungs, kidneys, liver, nervous system, etc.

2.1 Cadmium (Cd)

Cd pollution is the first of the five heavy metal pollutants (Wang et al., 2015), and its harmfulness can be imagined. Cadmium (Cd) is a biologically unfavourable and highly toxic heavy metal element with high mobility in the ecological system. It has been listed as one of the priority pollutants of concern by the United Nations Environment Programme (UNEP), the World Health Organization, and the United States Commission on Agriculture (Shi et al., 2008). Many studies have shown that cadmium is a severe hazard to human health and the most important channel of cadmium intake is dietary. Cadmium mainly enters the human body and accumulates in the body through the digestive tract and respiratory tract. Compared to ingested cadmium, inhaled cadmium is more easily absorbed and residual in the tissues: digestive absorption rate is generally less than 10%, and respiratory absorption rate is generally 10%~40%. Cadmium can be transported through blood to different parts of the body (Deng et al., 2010). Acute toxicity of cadmium is characterized by acute gastrointestinal irritation. Chronic toxicity is manifested in the inhibition of phagocytosis of macrophages, which not only triggers kidney damage caused by urinary stones, but also interferes with the metabolism of vitamin D to cause disorders of osteogenesis and bone metabolism and causes inflammatory reactions in brain tissues resulting in disorders of brain metabolism. Cadmium can even poison the lungs, causing respiratory irritation, bronchopneumonia, and pulmonary edema (Abe et al., 2001). At the same time, the chronic toxicity of cadmium will also damage the cardiovascular and cerebral vessels, interfere with the metabolism of copper, cobalt, zinc, and other trace elements, hinder the intestinal absorption of iron and inhibit the synthesis of haemoglobin (Qiuchan, 2007). Currently, the International Agency for Research on Cancer (IARC) classified cadmium as a class I carcinogen. Cadmium may also cause abnormal embryonic development, which is characterized by teratogenic effects, and induce DNA damage, which is characterized by mutagenic effects (Deng et al., 2010).

2.2 Lead (Pb)

The heavy metal ion lead has a huge toxic effect on human health and has no beneficial function. It can enter the body through food, drinking water, and air, and is harmful to the nervous system, bone hematopoietic function, digestive system, and reproductive system. Acute toxicity of lead (Pb) is characterized by gastrointestinal irritation. Chronic toxicity is characterized by the following conditions: First, decreased renal tubular reabsorption. The World Health Organization (WTO) reports that long-term lead exposure with blood lead levels of above 70 mg per 100 mL can lead to incurable chronic lead nephropathy. Second, long-term exposure to lead may cause peripheral neuritis, diffuse brain damage, and hypertensive encephalopathy. Third, reproductive dysfunction to infertility, not only affects the reproductive ability of women, making them infertile, miscarriage, and monster, but also may cause male infertility, directly poisoning all aspects of the reproductive process (Wei & Huang, 2008). Fourth, lead also harms the liver, causing hepatomegaly, jaundice, and even cirrhosis or liver necrosis. Lead is carcinogenic, teratogenic, and mutagenic in animals, but its carcinogenicity in humans has not been verified.

2.3 Arsenic (As)

Arsenic (As) is a non-metallic element widely distributed in nature, the elemental form of arsenic is insoluble in water, has almost no toxicity, toxic mainly for compounds, involving trivalent arsenic and pentavalent arsenic. Among them, trivalent arsenic compounds are more toxic than pentavalent arsenic compounds, and arsenic trioxide, which is commonly known as arsenic, is the most toxic compound. Acute arsenic poisoning is mainly manifested as acute gastroenteritis, but chronic arsenic poisoning is mainly manifested as neurological lesions, while polyneuritis or peripheral neuritis will appear at the ends of the limbs. Arsenic poisoning will also paralyze the vasomotor centre, resulting in a drop in blood pressure, ischemia of the heart and brain tissue, and symptoms such as collapse, loss of consciousness, and spasm. Not only that, accidental ingestion of arsenic will also produce corrosion of the digestive tract, bleeding, necrosis, degenerative changes in liver cells glycogen disappearance, and other serious consequences. Arsenic and its compounds have been recognized as carcinogens by IARC.

2.4 Mercury (Hg)

Mercury is the only liquid metallic element, silver-white, that evaporates at room temperature. Its vapor is colorless and odorless. Mercury poisoning can be caused when the mercury value exceeds 0.05 mg/L, and a person who consumes 0.1 g of mercury will be poisoned to death. Mercury invades the human body mainly through contact with the digestive tract, respiratory tract, and skin, causing lesions in the lungs, kidneys, liver, nervous system, and other parts of the body.

3. Status of Heavy Metal Pollution

"Everything is born in the soil, food comes from the soil", the soil is the material basis for human survival, and is the carrier of all things that grow. However, in recent decades, the continuous intensification of human activities has seriously affected the soil ecology, such as the highly intensive production of agriculture, the irrational use of pesticides and fertilizers, industrial and mining activities, and the large amount of "three wastes" generated by industrial pollution, resulting in soil heavy metal pollution problems become increasingly serious.

3.1 Domestic Status

In recent years, soil heavy metal pollution events have occurred frequently in China, such as the Liuyang cadmium pollution event in 2009, the "cadmium rice" event in 2013, and the heavy metal pollution event in Daxin County, Guangxi in 2014. Relevant investigation and research show that soil heavy metal pollution has become an important factor limiting the development of China's agricultural economy. The total area of soil heavy metal pollution in China has exceeded 50 million mu, and the value is still in the state of increasing year by year. Soil heavy metal pollution is difficult to manage and hidden, unfavorable to the normal production and life of human beings, and seriously restricts the process of China's sustainable development (Li, 2022). In addition, the results of environmental monitoring by the Ministry of Agriculture show that there are 320 key polluted areas in 24 provinces (municipalities) of China. The production and area of agricultural products with excessive heavy metal content accounted for more than 80% of the total amount of agricultural products with excessive pollutants and the area of the pollutants (Zhang et al., 2012). Taking the southern region of China as an example, the heavy metal Cd, Hg, and Pb contamination of farmland soil is the most serious, the As, Cu, and Cr content of facility farmland in the northern region is the highest, and the Ni content in the western region is the highest.

Guangxi is known as the "hometown of nonferrous metals", however, affected by mining exploitation as well as the geological environment, its heavy metal pollution problem is particularly prominent in the country. In the "Twelfth Five-Year Plan for Comprehensive Prevention and Control of Heavy Metal Pollution", Guangxi was listed as one of the 14 key provinces and regions in the country for heavy metal pollution prevention and control. The background value of cadmium in Guangxi soil is 0. 267 mg /kg, which is 2.75 times the national background value of cadmium in soil (0. 097). The results showed that the ecological risk of cadmium in rice paddy soil in Guangxi was moderate to high risk (Chen et al., 2015). Dechang et al. (2009) reported that lead was the main pollutant in the soil samples near the Shenyang-Harbin highway, and the area within 20-40 m of the highway was the most seriously polluted by heavy metals. Xu et al. (2014) studied the degree of heavy metal pollution in the soil of Jiaxing, Yangtze River Delta, and Pearl River Delta region, and the results showed that cadmium pollution covered 0.74% of the total percentage of the area. Liu et al. (Liu et al., 2013) assessed the current status of heavy metal pollution in soil along the Le'an River in Jiangxi Province and found that cadmium and zinc were the most seriously polluted in the soil.

3.2 Abroad status

There is also a good deal of research published about soil heavy metal pollution worldwide, indicating soil heavy metal pollution has become a global pollution problem. According to the Journal of Environmental Pollution-Special Issue Global Soil Pollution Status, the use of non-pharmaceutical chemicals will surge globally by 2030, leading to an increasing burden of environmental pollution (Yang et al., 2020). In the middle of the 20th century, the United States, Holland, Japan, and other countries randomly dumped chemical reagents, and the local soils were seriously contaminated (Zhao & Yang, 2006). The Ruff Canal incident in the United States is a typical case of international soil pollution. The Ruff Canal was constructed in the 1890s and abandoned from the 1920s onwards to become a waste disposal site for the city of Niagara, where military waste from World War II, including nuclear waste from the Manhattan Project, as well as at least 200 types of about 21,800 tons of chemical wastes were dumped into landfills. However, in the 1950s, the Niagara Board of Education built schools in the area, and community amenities were gradually developed. By 1978, about 800 single-family homes and 240 low-income apartments had been built in the canal area, and two schools were located nearby, in addition to the 99th Street Elementary School, which is in the center of the landfill site. Beginning in the 1970s, contaminants such as unusual chemical odors, leaks of liquid reagents, and burns on the skin of children playing outdoors were discovered (Rohrman, 2004).

As early as the 1930s, a serious public health incident of soil contamination occurred in the Kanda River Basin in Fuji Prefecture, Japan. The large number of cadmium-containing pollutants discharged from lead and zinc smelters, cadmium-containing wastewater, and exhaust gases entered the soil through irrigation and atmospheric deposition. Subsequently, cadmium can enter the human body through the medium of rice and accumulate, causing hundreds of people to suffer from bone pain; Morton-Bermea et al. (2009) evaluated urban soil in 135 different areas of Mexico City, and the study showed that lead is a heavy metal with very high content in urban soil, and the pollution index is as high as 23.8. Up to now, soil pollution has been spread across continents and oceans. Developed countries have implemented the management measures earlier, for example, the Netherlands began to take effective measures against soil pollution in 1985, and the cost of remediation of contaminated land in the Netherlands, which has a total land area of 45,000 km, amounts to RMB 31,000,000 per annum. The annual cost of remediation of contaminated land in the Netherlands, which has a land area of 45,000 km, has amounted to more than 3.1 billion RMB (Zhou et al., 2016).

4. Microbial Remediation Technology

There are some similarities and differences between Microbial remediation technology and other remediation technologies. Microorganisms themselves often exhibit a strong degradation effect. With the help of their specific system, the metabolism of enzymes, iron carriers, organic acids, and other substances can complex or dissolve some of the heavy metal ions (Ahemad, 2015; Guo et al., 2015; Hafsteinsdottir et al., 2015; Sowmya et al., 2014; Zhang et al., 2010), to transform toxic heavy metals into non-toxic forms. Some enzymes produced by certain microorganisms (e.g., bacteria) can reduce heavy metals and have a specific affinity with some heavy metals, thus effectively eliminating toxic heavy metals. Soil remediation technology using microorganisms can play the role of adsorption, transformation, and precipitation of heavy metal substances in soil. The main principle of microbial remediation is to reduce the harmful effects of heavy metals in soil through valence transformation, biosorption, extracellular chemical precipitation, and volatilization (Ren & Liu, 2021), as shown in Figure 1. Among them, bacteria, fungi, and algae can be utilized for soil remediation respectively (Liu, 2021). Here the focus will be on the remediation by bacteria and fungi.

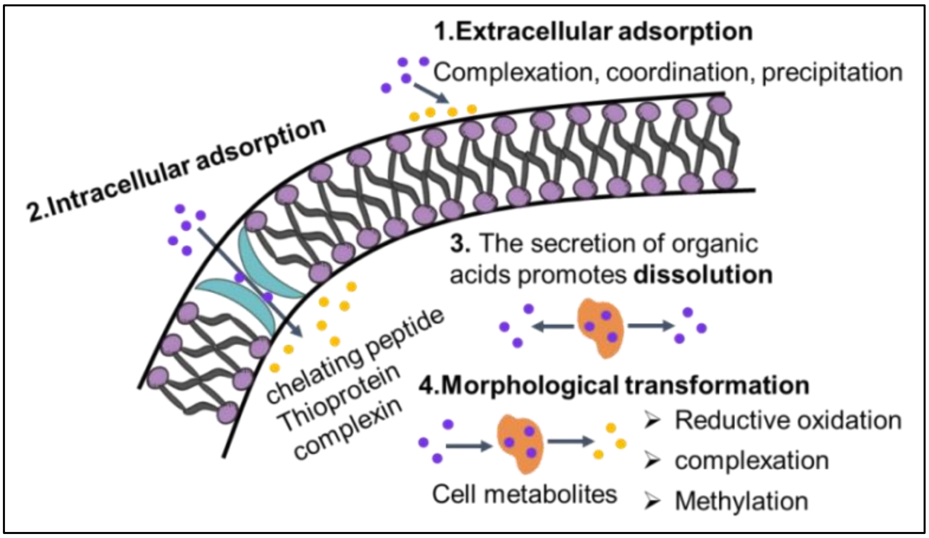

Figure 1. Action mechanism of microorganisms on heavy metals

4.1 Fungal Remediation Techniques-*Aspergillus Niger* as an Example

Aspergillus niger relies on chitosan on its cell wall to adsorb heavy metals and binds or passivate heavy metals through chemical reactions (Yao et al., 2008). Its adsorption mechanism includes surface complexation, redox reaction, electrostatic adsorption, ion exchange, and metabolite precipitation of heavy metals. However, the analysis of the interaction of these five adsorption mechanisms is a major difficulty, advanced characterization techniques will be used in future studies. These include FTIR, BET (specific surface area test), XPS (X-ray photoelectron spectroscopy technology), XRD (X-ray diffractometer technology), EDX (energy dispersion X-ray spectrometer), and others. Researchers also analyzed the adsorption mechanism from functional groups, morphology, and spatial structure, ion valence states, and equipotential to further promote practical applications.

4.1.1 Surface Complexation

Mannose, dextran, proteins, etc. existed on the cell wall of *Aspergillus niger*. The atoms of nitrogen, oxygen, phosphorus, and sulfur in these substances can form stable complexes with metal ions to provide lone-pair electron coordination for the metal ions. In specific, functional groups such as -COOH, -OH, $-NH_2$, -SH, $-SO_3H$, etc., can form stable complexes with the metal ions (Nourbakhsh et al., 2002). Wang Jingyao (Wang, 2017) analyzed the complexation on the surface of *Aspergillus niger* by FTIR (Fourier Transform Infrared Spectroscopy) and found that the C-H group at the characteristic peak at 2926 cm^{-1} and C=O group in carboxylate salt at the characteristic peak at 1740 cm^{-1} played an important role in the adsorption of Cu^{2+}. Chen Yingying (Chen, 2013) demonstrated that the active group for adsorption of Ni(II) was mainly -COOH by FTIR analysis of *Aspergillus Niger* before and after the adsorption of heavy metal ions. Drake (Drake et al., 1995) found that the ability of adsorption of heavy metals was reduced by 40% when esterification of -COOH on the surface of the cells occurred. Thus, it can be seen that different surface functional groups have different adsorption capacities for metals, and surface complexation is specific for the adsorption of heavy metals.

4.1.2 Redox Reaction

Due to the reducing nature of the organic acids secreted by *Aspergillus Niger,* when heavy metal ions are complexed by the surface-active groups, they can be passivated to nanoscale heavy metal particles through reduction reactions. Chakravarty et al. (Chakravarty et al., 2015) tested the reduction ability of five different fungi on heavy metals and found that gold nanoparticles could be reduced in large quantities from solution using *Aspergillus Niger* (NCIM616). Gu et al. (Gu et al., 2015) also found that the bioremediation of Cr^{6+} by *Aspergillus Niger* was mainly through reduction reaction and precipitation to remove the reduction product Cr^{3+}. The analysis of scanning electron microscopy and Raman spectroscopy showed that both Cr^{6+} and Cr^{3+} existed on the mycelium, which clearly proposed the removal mechanism of Cr^{6+} reduction, Cr^{3+} surface immobilization, and the intracellular accumulation in *Aspergillus Niger.* In the adsorption process, *Aspergillus Niger* mycelium will enhance the ability to secrete extracellular polymers and other organic small molecules under the stimulation of heavy metal ions, and the organic small molecules will reduce the biotoxicity of heavy metal ions at the same time as well as reducing the valence state of heavy metal. In general, the redox reaction accounts for a smaller proportion of the microbial adsorption of heavy metals in the process.

4.1.3 Electrostatic Adsorption

Electrostatic adsorption is the process by which charged functional groups on the surface of a fungus attract heavy metal ions with opposite charges to those they carry. Hydroxyl groups on the cell wall form many negative charges in the appropriate pH range, and the negative charges will adsorb the metals by electrostatic action when they are close to positively charged heavy metals. Galli (Galli et al., 2003) found that the functional groups on the surface of fungi ionize under acidic conditions and produce electrostatic charges, and electrostatic adsorption occurs on the surface of mycelium for metal cations when Cu^{2+} in solution binds to the negatively charged mycelium. Generally, main functional groups such as amino, carboxyl, and hydroxyl exist on the surface of *Aspergillus Niger*. Sun Fuhong (Sun et al., 2016) showed that the amino group binds heavy metal ions mainly through electrostatic action. At present, the greater influence on electrostatic adsorption is pH value, and other influencing factors need to be determined by further research.

4.1.4 Ion Exchange

Ion exchange technique is a new method of adsorption and release of heavy metal ions and an important mechanism of fungal adsorption. Chhikara (Chhikara et al., 2010) et al. treated *Aspergillus Niger* with acid and immobilized it in a calcium alginate matrix, and characterized the acid-treated *Aspergillus Niger* cell wall using FTIR. They found that there was an exchange of ions between -COOH, -OH, and $-NH_2$ before and after chromium adsorption. However, Raize (Raize et al., 2004) reported that the total amount of cations displaced was not significant relative to the adsorbed cations after studying the ion exchange of H^+ and OH^- in *Aspergillus Niger* cell walls using potentiometric titration. The multi-coordinated metal cations exchanged by ion exchange can further chelates with extracellular polymers. Therefore, ion exchange is often used as an auxiliary means in the adsorption of heavy metal elements together with other reactions.

4.1.5 Metabolite Precipitation of Heavy Metals

The mechanism of heavy metal adsorption by *Aspergillus Niger* is a complex process, in addition to surface adsorption, the metabolites of *Aspergillus Niger* also participate in the adsorption process. Yang et al. (Y. Yang et al., 2020) investigated the recovery ability of cobalt and nickel from the culture supernatant of *Aspergillus Niger* producing oxalic acid and found that the cobalt removal rate in the solution could be up to 90%. Proteomics analysis of Aspergillus Niger by Dias (Dias et al., 2019) showed that, under the condition of copper stress, the *Aspergillus Niger* produces response proteins that enhance its ability to absorb heavy metals. Zhao Nanshe (Nanshe, 2017) reported the inhibited the ras gene in *Aspergillus Niger* strains by RNA (ribonucleic acid) interference to analyze the role of heavy metal stress ras gene in the growth and metabolism of *Aspergillus Niger*. The study showed that the ras gene under heavy metal stress may inhibit the secretion of cellulase and acid by *Aspergillus Niger* through the regulation of related genes downstream of the signaling pathway, thus reducing the adsorption of heavy metals. Overall, heavy metal ions enter into the cells of *Aspergillus Niger*, followed by the occurrence of detoxification mechanisms as well as the expression of relevant genes under heavy metal stress. That means heavy metals can be metabolized and transformed through a series of chemically derived reactions. Therefore, metabolites chelate with heavy metals to play a major role in the intracellular adsorption process.

4.2 Bacterial Remediation

There are countless numbers of known bacteria in soil, and most of them will be adsorbed on the surface of the soil through activation, the migration of heavy metals in the soil will be transformed, and ultimately affect the environmental behavior of heavy metals in the soil (Huang et al., 2005). The three main ways to adsorb heavy metal ions are through extracellular adsorption, cell surface adsorption, and intracellular adsorption (Kotrba, 2011).

Extracellular adsorption is mainly through microbial secretion of polysaccharides, glycoproteins, lipopolysaccharides, and other extracellular polymeric substances (EPS) to complex or precipitate heavy metal ions. Studies have shown that EPS can rapidly and efficiently immobilize Pb^{2+}, Cu^{2+}, Zn^{2+}, and Cd^{2+} (Yu, 2019). Suh et al. studied the adsorption of Pb^{2+} by *A. thaliana*, and found that the secreted EPS could form a complex with Pb^{2+}, and the solubility of Pb^{2+} decreased with the increase of EPS secretion (Rahman et al., 2019).
Surface adsorption refers to the adsorption of heavy metal ions by microorganisms through charged cell surfaces. For example, *Staphylococcus hominis* AMB-2 adsorbs Pb^{2+} and Cd^{2+} to the cell surface, forming salt-like deposits. The adsorption of Pb^{2+} by AMB-2 is also higher due to the smaller hydration radius, greater electronegativity, and lower pKH of Pb^{2+}, and higher affinity with negatively charged functional groups such as hydroxyl groups and phenols (Aziz et al., 2008). In addition, microorganisms such as Bacillus, Mycobacterium, Lactobacillus, and Streptococcus also showed surface adsorption of heavy metal ions such as Cd, Pb, Zn, Ni, Cu, and Cr (Ledin, 2000).

Intracellular adsorption, on the other hand, involves the active uptake or adsorption of heavy metal ions by microorganisms during metabolism and the precipitation and immobilization of heavy metal ions within the cell to prevent their exposure to intracellular components. Intracellular sequestration is mainly through the metal-binding peptides in microorganisms to bind with heavy metals and form low or non-toxic complexes, thus alleviating the toxic effects of heavy metal ions. (Ybarra & Webb, 1999) investigated the effects of heavy metal ions, such as Cu^{2+}, Cd^{2+}, and Zn^{2+}, on the cyanobacterium PCC7942, and found that the exposure to heavy metals rapidly induced the expression of the gene encoding for MTs, smtA, which was still highly expressed after 2 hours of exposure. It was found that heavy metal exposure rapidly induced the expression of the gene encoding MTs, smtA, and the gene was still expressed at a high level after 2 hours of exposure, suggesting that MTs play an important role in organisms exposed to heavy metals for long periods of time (Ybarra & Webb, 1999). The secretion of glutathione, MTs, and PCs increased in Cd-stressing aquatic filamentous sporulation, and the intracellular biopeptide-Cd complexes increased gradually with the increase of Cd exposure (Jaeckel et al., 2005), and entered the vesicle under the action of the ABC-translocation protein (Ybarra & Webb, 1999). Entering protein into the vesicles reduced the toxic effects of heavy metals (Li et al., 1997). Here, two bacterial remediation techniques will be introduced in this paper.

4.2.1 Plant Growth-Promoting Bacteria Repair

Plant growth-promoting bacteria (PGPB) plays an important role in promoting the growth and development of plants and improving their adaptability to the environment and can increase the biomass of remediated plants accordingly through direct or indirect promotion mechanisms.

PGPB has mechanisms of activation, stabilization, transformation and detoxification for soil heavy metals. It affects the bioavailability of heavy metals by secreting chelating agents, acidification and redox reactions (Ma et al., 2016). Meanwhile, it consolidates heavy metal tolerance as well as its uptake and enrichment by regulating the expression of various heavy metal transporter proteins (e.g., ZRT-IRT-like proteins, heavy metaltransporting ATPase, and naturally resistant macrophage-associated proteins) and heavy metal chelators (e.g., biosurfactants, etc.) (Ma et al., 2022), as shown in Figure 2.

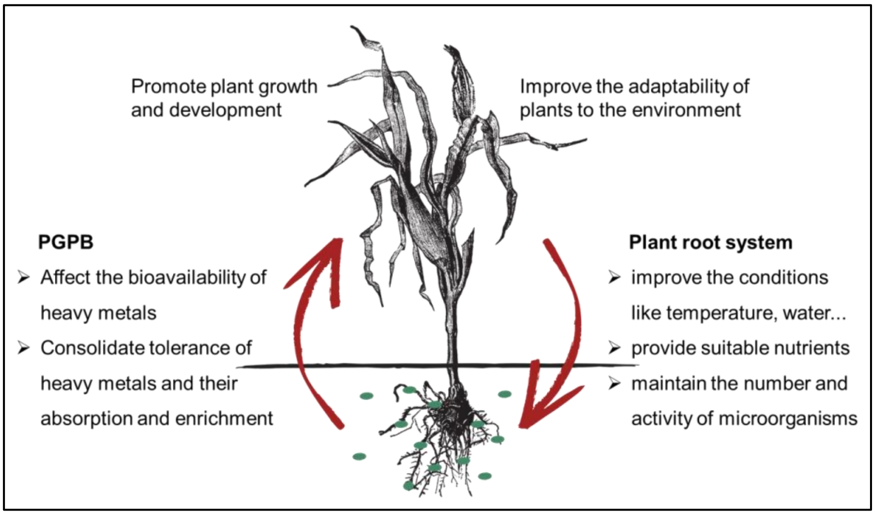

Figure 2. Mechanisms of PGPB to enhance heavy metal tolerance and promote growth in plants

Although PGPB have good effects on heavy metal soil remediation, their occurrence is also affected by many external environmental factors: the complexity and variability of the soil environment will affect the survival and function of PGPB affected; secondly, the microorganisms will also constitute a diverse community, which will interact with each other and inhibit their function; most importantly, the research on PGPB remediation is still in the initial stage of research and has not been effectively promoted.

4.2.2 Bacteria-Mineral Interaction and its Complex Repairing Role

Bacteria-mineral complexes act together on heavy metals in the soil environment to change the adsorption and migration behavior of heavy metal elements in the soil, which is of great significance in the remediation of heavy metal pollution. After bacteria and minerals act to form a complex, differences in the binding mode may lead to differences in the adsorption capacity of the complex (Feng et al., 2021). Due to the competitive adsorption of heavy metals by the bacterial and mineral components of the complex, the distribution and migration of heavy metals on the complex appear to be different, and many current studies have shown that the bacterial components of the complex play a major role in the immobilization of heavy metals. Walker et al. (Walker et al., 1989) investigated *E. coli K-12 extracellular membranes* in Ag^{+}, Cu^{2+}, Cd^{2+}, Ni^{2+}, Pb^{2+}, Zn^{2+}, and Cr^{3+} nitric acid solutions. *E. coli K-12 extracellular membrane*, *Bacillus subtilis* 168 cell wall interactions with montmorillonite and kaolinite found that the adsorption capacity of the complexes for heavy metals was in descending order: cell wall-montmorillonite, cell wall-kaolinite, extracellular membrane-montmorillonite, and extracellular membrane-kaolinite.

Fungi have a competitive relationship with indigenous microorganisms during soil remediation, and indigenous microorganisms will have a clear advantage in the natural state. Therefore, more research efforts are needed to make some progress in the field of macrofungi remediation of heavy metals in the future.

5. Conclusion and Perspectives

This review compares the principle of action, advantages and disadvantages, and applicability of different soil bioremediation technologies. Bioremediation technology has a wide range of application prospects, but the promotion of this technology is still in the experimental and demonstration stage and needs to be supported by the validation of many transformation results. From the long-term development consideration, bioengineering remediation technology, joint remediation technology, and combination application of highly efficient degrading microorganisms will be the main development direction of bioremediation technology in the future. If bioremediation technology is used solely to remediate heavy metal soils, its ability to act is also limited, and only through the joint action with other methods (physical, chemical, etc.) can the polluted soil with heavy metals be minimized (Mahvi et al., 2022).

Compared with other remediation methods, bioremediation technology focuses on the effect of ecosystem remediation, and the research in this area is still to be carried out in depth. However, due to the influence of geographic environment and climate, the effect of remediation cannot be correctly predicted, and how to overcome these shortcomings will become a research hotspot of heavy metal remediation technology (Li et al., 2020).

Through comparison, it can be found that soil heavy metal remediation is a high-cost and long-time ecological project, and the correct understanding of the mechanism of remediation methods is crucial to the applicability of heavy metal contaminated site remediation.

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Declaration of Conflicting Interests

All authors declare that they have no conflicts of interest.

References

Abe, T., Kobayashi, E., Okubo, Y., Suwazono, Y., Kido, T., Shaikh, Z., & Nogawa, K. (2001). Application of path analysis to urinary findings of cadmium-induced renal dysfunction. *Journal of Environmental Science and Health, Part A, 36*(1), 75-87.

Ahemad, M. (2015). Phosphate-solubilizing bacteria-assisted phytoremediation of metalliferous soils: a review. *3 Biotech, 5*(2), 111-121.

Aziz, H.A., Adlan, M.N., & Ariffin K.S. (2008). Heavy metals (Cd, Pb, Zn, Ni, Cu and Cr(III)) removal from water in Malaysia: Post treatment by high quality limestone. *Bioresource Technology: Biomass, Bioenergy, Biowastes, Conversion Technologies, Biotransformations, Production Technologies, 99*(6), 1578-1583.

Chakravarty, I., J Pradeepam, R., Kundu, K., K Singh, P., & Kundu, S. (2015). Mycofabrication of gold nanoparticles and evaluation of their antioxidant activities. *Current pharmaceutical biotechnology, 16*(8), 747-755.

Chen, C.-J., Chiou, H.-Y., Chiang, M.-H., Lin, L.-J., & Tai, T.-Y. (1996). Dose-response relationship between ischemic heart disease mortality and long-term arsenic exposure. *Arteriosclerosis, thrombosis, and vascular biology, 16*(4), 504-510.

Chen, G., Lei, J., Huang, Y., Xiong, L., & Huang, Y. (2015). Status of heavy metal contamination in paddy soil of Guangxi Province and effect of silicon fertilization on Cd content in brown rice. *Journal of Southern Agriculture, 46*(5), 772-776. https://doi.org/10.3969/j:issn.2095-1191.2015.5.772

Chen, Y. (2013). *Study on biological adsorption of heavy metal ions by aspergillus niger* [T, Shenyang: Shenyang Polytechnic University].

Chhikara, S., Hooda, A., Rana, L., & Dhankhar, R. (2010). Chromium (VI) biosorption by immobilized Aspergillus niger in continuous flow system with special reference to FTIR analysis. *Journal of Environmental Biology, 31*(5), 561-566.

Chowdhury, U.K., Biswas, B.K., Chowdhury, T.R., Samanta, G., Mandal, B.K., Basu, G.C., Chanda, C.R., Lodh, D., Saha, K.C., Mukheriee, S.K., Roy, S., Kabir, S., Quamruzzaman, Q., & Chakraborti D. (2000). Groundwater arsenic contamination in Bangladesh and West Bengal, India. *Environmental health perspectives, 108*(5), 393-397.

Dechang, H., Xiaoke, Z., Singh, T. V. V., Qi, L., Dazhong, W., & Wenju, L. (2009). Effects of heavy metal pollution of highway origin on soil nematode guilds in North Shenyang, China. *Journal of environmental sciences, 21*(2), 193-198.

Deng, X., Wen, L., & Chi, X. (2010). Cadmium hazards to human health and the prevention and treatment research New. *National Medical Frontiers of China, 5*(5), 4-5. https://doi.org/10.3969/j.issn.1673-5552.2010.10.0003

Dias, M., Gomes de Lacerda, J. T. J., Perdigão Cota de Almeida, S., de Andrade, L. M., Oller do Nascimento, C. A., Rozas, E. E., & Mendes, M. A. (2019). Response mechanism of mine-isolated fungus Aspergillus niger IOC 4687 to copper stress determined by proteomics. *Metallomics, 11*(9), 1558-1566.

Drake, L. R., Lin, S., Rayson, G. D., & Jackson, P. J. (1995). Chemical modification and metal binding studies of Datura innoxia. *Environmental Science & Technology, 30*(1), 110-114.

Feng, W., Lin, Z., Li, Y., Chi, H., Wang, S., Chao, Y., & Qiu, R. (2021). Interaction between bacteria and soil minerals and application of Bacterial-Mineral composites in remediation of heavy metals polluted soil. *Acta Pedologica Sinica, 58*(4), 851-861. https://doi.org/10.11766/trxb202007280143

Galli, E., Di Mario, F., Rapana, P., Lorenzoni, P., & Angelini, R. (2003). Copper biosorption by Auricularia polytricha. *Letters in Applied Microbiology, 37*(2), 133-137.

Gu, Y., Xu, W., Liu, Y., Zeng, G., Huang, J., Tan, X., Jian, H., Hu, X., Li, F., & Wang, D. (2015). Mechanism of Cr(VI) reduction by Aspergillus niger: enzymatic characteristic, oxidative stress response, and reduction product. *Environmental Science and Pollution Research, 22*(8), 6271-6279. https://doi.org/10.1007/s11356-014-3856-x

Guo, J. K., Ding, Y. Z., Feng, R. W., Wang, R. G., Xu, Y. M., Chen, C., Wei, X. L., & Chen, W. M. (2015). Burkholderia metalliresistens sp. nov., a multiple metal-resistant and phosphate-solubilising species isolated from heavy metal-polluted soil in Southeast China. *Antonie Van Leeuwenhoek, 107*, 1591-1598.

Hafsteinsdottir, E. G., Camenzuli, D., Rocavert, A. L., Walworth, J., & Gore, D. B. (2015). ChemInform Abstract: Chemical Immobilization of Metals and Metalloids by Phosphates. *ChemInform, 46*(33), no-no. https://doi.org/10.1002/chin.201533257

He, J., & Chen, J. P. (2014). A comprehensive review on biosorption of heavy metals by algal biomass: Materials, performances, chemistry, and modeling simulation tools. *Bioresource Technology: Biomass, Bioenergy, Biowastes, Conversion Technologies, Biotransformations, Production Technologies, 160*, 67-78. https://doi.org/10.1016/j.biortech.2014.01.068

Huang, Q., Chen, W., & Xu, L. (2005). Adsorption of copper and cadmium by Cu-and Cd-resistant bacteria and their composites with soil colloids and kaolinite. *Geomicrobiology Journal, 22*(5), 227-236.

Jaeckel, P., Krauss, G., Menge, S., Schierhorn, A., Rücknagel, P., & Krauss, G.-J. (2005). Cadmium induces a novel metallothionein and phytochelatin 2 in an aquatic fungus. *Biochemical and biophysical research communications, 333*(1), 150-155.

Kotrba, P. (2011). *Microbial biosorption of metals—general introduction*. Springer.

Ledin, M. (2000). Accumulation of metals by microorganisms—processes and importance for soil systems. *Earth-Science Reviews, 51*(1-4), 1-31.

Li, J. (2022). Analysis on the status quo of soil heavy metal pollution and detection technology. *Chemical Engineering Design Communications, 48*(2), 193-195. https://doi.org/10.3969/j.issn.1003-6490.2022.02.066

Li, T., Wu, M., Wang, Y., Yang, H., Tang, C., & Duan, C. (2020). Adances in research on the effects of human disturbance processes of heavy metals and remediation. *Acta Ecologica Sinica, 40*(13), 4679-4688.

Li, Z.-S., Lu, Y.-P., Zhen, R.-G., Szczypka, M., Thiele, D. J., & Rea, P. A. (1997). A new pathway for vacuolar cadmium sequestration in Saccharomyces cerevisiae: YCF1-catalyzed transport of bis (glutathionato) cadmium. *Proceedings of the National Academy of Sciences, 94*(1), 42-47.

Liu, G., Tao, L., Liu, X., Hou, J., Wang, A., & Li, R. (2013). Heavy metal speciation and pollution of agricultural soils along Jishui River in non-ferrous metal mine area in Jiangxi Province, China. *Journal of Geochemical Exploration, 132*, 156-163.

Liu, Y. (2021). Study on the role of microorganisms in the remediation of heavy metal contaminated soil. *Chemical Engineering Design Communications, 47*(10), 196-197. https://doi.org/10.3969/j.issn.1003-6490.2021.10.095

Ma, Y., Rajkumar, M., Zhang, C., & Freitas, H. (2016). Beneficial role of bacterial endophytes in heavy metal phytoremediation. *Journal of Environmental Management, 174*, 14-25. https://doi.org/10.1016/j.jenvman.2016.02.047

Ma, Y., Wang, Y., Shi, X., Chen, X., & Li, Z. (2022). Beneficial role of bacterial endophytes in heavy metal phytoremediation. *Journal of Environmental Management, 43*(9), 4911-4922. https://doi.org/10.13227/j.hjkx.202112007

Mahvi, A., Eslami, F., Baghani, A., Khanjani, N., Yaghmaeian, K., & Mansoorian, H. (2022). Heavy metal pollution status in soil for different land activities by contamination indices and ecological risk assessment. *International Journal of Environmental Science and Technology, 19*(8), 7599-7616.

Morton-Bermea, O., Hernandez-Alvarez, E., & Gonzalez-Hernandez, G. (2009). Assessment of heavy metal pollution in urban topsoils from the metropolitan area of Mexico City. *Journal of Geochemical Exploration: Journal of the Association of Exploration Geochemists, 101*(3), 218-224. https://doi.org/10.1016/j.gexplo.2008.07.002

Nanshe, Z. (2017). *Silencing of ras in aspergillus niger and primary studies of its effect on mycelial growth* [T, Harbin: Harbin Institute of Technology].

Nordberg, G. F. (2004). Cadmium and health in the 21st century–historical remarks and trends for the future. *Biometals, 17*, 485-489.

Nourbakhsh, M. N., Kiliçarslan, S., Ilhan, S., & Ozdag, H. (2002). Biosorption of Cr6+, Pb2+ and Cu2+ ions in industrial waste water on Bacillus sp. *Chemical Engineering Journal, 85*(2-3), 351-355.

Qiuchan, H. (2007). Review of the Toxicological Effect and the Mechanism of Cadmium to Human Health. *Journal of Anhui Agricultural Sciences, 35*(9), 2528.

Rahman, Z., Thomas, L., & Singh, V. P. (2019). Biosorption of heavy metals by a lead (Pb) resistant bacterium, Staphylococcus hominis strain AMB ‐ 2. *Journal of basic microbiology, 59*(5), 477-486.

Raize, O., Argaman, Y., & Yannai, S. (2004). Mechanisms of biosorption of different heavy metals by brown marine macroalgae. *Biotechnology and bioengineering, 87*(4), 451-458.

Ren, Z., & Liu, S. (2021). Research progress on remediation of heavy metal contaminated soil. *Bulletin of the Chinese Ceramic Society, 40*(6), 2042-2051.

Rohrman, D. (2004). Poisoned Love. *Frontiers in Ecology and the Environment, 2*(1), 51-51. https://doi.org/10.1890/1540-9295(2004)002[0051:Pl]2.0.Co;2

Shi, R., Zhao, Y., Peng, S., Zhang, T., Liu, F., & Zhou, Q. (2008). Cadmium accumulation in soil and crops and pollution risks to human Health under different land use types. *Resources Science, 30*(12), 1904-1909. https://doi.org/10.3321/j.issn:1007-7588.2008.12.019

Sowmya, S., Rekha, P., & Arun, A. (2014). Uranium (VI) bioprecipitation mediated by a phosphate solubilizing Acinetobacter sp. YU-SS-SB-29 isolated from a high natural background radiation site. *International Biodeterioration & Biodegradation, 94*, 134-140.

Sun, F., Liao, H., Chen, Y., Mu, Y., Li, H., & Wu, F. (2016). Studies on biosorption of antimony(V) by microcystis. *China Environmental Science, 36*(11), 3383-3389.

Walker, S., Flemming, C., Ferris, F., Beveridge, T., & Bailey, G. (1989). Physicochemical interaction of Escherichia coli cell envelopes and Bacillus subtilis cell walls with two clays and ability of the composite to immobilize heavy metals from solution. *Applied and Environmental Microbiology, 55*(11), 2976-2984.

Wang, J. (2017). *Biosorption efficiency and mechanism of heavy metal from aquous solution using aspergillus niger treated rice straw* Harbin: Harbin Institute of Technology].

Wang, J., Li, D., Liu, J., Hou, C., & Zhang, Q. (2015). Effects of cadmium tolerant bacteria on soil cadmium forms and microbial community structure. *Journal of Agro-Environment Science*(9), 1693-1699. https://doi.org/10.11654/jaes.2015.09.010

Wasserman, G. A., Liu, X., Parvez, F., Ahsan, H., Levy, D., Factor-Litvak, P., Kline, J., van, G. A., Slavkovich, V., LoIacono, N. J., Cheng, Z., Zheng, Y., & Graziano, J. H. (2006). Water manganese exposure and children's intellectual function in Araihazar, Bangladesh. *Environmental health perspectives, 114*(1), 124-129.

Wei, X., Liu, Y., & Pan, L. (2016). Heavy Metal Contamination in Farmland Soil and Bioremediation Measures: A Case Study of the Mining Area in Shaoguan. *Asian Agricultural Research*(7).

Wei, Y., & Huang, Q. C. (2008). The toxicological effect of lead on the human health and its measures of preventing. *Stud Trace Elem Health*, *25*(4), 62-64.

Xu, X., Zhao, Y., Zhao, X., Wang, Y., & Deng, W. (2014). Sources of heavy metal pollution in agricultural soils of a rapidly industrializing area in the Yangtze Delta of China. *Ecotoxicology and environmental safety, 108*, 161-167.

Yang, G., Zhang, M., Feng, T., Li, M., Zhang, H., Deng, Y., & Yan, J. (2020). Research status and prospect of remediation technology of heavy metal pollution soil. *Modern Chemical Industry, 40*(12), 50-54, 58.

Yang, Y., Song, W., Ferrier, J., Liu, F., & Csetenyi, L. (2020). Biorecovery of cobalt and nickelusing biomass - free culture supernatants from aspergillus niger. *Applied Microbiology and Biotechnology, 104*(1), 417 - 425.

Yao, R., Meng, F., Zhang, L., Ma, D., & Kang, X. (2008). Study and application of adsorption of heavy metal Ions by modified chitosan. *Materials Review, 22*(4), 65-70. https://doi.org/10.3321/j.issn:1005-023X.2008.04.017

Ybarra, G., & Webb, R. (1999). Effects of divalent metal cations and resistance mechanisms of the cyanobacterium Synechococcus sp. strain PCC 7942. *Journal of Hazardous Substance Research, 2*(1), 1.

Yu, J. (2019). *Study on adsorption of heavy metals by exopolysaccharide of endophytic bacteria from seabuckthorn nodules* Lanzhou: Northwest Normal University].

Zhang, X., Xia, H., Li, Z., Zhuang, P., & Gao, B. (2010). Potential of four forage grasses in remediation of Cd and Zn contaminated soils. *Bioresource technology, 101*(6), 2063-2066.

Zhang, Z., Cheng, L., Shang, H., & Li, Y. (2012). Review and trend of eco-compensation mechanism on river basin. *Acta Ecologica Sinica, 32*(20), 6543-6552. https://doi.org/10.5846/stxb201201310130

Zhao, Q., & Yang, K. (2006). Contaminated land redevelopment management of developed countries and the inspirations to China. *Environmental Pollution & Control, 28*(7), 540-544. https://doi.org/10.3969/j.issn.1001-3865.2006.07.016

Zhou, J., Zhou, J., & Feng, R. (2014). Status of China's heavy metal contamination in soil and its remediation strategy. *Chinese Academy of Sciences, 29*(3), 315-320,350,312. https://doi.org/10.3969/j.issn.1000-3045.2014.03.008

Zhou, Y., Wan, J., Lin, Y., Lie, Q., & Zhang, S. (2016). Discussion on characteristics of soil environmental problems in China and foreign experience reference on soil environmental management. *Chinese Journal of Environmental Management, 8*(3), 95-100. https://doi.org/10.16868/j.cnki.1674-6252.2016.03.095

Zhu, Y., Wu, J., Yu, Z., Deng, Y., Liu, D., Xu, C., Lv, Y., & Yang, G. (2024). Current situation and control research progress on heavy metal pollution in farmland soil in China. *Modern Agricultural Science and Technology*(5), 115-118,125. https://doi.org/10.3969/j.issn.1007-5739.2024.05.029