ISSN: 2710-0588

Research on the Adsorption of Soil Heavy Metals by Microalgal Biofilms: Mechanisms, Applications, and Prospects

Wen Sun[1,2,3,4,5, *]

[1] Institute of Land Engineering and Technology, Shaanxi Provincial Land Engineering Construction Group Co., Ltd., Xi'an, Shaanxi, China

[2] Shaanxi Key Laboratory of Land Consolidation, Chang'an University, Xi'an, Shaanxi, China

[3] Shaanxi Provincial Land Engineering Construction Group Co., Ltd., Xi'an, Shaanxi, China

[4] Key Laboratory of Degraded and Unused Land Consolidation Engineering, Ministry of Natural Resources, Xi'an, Shaanxi, China

[5] Land Engineering Quality Testing of Shaanxi Land Engineering Construction Group Co,, Ltd. , Xi'an, Shaanxi, China

Abstract

Soil heavy metal pollution stands as one of the significant challenges facing the global environment today, posing serious threats to human health and ecosystems. In addressing this issue, microalgal biofilms have emerged as a promising bioremediation tool due to their efficient adsorption capabilities. This article provides a comprehensive review of the current status, application cases, and future developments of microalgal biofilms in soil heavy metal adsorption research, aiming to offer insights and guidance for research and practices in the field of environmental remediation.

Keywords

Geopolymer; Environmental; Application.

1. Introduction

Soil heavy metal pollution is one of the major environmental challenges globally. With the acceleration of industrialization, agricultural activities, and urbanization, the concentration of heavy metal pollutants in soil continues to increase, posing serious threats to ecological environments and human health. Therefore, finding efficient and environmentally friendly soil remediation methods is crucial. Microalgal biofilms, as a novel type of biological adsorption material, have attracted considerable attention due to their excellent adsorption performance and environmental friendliness. This article systematically explores the mechanisms, applications, and future prospects of microalgal biofilms in the adsorption of soil heavy metals, aiming to provide references and guidance for research and practice in the field of environmental remediation[1].

2. Characteristics of Microalgal Biofilms

Microalgal biofilms, composed of microalgae cells embedded in a matrix of extracellular polymeric substances (EPS), exhibit unique characteristics that contribute to their diverse functions and ecological roles. Understanding these characteristics is essential for elucidating the behavior and ecological significance of microalgal biofilms in various environments. Below are some key characteristics of microalgal biofilms:

ISSN: 2710-0588

Structural Complexity: Microalgal biofilms possess a complex three-dimensional structure formed by microalgae cells and EPS. This structure provides a large surface area for colonization and interaction with the surrounding environment.

Composition and Diversity: The composition of microalgal biofilms varies depending on factors such as species composition, environmental conditions, and nutrient availability. These biofilms may consist of different species of microalgae, bacteria, fungi, and organic and inorganic particles, contributing to their diversity and functional versatility.

Extracellular Polymeric Substances (EPS): EPS play a crucial role in the formation and stability of microalgal biofilms. They consist of polysaccharides, proteins, lipids, and nucleic acids, providing structural support, adhesion, and protection to the biofilm community. EPS also serve as a matrix for nutrient and water retention, as well as the exchange of metabolites and signaling molecules.

Adhesion and Attachment: Microalgal cells within biofilms adhere to surfaces through various mechanisms, including physical entanglement, electrostatic interactions, and chemical adhesion. Adhesion is facilitated by surface appendages such as pili, flagella, and mucilage secretion, enabling microalgae to colonize diverse substrates such as rocks, sediments, and biotic surfaces.

Heterogeneity and Microscale Gradients: Microalgal biofilms exhibit spatial heterogeneity at micro- and macroscales, characterized by gradients in nutrients, light, oxygen, pH, and microbial communities. These microscale gradients result from the metabolic activities of biofilm organisms, creating microenvironments that support diverse microbial interactions and functions[2].

Metabolic Activity and Functionality: Microalgal biofilms are metabolically active communities capable of photosynthesis, respiration, nutrient cycling, and organic matter degradation. Microalgae within biofilms play essential roles in primary production, carbon fixation, oxygen generation, and nutrient uptake, influencing ecosystem processes and biogeochemical cycles.

Dynamic and Responsive Behavior: Microalgal biofilms exhibit dynamic responses to environmental changes, such as fluctuations in light intensity, temperature, nutrient availability, and hydrodynamics. These biofilms can adjust their composition, structure, and metabolic activities in response to environmental cues, enabling them to adapt to changing conditions and compete for resources.

Ecological Functions and Services: Microalgal biofilms provide various ecological functions and services in aquatic and terrestrial ecosystems, including habitat provision, food sources, nutrient cycling, pollutant removal, sediment stabilization, and carbon sequestration. They support diverse trophic interactions, biodiversity, and ecosystem resilience, contributing to the health and functioning of ecosystems.

3. Mechanisms of Soil Heavy Metal Adsorption by Microalgal Biofilms

Soil heavy metal pollution poses significant environmental concerns due to its adverse effects on ecosystems and human health. Microalgal biofilms have emerged as promising agents for the remediation of soil contaminated with heavy metals due to their efficient adsorption capabilities. Understanding the mechanisms underlying heavy metal adsorption by microalgal biofilms is crucial for optimizing remediation strategies and enhancing their effectiveness. Here, we discuss the primary mechanisms involved in soil heavy metal adsorption by microalgal biofilms:

Physical Adsorption: Physical adsorption involves the non-specific binding of heavy metal ions to the surface of microalgal biofilms through weak van der Waals forces, hydrogen bonding, and electrostatic interactions. The large surface area and complex structure of microalgal

ISSN: 2710-0588

biofilms provide ample binding sites for heavy metal ions. This mechanism is particularly effective for metals with high electronegativity, such as cadmium (Cd) and lead (Pb).

Chemical Complexation: Chemical complexation occurs when heavy metal ions form stable complexes with functional groups present in the EPS matrix of microalgal biofilms. Functional groups such as carboxyl (-COOH), hydroxyl (-OH), and amino (-NH2) groups can coordinate with heavy metal ions through chelation or ion exchange reactions. This mechanism enhances the specificity and selectivity of heavy metal adsorption by microalgal biofilms.

Ion Exchange: Ion exchange involves the substitution of metal ions in the solution with ions present in the EPS matrix of microalgal biofilms. Cations such as calcium (Ca2+) and magnesium (Mg2+) within the EPS matrix can exchange with heavy metal ions, leading to their immobilization and removal from the soil solution. This mechanism is influenced by factors such as pH, ionic strength, and the concentration of competing ions.

Biomineralization: Biomineralization is a process by which microorganisms, including microalgae within biofilms, precipitate heavy metal ions as insoluble mineral phases. Microalgae can secrete extracellular polymeric substances (EPS) containing organic ligands that bind to heavy metal ions and facilitate their precipitation as metal sulfides, carbonates, or hydroxides. Biomineralization reduces the bioavailability and toxicity of heavy metals in soil, contributing to their immobilization and long-term stabilization.

Reduction/Oxidation (Redox) Reactions: Redox reactions mediated by microalgal biofilms can influence the speciation and mobility of heavy metals in soil. Microalgae can release metabolites such as organic acids, enzymes, and electron shuttles that facilitate the reduction of toxic metal ions to less mobile and less toxic forms. Conversely, microalgae can also catalyze the oxidation of reduced metal species, enhancing their immobilization and sequestration in soil matrices.

4. Factors Affecting the Adsorption Behavior of Microalgal Biofilms

The adsorption behavior of microalgal biofilms plays a crucial role in their effectiveness for removing heavy metals from soil and water environments. Several factors influence this behavior, ranging from environmental conditions to biofilm characteristics. Understanding these factors is essential for optimizing the performance of microalgal biofilms in heavy metal remediation. Here, we discuss the primary factors affecting the adsorption behavior of microalgal biofilms:

pH: The pH of the surrounding environment significantly influences the adsorption behavior of microalgal biofilms. Changes in pH alter the surface charge of both the biofilm and heavy metal ions, affecting electrostatic interactions and chemical speciation. Generally, heavy metal adsorption increases at lower pH values due to protonation of functional groups on the biofilm surface, enhancing metal binding[3].

Temperature: Temperature impacts the metabolic activities and growth of microalgae within biofilms, thereby influencing their adsorption behavior. Higher temperatures typically accelerate biochemical reactions and microbial activity, leading to increased adsorption rates. However, extreme temperatures can also affect biofilm stability and integrity, potentially reducing adsorption efficiency.

Metal Ion Concentration: The concentration of heavy metal ions in the surrounding solution directly affects the adsorption capacity of microalgal biofilms. At low metal ion concentrations, adsorption sites may not be fully occupied, resulting in increased adsorption efficiency. However, at higher concentrations, adsorption sites become saturated, limiting further metal uptake by the biofilm.

Ionic Strength: Ionic strength, determined by the concentration of ions in solution, influences the electrostatic interactions between microalgal biofilms and heavy metal ions. High ionic

ISSN: 2710-0588

strength solutions can shield electrostatic forces, reducing the affinity of heavy metals for the biofilm surface. Conversely, low ionic strength solutions enhance electrostatic interactions, promoting metal adsorption.

Biofilm Characteristics: The composition, structure, and thickness of microalgal biofilms significantly impact their adsorption behavior. Biofilms with higher biomass and EPS content generally exhibit greater adsorption capacities due to increased surface area and functional groups available for metal binding. Additionally, biofilm architecture, such as porosity and roughness, can influence mass transfer processes and accessibility of adsorption sites.

Metal Species and Valence State: The chemical speciation and oxidation state of heavy metal ions influence their affinity for microalgal biofilms. Certain metal species may form stronger complexes with specific functional groups present in the biofilm matrix, leading to preferential adsorption. Additionally, redox-active metals can undergo reversible redox reactions within the biofilm, affecting their adsorption kinetics and stability.

Co-existing Ions: The presence of competing ions in the environment can interfere with heavy metal adsorption by microalgal biofilms. Competitive binding between metal ions and other cations or anions may reduce the availability of adsorption sites and hinder metal uptake. The selectivity of microalgal biofilms for specific metal ions may vary depending on the concentration and nature of co-existing ions.

Growth Conditions: Environmental factors such as light intensity, nutrient availability, and carbon source availability can influence the growth and metabolic activity of microalgae within biofilms, indirectly affecting their adsorption behavior. Optimal growth conditions promote biomass accumulation and metabolic rates, enhancing the overall adsorption capacity of microalgal biofilms.

5. Application Cases of Microalgal Biofilms in Soil Heavy Metal Remediation

Several studies have demonstrated the broad application prospects of microalgal biofilms in soil heavy metal remediation. For example, researchers have found that mixing microalgal biofilms with soil can effectively adsorb heavy metal ions in soil, reducing soil heavy metal pollution. Additionally, it has been shown that adding microalgal biofilms to soil remediation projects can effectively increase the nutrient content and biological activity of soil, promote plant growth, and achieve the goal of remediating soil heavy metal pollution.

6. Challenges and Prospects for Microalgal Biofilm Remediation of Soil Heavy Metal Pollution

Despite the potential of microalgal biofilms in soil heavy metal remediation, their application still faces challenges. Firstly, the adsorption of microalgal biofilms for heavy metals is subject to saturation, limiting their effectiveness in large-scale applications. Secondly, the high regeneration cost of microalgal biofilms needs to be further reduced to improve remediation efficiency. Future research should focus on enhancing the adsorption efficiency and regeneration of microalgal biofilms.

Acknowledgments

Funding: The project of Shaanxi Province Land Engineering Construction Group(Project No.:DJTD2023-02) ; Shaanxi Key Laboratory of Land Consolidation (Chang'an University) Open Fund (Project No.: 300102353506).

ISSN: 2710-0588

References

[1] Wang, H., & Li, M. (2020). Research progress on adsorption of soil heavy metals by microalgal biofilms. Environmental Science Research, 33(8), 1655-1662.

[2] Zhang, S., Li, S., & Wang, W. (2018). Application of microalgal biofilms in soil heavy metal remediation. Soil and Environment, 40(2), 215-221.

[3] Johnson, A. C., & Smith, D. R. (2017). The role of algae in heavy metal biosorption and recovery. Journal of Applied Phycology, 29(2), 909-920.