

# Zeolite, Humus and Biochar Remediation of Heavy Metal Contaminated Soil: A Review

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## ABSTRACT

With the swift advancement of industrialization and urbanization, soil heavy metal contamination has grown increasingly severe, presenting a grave menace to the environment and human health. As efficacious soil remediation substances, zeolite, humus, and biochar exhibit considerable potential in the treatment of heavy metal pollution. In this article, the research progress of zeolite, humus, and biochar in the remediation of heavy metal pollution in soil was reviewed, the remediation mechanisms, influencing factors, and practical application effects were analyzed, and the future research direction was prospected. Through comprehensive analysis and discussion, the aim is to offer useful references for the control of soil heavy metal pollution.

## KEYWORDS

Zeolite, Biochar, Humic Substances, Heavy Metals, Combined Remediation.

## 1. INTRODUCTION

Soil heavy metal pollution represents a significant ecological and environmental challenge globally. Human activities, such as mining and smelting, lead to the excessive accumulation of persistent heavy metal elements in the soil. Due to their resistance to degradation, high toxicity, and potential for bioaccumulation, these metals are challenging to remove naturally from the soil, resulting in long-term deterioration of soil quality, disruption of ecosystems, and reduced crop yields—thereby posing a threat to human health. Consequently, developing an efficient, cost-effective, and environmentally friendly technology for remediating soil heavy metal contamination is crucial. Natural or artificial amendments like zeolite, humus, and biochar exhibit considerable potential for remediating contaminated soils due to their distinctive physical and chemical properties. Biochar's porous structure and high specific surface area enable it to effectively adsorb and immobilize heavy metal ions. Zeolite possesses strong ion exchange capabilities along with selective adsorption characteristics that can mitigate the migration and bioavailability of heavy metals. As a vital component of soil organic matter, humus not only enhances soil structure but also forms complexes with heavy metal ions that reduce their biological toxicity. Based on the literature, this paper studies

the remediation effect of the combined application of three kinds of materials on soil heavy metal pollution, to provide useful reference for addressing soil contamination.

## **2. STUDY ON THE REMEDIATION OF SOIL HEAVY METAL POLLUTION USING ZEOLITE**

### **2.1. Fundamental Properties of Zeolite**

Zeolite is a hydrous aluminosilicate mineral characterized by a substantial internal surface area and porous structure, enabling it to accommodate numerous molecules while providing multiple active adsorption sites. The crystalline structure of zeolite features uniform and fixed pores and channels, which confer selective adsorption capabilities. Currently, various natural zeolites exist, with clinoptilolite and mercurite being extensively utilized in soil remediation efforts.

### **2.2. Mechanisms of Action for Zeolite**

Zeolite functions as a porous silico-aluminate mineral possessing an extensive specific surface area and rich pore architecture that effectively adsorbs heavy metal ions from soil through several mechanisms including electrostatic attraction, ion exchange, complexation reactions, and surface adsorption. Specifically, the negatively charged surface of zeolite attracts positively charged heavy metal ions, facilitating their immobilization via electrostatic interactions. Exchangeable cations (such as sodium, potassium, calcium) within the zeolitic framework are exchanged with heavy metal ions present in the soil matrix; this process diminishes the bioavailability of these metals. Complexation refers to interactions between hydroxyl groups, carboxyl groups, and other functional moieties on the zeolite's surface with heavy metal ions to form stable complexes that further mitigate both migration potential and toxicity associated with these metals. Surface adsorption involves removing heavy metal ions from contaminated soils through physical or chemical adhesion onto the surfaces and within the pores of zeolites.

### **2.3. Application Methods and Effectiveness Evaluation**

The application methods for utilizing zeolites in remediating soil contaminated by heavy metals primarily include direct addition techniques as well as compound amendment strategies. In direct applications, powdered or granular forms of zeolite are applied directly onto contaminated soil surfaces; subsequent mixing can be achieved through plowing or similar practices to integrate them into the soil profile effectively. Research indicates that zeolites exhibit significant remediation efficacy against heavy metals such as cadmium (Cd), lead (Pb), and copper (Cu); notably, incorporating zeolites has been shown to substantially reduce both concentration levels and bioavailability of these contaminants in soils. For example, following treatment with zeolites resulted in reductions in Cd bioavailability by 50% and Pb bioavailability by 60% [1]. Furthermore, beyond contaminant mitigation benefits provided by zeolite application also extend towards enhancing overall soil structure-improving aeration capacity alongside water retention-which promotes root development ultimately leading to increased crop yields.

The effectiveness of using zeolite for rehabilitating soils impacted by heavy metals is influenced not only by its intrinsic properties-including type selection-and dosage but also correlates significantly with fundamental characteristics inherent within target soils such as pH values along organic matter content levels [2]. Therefore, practical implementations necessitate careful consideration regarding appropriate selections concerning types and dosages tailored specifically according respective conditions whilst optimizing surrounding environmental factors aimed at maximizing restoration outcomes.

### **3. STUDY ON REMEDIATION OF SOIL HEAVY METAL POLLUTION BY BIOCHAR**

#### **3.1. Basic properties of biochar**

Biochar is a kind of carbon-rich porous solid product prepared by high temperature pyrolysis of biomass raw materials (such as plant stalks, animal feces, etc.) under the condition of hypoxia or limited oxygen. Biochar has a porous structure and high specific surface area, and has strong adsorption capacity for heavy metal ions. At the same time, biochar also contains rich mineral elements and organic functional groups, which can improve soil structure and fertility.

#### **3.2. Mechanism of biochar**

The remediation mechanisms of biochar to soil heavy metal pollution mainly include adsorption fixation, chemical precipitation and microbial action. The porous structure and high specific surface area of biochar enable it to adsorb many heavy metal ions. At the same time, the mineral components of biochar may chemically react with heavy metal ions to form insoluble precipitates. In addition, biochar also provides a habitat for soil microorganisms and promotes the transformation and fixation of heavy metals by microorganisms.

Bioremediation of soil heavy metals by biochar is mainly through adsorption, electrostatic attraction, ion exchange, complexation and precipitation. Among them, the adsorption of biochar can absorb heavy metal ions in soil by virtue of its porosity and large specific surface area, reducing its migration and bioavailability. The surface of biochar has negative charge and rich oxygen-containing functional groups (such as carboxyl group, hydroxyl group, etc.), which can adsorb heavy metal ions through electrostatic attraction and ion exchange. The functional groups on the surface of biochar react with heavy metal ions to form stable complexes and reduce the biological toxicity of heavy metals [3]. In addition, the mineral components of biochar react chemically with heavy metal ions to form an insoluble precipitate that immobilizes the heavy metals.

#### **3.3. Application method and effect evaluation**

The application methods of biochar in soil heavy metal remediation mainly include direct addition method and compound amendment method. Direct addition method means that biochar powder or particles are directly spread on the surface of contaminated soil and mixed with the soil by ploughing and other ways. The composite amendment rule is to mix biochar with other repair materials (such as zeolite, humus, etc.) to form a composite amendment to improve the repair effect.

The experimental results showed that the addition of biochar could significantly reduce the effective concentration and bioavailability of heavy metals in soil. For example, the bioavailability of Cd in soil decreased by more than 70% after biochar addition [4]. In addition, biochar can also improve soil pH, improve soil fertility, and promote crop growth. The restoration effect of biochar is also affected by many factors, including the type of biochar, preparation conditions, dosage and soil environment. In practical application, it is necessary to select the appropriate type and dosage of biochar according to the specific situation, and optimize the soil environment to improve the restoration effect.

### **4. MECHANISM AND APPLICATION OF HUMUS IN SOIL HEAVY METAL REMEDIATION**

#### **4.1. Basic properties of humus**

Humus is an important part of soil organic matter. It is formed by decomposition and transformation of animal and plant residues by microorganisms. It is rich in carbon, hydrogen, oxygen and many

functional groups (such as hydroxyl, carboxyl, phenolic hydroxyl, etc.). Humus contains rich functional groups and complexation sites, and its unique pore structure and surface properties make it have strong adsorption capacity, ion exchange capacity and complexation capacity, and can form stable complexes with heavy metal ions, thereby reducing its bioavailability and toxicity.

#### **4.2. Mechanism of action of humus**

Humus can repair heavy metal pollution mainly through complexation reaction and improvement of soil environment. Functional groups in humus can react with heavy metal ions to form stable complexes and reduce the migration and bioavailability of heavy metals in soil. At the same time, humus can also improve soil structure, improve soil fertility, and provide good environmental conditions for plant growth.

The pore structure and surface functional groups of humus can effectively adsorb heavy metal ions in soil, reduce their mobility and bioavailability, and also form stable complexes with heavy metal ions to fix them in the soil surface or internal micropores, further reducing the toxicity of heavy metals [5]. In addition, humus has a certain pH regulation ability, can change the soil pH value, humus for soil microorganisms to provide energy and nutrients, promote microbial reproduction and activities, thereby promoting the transformation and degradation of heavy metals.

#### **4.3. Application method and effect evaluation**

The repair effect of humus on soil heavy metal pollution is affected by many factors, including the type, content and molecular weight of humus, soil pH value and REDOX potential. Moderate addition of humus can significantly reduce heavy metal content and biological toxicity in soil, but excessive addition may lead to soil salinization and other problems [6]. Therefore, it is necessary to control the amount of humus added in practical applications, and optimize and adjust according to the soil environment.

The application methods of humus in soil heavy metal remediation mainly include direct addition method and compound remediation method. Direct addition method means that the humus powder or particle is directly spread on the polluted soil surface, and it is mixed with the soil by ploughing and other ways. The principle of composite repair is to mix humus with other repair materials (such as zeolite, biochar, etc.) to form a composite repair agent to improve the repair effect.

### **5. DISCUSSION ON THE JOINT REMEDIATION OF HEAVY METALS IN SOIL BY ZEOLITE, HUMUS AND BIOCHAR**

#### **5.1. Joint repair mechanism**

There are often limitations of single remediation material in soil heavy metal remediation, and it is difficult to achieve the ideal remediation effect. Therefore, the combined use of multiple repair materials has become the focus of current research. Zeolite, humus and biochar are excellent soil remediation materials. The combined use of zeolite, humus and biochar may produce synergistic effects and further improve the remediation effect.

Zeolite, humus and biochar have their own unique repair mechanisms, which can play a synergistic role when combined to further improve the repair effect. All the three materials have strong adsorption capacity, which can jointly adsorb heavy metal ions in soil and reduce their migration and bioavailability. The exchangeable cations and functional groups in zeolite and biochar undergo ion exchange and complexation reactions with heavy metal ions to form stable complexes or precipitates. For example, the adsorption and fixation of zeolite and biochar can rapidly reduce the heavy metal content in soil. The complexation of humus can stabilize heavy metal ions and reduce their migration

and bioavailability [7]. In addition, the addition of three materials can improve the physical, chemical and biological properties of soil, improve soil fertility and microbial activity, promote crop growth and the transformation and degradation of heavy metals.

## **5.2. Application methods and effects**

Combined remediation can significantly reduce the heavy metal content and biological toxicity in soil, and improve soil fertility and microbial diversity. The specific application of the combined remediation method should be designed and optimized according to the soil pollution status and remediation objectives. Generally speaking, zeolite, humus and biochar can be mixed in accordance with a certain proportion and directly spread on the surface of the contaminated soil, and it can be mixed with the soil by ploughing and other ways. According to the study, a joint remediation test was carried out in a tungsten ore area in Jiangxi Province, and it was found that the bioavailability of Cd, Pb, As and W decreased by 57.4%, 62.7%, 56.4% and 22.5%, respectively, and the total bio effective toxicity decreased from 335.5 to 143.4[8]. The experimental data showed that the combined remediation method could significantly improve the remediation effect of soil heavy metals.

The effect of combined restoration is affected by many factors, including the type, ratio, dosage and soil environment of restoration materials. To improve the effect of joint restoration, it is necessary to optimize and adjust different soil types and pollution levels [9]. According to the characteristics of soil heavy metal pollution, appropriate remediation materials and their ratio were selected, the dosage was optimized to balance the remediation effect and cost, and the soil environment (such as pH, organic matter content, etc.) was adjusted to promote the adsorption and fixation of remediation materials.

## **6. CONCLUSION AND PROSPECT**

Zeolite, humus and biochar, as soil amendments and heavy metal fixatives, show significant potential in soil heavy metal pollution remediation. Combined application can play a synergistic role, significantly reduce heavy metal content and biological toxicity in soil, improve soil environment and promote plant growth and microbial activity. In the future, we can further study the mechanism of multi-material combined repair of heavy metals, and reveal the interaction between different repair materials and their influence on the transformation of heavy metals. Optimize the combined repair technology to improve the repair effect and economic benefit. Explore the application potential of joint remediation technology in different types of soil and pollution scenarios, and provide technical support and demonstration cases for practical projects.

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