ISSN: 2688-8645

Multidimensional Regulatory Mechanisms of *Arbuscular Mycorrhizal Fungi* on the Migration and Transformation of Heavy Metals in Soil

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Abstract

With the rapid development of industrialization and urbanization, soil heavy metal pollution has become a global ecological environment and health problem. Heavy metals such as Cd, Pb, and Hg enter the soil environment through mining, industrial emissions, and agricultural activities, and pose a serious threat to soil ecological function, food security, and human health due to their concealment, refractory degradation, and bioaccumulation. Traditional remediation technologies have limitations such as high cost and high risk of secondary pollution, while bioremediation technologies have attracted extensive attention due to their eco-friendliness and sustainability. Among them, AMF has shown significant potential in the remediation of heavy metal contaminated soil by forming a symbiotic system with plants. In this paper, we systematically reviewed the regulatory mechanism of AMF-plant symbiosis system on the migration and transformation of heavy metals, including the multi-dimensional effects of physical barrier, chemical fixation and biotransformation. At the physical level, AMF promotes the formation of soil aggregates through hyphal network and balloon-related soil protein (GRSP), which effectively intercepts heavy metal ions. At the chemical level, AMF changes the occurrence form of heavy metals and reduces their bioavailability by secreting organic acids, regulating rhizosphere pH and redox potential (Eh). In addition, the effects of environmental factors such as soil characteristics, climatic conditions and agricultural activities on the colonization and remediation efficiency of AMF have also been deeply explored. This paper provides a theoretical basis for the application of AMF in the remediation of heavy metal contaminated soil, and looks forward to future research directions, including efficient strain screening, field technology optimization, and analysis of multi-factor collaborative regulation mechanism. The synergistic regulatory mechanism mediated by it and the derived rhizosphere multi-dimensional restoration system can significantly improve the expression of plant stress resistance genes and reduce the bioavailability of heavy metals, which is an irreplaceable long-term solution in the current heavy metal pollution control.

Keywords

AMF; Heavy Metal Pollution; Soil Remediation.

1. Introduction

With the rapid advancement of industrialization and urbanization, soil heavy metal pollution has become a serious problem that threatens global ecological security and human health. Heavy metals (heavy metals) such as cadmium, lead, and mercury continue to enter the soil

ISSN: 2688-8645

environment through mineral mining, industrial wastewater discharge and excessive use of agricultural chemicals. Although traditional remediation technologies (such as chemical fixation and physical isolation) can reduce the activity of heavy metals in the short term, they generally have disadvantages such as high cost, high risk of secondary pollution, and difficulty in large-scale application. In this context, bioremediation technologies that are both eco-friendly and sustainable have attracted much attention, among which AMF has become a research hotspot due to its unique ecological function. By analyzing the dual repair mechanism of AMF fixing heavy metals and regulating plant physiological metabolism, it can provide technical support for the targeted screening of high-efficiency stress-resistant strains and the optimization of field remediation technology.

2. Migration Process of Heavy Metal Ions In Soil

In the soil environment, the migration and transformation of heavy metal ions is a complex process of physical, chemical and biological processes, and its pathways are regulated by multiple factors and present multi-dimensional interaction characteristics. First, physical transport is mainly achieved by wind and hydraulic forces: the wind carries soil particles attached to heavy metals to form dust, which is transported by the atmosphere and redistributed with subsidence or precipitation. Hydraulics promotes the accumulation of heavy metals to low-lying areas through surface runoff, or pollutes the groundwater system with water infiltration, so as to complete the spatial transfer across media. Secondly, the chemical transformation depends on the soil acid-alkali environment (pH), redox potential (Eh) and ion exchange adsorption mechanisms: under acidic conditions, heavy metals are desorbed and activated from soil particles, and the reducing environment changes their valence solubility, while the adsorption-desorption equilibrium of soil colloids dynamically regulates the distribution of heavy metals in the solid-liquid phase, which jointly affects their chemical activity and migration ability. On the basis of physical migration and chemical transformation, biological processes further regulate the migration pathways of heavy metals through multi-dimensional mechanisms, which has become a key link in determining their environmental fate. By secreting metabolites such as organic acids and polysaccharides, soil microorganisms complexed or chelated with heavy metal ions, which significantly improved their solubility in soil solution and promoted migration. Plant roots change the pH and Eh of the rhizosphere microenvironment by releasing exudates to enhance the bioavailability of heavy metals, and at the same time, through absorption, transport, and enrichment, they transfer heavy metals from soil to plants, and reconstruct their distribution pattern between soil and plant ecosystems[1]. In addition, the bioturbation behavior of soil fauna (such as earthworms) improves soil pore structure and indirectly affects the diffusion path of heavy metal ions. These biological processes are not only coupled with physical and chemical processes, but also reshape their migration and transformation trajectories at the microscopic scale by changing the occurrence morphology and bioavailability of heavy metals. In general, the migration and transformation of heavy metal ions in soil is not dominated by a single mechanism, but the physical migration lays the foundation for spatial distribution, the chemical transformation regulates the occurrence of morphology and activity, and the biological process deepens its environmental effects through multiple pathways such as metabolism, absorption and habitat modification.

3. Application and Limitations of Traditional Soil Heavy Metal Remediation Technology

The traditional soil heavy metal remediation technology directly intervenes in the polluted medium through engineering means, and although it achieves short-term risk control in specific scenarios, its technical defects will gradually emerge with the remediation process. Although the remediation strategy focusing on pollutant removal or passivation can quickly reduce the concentration of heavy metals in the surface layer, the treatment cost remains high due to the over-reliance on external energy and material input, and it is often difficult to restore the soil ecosystem function simultaneously after restoration. Although the soil replacement technology blocks the pollution exposure pathway through media substitution, the large-scale earthwork not only significantly destroys the original soil structure, but also causes secondary environmental problems, and its ecological reconstruction period is far longer than expected. Although chemical fixation technology can temporarily reduce the activity of heavy metals, the environmental stability of passivators is subject to complex geochemical processes, and passivation failure is easy to occur with the fluctuation of soil physical and chemical conditions, resulting in pollution rebound. The sensitivity of leaching technology to soil texture limits its applicability, especially in fine soils, and the treatment efficiency decreases sharply, while the residue of chemical reagents may activate deep pollution migration and exacerbate ecological risks [2]. Furthermore, although phytoremediation has the advantage of in-situ implementation, its slow pollutant removal rate is difficult to meet the actual remediation needs, and long-term planting may change the local heavy metal occurrence pattern through root activities, inducing the spread of secondary pollution. What's more serious is that there is an imbalance between energy efficiency and ecological benefits in the existing technical system, and most remediation projects cause irreversible damage such as soil biological activity inhibition and organic matter loss while reducing the effectiveness of heavy metals.

4. Biological Characteristics of the Arbuscular Mycorrhizal Fungal-Plant Symbiotic System

AMF is an obligate symbiotic fungus in the root system of land plants, which can form a complex interaction network with more than 80% of terrestrial plants, and construct a symbiotic structure including intra-root hyphae, arbuscular branches and extra-rhizophal networks. The symbiotic system interaction begins at the chemical signal recognition stage, where flavonoids secreted by plant roots and lipid chito-oligosaccharides released by fungi activate the host signaling pathway through molecular interaction, which in turn initiates the symbiotic gene expression network, laying the foundation for the subsequent structural establishment [3]. Subsequently, the hyphae invade the plant cortex through the intercellular space of the epidermis, forming a highly branched arbuscular structure within the cell, and constructing a symbiotic membrane system containing bidirectional material exchange channels. In such an interactive system, the host transports fatty acid-based carbon sources to fungi through glycotransporters, while AMF transports phosphorus, nitrogen and other mineral elements to plants with the help of PT4 transporters, which can significantly improve the host's capture efficiency of soil nutrients. It is worth noting that the system showed relatively stable regulatory ability in different stress environments, and AMF could enhance the activity of antioxidant enzymes such as superoxide dismutase of the host and regulate ion homeostasis in salinized soil, so as to maintain the stability of symbiotic function. However, under heavy metal contamination conditions, fungal cell wall polysaccharides showed high chelation efficiency for cadmium and lead and other ions, and combined with the physical barrier formed by the hyphal network, it could significantly reduce the absorption of toxic elements by plants. Molecular evolution studies have shown that the conserved symbiotic functional gene clusters in the AMF genome have co-evolutionary characteristics with host root-specific genes, in which mi RNA maintains the functional stability of the arbuscular structure by dynamically regulating the metabolism of host cells, revealing the precise interaction mechanism formed by the two in the long-term co-evolution.

5. Physical Regulation of Heavy Metal Migration by Arbuscular Mycorrhizal Fungal-Plant Symbiotic System

At the level of physical regulation of heavy metal migration, arbuscular mycorrhizal fungi establish a symbiotic relationship with the host plant roots, enabling plants to isolate heavy metal elements in root tissues and peripheral mycelium, and the symbiotic system effectively alleviates the toxic effects of heavy metals on plants by enriching and fixing heavy metals in mycorrhizal structures such as mycelium and vesicles, and this regionalized storage strategy of heavy metals based on mycorrhizal structure significantly inhibits the transport process of heavy metals to aerial plant tissues [4]. Studies have shown that hyphal density is significantly positively correlated with the diffusion restriction efficiency of heavy metal ions, and there are significant differences in physical barrier efficacy between different AMF species, such as Glomus intraradices and Rhizophagus irregularis due to differences in hyphal diameter, branch frequency, and network connectivity [5]. It is worth noting that the balloonmycin-associated soil protein (GRSP) secreted by hyphae promotes the formation of soil aggregates through cementation, in which the easily extractable state (EE-GRSP) and the difficult-to-extract state (IE-GRSP) form nanoscale organic coatings on the surface of the aggregates, which can produce electrostatic adsorption and coordination chelation of heavy metal ions such as Cd^{2+} and Pb^{2+}. Further studies showed that the formation of such aggregates had a significant particle size differentiation effect. Microagglomerates achieve specific enrichment of heavy metals through ligand exchange and cation exchange adsorption through ligand exchange and cation exchange adsorption due to their high specific surface area and abundant GRSP coatings, while macroagglomerates form physical retention regions through closed pore structures, and their internal hypoxic microenvironment can significantly inhibit the water-soluble migration of heavy metals (Six et al., 2023). The synergistic effect of spatial heterogeneity makes the stability indexes of soil aggregates, such as average weight, diameter, MWD, water-stable aggregate content, WSA, etc., significantly positively correlated with the fixation efficiency of heavy metals. Among them, the contribution of GRSP cementation is 40%-60%, which fully confirms the key regulatory role of AMF-mediated soil structure optimization on heavy metal migration [6]. In addition, the multi-scale structural characteristics of the hyphal network further strengthened the heavy metal retention effect. The pore structure of the hyphal network selectively retained heavy metal particles with a particle size greater than 10 μm, while the nanoscale hyphal secretion membrane with a thickness of about 50-100 nm inhibited the migration of ionic heavy metals through steric hindrance. It is worth noting that these physical barriers complement the above-mentioned hierarchical blocking mechanism of aggregates, and when heavy metals break through the peripheral defense line of the hyphal network, the differentiated adsorption and retention capabilities of aggregates with different particle sizes can construct multiple defense systems, thereby effectively alleviating and blocking the diffusion of heavy metal particles.

6. Chemical Regulation of Heavy Metal Migration by Arbuscular Mycorrhizal Fungal-Plant Symbiosis Systems

The chemical regulation mechanism of arbuscular mycorrhizal fungal-plant symbiosis system on heavy metal migration shows multi-level synergistic effects. At the level of rhizosphere environmental regulation, AMF significantly reduces the pH of rhizosphere microregions by inducing organic acids such as oxalic acid and citric acid secretion by plant roots, promotes the dynamic equilibrium of dissolution and reprecipitation of heavy metal phosphates, and induces heavy metal phosphates (such as $Cd_3(PO_4)_2$) to form a stable precipitation system. At the molecular binding level, the balloon mycelium secreted by hyphae forms a multi-tooth coordination structure with heavy metal ions by virtue of its multifunctional groups, and the binding strength shows regular differences with the change of metal valence gradient, while the activity enhancement of the oxidoreductase system mediates the valence transformation of specific heavy metals, with the help of advanced spectroscopy technology, the characteristic coordination morphology of heavy metals in the rhizosphere environment can be resolved, and the expression of phosphorus transporters such as PtPT4 and GintPT unique to the symbiotic system is up-regulated, which promotes the enrichment of phosphate ions in the rhizosphere. It can also induce the formation of insoluble phosphate precipitation of heavy metals. AMF significantly improved the fixation efficiency of iron and manganese oxides to arsenate by establishing a local reducing microenvironment, and synergistically activated the plant antioxidant enzyme system to enhance the detoxification ability of chromate, and the carboxyl (-COOH), hydroxyl (-OH) and amino (-NH_2) groups in the balloon mycin molecule formed coordination bonds with heavy metal ions, and their chelating ability increased with the increase of the valence state of metal ions (Cu^{2+}>Zn^{2+}>Ni^{2+})[7]. At the level of redox regulation, AMF can regulate the rhizosphere redox potential (Eh), form local reduction microregions in the mycelial dense region, and promote the reduction and fixation of As (V) by Fe/Mn oxides and the reduction and detoxification of Cr (VI). At the level of biogeochemical cycles, the AMF symbiotic system can reduce the migration activity of heavy metals by changing the occurrence form of heavy metals from water-soluble state to carbonate-bound or organically bound state, and the conversion efficiency can reach 40%-70%). X-ray absorption fine structure (XAFS) analysis showed that Cd predominantly existed in the form of Cd-O-C (carboxy-coordination) and Cd-P (phosphate-binding) around the symbiotic roots, while Pb formed Pb-CO_3^{2-} and Pb-S (balloonmycin sulfhydryl coordination) complexes. This morphological transformation is closely related to the activity of oxidoreductases such as laccase and peroxidase secreted by hyphae (20%-30% increase in enzyme activity), which can mediate the equivalent state transition of As(III) oxidation to As (V) and Cr(III) oxidation to Cr(VI), which in turn affects their migration characteristics. In addition, at the cellular compartmentalization level, AMF promotes the selective enrichment of heavy metal-sulfhydryl complexes in specific organelles by regulating the expression of key genes in the metal-binding protein synthesis pathway, thus forming a progressive prevention and control network from physical interception of mycelium and transformation of rhizosphere chemical morphology to subcellular spatial sequestration.

7. Influence of Environmental Factors on AMF Colonization

The influence of environmental factors on the colonization process of arbuscular mycorrhizal fungi involves many aspects. Among them, soil characteristics are the basic conditions that affect colonization, and pH, nutrient content and water status play an important role. Neutral or slightly acidic soil environments are generally conducive to the growth and reproduction of fungi, while excessively acidic or alkaline soils can inhibit the normal development of fungi. When the phosphorus content is too high, the dependence of plants on fungi will be reduced, which will affect the planting effect. Climatic conditions affect the colonization process through a combination of temperature and humidity, with suitable temperature and humidity promoting fungal growth, while extreme drought or stagnant water can disrupt normal communication between fungi and plant roots. The characteristics of the plant itself are also a key factor influencing colonization. Root exudates vary from plant to plant, and these substances attract fungi and send symbiotic signals to them. At the same time, certain secondary metabolites produced by plants are capable of activating specific genes of fungi, which in turn affect the efficiency of colonization and the composition of fungal communities [8]. Anthropogenic agricultural activities can also have a significant impact on the colonization process, such as tillage practices that alter soil structure, fertilization strategies that affect the rhizosphere environment, and pesticide use that may interfere with the normal physiological activities of fungi. In contrast, reducing soil disturbance or using organic amendments can provide a more stable environment for fungi to grow. In addition, different environmental factors do not act independently, but rather interact with each other. For example, soil organic matter both mitigates the toxicity of harmful substances to fungi and acts as an energy source to support their growth. The diversity of plant communities also affects the distribution and colonization of fungi, and the differences in the spatial distribution and exudate composition of different plant roots will promote the formation of different adaptation strategies of fungi. These complex interactions suggest that the colonization process of arbuscular mycorrhizal fungi is highly environmentally adaptable, and understanding these mechanisms can help optimize the effects of mycorrhizal symbiosis in practical applications [9].

8. Summary

In this context, the symbiotic system constructed by AMF and host plants shows unique governance advantages, which systematically reshapes the environmental behavior of heavy metals through a multi-dimensional synergistic mechanism, which is manifested in the synergy between the hyphal network and the soil matrix to form a multi-level spatial barrier system, which not only achieves initial interception with the help of pore screening effect, but also further inhibits the diffusion of heavy metals through nano-scale interfacial adsorption and aggregate heterogeneous distribution. At the same time, the regulation of rhizosphere microdomain can effectively trigger the precipitation equilibrium reconstruction and coordination morphological evolution of heavy metals, especially the deep inhibition of heavy metal activity by combining specific macromolecular chelation, and the precise partition and storage mechanism in the symbiotic interface can directionally enrich heavy metals in specific functional units through an efficient material transport network, and finally form a gradient prevention and control system. This control model, which organically integrates structural barrier, morphological transformation and functional storage, not only successfully breaks through the inherent limitations of traditional technologies such as high cost, long period and ecological damage, but more importantly, realizes the continuous attenuation of heavy metal migration ability based on the co-evolution characteristics of mycorrhizal-soil system, which fully demonstrates the broad-spectrum symbiotic characteristics, significant in-situ remediation advantages and excellent environmental compatibility characteristics of AMF technology system. These outstanding features make this technology show great application prospects in the construction of a green and sustainable soil remediation system, and its theoretical innovation value and practical promotion potential will open up a broader development space for soil heavy metal pollution control in the future.

Acknowledgments

The Young Talent Fund of Association for Science and Technology in Shaanxi, China (20240517), the Technology Innovation Center for Land Engineering and Human Settlements, Shaanxi Land Engineering Construction Group Co., Ltd and Xi'an Jiaotong University (2024WHZ0244).

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