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Long-Term Efficacy of Biochar-Based Immobilization for Remediation of Heavy Metal-Contaminated Soil and Environmental Factors Impacting Remediation Performance

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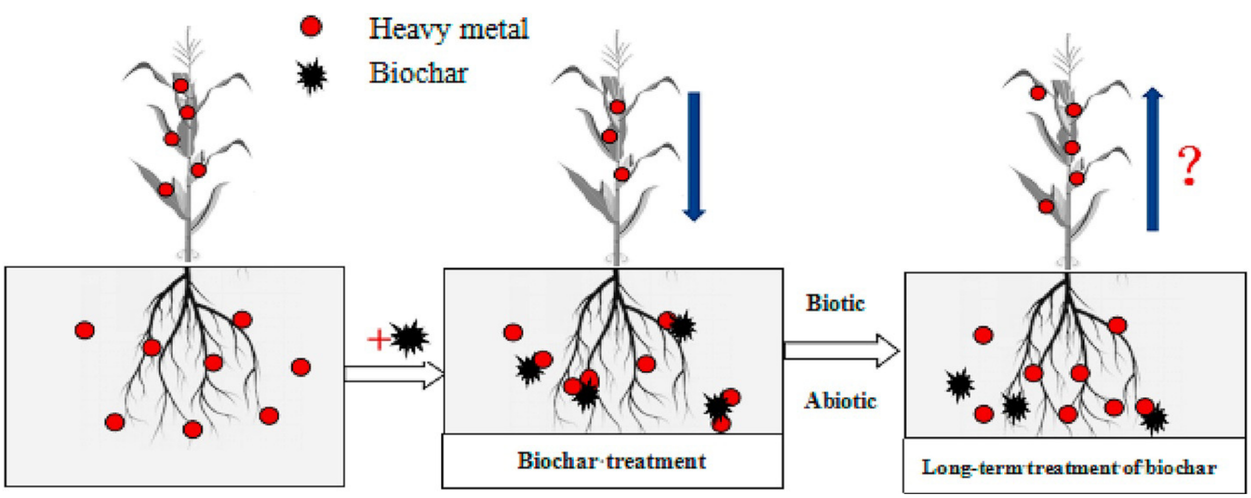

Abstract
The contamination of soil with heavy metals poses significant environmental and public health concerns. In recent years, biochar-based immobilization has emerged as a promising technique for remediating heavy metal-contaminated soil. This review article aims to provide a comprehensive overview of the long-term efficacy of biochar-based immobilization for remediating heavy metal-contaminated soil, along with an analysis of the environmental factors that impact the performance of this remediation strategy. We discuss the mechanisms underlying biochar effectiveness in immobilizing heavy metals and its role in enhancing soil quality. Furthermore, we explore the interactions between biochar, soil microorganisms, and plants, and their combined influence on the overall remediation process. The review also delves into the challenges and future prospects of utilizing biochar-based immobilization for sustainable and efficient soil remediation.

Keywords: **Biochar, heavy metals, soil contamination, immobilization, remediation efficacy, environmental factors.**

1. Introduction

Soil contamination with heavy metals refers to the presence of elevated levels of metallic elements that have a high density and are toxic to living organisms in the soil. These heavy metals, including but not limited to lead (Pb), cadmium (Cd), mercury (Hg), chromium (Cr), and arsenic (As), are naturally occurring elements but can become pollutants when their concentrations exceed safe levels due to human activities. Human activities such as industrial processes, mining, agriculture, and improper waste disposal can introduce heavy metals into the soil. These metals can accumulate in the soil over time and pose significant risks to both the environment and human health. They can impact soil quality, disrupt ecosystems, and enter the food chain through plant uptake, leading to potential health hazards for humans who consume contaminated crops, animals, or water [1]. Heavy metals are a group of metallic elements with high atomic weights that can be toxic to both ecosystems and human health due to their persistence and bioaccumulation potential. These elements include lead (Pb), mercury (Hg), cadmium (Cd), chromium (Cr), arsenic (As), and nickel (Ni), among others. They are released into the environment through natural processes like weathering of rocks and volcanic activities, but anthropogenic activities such as industrial processes, mining, and improper waste disposal have significantly increased their presence in the environment. This has led to various detrimental effects on ecosystems and human health. Accumulation of heavy metals in soil can occur either through atmospheric deposition or runoff from the land. This contamination has detrimental effects on the microbial communities within the soil, disrupting nutrient cycling and subsequently impacting the growth of plants and the overall health of the ecosystem. The presence of heavy metals can also extend to water bodies, causing contamination in aquatic environments. This pollution serves to disturb aquatic ecosystems, causing harm to various organisms including fish, amphibians, and aquatic plants. Furthermore, it has the potential to interfere with the natural food chain, initiating a process of bioaccumulation as higher trophic levels experience an increase in heavy metal concentration. This tendency for heavy metals to accumulate in organisms signifies their capacity to build up within tissues at levels surpassing those found in the surrounding environment. This phenomenon of bioaccumulation is heightened through biomagnification, wherein predators ingesting prey with accumulated heavy metals result in even greater concentrations within the top predators. The toxic nature of heavy metals can precipitate a decline in biodiversity, particularly affecting species that are susceptible to their effects. This cascade effect has the potential to disrupt the equilibrium of ecosystems and curtail the provision of essential ecosystem services [2]. The human body can be exposed to heavy metals through tainted water and food supplies. Ingesting fish sourced from polluted waters and crops cultivated in soils contaminated with heavy metals can result in direct exposure. Even low-level exposure to lead can have serious neurological repercussions for children, leading to cognitive deficiencies, delays in development, and behavioral anomalies. Specific heavy metals like arsenic and cadmium are categorized as carcinogens. Prolonged contact with these metals via polluted air, water, or food can heighten the likelihood of several types of cancers, including those affecting the lungs, skin, and bladder. Over time, heavy metals can amass in vital organs such as the liver, kidneys, and lungs, resulting in organ damage and disruption of their proper function. Being subjected to certain heavy metals like mercury and cadmium can trigger reproductive problems, congenital abnormalities, and developmental irregularities [3].

Remediation refers to the process of addressing and mitigating environmental contamination or pollution. It involves implementing various strategies to clean up or reduce the harmful effects of pollutants in soil, water, or air. One such strategy is "biochar-based immobilization," which has garnered substantial interest within the field of environmental remediation. Biochar is a type of charcoal that is produced through the pyrolysis (thermal decomposition) of organic materials, such as agricultural residues, wood chips, and biomass. It is characterized by its high surface area, porosity, and ability to adsorb or bind to various substances, including contaminants like heavy metals and organic pollutants. Biochar-based immobilization involves applying biochar to contaminated sites to trap or immobilize pollutants, preventing their migration and uptake by plants or animals. This process can effectively reduce the bioavailability and mobility of contaminants in the environment. Several research studies and scientific investigations have focused on exploring the efficacy of biochar-based immobilization as a remediation strategy. Researchers have examined its application in different types of contaminated environments, such as industrial sites, agricultural lands, and mine tailings. These studies have evaluated parameters such as biochar type, application rates, environmental conditions, and the specific contaminants of concern [4].

In this review, our primary focus will be on a variety of strategies aimed at mitigating the toxicity associated with heavy metals. These metals are recognized for their detrimental effects on the surrounding ecosystem. Addressing the pollution attributed to heavy metals is of utmost significance due to its manifold adverse repercussions on human health.

2. Mechanisms of Biochar-Metal Interactions

Biochar-metal interactions refer to the processes that occur when biochar, a carbon-rich material produced from biomass through pyrolysis, comes into contact with metal ions or metals in various environmental settings. These interactions can have important implications for environmental remediation, agriculture, and other applications. Here are some mechanisms of biochar-metal interactions:

2.1.Adsorption

One of the primary mechanisms of biochar-metal interactions is adsorption. Biochar high surface area and porous structure provide ample sites for metal ions to attach and be immobilized. This can involve physical adsorption (van der Waals forces) as well as chemical adsorption (ion exchange, complexation, chelation) depending on the specific metal and biochar properties." Adsorption is a fundamental process by which molecules or ions from a liquid or gas adhere to the surface of a solid material. In the context of biochar-metal interactions, adsorption refers to the binding of metal ions to the surface of biochar. Biochar is a carbon-rich material produced through biomass pyrolysis, such as agricultural waste or wood chips. Its high surface area and porous structure make it effective for adsorbing various substances, including metal ions. Biochar-metal interactions are of great interest due to their potential applications in environmental remediation, water treatment, and soil fertility improvement. The statement describes two main types of adsorption involved in biochar-metal interactions (i) Physical Adsorption (Van der Waals Forces): This type of adsorption occurs due to weak attractive forces between metal ions and the biochar surface. Van der Waals forces are electrostatic interactions arising from electron distribution fluctuations. Because of biochar high surface area and porous structure, metal ions can adhere to its surface through these weak forces. However, chemical adsorption may be stronger and more selective than physical adsorption. (ii) Chemical Adsorption (Ion Exchange, Complexation, Chelation): Chemical adsorption involves stronger and more specific interactions between metal ions and functional groups on the biochar surface. Biochar contains a variety of functional groups, such as hydroxyl (-OH), carboxyl (-COOH), and amine ($-NH_2$) groups. These groups can participate in chemical reactions with metal ions [5].

2.2.Surface Functional Groups

Biochar surface contains various functional groups, such as carboxyl, hydroxyl, and phenolic. These groups can complex with metal ions through coordination bonds, forming stable complexes on the biochar surface." Biochar is a carbonaceous material produced through the pyrolysis (thermal decomposition in the absence of oxygen) of organic biomass, such as agricultural residues, wood chips, or other plant materials. It has gained attention for its potential applications in environmental remediation, soil improvement, and water treatment due to its unique physicochemical properties, including its surface functional groups. Surface functional groups are specific chemical entities located on the outer surface of biochar particles. These groups play a crucial role in interactions between biochar and other substances, such as metal ions. The mentioned functional groups—carboxyl, hydroxyl, and phenolic groups—are commonly found on the biochar surface. Carboxyl groups consist of a carbon atom double-bonded to an oxygen atom and single-bonded to a hydroxyl group (–COOH). They are acidic functional groups that can donate protons (H^+) and form coordination bonds with metal ions through oxygen atoms. This coordination bonding process involves the sharing of electron pairs between the metal ions and the oxygen atoms of the carboxyl groups. Hydroxyl groups (-OH) are polar functional groups that contain an oxygen and a hydrogen atom bonded to a carbon atom. They are also capable of forming coordination bonds with metal ions through their oxygen atoms, contributing to the overall reactivity of the biochar surface. Phenolic groups are aromatic compounds containing a hydroxyl group attached to a benzene ring. These groups possess both hydroxyl and aromatic characteristics, making them capable of participating in complexation reactions with metal ions through multiple bonding sites. The process of metal ion complexation on the biochar surface involves the binding of metal ions to the aforementioned functional groups. This binding occurs through coordination bonds, where electron pairs from oxygen atoms in the functional groups are shared with metal ions, forming stable complexes. These complexes are often immobilized on the biochar surface, which can have implications for various applications, such as removing heavy metals from contaminated water or enhancing nutrient retention in soils [6].

2.3.pH and Ionic Strength

The pH of the environment influences biochar-metal interactions. At different pH levels, both the biochar surface charge and the speciation of metal ions can change, affecting adsorption and precipitation processes. Ionic strength, determined by the concentration of salts, can also impact metal adsorption by influencing electrostatic interactions.

The pH of a solution refers to its acidity or alkalinity, determined by the concentration of hydrogen ions (H^+) present. The pH of the environment plays a significant role in the interactions between biochar (a carbon-rich material derived from biomass) and metal ions. The surface charge of biochar particles is influenced by the pH of the surrounding solution. At different pH levels, the surface charge of biochar can become more positively or negatively charged. This charge variation affects the attraction and repulsion between the biochar surface and metal ions in the solution [7]. Moreover, the speciation of metal ions, which refers to the different forms in which metal ions exist based on their chemical state and bonding with other molecules, can also change with varying pH levels. This speciation change can impact how effectively metal ions interact with biochar. Certain pH conditions might favor the formation of metal hydroxides or metal complexes, which can affect adsorption and precipitation processes on the biochar surface [8].

Ionic strength is a measure of the concentration of ions, particularly salts, in a solution. It affects the overall electrostatic interactions between charged particles, including biochar and metal ions. When the ionic strength of a solution is increased due to the presence of salts, the electrostatic interactions between biochar and metal ions may be altered. This can influence the adsorption of metal ions onto the biochar surface. High ionic strength conditions can enhance electrostatic attraction between metal ions and the oppositely charged biochar surface, leading to increased metal adsorption. Conversely, low ionic strength may weaken these interactions and reduce metal adsorption [9].

The interactions between pH, ionic strength, biochar, and metal ions are complex and interdependent. Researchers studying these interactions aim to understand the mechanisms governing metal adsorption onto biochar surfaces under different environmental conditions. This understanding is important for various applications, such as environmental remediation and water purification.

2.4.Reduction and Oxidation

Biochar can act as a redox mediator, facilitating the reduction or oxidation of metal ions. Reducing conditions on the biochar surface can lead to the reduction of metal ions to their elemental forms, which can either be immobilized on the biochar or released into the environment.

Redox stands for reduction-oxidation, which are chemical reactions involving the transfer of electrons between substances. A redox mediator facilitates these electron transfer reactions between different substances. In the context of biochar, it means that biochar can participate in redox reactions by either accepting or donating electrons, thereby facilitating the reduction or oxidation of other substances. Metal ions are positively charged atoms of metallic elements that have lost one or more electrons. These ions can interact with other substances and have environmental implications due to their potential toxicity and mobility [7]. Biochar can influence the transfer of electrons between metal ions and other substances, which leads to their reduction (gain of electrons) or oxidation (loss of electrons). The biochar surface can create conditions that promote the gain of electrons, resulting in the reduction of metal ions to their elemental forms. This means that metal ions, which were previously in a charged state, can be converted to their neutral elemental forms. The reduced metal ions can either be immobilized on the surface of the biochar, meaning they are trapped and held by the biochar material, or they can be released into the environment. The outcome depends on various factors, including the type of metal, the characteristics of the biochar, and the surrounding conditions [9].

2.5.Mineral Precipitation

Metal ions can form precipitates with minerals present in the biochar or in the surrounding environment. These precipitates may be insoluble metal compounds that can either adhere to the biochar surface or settle out in the environment.

Mineral precipitation refers to the process by which dissolved metal ions in a solution come together to form solid, insoluble compounds known as precipitates. These precipitates can be formed through various chemical reactions involving metal ions and other compounds present in the solution. In the context of biochar, which is a carbon-rich material derived from organic matter that has been heated in a low-oxygen environment, mineral precipitation can have significant implications for its properties and interactions with the environment. In the case of biochar, metal ions can interact with minerals present within the biochar itself or with minerals in the surrounding soil or water. The process of mineral precipitation can lead to the formation of solid metal compounds that may adhere to the surface of the biochar particles or settle out in the environment [10].

The precipitated metal compounds can adhere to the surface of the biochar particles, altering their chemical composition and surface properties. This modification can influence the biochar reactivity, adsorption capacity, and interactions with other substances. If the metal ions originate from the surrounding environment (such as soil or water), their precipitation onto the biochar can lead to the immobilization of these metal ions. This immobilization can be beneficial in reducing the mobility and potential toxic effects of certain metal ions in the environment. Precipitation of metal ions onto biochar surfaces can also impact nutrient cycling in soils. Certain metal ions are essential nutrients for plant growth, and their availability can be influenced by their interactions with biochar [11].

2.6.Competitive Adsorption

The statement "When multiple metal ions are present, they can compete for adsorption sites on the biochar surface. Some ions might be preferentially adsorbed due to their affinity for certain functional groups" refers to the phenomenon where various metal ions in a solution containing biochar (a type of charcoal produced from organic matter) can interact with and bind to the surface of the biochar particles. The interactions between metal ions and biochar are of interest in various environmental and water treatment applications, as biochar has been shown to have adsorptive properties that can help remove heavy metals and other pollutants from water. When multiple types of metal ions are present in a solution that comes into contact with biochar, these ions can compete for available binding sites on the biochar surface [12]. The biochar surface contains various functional groups, such as hydroxyl (-OH), carboxyl (-COOH), and amino (-NH2) groups, which can serve as potential binding sites for metal ions. The competition arises because the different metal ions have varying affinities for these functional groups. Metal ions might have a stronger attraction or affinity for specific functional groups on the biochar surface, allowing them to bind more readily compared to other metal ions [13]. The preferential adsorption of certain metal ions occurs when a particular type of metal ion has a higher affinity for a specific functional group present on the biochar surface. This can be influenced by factors such as the charge, size, and chemical properties of the metal ions as well as the characteristics of the functional groups on the biochar surface. As a result, certain metal ions might outcompete others and become more strongly adsorbed onto the biochar particles [14].

2.7.Particle Size and Porosity

Biochar is a carbon-rich material produced from the pyrolysis (thermal decomposition in the absence of oxygen) of organic biomass, such as agricultural residues and wood waste. It has gained attention for its potential to remediate contaminated soils and waters through the process of adsorption, where contaminants such as heavy metals are attracted and bound to the biochar surface. The statement highlights two key factors that influence the adsorption capacity of biochar for heavy metals: particle size and porosity. Smaller biochar particles generally have a higher surface area per unit mass compared to larger particles. This increased surface area provides more active sites where metal ions can interact and be adsorbed onto the biochar material. As a result, smaller biochar particles tend to exhibit greater adsorption capacities for heavy metals due to their larger available surface area. Porosity refers to the presence of open spaces or pores within the biochar structure. Porous biochar materials have a larger internal surface area, which can accommodate more metal ions. The pores also provide pathways for metal ions to diffuse into the interior of the biochar particle, enhancing the overall adsorption process. Higher porosity can contribute to increased adsorption capacity [15].

2.8.Aging and Weathering

Over time, biochar can undergo aging and weathering processes that alter its surface properties, which in turn can impact metal adsorption behavior.
Biochar, when introduced into the environment, is exposed to various physical, chemical, and biological processes collectively known as aging and weathering. These processes include exposure to sunlight, moisture, microbial activity, and chemical reactions with soil components. As a result of these interactions, biochar surface undergoes changes such as the formation of new functional groups, the alteration of its porosity, and the development of a thin organic coating. These changes can lead to the transformation of its original properties [16]. The altered surface properties of aged and weathered biochar can have a significant impact on its ability to adsorb metal ions from its surroundings. Metal adsorption on biochar primarily occurs through mechanisms such as surface complexation, ion exchange, and precipitation. The changes in biochar surface chemistry, structure, and composition can influence the availability of functional groups and binding sites responsible for metal adsorption [17]. For instance, the development of new functional groups or the modification of existing ones on biochar surface can enhance its affinity for certain metal ions due to the formation of specific chemical bonds. Likewise, changes in porosity and the organic coating can affect the diffusion of metal ions into the biochar matrix, altering the accessibility of adsorption sites [18].

2.9.Biochar Properties

The characteristics of biochar, such as feedstock type, pyrolysis conditions, and post-treatment, influence its surface chemistry and porosity. These properties ultimately affect the biochar ability to interact with metals.
Biochar is a carbon-rich material produced through the pyrolysis (thermal decomposition in the absence of oxygen) of biomass, such as agricultural residues, wood, and organic waste. It has gained attention as a potential tool for environmental remediation, particularly in the context of removing and immobilizing heavy metals from soil and water. The quoted statement highlights the key factors that determine how effective biochar can be in interacting with metals for environmental applications [19]. The type of biomass used as feedstock for biochar production plays a crucial role in influencing the resulting biochar characteristics. Different feedstocks contain varying amounts of organic compounds, minerals, and other components. These components can impact the biochar surface chemistry and its ability to adsorb metals. For instance, feedstocks with higher lignin content might produce biochar with a greater capacity to bind metals due to the presence of functional groups on the surface of the biochar [20]. The pyrolysis conditions, including temperature, heating rate, and residence time, determine the degree of thermal decomposition and transformation of the biomass into biochar. Higher pyrolysis temperatures generally result in biochar with higher carbon content, reduced volatile matter, and increased porosity. These characteristics influence the biochar surface area and the presence of active sites that can adsorb metals. The specific pyrolysis conditions can affect the surface chemistry and structural properties of the biochar, impacting its interaction with metals. Post-treatment processes, such as washing, acid/base treatment, and activation, can further modify the properties of biochar. These treatments can enhance its surface area, porosity, and the availability of functional groups that can interact with metals. Activation, for example, involves subjecting biochar to high temperatures or chemical treatments to increase its adsorption capacity. The choice of post-treatment can greatly influence the final biochar ability to sequester or

immobilize metals from the environment. The interaction of biochar with metals is primarily driven by its surface chemistry, porosity, and the availability of functional groups (such as carboxyl, hydroxyl, and phenolic groups) that can bind to metal ions through adsorption processes. The properties of biochar can influence mechanisms such as ion exchange, complexation, and physical adsorption, which determine its effectiveness in metal removal and remediation applications [21].

2.10. Environmental Context

The specific environmental conditions, such as soil type, moisture content, and presence of other organic and inorganic substances, can significantly influence biochar-metal interactions. Biochar-metal interactions refer to the processes and mechanisms by which biochar, a carbon-rich material produced from biomass through pyrolysis, interacts with metals in various environmental contexts. These interactions can impact metal mobility, bioavailability, and potential remediation strategies for contaminated soils or water. The statement highlights that the outcome of these interactions is heavily dependent on the specific environmental conditions in which they occur.

Different types of soils possess distinct physicochemical properties that influence biochar-metal interactions. The composition of soil, including its mineral content, cation exchange capacity, and pH, can affect the adsorption, desorption, and mobility of metals in the presence of biochar. For example, clay-rich soils may have different interactions compared to sandy soils due to their varying surface area and binding capacities. The moisture content of soil plays a role in the availability of metals for interactions with biochar. Higher moisture levels can enhance microbial activity and the movement of water, potentially affecting metal leaching and biochar-metal complex formation [22].

3. Long-Term Field Studies and Case Examples

Long-term field studies and case examples provide valuable insights into the practical applications and effectiveness of biochar-metal interactions in real-world scenarios. These studies help to understand how biochar can be used for various purposes, including soil remediation, agricultural improvement, and environmental protection. Here are a few examples:

3.1.*Review of Long-Term Field Studies*

Long-term field studies involve monitoring the effects of biochar application to agricultural soils over several growing seasons or years. Researchers collect data on soil nutrient levels, crop yields, and other relevant parameters to assess the sustained impact of biochar on nutrient retention. These studies provide valuable insights into the long-term benefits of using biochar in agriculture. Long-term field studies begin by adding biochar to agricultural soils. Biochar is a carbon-rich material produced through biomass pyrolysis, such as crop residues or wood. It is incorporated into the soil to assess its impact on soil properties and crop performance. Researchers closely monitor and track various aspects of the agricultural system over time. This involves collecting data regularly, often during each growing season, to observe changes and trends. One of the main focuses of these studies is to examine how biochar influences soil nutrient levels. Biochar can enhance nutrient retention in soil by adsorbing and holding onto essential plant nutrients like nitrogen, phosphorus, and potassium. Researchers measure and analyze these nutrient levels in the soil to assess the biochar impact. In addition to nutrient levels, researchers also measure crop yields. They assess how the presence of biochar affects the quantity and quality of crops grown in the treated soil. This is a crucial parameter because it directly relates to the economic and practical implications of using biochar in agriculture. Besides nutrient levels and crop yields, researchers may collect data on a range of other relevant factors. These could include soil pH, moisture retention, microbial activity, carbon sequestration, and even environmental factors like temperature and precipitation. The primary objective of long-term field studies is to evaluate the sustained or long-lasting impact of biochar on agricultural systems. By observing trends and changes over multiple years, researchers can determine whether the benefits of using biochar persist over time or if there are any diminishing returns. Long-term field studies provide valuable insights into the long-term benefits and challenges associated with incorporating biochar into agricultural practices. This information can inform farmers, policymakers, and researchers about the potential advantages and limitations of using biochar for improving soil fertility, nutrient retention, and overall crop production [23].

3.2.Nutrient Retention in Agricultural Soils

The focus of this analysis is to determine how biochar affects the retention and availability of essential nutrients (e.g., nitrogen, phosphorus, potassium) in agricultural soils. It explores how biochar porous structure and chemical properties enhance nutrient holding capacity, reduce leaching, and promote nutrient availability to crops, contributing to improved soil fertility and crop productivity. The primary objective or scope of the analysis is to investigate the influence of biochar on certain aspects of soil quality and crop growth in agricultural settings. In particular, it is interested in how biochar affects the retention and availability of essential nutrients. The study is concerned with two critical aspects of nutrients in soils. Soil nutrient retention is crucial because it ensures that these nutrients remain available for plant uptake. Availability of nutrients in the soil means that they are present in forms that plant roots can easily absorb and utilize for growth. Nutrient availability is essential for healthy plant development. The analysis specifically mentions three essential nutrients: nitrogen, phosphorus, and potassium. These are often referred to as NPK nutrients and are vital for plant growth. Ensuring an adequate supply of these nutrients is a fundamental goal in agriculture. The analysis seeks to understand how biochar contributes to changes in nutrient retention and availability. Biochar is a carbon-rich material produced from biomass through pyrolysis. It has unique properties that can impact soil nutrient dynamics. The passage mentions two key aspects of biochar that are relevant to its impact on nutrient retention and availability. Biochar has a porous structure, which means it has many tiny spaces or "pores." These pores can serve as storage sites for nutrients, preventing them from being lost through leaching (washing away) and making them available for plants over time. Biochar chemical properties, such as its surface functional groups, can interact with nutrients in the soil. These interactions can enhance nutrient holding capacity, making nutrients more available to crops. One of the benefits of biochar is that it can help reduce nutrient leaching. Leaching occurs when nutrients are carried away by water, often ending up in water bodies like rivers and lakes. Biochar can act as a "buffer," slowing down the movement of water and allowing more nutrients to be absorbed by plants instead of being lost through leaching. The ultimate goal of studying biochar impact on nutrient retention and availability is to determine how it contributes to enhanced soil fertility and increased crop productivity. Soil fertility refers to the ability of the soil to provide the necessary nutrients and conditions for robust plant growth [24].

4. Environmental Factors Influencing Remediation Performance

Environmental factors play a significant role in shaping the performance of biochar-based remediation processes for contaminated soils. The efficacy of biochar in immobilizing contaminants, such as heavy metals and organic pollutants, is influenced by several key environmental factors. Understanding and managing these factors can enhance the outcomes of biochar-based remediation.

4.1.pH

Soil pH strongly influences the sorption and chemical speciation of contaminants. Biochar has the potential to alter soil pH due to its alkaline nature. An increase in soil pH can affect the solubility and mobility of certain contaminants, making them less available for plant uptake or leaching into groundwater. Monitoring and adjusting soil pH to the appropriate range for the specific contaminants of concern can optimize biochar effectiveness. Buffering soil pH with biochar may be beneficial in acidic soils. Soil pH is a measure of the acidity or alkalinity of the soil. It strongly influences the chemical speciation of contaminants, especially heavy metals. Contaminants can exist in different forms (ions or complexes) depending on the pH of the soil. The pH affects their solubility and mobility. In acidic conditions, some contaminants like heavy metals become more soluble and mobile, increasing the risk of leaching into groundwater or being taken up by plants. Conversely, these contaminants tend to form less soluble compounds or precipitate in alkaline conditions, reducing their mobility and bioavailability. Biochar is often alkaline due to its high pH. When incorporated into acidic soils, biochar can raise the soil pH towards a more neutral or alkaline range. This increase in soil pH can have several beneficial effects, including reducing the solubility and mobility of certain contaminants like heavy metals. Biochar alkalinity can also provide a stable buffer against further acidification of the soil, helping to maintain a more favorable pH range for plant growth and contaminant immobilization. Monitoring soil pH is crucial when using biochar for remediation. It allows for adjustments to be made to ensure that the pH is within the appropriate range for the specific contaminants of concern. By maintaining the pH in a range that minimizes the solubility and mobility of contaminants, biochar can be more effective in reducing their potential impact on the environment. This optimization of soil pH with biochar can enhance the overall success of remediation efforts, whether it's reducing contaminant leaching, minimizing plant uptake, or promoting immobilization. Biochar can act as a pH buffer in acidic soils, helping to stabilize and maintain a more neutral pH over time. In addition to its alkaline properties, biochar high cation exchange capacity (CEC) allows it to adsorb and release nutrients and ions, further influencing pH buffering [25].

4.2.Moisture Content

Soil moisture content affects both the physical and chemical interactions between biochar and contaminants in several ways. Adequate moisture is essential for facilitating the movement of contaminants within the soil matrix, allowing them to come into contact with biochar particles. Soil moisture is vital for the activity of soil microorganisms. Microbes play a significant role in the degradation and transformation of contaminants. Microbial activity can be enhanced by maintaining appropriate moisture levels, as many microbial processes require water as a medium for metabolic reactions. Moisture facilitates the diffusion of contaminants through the soil. When contaminants are mobile and can move towards biochar particles, they have a higher chance of coming into contact with and interacting with the biochar. Biochar porous structure provides numerous sorption sites for contaminants, and adequate moisture helps transport the contaminants to these sites. The presence of moisture can promote contaminant sorption to biochar surfaces. Contaminants that are in solution or in a dissolved state are more likely to be adsorbed by biochar when moisture is available. Biochar high surface area and numerous functional groups can interact with contaminants and immobilize them. In practical remediation applications, maintaining appropriate moisture levels can be achieved through irrigation or rainwater management. Controlled irrigation can help ensure that the soil remains at an optimal moisture level for microbial activity and contaminant interactions. Rainwater management strategies can include proper drainage to prevent waterlogging or the use of rain barrels to capture and manage rainwater for maintaining moisture levels [26].

4.3.Organic Matter

Organic matter in soil contains organic molecules with functional groups that can serve as sorption sites for contaminants, similar to biochar. Contaminants may compete for available sorption sites between organic matter and biochar. This competition can affect the extent to which contaminants are adsorbed by either organic matter or biochar. Organic matter is a source of carbon and energy for soil microorganisms. Its presence can enhance microbial activity in the soil. Microbes play a crucial role in the degradation and transformation of organic contaminants. Their increased activity, fueled by organic matter, can contribute to the breakdown of certain pollutants. Achieving an optimal balance between organic matter and biochar in the soil is essential for effective remediation. While organic matter can compete with biochar for contaminant sorption sites, biochar unique properties, such as its high surface area and surface chemistry, can make it a more effective sorbent for certain contaminants. The appropriate application rates of biochar should be considered based on the specific soil conditions and the contaminants of concern. In some cases, it may be beneficial to combine biochar with organic amendments to harness the benefits of both. This strategy can enhance sorption capacity, microbial activity, and contaminant degradation simultaneously. Understanding the dynamics between organic matter and biochar in the soil is crucial for tailoring remediation strategies. Managing the competition between these two sorbents can optimize the removal and immobilization of contaminants in the soil. Careful consideration of the site-specific conditions, including the types and concentrations of contaminants and the soil's organic matter content, is essential for achieving successful remediation outcomes [27].

4.4.Microbial Activity

Microbial activity involves the metabolic processes of microorganisms, including bacteria, fungi, and other soil organisms, that can break down organic contaminants and transform certain metals. Microbes are natural agents in soil remediation, as they can biodegrade organic pollutants and participate in processes like metal reduction or oxidation, which can immobilize or detoxify metals. Biochar, with its porous structure and high surface area, can provide a favorable habitat for beneficial microorganisms. The pores within biochar particles offer protection and shelter for microbes from adverse environmental conditions, such as extreme temperatures or desiccation. Biochar high surface area provides ample attachment sites for microbial colonization. Biochar can adsorb and concentrate organic compounds, serving as a food source for microorganisms and promoting their growth. Biochar alkaline properties can buffer soil pH, creating more favorable conditions for microbial activity. Enhanced microbial activity, facilitated by biochar, can lead to more efficient degradation of organic contaminants. Microbes can break down complex organic molecules into simpler, less toxic forms. Biochar can also help reduce organic contaminants' bioavailability by adsorbing them, making them less accessible to organisms higher up the food chain. In the context of metal-contaminated soils, certain microorganisms can transform metals into less toxic or less mobile forms through processes like reduction or oxidation. Biochar can indirectly support these microbial activities by providing a conducive habitat and maintaining suitable pH condition. The choice of biochar type and source can influence its suitability for promoting microbial activity. Some biochar may have specific properties or surface chemistries that are more conducive to microbial colonization. Proper application practices, such as mixing biochar thoroughly into contaminated soil, should be considered to ensure effective microbial interactions [28].

5. Holistic Approaches: Biochar, Microorganisms, and Plants

The interactions between biochar, soil microorganisms, and plants in the context of heavy metal remediation are complex and multifaceted. Biochar can have a significant influence on soil microbial communities and plant health, offering potential benefits for reducing heavy metal uptake. These interactions hold the potential for synergistic effects that enhance the overall effectiveness of long-term remediation efforts.

5.1.Influence of Biochar on Soil Microbial Communities

Biochar porous structure, large surface area, and carbon-rich composition make it an attractive habitat and substrate for soil microorganisms. Microorganisms can colonize the pore spaces and surfaces of biochar particles, using them as a sheltered environment and a source of organic carbon. Biochar presence in soil can lead to an increase in microbial diversity, as different microbial species may find favorable conditions within the biochar matrix. Increased microbial diversity can contribute to a more robust and versatile soil microbial community, potentially including beneficial microorganisms. Biochar can promote the proliferation of beneficial microorganisms involved in various soil processes, such as nutrient cycling and metal transformation. Examples of beneficial microorganisms include mycorrhizal fungi that enhance plant nutrient uptake and metal-reducing bacteria that can transform toxic metal ions into less harmful forms. The carbon-rich nature of biochar can serve as a source of energy and nutrients for microorganisms, stimulating their growth and activity. Increased microbial activity can lead to improved soil health and fertility. The presence of biochar in contaminated soils can lead to enhanced microbial activity, which can play a crucial role in the biological transformation of organic pollutants and heavy metals. Microbes can metabolize and break down complex organic compounds, reducing their bioavailability and toxicity. Some microorganisms are capable of transforming heavy metals through processes like reduction or oxidation, rendering them less mobile or toxic. As biochar-supported microbial communities work to break down and transform contaminants, the bioavailability of these contaminants to plants and other organisms is reduced. This reduction in bioavailability can help mitigate the ecological and human health risks associated with contaminated soils [29].

5.2.Biochar-Mediated Reduction of Heavy Metal Bioavailability

Biochar is known for its exceptionally high surface area due to its porous structure. This large surface area provides a vast number of adsorption sites where heavy metal ions can attach. Biochar contains various functional groups, such as carboxyl, hydroxyl, and phenolic groups, on its surface. These groups have the ability to form bonds with heavy metal ions through chemical interactions, such as ion exchange, complexation, and chelation. Physical Adsorption: Heavy metal ions can be physically adsorbed onto the surface of biochar particles through weak van der Waals forces. This process occurs when metal ions are attracted to the biochar surface due to electrostatic interactions. Chemical Adsorption: Biochar functional groups can chemically interact with heavy metal ions. For instance, carboxyl and hydroxyl groups can donate electron pairs to form coordinate covalent bonds with metal ions. This results in the formation of stable complexes. When heavy metal ions are adsorbed onto biochar, they become less soluble in the soil solution. This reduced solubility limits their mobility and leaching potential, preventing them from contaminating groundwater or adjacent ecosystems. Biochar ability to form stable complexes with heavy metals results in lower concentrations of free metal ions in the soil solution. As a consequence, the bioavailability of heavy metals to plants is reduced. Plants typically take up metal ions in their free, dissolved form. When heavy metals are complexed with biochar, they are less readily taken up by plant roots, helping to protect crops from metal contamination. Biochar adsorption of heavy metals can be long-lasting. Once bound to biochar, heavy metals may remain relatively immobile for extended periods, reducing the risk of recontamination [30].

5.3.Enhancement of Plant Health

Biochar has a high cation exchange capacity (CEC), which means it can adsorb and retain cations (positively charged ions), including essential nutrients like calcium, magnesium, and potassium. By enhancing CEC, biochar increases the nutrient-holding capacity of the soil, making essential nutrients more available for plant uptake over an extended period. This improved nutrient availability can benefit plant growth by ensuring a consistent supply of essential elements. The presence of biochar in the soil can stimulate the growth and activity of beneficial soil microbial communities, including mycorrhizal fungi. Mycorrhizal fungi form symbiotic relationships with plant roots. They extend the plant's root system, increasing the surface area for nutrient absorption and enhancing the plant's ability to access nutrients, particularly phosphorus and nitrogen. This symbiosis can result in improved nutrient uptake and overall plant health. As mentioned earlier, biochar can reduce the bioavailability of heavy metals in the soil by adsorbing and immobilizing these contaminants. When heavy metals are less available in the soil, plants are less likely to take them up through their roots, reducing the risk of heavy metal toxicity (phytotoxicity). This protective effect is crucial for both agricultural crops and native vegetation in contaminated environments [31].

5.4.Synergistic Effects for Effective Remediation

Combining biochar application with phytoremediation or bioremediation can create synergistic effects, where the combined action of these techniques is more effective than the sum of their individual effects. Biochar can enhance the overall remediation process by improving soil quality and supporting the growth of beneficial microbial communities and plants. Phytoremediation involves the use of plants to remove, stabilize, or detoxify contaminants from the soil. Some plants, known as hyperaccumulators, can accumulate high concentrations of heavy metals in their tissues. Biochar can improve the success of phytoremediation by enhancing nutrient availability, providing a stable substrate for plant growth, and reducing the bioavailability of heavy metals. Additionally, the presence of biochar can support beneficial microbial communities that enhance nutrient cycling and support plant health. Bioremediation relies on microorganisms to degrade or transform contaminants in the soil. Some soil bacteria are capable of reducing or immobilizing heavy metals. Biochar can provide a habitat for these beneficial microorganisms and support their growth and activity, contributing to the biological transformation of heavy metals. Biochar long-lasting presence in the soil contributes to sustained microbial activity and plant health over an extended period. The gradual release of nutrients from biochar and its positive impact on soil structure continue to benefit plant growth and microbial communities, allowing for ongoing remediation efforts. Over time, the combined action of biochar, plants, and microbes can lead to a gradual reduction in heavy metal contamination levels [32].

Conclusion

In conclusion, the long-term efficacy of biochar-based immobilization as a remediation strategy for heavy metal-contaminated soil. They also shed light on the critical environmental factors that influence the performance of biochar-based remediation. The reviews emphasize that biochar has shown promise as an effective means of reducing the mobility and bioavailability of heavy metals in contaminated soils. Its high surface area, porous structure, and chemical properties make it a suitable candidate for immobilizing a range of heavy metal contaminants. Long-term studies highlighted in the articles provide evidence of biochar sustained impact on heavy metal-contaminated soils. These studies showcase the enduring nature of biochar effects, making it a valuable component of remediation strategies designed for lasting results. The reviews underscore the significance of environmental factors in shaping the outcomes of biochar-based remediation. pH, moisture content, organic matter, and microbial activity are crucial factors that can either enhance or impede the remediation process. The potential for synergistic effects between biochar, soil microorganisms, and plants is highlighted. These interactions offer opportunities to optimize remediation outcomes by promoting microbial activity, enhancing nutrient retention, and reducing heavy metal uptake by plants.

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