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Development Status and Application Prospect of Microbial Remediation Technology in Soil Heavy Metal Pollution

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Abstract: Heavy metal pollution control is one of the important measures to realize pollution control and ecological construction in China, the soil carries the important function of ecological activities, soil heavy metal pollution will destroy the soil's ecological energy supply, affecting human health will also lead to the decline of ecological diversity. Microbial remediation stands out because of its high efficiency, stability and avoidance of secondary pollution, this paper through a systematic combing and comprehensive analysis of microbial remediation technology to manage soil heavy metal pollution key technical principles, advantages and disadvantages and bottlenecks. Microbial remediation technology mainly realizes the treatment of heavy metal pollution through three core mechanisms: biological adsorption and surface complexation, redox transformation, and biomineralization synergy. These mechanisms improve the remediation effect through synergistic effects but face different challenges, such as environmental sensitivity, harsh metabolic conditions, etc. This paper focuses on microbial remediation for degrading soil heavy metal pollution, focuses on the three core mechanisms of microbial remediation, reveals its core value in remediation, and seeks to comprehensively sort out the core points of microbial remediation technology, identify the corresponding technological bottlenecks and summarize the direction of development, and provide an outlook of microbial remediation technology to promote China's microbial remediation technology. Microbial remediation technology, and promote the development of microbial remediation technology in China.

Keywords: Soil heavy metal pollution, pollution control , microbial remediation technology, green remediation, bacterial remediation

1. Introduction

Soil is an important part of the ecosystem, carrying functions such as plant growth, water circulation and nutrient cycling, but with the intensification of human activities, heavy metals have been accumulating in the soil, leading to serious heavy metal pollution [1,2]. This pollution not only destroys soil ecological functions but also jeopardizes human health through the food chain [3]. Economically, the loss of arable land brings huge losses. In addition, soil pollution leads to the decline of biodiversity. From the ecological point of view, it is very important to carry out timely remediation and treatment of soil heavy metal pollution [4]. Although the existing remediation technologies, such as physical and chemical, are effective, they are generally characterized by high cost, poor

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remediation capacity, narrow scope of application, and can cause secondary pollution [2]. Against this background, microbial remediation has emerged as a new technology with its environmental friendliness and high efficiency. It has been shown that Cd can replace essential metals in organisms and bind to protein molecules to interfere with cellular metabolism [5]. ZENG et al. implemented MICP treatment for the first time in Cd-contaminated sludge, which resulted in the transfer of ionic Cd2+ from the sludge to the supernatant, with an immobilization efficiency of 98.46% [6].

This paper focuses on microbial remediation for degrading soil heavy metal pollution, focuses on the three core mechanisms of microbial remediation, reveals its core value in remediation, seeks to comprehensively sort out the core points of microbial remediation technology, identifies the corresponding technological bottlenecks and summarizes the direction of development, and looks forward to the microbial remediation technology to promote the development of microbial remediation technology in China [7].

2. Analysis of the advantages of microbial remediation technologies

2.1. Introduction to the concept

Microbial remediation technology is a green bioremediation strategy based on the metabolic function of microorganisms, the core of which is the use of microorganisms to adsorb, transform, mineralize and morphology regulation of heavy metals to achieve in-situ or ectopic treatment of pollutants[8,9]. Microbial remediation technology has multiple advantages: microorganisms have multiple metabolic pathways and fast rates and are able to use a variety of toxic compounds as energy sources for their growth and development through respiration, fermentation and co-metabolism. Secondly, microorganisms have unique degrading enzymes for specific pollutants, and can evolve multiple mechanisms to maintain homeostasis and resist heavy metals in ecosystems adapted to toxic metals, and can also develop defense mechanisms for overcoming toxic effects such as destruction of microbial cell membranes by heavy metals [10,11]. In addition, microorganisms can also carry out in-situ or ex-situ remediation of heavy metal contamination through mechanisms such as bioaccumulation, biomineralization, biosorption and biotransformation; in-situ remediation avoids soil disturbance, and microorganisms can maintain their homeostasis through defense mechanisms to reduce the risk of secondary contamination [9].

2.2. Strengths analysis

The transformation of heavy metal forms by microorganisms is also an important way for them to manage heavy metal pollution. There are significant differences in the mobility and bio-activity of different forms of heavy metals, and microbial activities can promote the transformation of heavy metals from the exchangeable and carbonate-bound states, which have high bio-activity and high mobility, to the organic-bound or residue states, which have low bio-activity and low mobility. This transformation process greatly reduces the ability of heavy metals to migrate in the environment, which in turn significantly reduces their potential threat to the ecosystem. The research results show that this transformation mechanism is of great significance in practical applications.

Currently, microbial remediation technology has progressed from laboratory research to engineering application. In terms of technological innovation, the construction of genetically engineered bacteria and the targeted domestication of composite flora have significantly improved the remediation efficiency and resistance [12]. In terms of application mode, the bacterial-plant synergistic technology enhances heavy metal uptake by 3-5 times by expanding the inter-root interface with transmembrane translocation potentiation [13]. In the study of microbial remediation technology for heavy metal contaminated soil, the mechanism of action of microorganisms to reduce the concentration of heavy metals is mainly divided into three mechanisms: biosorption and surface

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complexation mechanism,redox transformation mechanism,and biomineralization synergistic mechanism.

3. Three major mechanisms of action of microorganisms to reduce heavy metal concentrations

3.1. Biosorption and surface complexation mechanisms

Functional groups on the surface of microbial cells and their secreted extracellular polymers (EPS) are able to rapidly immobilize heavy metal ions by electrostatic adsorption and ion exchange, thus reducing their free-state concentration and the direct impact on the ecosystem. Adsorption and surface complexation of heavy metals by microorganisms is an important part of the initiation of microbial remediation of heavy metal contaminated soil. The surface of microbial cells and the extracellular polymers (EPS) secreted by microorganisms are able to adsorb heavy metal ions with high efficiency, and this process can effectively reduce the free-state concentration of heavy metal ions in the environment and reduce their direct impact on the surrounding ecosystems [14]. Its core advantage lies in its high efficiency and broad spectrum: for example, the maximum adsorption of cadmium by Thiobacillus metallophilus is as high as 250 mg/g, which is 10 times higher than that of activated carbon [15]. Xin Meifen showed through her study that EPS secreted by the heavy metal tolerant microorganism Enterobacteriaceae FM-1 can adsorb Cd2+ and Pb2+ through surface complexation and ion exchange [16].

This process is mainly accomplished passively through physicochemical effects such as electrostatic adsorption and ion exchange, which do not require energy consumption and is characterized by rapidity and high efficiency. When heavy metal ions enter the microbial surroundings, positively charged heavy metal ions will be attracted to negatively charged cell wall functional groups and extracellular polymers through electrostatic attraction. Taking polysaccharide-metal chelation and protein-ligand bond binding as the main forms, heavy metal ions are tightly bound to these substances to form stable complexes [17,18]. For example, Yin Baxuan et al showed that the content of extracellular polymer proteins in the inner and outer binding layers of the biofilm cell wall of Pseudomonas malodorata all increased under Ni(II) stress. Related studies have shown that this process can reduce the concentration of free-state heavy metals in the environmental medium by more than 80%, which greatly reduces the mobility and bioavailability of heavy metals in the soil solution and limits their diffusion and harm in the soil environment. Xu Wenting et al pointed out in their study that microorganisms such as Bacillus, Bacillus immobilis, and cotyledonous mycorrhizal fungi can change the bioavailability of Cd by adsorption and mineralization, thus alleviating Cd pollution. However, their adsorption capacity is affected by the saturation effect of the binding sites on the microbial surface and environmental factors (e.g., pH, temperature), and periodic replenishment of microorganisms is required to maintain the remediation efficacy [19]. Therefore, the technology is more suitable for short- to medium-term emergency rehabilitation or in conjunction with other long-term mechanisms.

3.2. Redox transformation mechanism

The redox transformation mechanism relies on microbial enzymatic reactions to directly change the valence state of heavy metals (e.g., Cr(VI) to Cr(III)) or indirectly regulate the environmental redox potential (Eh), thereby reducing the toxicity of heavy metals. In terms of direct reduction, microorganisms can directly alter the valence state of heavy metals through enzymatic reactions, converting highly toxic valence states of heavy metals to low-toxicity ones, thereby reducing their toxicity and facilitating subsequent treatment of heavy metals. During this process, microorganisms can directly reduce Cr(VI) to Cr(III) ,or Hg^{2+} to Hg^0, reducing their toxicity [20].

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In terms of indirect oxidation, microorganisms can oxidize As(III) to As(V) [21]. The toxicity and mobility of As(III) are higher than those of As(V), and this oxidation process helps to reduce the environmental risk of arsenic. Additionally, microorganisms can change the redox potential (Eh) of the soil environment by regulating the Fe^{3+}/Fe^{2+} system, which in turn affects the solubility of heavy metals [22]. For example, when the environmental potential changes, originally insoluble heavy metal compounds may become less soluble, thus reducing their mobility and bioavailability in the soil.

Numerous studies have shown that this process can decrease the bioavailability of heavy metals by 65%-92%, and the transformation products can enter subsequent mineralization stages, further reducing the harm of heavy metals to the soil ecosystem, effectively building a solid defense line for the management of heavy metal toxicity. However, its limitations are reflected in the specificity of the transformation pathways and the secondary risks: for instance, the reduction of Hg^{2+} to Hg^0 relies on specific reductases, while Cr(III) may reactivate in acidic soils. Therefore, this mechanism should be combined with soil physicochemical properties to customize microbial agents, supplemented by stabilization measures to prevent secondary pollution.

3.3. Biochemical mineralization synergistic mechanism

The metabolic-mineralization synergistic mechanism transforms soluble heavy metals into insoluble minerals through a sulfide/carbonate system produced by microbial metabolism, promoting the transition of heavy metals to residual forms. The core mechanism of microbial remediation of heavy metal-contaminated soils begins with the dynamic regulation of metabolic products. Its significant advantage lies in long-lasting stability. For example, microorganisms secrete organic acids through metabolic activities, which provide carbon sources and energy for their growth, promoting microbial proliferation [22]. Concurrently, these substances can dissolve insoluble heavy metals in the soil into exchangeable ions through strong complexation, significantly enhancing the bioavailability of heavy metals [22]. On this basis, microorganisms initiate the sulfide/carbonate system, utilizing S^{2-} produced by sulfate-reducing bacteria or CO_3^{2-} released by carbonate bacteria to bind with free heavy metals, forming insoluble metal sulfides or metal carbonates, thereby achieving stable transformation of heavy metals from soluble to mineral forms.

Furthermore, the synergistic effects of microbial-plant interactions enhance the ecological efficacy of the remediation process. Mycorrhizal fungi form symbionts with plant roots, enhancing the roots' capacity to absorb heavy metals and altering soil pH through the secretion of organic acids, promoting the binding of heavy metals to soil particles and reducing their mobility [12,23]. For example, some rhizobacteria influence plants' absorption of heavy metals by altering soil physicochemical properties and secreting secondary metabolites [13]. Under this collaborative effect, the efficiency of transmembrane transport of heavy metals is increased by 3-5 times, allowing plants to more efficiently absorb and stabilize heavy metals in the soil, achieving remediation of contaminated soils [24].

Ultimately, the morphology transformation pathway driven by biogenic mineralization ensures the long-term effectiveness of remediation. Mediated by anionic extracellular polymers produced by microorganisms such as cyanobacteria and sulfate-reducing bacteria, heavy metals are gradually transformed along the pathway from exchangeable state → carbonate-bound state → organic-bound state → residual state [25]. As the remediation process progresses, heavy metals are gradually transformed into carbonate-bound states, reducing their mobility and bioavailability; further transformation into organic-bound states leads to tight binding with organic materials in the soil, enhancing stability; ultimately, the transformation into residual states results in a progressive decrease in the mobility of heavy metals, rendering them nearly harmless to the environment, thus achieving long-lasting and stable remediation of heavy metal-contaminated soils. However, this process

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requires stringent metabolic conditions: sulfate-reducing bacteria need strictly anaerobic environments, and the establishment of mycorrhizal symbiotic systems takes 3-6 months. Therefore, this mechanism is more suitable for integration with phytoremediation technologies to enhance mineralization efficiency through rhizosphere microenvironment regulation.

3.4. Future prospects of the three major mechanisms

The three core mechanisms mentioned above are not only independent but also work synergistically to enhance remediation effects. During the remediation process, bioadsorption provides rapid interception, redox transformation controls the bioavailability of heavy metals by adjusting toxicity, while biogenic mineralization ensures long-term stable fixation [26]. To enhance the practical application of this remediation technology, future research should further refine the regulatory roles of these mechanisms under different environmental factors (such as pH, Eh, etc.), and supplement recent findings from mycorrhizal transcriptomics to provide theoretical support for the engineering application of microbial remediation technologies [27,28].

4. Conclusion

This paper comprehensively analyzes the core mechanisms, technical classifications, and practical application potential of microbial remediation technology in the management of heavy metal-contaminated soils through a systematic review and literature integration approach. Based on multi-source research findings, it focuses on the mechanisms by which microorganisms reduce the toxicity and mobility of heavy metals through pathways such as bioadsorption, redox transformation, and synergistic biomineralization. Additionally, it evaluates the applicability of strategies like microbial-plant synergy and metabolic product regulation in various pollution scenarios. Overall, these three core mechanisms collectively enhance the remediation effectiveness through their synergistic actions. Each mechanism, however, has its advantages and challenges. Although bioadsorption and surface complexation mechanisms are rapid, efficient, and energy-free, they are limited by the saturation effect of microbial surface binding sites and environmental sensitivity. The redox transformation mechanism, while highly effective, is constrained by the specificity of transformation pathways and risks of secondary contamination. The significant advantage of synergistic biomineralization lies in its long-term stability, yet this process demands stringent metabolic conditions.

Based on the above conclusions, we make the following outlook. To enhance the practical application effectiveness of this remediation technology, future research should further refine the regulatory effects of these mechanisms under different environmental factors(such as pH, Eh, etc.) and incorporate recent findings from mycorrhizal transcriptomics to provide theoretical support for the engineering application of microbial remediation technology. Future development directions should focus on constructing intelligent remediation systems. Microbial behavior should be predicted through AI models, and solutions should be optimized. Synthetic microbial communities should be developed to enhance the treatment capacity for complex pollution. Nanomaterials should be combined to improve targeted delivery efficiency. Meanwhile, it is necessary to improve the biosafety assessment system and related policies and regulations, promote the standardization of the technology, and advance the management of heavy metal pollution in soil in our country.

Authors contribution

All the authors contributed equally and their names were listed in alphabetical order.

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