

Review

Review of Preparation, Application, and Microbiological Reaction of Magnetic Biochar for Heavy Metal Removal from Polluted Soils

Ahmed El-Hussein ^{1,2}, Alexandra Ioanid ^{3,4,*}, Adel A. Surour ^{5,6}, Mahmoud M. Ashry ⁷, M. N. Sanad ⁸, Mohamed Farouz ⁸, Mohamed M. Elfaham ^{8,9} and M. S. Abd El-Sadek ^{10,11,12,*}

- ¹ Department of Biology, Faculty of Science, Galala University, Galala City 43511, Egypt; a.elhusseiny@gu.edu.eg
 - ² Department of Laser Applications in Meteorology, Photochemistry, and Biotechnology, The National Institute of Laser Enhanced Science, Cairo University, Cairo 12613, Egypt
 - ³ Department of Entrepreneurship and Management, Faculty of Entrepreneurship, Business Engineering and Management, National University of Science and Technology Politehnica Bucharest, Splaiul Independentei 313, 060042 Bucharest, Romania
 - ⁴ Academy of Romanian Scientists, Ilfov 3, 050044 Bucharest, Romania
 - ⁵ Geology Department, Faculty of Science, Cairo University, Giza 12613, Egypt; adel-surour@gu.edu.eg
 - ⁶ Department of Geological Sciences, Faculty of Science, Galala University, Galala City 43511, Egypt
 - ⁷ Scientific Departments, College of Computing and Information Technology, Arab Academy for Science, Technology, and Maritime Transport, Smart Village, Giza 12577, Egypt
 - ⁸ Benha Faculty of Engineering, Benha University, Benha 13511, Egypt; dr.mmostafa.elfaham@bhit.bu.edu.eg (M.M.E.)
 - ⁹ Faculty of Computer Science and Artificial Intelligence, Al Ryada University for Science and Technology, Monufia 32897, Egypt
 - ¹⁰ Physics Department, Faculty of Science, Galala University, Galala City 43511, Egypt
 - ¹¹ Physics Department, Faculty of Science, Luxor University, Luxor 85951, Egypt
 - ¹² National Physics Committee, Academy of Scientific Research and Technology (ASRT), 101 Kasr Al-Aini St, Cairo 11516, Egypt
- * Correspondence: alexandra.ioanid@upb.ro (A.I.); mahmoud.abdelsadek@sci.luxor.edu.eg (M.S.A.E.-S.)

Abstract

Magnetic biochar (MBC), a magnetically responsive soil amendment, has attracted considerable attention due to its efficient magnetic separation capability and strong potential for remediating heavy metal-contaminated soils. Despite extensive research, a comprehensive evaluation of its raw materials, synthesis routes, performance-influencing factors, removal mechanisms, and microbial interactions remains limited. This review systematically examines biomass feedstocks and magnetic precursors used in MBC production and critically evaluates preparation methods, including hydrothermal carbonization, co-precipitation, ball milling, microwave pyrolysis, and impregnation–pyrolysis. Key factors affecting heavy metal removal—such as metal speciation, pyrolysis temperature, soil properties, dosage, and feedstock type—are discussed in detail. The primary immobilization mechanisms, including redox reactions, surface and co-precipitation, ion exchange, functional group complexation, physical adsorption, π – π interactions, and electrostatic attraction, are comprehensively analyzed. Furthermore, the interactions between MBC, soil physicochemical parameters, and microbial communities are evaluated to assess ecotoxicological implications. Finally, we provide valuable recommendations for the future direction of magnetic biochar research to advance its application in heavy metal removal from soil.

Academic Editor: Gurumurthy Hegde

Received: 27 January 2026

Revised: 4 March 2026

Accepted: 6 March 2026

Published: 7 April 2026

Copyright: © 2026 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\) license](https://creativecommons.org/licenses/by/4.0/).

Keywords: soil; influencing factors; heavy metals; mechanism; microbial response; magnetic biochar preparation

1. Introduction

Soil contamination by heavy metals and quasi-metals has become a pressing environmental issue with profound implications for ecosystems and human health [1–3]. Elevated levels of toxic elements such as Arsenic (As), Cadmium (Cd), Chromium (Cr), Lead (Pb), Copper (Cu), and Zinc (Zn) in soil, even at trace concentrations, pose substantial ecological and health risks [4–7]. These risks encompass adverse effects on red blood cells, neurological disorders, hypertension, and a spectrum of other health concerns [1,8,9] (See Figure 1). This concern has driven extensive research toward developing effective strategies for remediating heavy metal pollution in soils [1,2,10]. In recent years, biochar, a carbonaceous material known for its porous structure, has emerged as a promising solution for addressing heavy metal contamination in soils [11–17]. Biochar offers various advantages, including cost-effectiveness, high porosity, and the presence of functional groups capable of adsorbing heavy metal ions [18–23]. However, the challenge of separating biochar from the soil matrix has impeded its practical application, leading to reduced efficiency and the generation of secondary pollution, necessitating additional purification steps [19–22]. The solution to this challenge lies in the emergence of magnetic biochar (MBC), a novel composite material that combines the inherent qualities of conventional biochar with magnetic properties [23–25] (See Figure 1). MBC exhibits an expanded surface area, an improved pore structure, additional functional groups, heightened stability, and an enhanced adsorption capacity for heavy metals compared to conventional biochar. Notably, MBC can be magnetically separated from its surrounding environment, streamlining the separation process, conserving energy, and facilitating its reuse [26–28]. Using biomass to produce MBC mitigates the scarcity of biochar in manufacturing processes and broadens its applicability. MBC has effectively reduced pollution across various environmental contexts, encompassing soil, gas, and wastewater. Significantly, a search in the Web of Science database conducted in October 2022 unveiled a substantial body of research—1680 research papers, to be exact—underscoring the burgeoning interest in MBC and its multifaceted applications. This surge in research activity underscores the growing recognition of MBC as a transformative asset in environmental remediation. While there has been extensive research on the physical and chemical properties of MBC, limited attention has been given to its influence on soil microbial ecosystems. Understanding the intricate interplay between MBC and soil microorganisms is paramount for ensuring its responsible and informed utilization. Considering these considerations, this manuscript offers a comprehensive review of recent developments and applications of MBC in the context of heavy metal removal from soils. The manuscript is organized into four pivotal sections: (1) The Fundamental Ingredients for MBC Preparation: This section delves into the raw materials and magnetic precursors essential for the synthesis of MBC, exploring the diversity of feedstocks and the mechanisms behind their magnetization. (2) MBC Preparation Methods: A comprehensive overview of the various techniques for manufacturing MBC, including co-precipitation, impregnation pyrolysis, hydrothermal carbonization, microwave pyrolysis, and ball milling, is provided. (3) Factors Influencing MBC and Mechanisms of Heavy Metal Removal from Polluted Soils: This segment dissects the intricate factors affecting MBC's performance in soil remediation and elucidates the underlying mechanisms governing the removal of heavy metals. (4) Soil Microbial Responses to MBC Immobilization of Heavy Metals: A deep dive into the interaction between MBC and soil microorganisms, exploring how MBC amendments impact microbial communities

and their functions in contaminated soils (See Figure 1). This review is intended to enrich the understanding of MBC and its potential in soil remediation while highlighting avenues that warrant further scientific exploration.

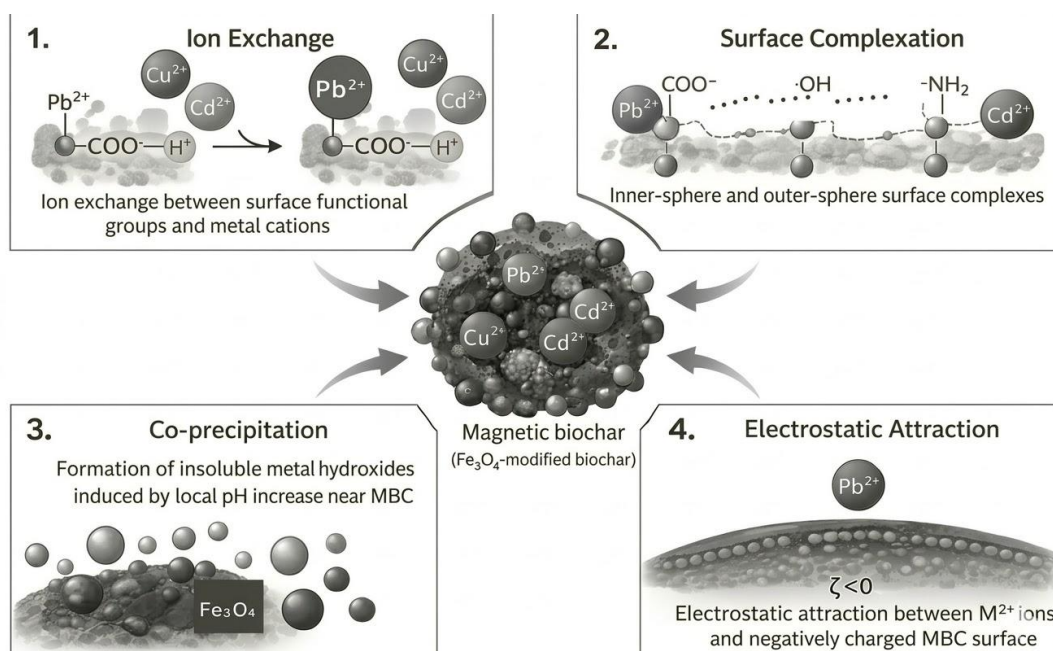


Figure 1. Adsorption Mechanisms of divalent heavy metal cations onto magnetic biochar (MBC); 1. Ion Exchange: Stoichiometric displacement of surface-active protons (H⁺) or alkali metal ions (Na⁺), 2. Surface Complexation: Formation of stable inner-sphere and outer-sphere coordination complexes with -COO⁻, -OH, and -NH₂ groups. 3. Co-precipitation: Nucleation of insoluble metal hydroxides on the Fe₃O₄ phase and 4. Electrostatic Attraction: Coulombic attraction facilitated by a negative zeta potential ($\zeta < 0$).

2. Materials Used in the Production of MBC

The selection of materials for creating Magnetic Biochar (MBC) is a crucial step influencing its effectiveness in heavy metal removal. This section will explore the various materials employed in MBC production, emphasizing the role of magnetic precursors and the different types of biomass feedstocks.

2.1. Biomass and Magnetic Precursors

The transformation of biomass into magnetic particles adhering to the biochar's surface necessitates the incorporation of magnetic precursors [23], as shown in Figure 2. Biomass, typically characterized by its low iron content, requires these precursors to confer magnetic properties. Various types of biomasses can be used for MBC production, primarily categorized into four groups: animals, plants, sludge, and microbes. The prevalence of plant-based biomass in MBC production stems from its diversity and abundance and the opportunity to recycle plant residue.

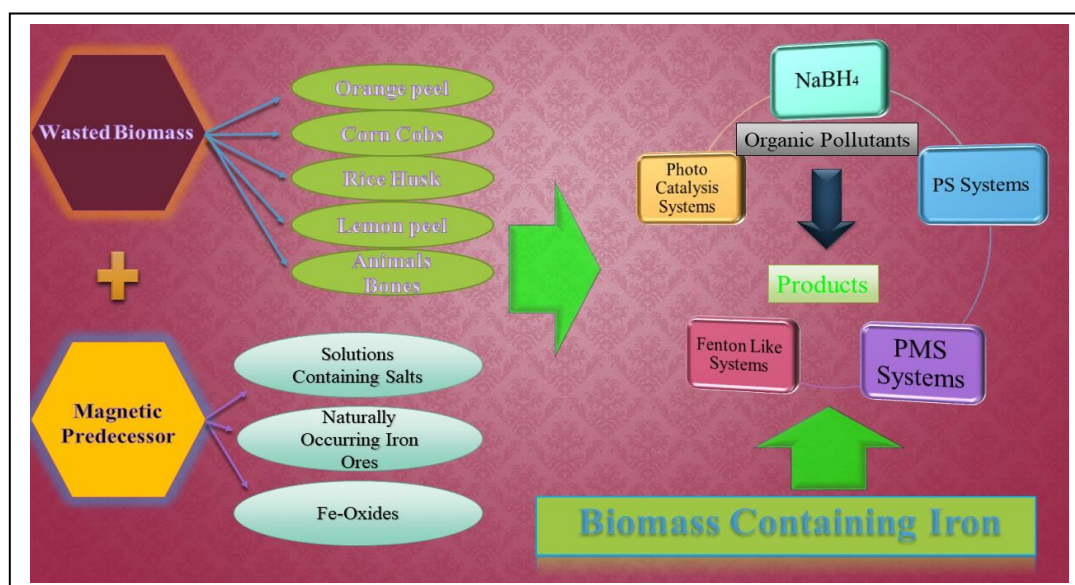


Figure 2. MBC raw materials and preparation.

Magnetic precursors are classified into three categories: transition metal solutions containing salts, naturally occurring iron ores, and iron oxides. While non-magnetic in their natural state, transition metal solutions can be chemically precipitated or thermally reduced to form magnetic materials. They are favored among researchers due to their cost-effectiveness and safety. Notable metals found in these solutions include calcium, iron, manganese, and others [5,29–32]. Iron ores encompass magnetite, hematite, pyrite, and various other forms. Iron oxides, such as Fe_3O_4 , Fe_2O_3 , and FeO , represent the primary categories of Fe-oxides [5,6,33,34]. It is important to note that Fe-oxides and transition metal salts, while more expensive, offer higher purity [35–39]. Achieving magnetic precursors with superior purity at an acceptable price is a crucial challenge for future research. Researchers aim to reduce the required amount of transition of metal salts while maintaining magnetic effectiveness. This reduction is vital for optimizing the cost-effectiveness of MBC production. The raw materials that are used for MBC synthesis are summarized in Table 1 as follows:

Table 1. The classification of MBC raw materials and wasted biomass.

Classification of Biomasses	Particular Kinds	Example	References
Plants	Cash crop squandering	Wheat straw, corn straw, rice straw, durian peel, banana peel, and other similar materials.	[5,40–43]
	Waste from the forest	Rice straw, fenugreek, etc.	[44,45]
	Aquatic plants	Pine, cedar sawdust, eucalyptus, bamboo, etc.	[3,46,47]
Animals	Poultry excrement	Chicken bones, pork bones, etc.	[14,48,49]
	Bones from animals	Cow manure, pig manure, etc.	[50,51]
	Shells	-	[52]
Sludge	Agricultural sludge	Sludge from pig houses, etc.	[53]
	Sludge from municipal sewage	-	[54]
Microbes		White rot fungus, <i>N. crassa</i> , etc.	[55,56]

2.2. Iron-Containing Waste Biomass

In contrast to Fe-free biomass, iron-containing waste biomass is naturally endowed with magnetic properties. This innate magnetization capability eliminates the need for additional magnetic precursors and significantly enhances the overall cost-effectiveness

of MBC production. Iron-containing waste biomass includes iron sludge, iron-containing furfuryl residue, iron-rich Fen-tone sludge, and nano-zero-valent iron (nZVI) sludge. Among these, iron sludge is extensively used to enhance the magnetic properties of sludge-based MBC [35–37,57–60]. Demonstrated that using iron sludge as a source of iron in the microwave-assisted synthesis of Magnetic Biochar (MBC) facilitated rapid separation from water through magnetic means and ensured efficient recoverability [61,62]. Furthermore, Liu et al., [63] introduced an innovative approach to wastewater treatment by employing a one-step pyrolysis process involving sewage sludge and nano-zero-valent iron (nZVI) particles, producing MBC. This method can potentially remove Cr(VI) from wastewater, signifying its practical utility in environmental remediation [64]. The synthesis of MBC using iron-containing sludge presents a compelling research avenue, particularly in ecological restoration materials. This approach addresses the challenge of iron recovery from sludge and contributes to sludge minimization and resource utilization, aligning with sustainable practices.

3. Magnetic Biochar (MBC) Preparation Procedures

Magnetic Biochar (MBC) can be synthesized through various techniques, each offering distinct advantages and disadvantages and involving varying raw materials, pH conditions, temperatures, and procedural steps [21]. This section explores the detailed procedures of different MBC preparation methods, providing insights into the scientific intricacies and humane implications of each (See Figure 3). Siddiqui et al., [65] noted that the production cost of magnetic biochar remains significantly higher than that of conventional biochar because of additional modification steps, chemical reagents, and energy-intensive activation processes. However, economic feasibility can be improved by using waste-derived modifying agents, optimizing reaction parameters to reduce energy demand, and integrating circular-economy principles such as reagent recycling and energy recovery. These strategies can substantially enhance the practicality of MBC for environmental remediation applications [66–69].

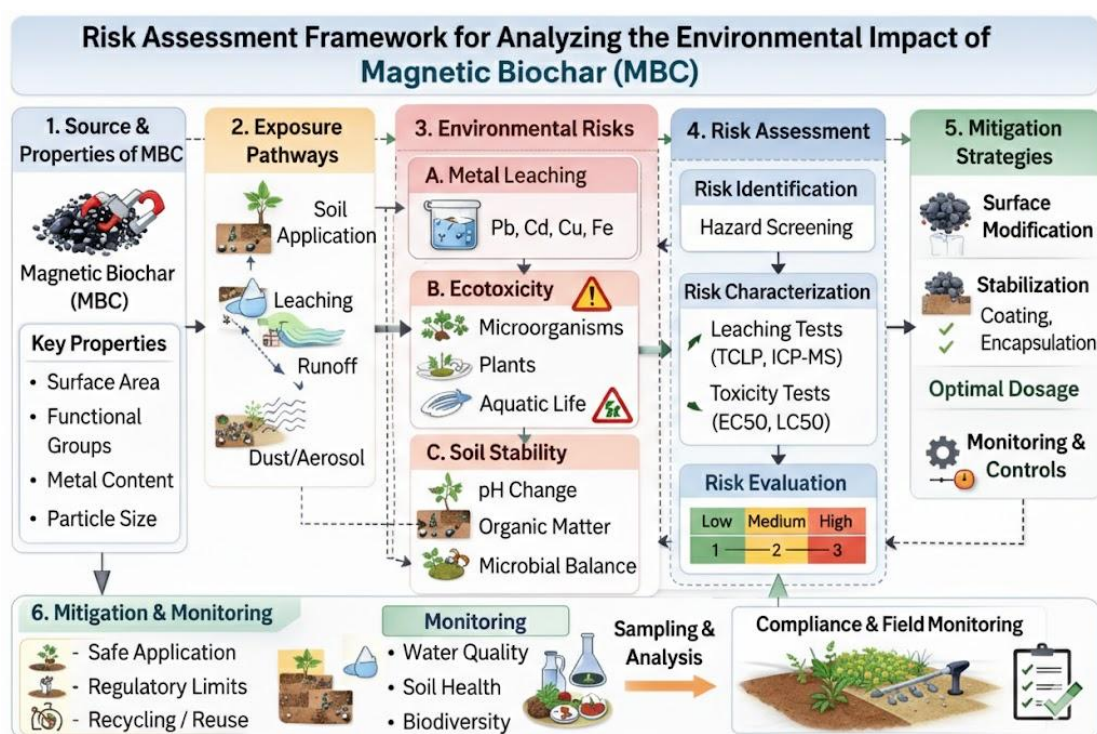


Figure 3. Risk Assessment Framework for Analyzing the Environmental Impact of Magnetic Biochar.

3.1. Co-Precipitation

The co-precipitation method entails the dissolution of biochar (BC) in solutions containing transition metal salts like Co, Fe, Ni, and others. Subsequently, alkaline solutions such as NH_4OH and NaOH or reducing agents like KBH_4 and NaBH_4 are introduced at specific temperatures to induce the precipitation of metal compounds. The MBC is produced from the residual material following purification and drying. The co-precipitation method can be subdivided into chemical and reductive co-precipitation based on the choice of solution reagents. For instance, Dong et al. [46] reported that the Fe content of FWFe(2) samples was 1.2–1.8 times higher than that of FWFe(3) samples, indicating that the FWFe(2) preparation conditions were more effective in retaining Fe when both pyrolysis and chemical co-precipitation methods were employed, suggesting that co-precipitation is more efficient in preserving iron than the impregnation method. In another study, Wang et al., [47] utilized combined chemical co-precipitation and hydrothermal carbonization to generate Ce-doped MBC, demonstrating the effectiveness of the co-precipitation approach in specific contexts. It is worth noting that while co-precipitation may involve harmful reducing agents, it offers a more controlled magnetic adherence to the charcoal substrate, setting it apart from pyrolysis and hydrothermal carbonization methods.

3.2. Impregnation Pyrolysis: A Robust Method for MBC Synthesis

Impregnation pyrolysis is a critical technique for synthesizing Magnetic Biochar (MBC), renowned for its versatility and comprehensive utilization. This method, of paramount scientific interest, entails either biomass or pristine biochar (BC) saturation with a solution containing transition metal salts, functioning as essential precursors for forming MBC. Subsequently, this impregnated material undergoes a pyrolysis process, often conducted within the controlled environment of a muffle or tube furnace under minimized oxygen conditions or inert gas atmospheres. A noteworthy feature of impregnation pyrolysis is its ability to amalgamate the pyrolysis and magnetization stages into a unified, single-phase process, eliminating the requirement for a separate and distinct magnetization step [35–37]. Illustrating the proficiency of impregnation pyrolysis, the work of Li et al., [70] is particularly enlightening. In their pioneering study, MBC was meticulously fashioned by pyrolyzing fermentation residue from dry anaerobic fermentation. This residue was thoughtfully combined with pig manure and straw, facilitating an efficient, integrated approach. Comprehensive characterization, including Scanning Electron Microscopy and energy-dispersive X-ray Analysis (SEM-EDX), unveiled a porous structural configuration within the MBC. Furthermore, X-ray Diffraction (XRD) analysis delineated the presence of dominant elements, notably Fe, O, Na, and Cl, indicative of a successful transformation into a magnetic state. This discovery underscores the substantial potential of MBC for the adsorption and immobilization of heavy metals, particularly within polluted soil matrices. The strategic integration of Fe-oxides further extends this material's capabilities by augmenting the active surface area, thereby facilitating the extraction and retrieval of magnetic constituents from the soil—a development with far-reaching implications in environmental remediation [5,31,70]. Pyrolysis temperature and feedstock type strongly influence MBC surface area, functional groups, and magnetic phase stability, thereby affecting heavy metal immobilization efficiency and environmental performance.

3.3. Hydrothermal Carbonization: A Complex Yet Effective Method for MBC Synthesis

The hydrothermal carbonization technique, while sophisticated, is undoubtedly an effective process for MBC synthesis underpinned by rigorous scientific principles. This process commences with the synchronized interaction between biochar (BC) and magnetized precursors within specialized equipment, often an autoclave or a similar reactor. This transformative process unfolds at precise temperatures, typically ranging from 100 to

300 °C. Notably, this method incorporates the introduction of alkaline salts, such as CH_3COONa and NaOH , and includes surfactants like $\text{HO}(\text{CH}_2\text{CH}_2\text{O})_{\text{nH}}$ within the reaction solution to meticulously prevent undesirable particle aggregation. This process does not require strong reducing agents or excessive alkaline additives, making it a comparatively mild and environmentally compatible synthesis route.

The groundbreaking research conducted by Zhang et al. [59] exemplifies an essential advancement within this realm. Their complicated work resulted in the delicate extraction of MBC from biosludge and iron sludge through hydrothermal carbonization. This method brought forth MBC, characterized by exceptional properties, cementing its role as a catalyst for non-uniform Fenton reactions—a promising scientific innovation within MBC synthesis. Moreover, in a comprehensive analysis conducted by Wu et al. [31], the hydrothermal carbonation method emerged as a triumphant frontrunner compared to alternative thermochemical methods, such as pyrolytic and pyrolysis. Materials produced through this method showcased heightened ferromagnetic characteristics, rendering them remarkably amenable to magnetic separation, a feature of great scientific significance. Perhaps most notably, the hydrothermal carbonization process bypasses the need for substantial alkali or reducing agents, resulting in a milder and more harmonious approach—a testament to its promising potential for both scientific advancement and practical applications.

3.4. Leveraging Microwaves for Enhanced MBC Synthesis

Microwave pyrolysis is a technique that demonstrates the potential for highly efficient Magnetic Biochar (MBC) production. In this process, the primary step involves saturating biomass feedstock with magnetic precursors to create a magnetic slurry, followed by a drying process to form MBC briquettes. The unique aspect of microwave pyrolysis is its utilization of high-frequency, deeply penetrating microwaves. These microwaves are employed to polarize the particles within the material based on the dielectric heating principle. As a result, the rapid oscillation of the microwave's high-frequency field generates an electric field that triggers friction and collisions among the particles, leading to a substantial temperature increase. This transformation of electromagnetic energy into thermal energy occurs throughout the material, creating a temperature gradient from the core to the surface [65]. Notable research, such as the work of Shepherd et al., [71], has demonstrated the efficacy of microwave pyrolysis by utilizing Plam oil empty fruit bunches as a raw material. The results underscore the value of this method. MBC produced through microwave pyrolysis exhibits commendable ferromagnetic characteristics, and it is particularly noteworthy that under microwave heating, the MBC exhibits a saturation magnetization of 8.16 emu/g, surpassing the 4.20 emu/g achieved through conventional heating [32]. Furthermore, when combined with classical pyrolysis, one-step microwave pyrolysis results in MBC with extensive microporosity. This translates to a ninefold increase in the total porosity volume and an impressive ninefold expansion in effective surface area compared to conventional pyrolysis. This is primarily attributed to the ability of microwaves to heat the feedstock from the exterior to the interior homogeneously. Microwave pyrolysis stands out as a highly effective technique for MBC synthesis. It offers precise temperature control, high selectivity, and cost-effectiveness, with resultant MBC products possessing a greater surface area and pore volume, making it an invaluable tool for scientific and environmental applications [72].

3.5. Ball Milling: Crafting MBC Through Mechanical Precision

The ball milling method involves controlled mechanical interactions between grinding balls, milling jars, and feedstock particles under externally applied mechanical force [66]. The kinetic energy generated during milling disrupts chemical bonds, reduces

activation energy, and enables reactions to occur at lower temperatures. A major advantage of this method is the enhancement of surface properties and structural uniformity, resulting in improved adsorption capacity. Studies, such as the research conducted by Bai et al. [67], have searched the adsorption capabilities of MBC following ball milling. Their findings are impressive, with MBC displaying a maximum adsorption capacity of approximately 15.90 mg/g, a fivefold increase compared to the original MBC. This is attributed to MBC's efficiency in adsorbing substances on its surface, which sets it apart from materials with slower macromolecule diffusion in porous structures. With its mesmerizing precision and meticulous mechanical force, ball milling plays a crucial role in transforming particles into a unified composition with remarkable adsorption capabilities. It opens the door to various scientific possibilities, particularly environmental solutions [68].

3.6. The Diverse Array of MBC Synthesis Techniques

Magnetic Biochar (MBC) synthesis encompasses a diverse range of techniques, each contributing distinct structural and functional properties. These include nZVI-loaded biochar composites [22], molten-salt synthesis [52], chitosan cross-linking [69], combined co-precipitation–pyrolysis approaches [50], oxidative hydrolysis, and electrically assisted pyrolysis [73–75]. Collectively, these methods demonstrate the versatility of MBC synthesis and its adaptability to diverse environmental remediation scenarios. These techniques showcase the immense potential of MBC in various scientific applications and underscore the multifaceted nature of its synthesis. The different techniques used for MBC are summarized in Table 2 adopted from Xiao et al. [76].

Table 2. Analysis and evaluation of MBC preparation methods and techniques (adopted from Xiao et al. [76]).

Methods of Preparation	Material	Conditions	Place	Benefits and Drawbacks	References
Co-precipitation	Base/reducing agent, transition metal salt solution	(Chemical precipitation) pH from 9 to 11.	-	Short processing time, simple and stable reaction conditions, and high product purity; additional reagents raise costs and may be hazardous, and there are some safety concerns.	[63,73,77]
Impregnation–Pyrolysis	Transitioning metal salt solution, BC/biomass	Temperature from 300 to 1000 °C	Tube furnace/muffle furnace	Simple operation, good MBC stability, tight control of operational parameters (e.g., pyrolysis temperature, inert gas, and pyrolysis time); pyrolysis produces much energy, gaseous pollutants, and tar.	[35,74,78]
Hydrothermal carbonization	Alkaline salt/surfactant, transitional metal salt solution	Temperature from 130 to 260 °C	High-pressure reactor	The reaction can be considered moderate, requiring no high temperatures, strong bases, or reducing agents. insufficient stability	[79,80]
Microwave pyrolysis	Magnetic precursor, biomass	Temperature from 1000 to 2000 °C	Microwave oven	Rapid and uniform heating, high selectivity, and low cost; Lower yield than standard pyrolysis.	[43,71,81]
Ball milling	Biomass/BC, Grinding Ball	-	jar for grinding	Ball milling might hurt the MBC due to its ease of operation, efficiency, and low cost.	[35,68]
Other preparation methods	BC/Biomass, depending on the approach selected	-	-	Improved MBC stability and operation during preparation.	[69,82]

3.7. Economic Feasibility and Comparative Analysis of MBC

The process of producing Magnetic Biochar (MBC) for heavy metal remediation incurs higher costs than conventional biochar because of extra modification stages and the use of chemical reagents along with energy-demanding activation methods [83–85]. Optimizing production strategies, including the use of waste biomass and energy recovery systems, along with circular economy principles, can enhance economic feasibility by reducing both raw material and operational costs [83]. Among remediation systems, such as chemical precipitation methods and phytoremediation techniques, MBC stands out for its sustainable long-term benefits alongside its reusability and minimal secondary pollution generation [84]. Despite its high initial production cost, MBC proves to be cost-effective over time because of its excellent adsorption capacity combined with easy magnetic separation alongside its capacity for multiple reuse cycles. The economic evaluation comparing MBC technology to traditional remediation methods needs to demonstrate its operational efficiency and environmental advantages while showcasing its scalability for extensive soil and water treatment projects [85,86].

3.8. Assessing and Managing Environmental Risks of Trace Metal Ion Release

The environmental impact of trace metal ion release is an important factor in determining how sustainable and safe biosorbents are. This review talks about the potential dangers of metal leaching, but we need a more thorough risk assessment to understand the long-term effects on the environment. Future studies should look at systematic toxicity analyses, regulatory framework considerations, and real-world application scenarios to ensure that biosorbents can be used effectively.

We also need to explore ways to reduce metal release and improve environmental safety through mitigation strategies such as:

- Optimizing the desorption process.
- Integrating biosorbents with secondary treatment methods.
- Employing stabilization techniques.

These methods will help us create better biosorption technologies that are both sustainable and effective.

To assess more fully the environmental hazards of MBC, such as trace metal leaching and its impact on water and soil quality, a risk assessment framework is presented (Table 3). Figure 3 presents a structured risk-assessment framework for evaluating potential environmental hazards associated with MBC application, including trace-metal leaching, ecotoxicity, and long-term soil stability. The framework integrates risk identification, data collection, impact assessment, mitigation strategies, regulatory compliance, and field monitoring, thereby supporting informed decision-making for safe and sustainable MBC deployment. By applying this systematic framework, researchers and practitioners can facilitate the safe and sustainable use of MBC for environmental remediation.

Table 3. Risk assessment framework for evaluating the environmental impact of magnetic biochar (MBC).

Step	Key Actions	Objectives	Reference
Identification of Risks	- Evaluate trace metal leaching potential. - Assess soil and water quality effects. - Identify ecotoxicity hazards.	Determine the possible environmental risks of MBC use.	[3,5]
Data Collection	- Collect baseline water/soil data. - Describe MBC composition. - Perform leaching tests.	Develop baseline conditions and understand properties of MBC.	[5,31]
Risk Assessment	- Measure leaching rates. - Measure metal bioavailability. - Conduct ecotoxicity tests. - Assess long-term stability.	Measure MBC environmental impacts and risks.	[35]
Modeling and Prediction	- Employ fate/transport models. - Predict long-term hazards. - Replicate environmental conditions.	Predict future risks and streamline MBC application strategies.	[5,31]
Mitigation Strategies	- Optimize MBC production. - Utilize stabilization methods. - Combine with secondary treatments. - post-application monitoring.	Reduce risks and enhance the performance of MBC.	[35,87]
Regulatory Compliance	- Ensure compliance with regulations. - Develop safety procedures. - Train stakeholders.	Ensure safe and legal usage of MBC.	[5]
Field Trials and Monitoring	- Conduct field trials. - Record case studies. - Establish long-term monitoring.	Confirm laboratory findings and assess actual effects.	[30,87]
Reporting and Decision-Making	- Prepare risk assessment report. - Offer a framework for decision-making. - Enhance practice through feedback.	Facilitate knowledge-based decision-making and foster ongoing improvement.	[5,30]

4. MBC for Enhanced Heavy Metal Removal from Soil

4.1. Factors Influencing Heavy Metal Removal by MBC

Several critical factors come into play in the effective removal of heavy metals from soil using Magnetic Biochar Composites (MBCs). These factors include the intrinsic properties of the heavy metals themselves [88], the characteristics of the soil [89], the type of feedstock used for producing MBC, the pyrolysis temperature [67], and the amount of MBC applied to the soil [5,6].

4.1.1. Heavy Metal Intrinsic Properties

Heavy metals in the environment can pose a significant risk to human health, particularly when they enter the food chain. These heavy metals exhibit diverse properties that can be categorized as cationic or anionic based on their physical characteristics. Among the anionic heavy metals, prominent examples include As(III), Cr(VI), and As(V). At the same time, the more common cationic elements encompass Pb(II), Cd(II), Ni(II), Hg(II), and Sb(II). Extensive research has been dedicated to finding the most effective adsorbents for removing heavy metals from the environment. A crucial aspect is the influence of pH on heavy metal removal. Higher pH levels can promote the deprotonation of acidic functional groups, such as phenols, hydroxyls, and carboxylic acids, in the soil, making them more receptive to metal cations [69,90,91]. However, as pH increases, metal anions tend to repel each other. Alterations in the negative charge on the surface of MBC influence the

electrostatic attraction of metal ions to negatively charged functional groups, ultimately enhancing the material's electronegativity. The properties of the soil itself, such as organic matter content, pH, and cation exchange capacity (CEC), play pivotal roles in the efficiency of heavy metal removal [79].

4.1.2. Soil Characteristics

The introduction of MBC into the soil can significantly impact soil characteristics. Soil organic matter, rich in various functional groups (e.g., $-\text{COOH}$, $-\text{OH}$, $-\text{NH}_2$), changes as MBC is incorporated. Notably, the breakdown of organic matter produces small organic and humic acids, which can form stable complexes with heavy metal ions, reducing their mobility in the soil. The soil organic matter content plays a vital role in the effectiveness of heavy metal removal. For instance, in a study focusing on the influence of sulfur-iron modified BC (SF-BC) on the removal of Cd from contaminated soil, it was observed that the content of soil organic matter was a key factor influencing Cd removal efficacy [80]. Linear regression analysis revealed a negative correlation between organic matter content and the effectiveness of Cd removal. The presence of organic matter facilitates the adsorption and complexation of organic molecules through surface catalysis. Furthermore, MBC can alter the soil's cation exchange capacity (CEC), thereby enhancing the capacity for sorbing heavy metals through ion exchange. CEC is one of the critical soil properties influencing the fixation of heavy metals [32,33].

4.1.3. The Raw Materials for MBC

The composition of MBC consists of substantial carbon-rich magnetization, accompanied by critical elements such as Fe, C, N, O, and H. The selection of the feedstock used for magnetization and biomass source has a profound impact on the adsorption capacity for heavy metals. Notably, MBC typically exhibits an alkaline nature, owing to the presence of inorganic minerals that serve as additional sites for the adsorption of heavy metals. These minerals enhance ion exchange and surface complexation while also releasing soluble ions such as $(\text{SO}_4)^{2-}$, $(\text{PO}_4)^{3-}$, and $(\text{CO}_3)^{2-}$, contributing to the formation of metal precipitates [92]. Different raw materials for MBC exhibit varying properties, including carbon content, ash content, pH, and specific surface area. For example, plant-derived BC is characterized by lower ash content but higher carbon content when compared to sludge and manure BC. Understanding these variations is crucial in optimizing the production of MBC tailored for effective heavy metal removal [30,93].

4.1.4. The Temperature of Pyrolysis

In the production of MBC, two primary processes are commonly employed: co-precipitation and impregnation-pyrolysis. The temperature at which pyrolysis is conducted significantly influences the yield and properties of MBC. Changes in pyrolysis temperature affect several physicochemical parameters, including specific surface area, pore size, functional groups, and saturation magnetization [31]. While there may not be a uniform relationship between alterations in pyrolysis temperature and MBC magnetic properties, it is generally observed that the magnetic characteristics of MBC improve with higher pyrolysis temperatures. High pyrolysis temperatures tend to disrupt the functional structures of MBC, resulting in diminished magnetic properties [45]. The choice of raw material also directly impacts the pyrolysis temperature. Various materials undergo distinct reactions during pyrolysis, leading to variations in the properties of MBC [92]. Understanding these temperature-related variances is critical for the tailored production of MBC optimized for heavy metal removal.

4.1.5. The Dosage of MBC

The quantity of MBC applied is a crucial consideration in the remediation of heavy metal-polluted soil. The dosage choice has a direct and intuitive impact on the effectiveness of the remediation process. Excessive additions of MBC should be avoided to prevent potential secondary contamination. Studies have shown that increasing the dosage of MBC can enhance the removal of heavy metals from the soil [94]. For instance, applying iron-modified BC (NBC-Fe) to As-polluted soil at various concentrations increased the concentration of bound crystalline aqueous oxides. Selecting the appropriate dosage is critical in achieving the desired outcome of the remediation process while minimizing any potential adverse effects on the environment.

5. The Influence of Heavy Metal Forms in Soil and the Degree of Passivation After MBC Application

The form of heavy metals in the soil is a critical factor that profoundly impacts their mobility, biodegradability, and biotoxicity. Heavy metals exist in different chemicals, valence, mixed states, or structural forms within the environment, significantly affecting their behavior [95]. The transformation of these heavy metals to reduce their bioavailability is a primary focus of research, considering that heavy metals in soil are non-degradable and challenging to remediate [10,50] (See Figure 4). To gain a comprehensive understanding of heavy metal behavior, studies on metal ion sorption in water provide detailed insights into their availability, mobility, and sources [96,97]. The “Tessier” sequential extraction method and the BCR ordered extraction technique are commonly used to study the geochemical fractions of heavy metals in soils post-MBC application [95,98]. The BCR process involves the identification of several fractions: the acid-soluble phase (carbonates), exchangeable phase, reducible phase (hydrogen oxides of iron and manganese), oxidizable phase (organics and sulfides), and residual phase [10,99]. As heavy metals enter the soil through leaching, complexation, precipitation, and adsorption, they assume various forms. These forms are not static; they change and interact with each other as soil environmental conditions fluctuate [100,101]. The heavy metal in the soil significantly impacts its biological effectiveness and mobility. Introducing MBC to the soil can modify the electrical conductivity and pH, reduce the availability of metals while increase the amount of residual state metals [102] (See Figure 4). This transformation indicates reduced metal mobility and bioavailability, contributing to long-term soil stabilization. This alteration aligns with the concept of MBC acting as a form of soil heavy metal passivation remediation, encapsulating heavy metals and reducing their release. In a study by Huang et al., [103], MBC derived from reed straw was synthesized to investigate its impact on the passivation of Cd and Pb in pigment sludge. The results indicated that adding both BC and MBC led to a substantial increase in heavy metal passivation. Specifically, the Cd passivation efficiency increased by 12.7% and 41.9%, and the Pb passivation efficiency increased by 10.1% and 40.5% compared to the control group. This enhancement in heavy metal passivation can be attributed to MBC’s effective metal passivation capability and binding solid capacity, facilitating ion exchange processes [103]. In another investigation by Ruan et al., [104], calcium-based MBC (Ca-Fe-B) was synthesized and applied to Cr(VI)-polluted soil at varying concentrations. The results demonstrated that the passivation efficiency was 72.57%, 67.07%, and 59.88% at Cr(VI) pollution concentrations of 100, 200, and 1000 mg/kg, respectively. This process effectively converted some exchangeable Cr into comparable and residual Cr forms [104].

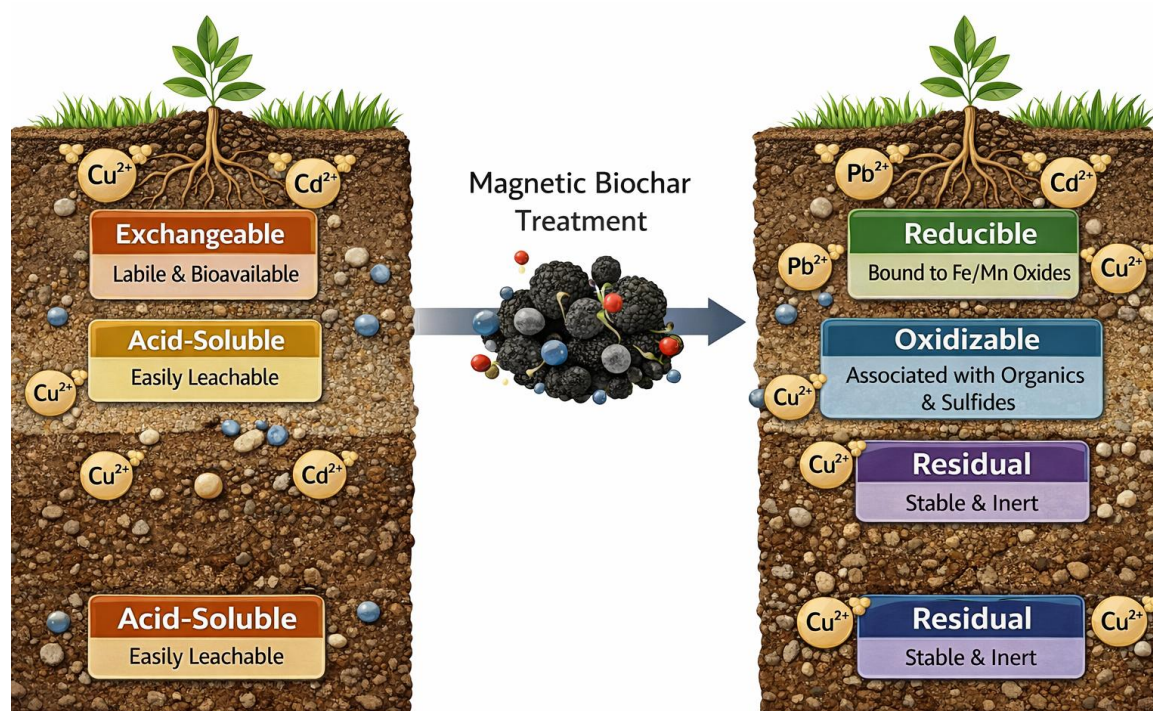


Figure 4. Impact of heavy metal speciation in soil and passivation efficiency following MBC application, illustrating the transformation of exchangeable and acid-soluble metal fractions into more stable reducible, oxidizable, and residual forms.

5.1. Mechanisms of Heavy Metal Removal from Soil by MBC

Extensive research has been conducted on how MBC removes heavy metals from polluted soil, as summarized in Table 2. Remediating heavy metal-polluted soil using MBC typically involves multiple mechanisms working in concert.

5.1.1. Physical Adsorption

Physical adsorption in MBC is facilitated by the stirring and heating processes used in magnetization, which dissolve and remove metals and organic substances from the BC pores [105]. This increases the specific surface area and porosity of MBC, allowing heavy metal ions to be immobilized through surface physio sorption. While MBC has proven more effective than non-magnetized BC in reducing the availability of heavy metals in soil, as noted by Wu et al., [93], the specific surface area of MBC can be significantly enhanced. Their study increased the specific surface area, leading to improved heavy metal adsorption capacity. Additionally, research on soil remediation using granular MBC (gMBC) found that a particle size of 1–2 mm for gMBC was the most effective, as it did not integrate into the soil matrix and could be quantitatively retrieved through magnetic attraction in wet and dry soils. Furthermore, the equilibrium between adsorption and soluble forms of heavy metals was found to be dynamic, with a decrease in heavy metal elimination efficiency after an initial peak, suggesting the possibility of resorption [106].

5.1.2. Ion Exchange

MBC reduces the activity of heavy metals in soil and immobilizes them through ion exchange processes. By replacing ionizable cations or protons on the MBC surface, the activity of heavy metals is reduced, and their immobilization in the soil is achieved [50]. Demonstrated that despite a significant reduction in the leaching of toxic metals such as Pb in the soil, it did not decrease the amount of acid-soluble Pb [50]. This is because the primary mechanism by which MBC reduces heavy metal concentration in the soil solution

is cation exchange, which involves a relatively weak bond between the metal and MBC. The study by Wu et al., [93] found that Cd, Zn, and Pb concentrations increased significantly when MBC was magnetically recycled, indicating the importance of cation exchange in reducing heavy metal concentration in the soil solution [93]. In another study, sulfide MBC (SMBC) was created to remediate metal-containing sediments. FeS was crucial in limiting heavy metal release through adsorption, ion exchange, and sulfide precipitation [107].

5.1.3. Surface/Co-Precipitation

MBC plays a vital role in immobilizing heavy metals by forming precipitates. These precipitates result from the reactions between heavy metal cations and mineral elements in MBC, such as SO_4^{2-} , PO_4^{3-} , and CO_3^{2-} . As a result of the addition of MBC, changes in the heavy metal form in the soil occur, influencing its biological effectiveness and mobility [36]. Environmental conditions, such as pH and temperature, can significantly impact the formation of heavy metals in soil. Hsu et al. [108] emphasized the formation of distinct sediments, such as $\text{FeAsO}_4 \cdot \text{H}_2\text{O}$ and $\text{FeAsO}_4 2\text{H}_2\text{O}$, under different environmental conditions, reducing the ability of (As) to migrate [108]. Furthermore, Fan et al. [109] reported that incorporating a biochar-based curing agent into soil immobilizers increased soil alkalinity, thereby decreasing Pb solubility and reducing its loss through cation exchange, complexation, and co-precipitation.

5.1.4. Metal-Functional Group Complexation

The complexation of heavy metal ions with functional groups on the surface of MBC plays a significant role in immobilizing heavy metals. Functional groups like $-\text{COOH}$ and $-\text{OH}$ in MBC form polyatomic structures or complexes with heavy metals. This results in reduced acid-soluble fractions of heavy metals, such as Cd and Cu, and an increase in the residual state of Zn and the oxidizable fraction of Cu [27,28]. Mandal et al., [29] observed a reduction in the acid-soluble Cd and Cu fractions and an increase in the residual state Zn and oxidizable fraction Cu, suggesting that complexation with functional groups like $-\text{COOH}$ or $-\text{OH}$ in MBC contributes to the immobilization of Zn and Cd. In contrast, complexation via organic functional groups like hydroxyl, phenolic, aldehydes, carboxylic acids, carbonyl, and quinones contributes to Cu immobilization [28].

5.1.5. Electrostatic Attraction

The electrostatic interaction between heavy metal ions and the surface charge of MBC is a crucial mechanism for immobilizing heavy metals. When mixed with soil, MBC, primarily alkaline, creates a lime effect, increasing the negative charge on soil particles' outermost layers. This enhances the electrostatic interaction between the negatively charged surface of MBC and heavy metal cations. The electrostatic impact is influenced by the pH of the surrounding medium and the zero charge point (pH_{pzc}) of MBC. When the medium pH exceeds the pH_{pzc} of MBC, the MBC surface becomes negatively charged and attracts heavy metal cations. Conversely, when the pH is lower, the MBC surface becomes positively charged and repels heavy metal cations [35].

5.1.6. Interaction Between Oxidation and Reduction

MBC employs oxidation-reduction processes to remove heavy metals, utilizing functional groups such as phenolic hydroxyl groups to transfer electrons and reduce Cr(VI) or oxidize As(III) [100]. In a study conducted by [37], the use of rice husk-derived BC and nZVI significantly reduced Cr(VI) bioavailability [37]. The principal redox compounds produced by Cr(VI) were FeCr_2O_4 , $\text{Cr}(\text{OH})_3$, and Cr_2O_3 , while dissolved organic carbon played a role in reducing Cr(VI) by oxidizing Fe^0 to Fe^{+2} and Fe^{+3} .

5.1.7. π - π Interactions

π - π interactions occur when heavy metal complexes interact with the abundant hydroxyl and aromatic groups in MBCs. It was evident that BC loaded with FeO demonstrated a greater affinity and adsorption capacity for Cd(II) in natural water-saturated soils [110]. These interactions, involving electrostatic attraction, complexation with hydroxyl groups, and interactions with aromatic complexes, enhance Cd's adsorption capacity and transport potential (II).

5.2. MBC's Ecotoxicity

The evaluation of MBC's effectiveness for heavy metal remediation in soil goes beyond assessing the bio-effectiveness of heavy metals. It is essential to comprehensively assess pollutant bioaccumulation and ecotoxicity, considering potential impacts on phytotoxicity, soil microbes, and enzymatic toxicity. MBC can potentially restore damaged soil, enhance its physical and chemical properties, sequester carbon, and mitigate the greenhouse effect. However, during biomass pyrolysis to create MBC, heavy metal components inherent in raw materials can become concentrated. Inefficient combustion and pyrolysis of biomass may also generate organic pollutants like tar and polycyclic aromatic hydrocarbons (PAHs). Over time, these contaminants can leach into the soil and accumulate, posing risks to the soil's ecosystem. It is worth noting that iron in MBC, though considered benign, has been shown to have potential negative impacts on organisms [87]. In Lei et al., [111] reviewed the ecotoxicity of MBC by investigating the *Vibrio fischeri*'s luminescence reduction. MBC exhibited acute toxicity to *Vibrio fischeri*, with EC50 values of 1.1×10^4 $\mu\text{g/mL}$ and 9.9×10^3 $\mu\text{g/mL}$ after 15 and 30 min of incubation, respectively [80]. It is important to note that, compared to other magnetic carbon-based carrier materials, MBC demonstrated a significantly lower level of toxicity [111]. Another study by Li et al., [70] focused on phytotoxic effects and ZVI was more effective than magnetic biochar, as it significantly reduced arsenic leaching below the Japanese environmental standard (10 $\mu\text{g/L}$) after 180 days of incubation [70]. Beyond direct ecotoxicity and phytotoxicity, the broader environmental behavior of magnetic biochar and related magnetic carbon-based amendments also warrants consideration. Gouma et al., [107] proposed a sorbent-based remediation strategy for soil impacted by organic micropollutants and heavy metals using granular biochar amendment combined with magnetic separation. Hsu et al., [108] demonstrated the use of recoverable sulfurized magnetic biochar for active capping of multiple heavy-metal-contaminated sediment. Fan et al., [109] reported one-pot synthesis of nZVI-embedded biochar for remediation of mining arsenic-contaminated soils, while Wu et al., [110] showed remediation of arsenic-contaminated paddy soil by iron-modified biochar. Lei et al. [111] further reviewed the environmental transformations and ecological effects of iron-based nanoparticles.

6. Microbial Response in Soil Following MBC Application

Soil microorganisms play a pivotal role in reflecting disturbances in soil ecosystems, serving as sensitive indicators of changes [112]. Their significance lies in their contribution to soil fertility through various biogeochemical processes [113]. Introducing Magnetic Biochar Composites (MBCs) into soil environments can profoundly affect the intricate interactions among soil, plants, and microorganisms. This subsequently influences soil microbial communities, enriches soil carbon sources, and augments soil physicochemical properties, such as pH and Total Organic Carbon (TOC) content [114]. Notably, the application of MBC has been shown to have transformative effects on microbial communities, increasing their abundance and rejuvenating microbial activity in heavy metal-polluted soils [5,115].

6.1. Rise in Abundance and Diversity of Microbial Communities

Wu et al., [116] investigated Cd immobilization and the associated changes in microbial community structure following the application of sulfur- or sulfur–iron-modified biochar (SF-BC). Their results showed increased species richness and diversity, along with a notable increase in the relative abundance of Proteobacteria, Bacteroidota, and Actinobacteria. This increase in relative abundance was likely attributed to a more nutrient-rich environment and additional organic materials brought about by SF-BC application. It is essential to recognize that SF-BC can influence not only Cd availability but also the local microbial ecosystem, underscoring the multifaceted nature of its effects. Moreover, Zhao et al. [94] examined the heterogeneity of biochar properties as a function of feedstock source and production temperature. The introduction of Fe/Zn-YBC led to a marked increase in the number and diversity of the microbial community [94]. Bacterial diversity was found to correlate positively with soil pH [117]. This could be attributed to the higher specific surface area and total porosity of Fe/Zn-YBC, which creates more favorable conditions for microorganisms and enhances microbial community richness. Notably, the dominance of Proteobacteria in acidic soils saw a significant decrease following the addition of Fe/Zn-YBC, while the population remained relatively stable in alkaline soils. This shift was linked to Actinobacteria's potential to degrade polymers, with their population increasing in acidic soils while showing no substantial changes in alkaline soils [25]. This underscores how environmental conditions significantly impact microbial community diversity [30].

6.2. Evolution of Microbial Communities

Diao et al. [118] investigated the evolution of microbial communities following the application of rice straw biochar (RSB) and magnetic sewage sludge biochar (SSB). Their results showed a significant increase in total organic carbon (TOC) after both SSB and RSB treatments, which may have promoted microbial growth by increasing the availability of organic carbon [118]. Actinobacteria substantially increased in both the SSB and RSB incubation groups, whereas Bacteroidota were significantly less abundant. This shift in microbial populations consistent with the immobilization effects observed for Cd and Pb [34]. Furthermore, the rise in Actinobacteria abundance was inversely correlated with the level of Cd in the soil, highlighting the potential of these bacteria to thrive under heavy metal stress. On the other hand, Bacteroidota demonstrated a higher tolerance to heavy metal contamination [119]. In a separate study, Wang et al. [120] investigated the growth and remediation-related role of *Bacillus* sp. in a magnetic biochar–microbe composite applied to Cd-contaminated paddy soil. K1 on MBC to explore its effects on the structure and diversity of native microorganisms. *Bacillus* has a history of use in Cd cleanup due to its extensive distribution and high resistance to adverse environmental conditions. The results indicated a notable increase in *Bacillus* relative abundance, particularly under aerobic conditions in MBC and SBC treatments, which featured high toxic metal concentrations, elevated temperatures, and dry soil [120]. *Bacillus* is known as a prevalent genus of metal-reducing bacteria under aerobic conditions [121,122]. This increase is associated with *Bacillus*'s ability to ferment glucose exclusively for energy production under anaerobic conditions [16]. Consequently, its relative abundance is considerably lower in anaerobic environments [123]. The pH of the soil and biomass carbon content emerged as crucial variables governing microbial community survival, particularly for *Bacillus*, in aerobic and anaerobic conditions. This shift in microbial communities following MBC application has cascading effects on the soil environment. The interplay between microbial diversity and heavy metal stabilization is underscored by the influence of MBC, which alters soil physicochemical properties and enhances carbon sequestration. Consequently, in addition to its role in heavy metal immobilization, MBC's impact on soil microorganisms

has become an area of intense research interest. Further comprehensive studies are needed to deepen our understanding of the interactions between MBC and microbial activity in heavy metal-polluted soils and to elucidate the mechanisms by which MBC and microorganisms collaborate to immobilize heavy metals.

6.3. The Effects of Microbial Competition in Soil on the Environment

The dynamics of microbial communities can be drastically changed by introducing foreign or modified bacterial strains into soil environments. The effectiveness of bioaugmentation techniques and their long-term ecological effects are largely determined by the competition between native and introduced bacteria [115]. Introduced bacteria can increase soil fertility or biodegradation efficiency, but they can also outcompete native microbial populations, which reduce microbial diversity [119]. This change may interfere with vital soil processes as pathogen control, nitrogen cycling, and organic matter breakdown [120–122]. Additionally, unintentionally selected pressures caused by introduced bacteria may benefit some microbial communities while suppressing others, thereby decreasing soil tolerance to environmental stressors [31, 94,102]. Predicting possible ecological effects and ensuring that microbial interventions promote sustainable soil health rather than creating imbalances require understanding these competition dynamics [113]. Future studies should concentrate on tracking changes in the microbial population over an extended period and evaluating the overall impact of bacterial competition on the stability of soil ecosystems. Table 4 summarizes the case studies of successful MBC applications in soil remediation.

Table 4. Successful Applications of Magnetic Biochar in Heavy Metal-Contaminated Soils.

Case Study	Study	Results	Reference
Remediation of Arsenic and Cadmium Co-Contaminated Soil	Simultaneous removal of arsenic (As), cadmium (Cd), and lead (Pb) from soil using iron-modified magnetic biochar.	MBC had a significant impact on As and Cd levels, reducing them by up to 90% for As and 85% for Cd. This made toxic metals less mobile, reducing environmental and health risks.	[3]
Chromium (Cr) Removal from Contaminated Soil	MBC derived from rice husk and nano-zero-valent iron (nZVI) for the remediation of Cr(VI) contaminated soil.	MBC converted Cr(VI) to Cr(III) with over 95% success rate. MBC could be easily removed from the soil using a magnet, making it suitable for cleaning up large areas.	[20]
Lead (Pb) Immobilization in Agricultural Soil	MBC is derived from pig manure and straw for Pb-contaminated agricultural soil.	MBC reduced the availability of Pb by 70% and promoted the growth of various types of microbes. This indicated improved soil health while also sequestering heavy metals.	[22]
Phosphate Removal from Water-Saturated Soils	MBC synthesized from NaLa(CO ₃) ₂ -decorated magnetic biochar to remove phosphate from water-saturated soils.	MBC removed over 80% of phosphate and could be regenerated and reused multiple times without significant loss of efficacy.	[24]
Cadmium (Cd) Passivation in Pigment Sludge	MBC derived from reed straw for the passivation of Cd and Pb in pigment sludge.	MBC increased the passivity of Cd by 41.9% and Pb by 40.5%, transforming mobile heavy metals into more stable forms that are less available to living organisms.	[31]
Mercury (Hg) Removal from Contaminated Soil	MBC is derived from sawdust for the removal of mercury (Hg) from contaminated soil.	MBC demonstrated the ability to remove over 90% of Hg and could be easily separated from the soil using a magnetic field, making it effective for cleaning up Hg-contaminated soil.	[103]

Zinc (Zn) and Copper (Cu) Immobilization in Acidic Soils	Applied calcium-based MBC to acidic soils contaminated with Zn and Cu.	MBC reduced Zn availability by 60% and Cu by 50% while also increasing soil pH and enhancing microbial activity. This indicates improved soil health and effective trapping of heavy metals.	[104]
Nickel (Ni) and Iron (Fe) Removal from Water-Saturated Soils	MBC is derived from switchgrass for the removal of Ni and Fe from water-saturated soils.	MBC showed over 85% efficiency in removing Ni and Fe and could be reused multiple times without significant loss of effectiveness.	[64]
Polycyclic Aromatic Hydrocarbons (PAHs) Removal from Contaminated Soil	MBC derived from bamboo biomass for the removal of PAHs from marine sediments.	MBCs eliminated over 90% of PAHs and could be easily extracted from the soil using a magnet, making it convenient for cleaning up PAH-contaminated soil.	[82]
Sulfur-Modified MBC for Cadmium (Cd) Immobilization	Sulfur-modified MBC (SMBC) for the immobilization of Cd in contaminated soils.	MBC reduced the uptake of Cd by living organisms by 70% and promoted the growth of various microorganisms in the soil, indicating improved soil health and effective immobilization of heavy metals.	[96].

7. Conclusions

Magnetic biochar (MBC) has been widely promoted as a multifunctional material offering significant environmental advantages; however, systematic comparisons with conventional biochar remain limited. Although laboratory-scale studies demonstrate promising performance, large-scale field validation and long-term ecological assessments are still required. The current studies have not provided any case studies that give evidence about economic viability, stability, and tangible environmental impacts. Future investigations should be based on the analysis of MBC technology after its experimental applications in controlled and field-scale settings are made a success. The development of long-term field trials is obligatory for the sake of record keeping of the ecological effects of biochar on the microbial life in soil and the general health of the soil. They must follow undisturbed practices of microbial diversity, abundance, and functionality over time, as well as take the heavy metal immobilization and soil properties stability into account. This study is particularly intended to be the source of necessary information on renewable energy and environmental restoration that is indispensable for the safe and good use of MBC. To enhance the sustainability of MBC production, new experiments need to be conducted to find new and alternative sources of biomass, such as algae, forestry residues, and underutilized agricultural or industrial wastes. These feedstocks enable the reduction in waste disposal burden and the improvement of economic feasibility by using a low-cost, readily available material. In addition, waste biomass with iron contents, such as iron-rich sludge and nano-zero-valent iron (nZVI) sludge, will also be a subject of a study that will test their efficiency in creating a magnetic precursor and compare it to the use of external magnets. The circular economy principles will be maintained in the development of MBC as the reuse of waste materials for environmental remediation will be the priority. The MBC incorporation with waste biomass in the production sector ensures that heavy metals are removed not only in a green but also in a scalable manner. Cross-disciplinary cooperation between soil scientists, environmental engineers, microbiologists, and toxicologists is crucial to fit the complex riddling MBC puzzle together and provide a comprehensive view of its environmental influence. The MBC's potential is highlighted in a laboratory study, but an on-field validation performance epitomizes real-world situations. Future research should focus on large-scale trials to evaluate MBC's applicability in diverse settings, including agricultural and urban soils.

Author Contributions: A.E.-H. conceived the review topic, conducted the literature search, analyzed and synthesized the published studies, and prepared the original draft of the manuscript. A.I. contributed to the conceptual development of the review, supervised the work, and critically reviewed and edited the manuscript. A.A.S. and M.M.A. contributed to the interpretation of the literature and participated in reviewing and improving the manuscript. M.N.S., M.F., and M.M.E. assisted with literature collection, organization of references, and preparation of figures and tables. M.S.A.E.-S. supervised the study, contributed to the critical revision of the manuscript, and supported the research framework. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: This article contains no studies involving human participants performed by any authors.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors have no conflicts of interest to declare relevant to this article's content.

References

- Sanad, M.N.; El-Dek, S.I.; Eldemerdash, U.; ElFaham, M.M. Study of the adsorptive removal of (Fe^{+2}) and (Ni^{+2}) from water by synthesized magnetite/corn cobs magnetic nanocomposite. *Nano Futures* **2022**, *6*, 025004. <https://doi.org/10.1088/2399-1984/ac6a31>.
- Farouz, M.; El-Dek, S.I.; ElFaham, M.M.; Eldemerdash, U. Ecofriendly sustainable synthesized nanocomposite for removal of heavy metals from aquatic environment. *Appl. Nanosci.* **2022**, *12*, 1585–1600.
- Wan, X.; Li, C.; Parikh, S.J. Simultaneous removal of arsenic, cadmium, and lead from soil by iron-modified magnetic biochar. *Environ. Pollut.* **2020**, *261*, 114157.
- Qu, J.; Akindolie, M.S.; Feng, Y.; Jiang, Z.; Zhang, G.; Jiang, Q.; Deng, F.; Cao, B.; Zhang, Y. One-pot hydrothermal synthesis of $\text{NaLa}(\text{CO}_3)_2$ decorated magnetic biochar for efficient phosphate removal from water: Kinetics, isotherms, thermodynamics, mechanisms and reusability exploration. *Chem. Eng. J.* **2020**, *394*, 124915.
- Wu, J.; Li, Z.; Huang, D.; Liu, X.; Tang, C.; Parikh, S.J.; Xu, J. A novel calcium-based magnetic biochar is effective in stabilization of arsenic and cadmium co-contamination in aerobic soils. *J. Hazard. Mater.* **2020**, *387*, 122010.
- Xu, Y.; Seshadri, B.; Sarkar, B.; Wang, H.; Rumpel, C.; Sparks, D.; Farrell, M.; Hall, T.; Yang, X.; Bolan, N. Biochar modulates heavy metal toxicity and improves microbial carbon use efficiency in soil. *Sci. Total Environ.* **2018**, *621*, 148–159.
- Zhang, Z.; Yang, X.; Wang, J.; Zhuang, T.; Liu, S.; Dou, M.; Huo, K.; Zhou, Y.; Ding, G. Magnetic biochar pyrolyzed from municipal sludge for Fenton-like degradation of thiamethoxam: Characteristics and mechanism. *J. Water Process Eng.* **2023**, *51*, 103391.
- Patel, S.K.S.; Choi, S.H.; Kang, Y.C.; Lee, J. Eco-friendly composite of Fe_3O_4 -reduced graphene oxide particles for efficient enzyme immobilization. *ACS Appl. Mater. Interfaces* **2017**, *9*, 2213–2222. <https://doi.org/10.1021/acsami.6b05165>.
- Samuel, M.S.; Shang, M.; Klimchuk, S.; Niu, J. Novel regenerative hybrid composite adsorbent with improved removal capacity for lead ions in water. *Ind. Eng. Chem. Res.* **2021**, *60*, 5124–5132.
- Bolan, N.; Kunhikrishnan, A.; Thangarajan, R.; Kumpiene, J.; Park, J.; Makino, T.; Kirkham, M.B.; Scheckel, K. Remediation of heavy metal (loid)s contaminated soils—to mobilize or to immobilize? *J. Hazard. Mater.* **2014**, *266*, 141–166.
- Ahmad, M.; Rajapaksha, A.U.; Lim, J.E.; Zhang, M.; Bolan, N.; Mohan, D.; Vithanage, M.; Lee, S.S.; Ok, Y.S. Biochar as a sorbent for contaminant management in soil and water: A review. *Chemosphere* **2014**, *99*, 19–33.
- Dey, A.; Singh, R.; Purkait, M.K. Cobalt ferrite nanoparticles aggregated schwertmannite: A novel adsorbent for the efficient removal of arsenic. *J. Water Process Eng.* **2014**, *3*, 1–9.
- Lehmann, J. A handful of carbon. *Nature* **2007**, *447*, 143–144.
- Novotny, E.H.; Auccaise, R.; Velloso, M.H.R.; Corrêa, J.C.; Higarashi, M.M.; Abreu, V.M.N.; Rocha, J.D.; Kwapinski, W. Characterization of phosphate structures in biochar from swine bones. *Pesqui. Agropecuária Bras.* **2012**, *47*, 672–676.

15. Tessier, A.; Campbell, P.G.; Bisson, M. Sequential extraction procedure for the speciation of particulate trace metals. *Anal. Chem.* **1979**, *51*, 844–851.
16. Vijayaraghavan, K.; Yun, Y. Bacterial biosorbents and biosorption. *Biotechnol. Adv.* **2008**, *26*, 266–291.
17. Zhang, Y.; Qu, J.; Yuan, Y.; Song, H.; Liu, Y.; Wang, S.; Tao, Y.; Zhao, Y.; Li, Z. Si-multaneous scavenging of Cd(II) and Pb(II) from water by sulfide-modified magnetic pinecone-derived hydrochar. *J. Clean. Prod.* **2022**, *341*, 130758.
18. Cheng, S.; Chen, T.; Xu, W.; Huang, J.; Jiang, S.; Yan, B. Application research of biochar for the remediation of soil heavy metals contamination: A review. *Molecules* **2020**, *25*, 3167.
19. Devi, P.; Saroha, A.K. Synthesis of the magnetic biochar composites for use as an adsorbent for the removal of pentachlorophenol from the effluent. *Bioresour. Technol.* **2014**, *169*, 525–531.
20. Li, X.; Wang, C.; Zhang, J.; Liu, J.; Liu, B.; Chen, G. Preparation and application of magnetic biochar in water treatment: A critical review. *Sci. Total Environ.* **2020**, *711*, 134847. <https://doi.org/10.1016/j.scitotenv.2019.134847>.
21. Liu, L.; Liu, X.; Wang, D.; Lin, H.; Huang, L. Removal and reduction of Cr(VI) in simulated wastewater using magnetic biochar prepared by co-pyrolysis of nano-zero-valent iron and sewage sludge. *J. Clean. Prod.* **2020**, *257*, 120562. <https://doi.org/10.1016/j.jclepro.2020.120562>.
22. Liu, X.; Yang, L.; Zhao, H.; Wang, W. Pyrolytic production of zerovalent iron nanoparticles supported on rice husk-derived biochar: Simple, in situ synthesis and use for remediation of Cr(VI)-polluted soils. *Sci. Total Environ.* **2020**, *708*, 134479. <https://doi.org/10.1016/j.scitotenv.2019.134479>.
23. Yang, L.; Mei, H.; Fei, S.; Haiyan, G.; Qing, W. Investigations on cultivation methods for assessing the early phytotoxicity of biochar [investigations on cultivation methods for assessing the early phytotoxicity of biochar]. *Asian J. Ecotoxicol.* **2016**, *11*, 168–175. <https://doi.org/10.7524/AJE.1673-5897.20151217001>.
24. Feng, Z.; Yuan, R.; Wang, F.; Chen, Z.; Zhou, B.; Chen, H. Preparation of magnetic biochar and its application in catalytic degradation of organic pollutants: A review. *Sci. Total Environ.* **2021**, *765*, 142673.
25. Yi, Y.; Huang, Z.; Lu, B.; Xian, J.; Tsang, E.P.; Cheng, W.; Fang, J.; Fang, Z. Magnetic biochar for environmental remediation: A review. *Bioresour. Technol.* **2020**, *298*, 122468.
26. Zheng, J.; Chen, J.; Pan, G.; Liu, X.; Zhang, X.; Li, L.; Bian, R.; Cheng, K.; Jinwei, Z. Biochar decreased microbial metabolic quotient and shifted community composition four years after a single incorporation in a slightly acid rice paddy from southwest China. *Sci. Total Environ.* **2016**, *571*, 206–217.
27. Kazemi Shariat Panahi, H.; Dehghani, M.; Ok, Y.S.; Nizami, A.; Khoshnevisan, B.; Mus-satto, S.I.; Aghbashlo, M.; Tabatabaei, M.; Lam, S.S. A comprehensive review of engineered biochar: Production, characteristics, and environmental applications. *J. Clean. Prod.* **2020**, *270*, 122462. <https://doi.org/10.1016/j.jclepro.2020.122462>.
28. Mandal, S.; Pu, S.; He, L.; Ma, H.; Hou, D. Biochar induced modification of graphene oxide & nZVI and its impact on immobilization of toxic copper in soil. *Environ. Pollut.* **2020**, *259*, 113851.
29. Mandal, S.; Pu, S.; Wang, X.; Ma, H.; Bai, Y. Hierarchical porous structured poly-sulfide supported nZVI/biochar and efficient immobilization of selenium in the soil. *Sci. Total Environ.* **2020**, *708*, 134831.
30. Philippou, K.; Anastopoulos, I.; Dosche, C.; Pashalidis, I. Synthesis and characterization of a novel Fe₃O₄-loaded oxidized biochar from pine needles and its application for uranium removal. Kinetic, thermodynamic, and mechanistic analysis. *J. Environ. Manag.* **2019**, *252*, 109677.
31. Wu, J.; Li, Z.; Wang, L.; Liu, X.; Tang, C.; Xu, J. A novel calcium-based magnetic biochar reduces the accumulation of As in grains of rice (*Oryza sativa* L.) in As-contaminated paddy soils. *J. Hazard. Mater.* **2020**, *394*, 122507. <https://doi.org/10.1016/j.jhazmat.2020.122507>.
32. Zubrik, A.; Matik, M.; Lovás, M.; Stefusova, K.; Danková, Z.; Hredzák, S.; Václavíková, M.; Bendek, F.; Briancin, J.; Machala, L. One-step microwave synthesis of magnetic biochars with sorption properties. *Carbon Lett.* **2018**, *26*, 31–42.
33. Zhang, M.; Gao, B.; Varnoosfaderani, S.; Hebard, A.; Yao, Y.; Inyang, M. Preparation and characterization of a novel magnetic biochar for arsenic removal. *Bioresour. Technol.* **2013**, *130*, 457–462.
34. Fauiod, O.G.; Fadel, M.; El-Hussein, A.; Fadeel, D.A. Aluminum phthalocyanine tetrasulfonate conjugated to surface-modified iron oxide nanoparticles as a magnetic targeting platform for photodynamic therapy of Ehrlich tumor-bearing mice. *Photodiagnosis Photodyn. Ther.* **2024**, *50*, 104356.
35. Li, P.; Yu, J.; Huangfu, Z.; Chang, J.; Zhong, C.; Ding, P. Applying modified biochar with nZVI/nFe₃O₄ to immobilize Pb in contaminated soil. *Environ. Sci. Pollut. Res.* **2020**, *27*, 24495–24506.

36. Li, Y.; Ma, S.; Xu, S.; Fu, H.; Li, Z.; Li, K.; Sheng, K.; Du, J.; Lu, X.; Li, X. Novel magnetic biochar as an activator for peroxymonosulfate to degrade bisphenol A: Emphasizing the synergistic effect between graphitized structure and CoFe_2O_4 . *Chem. Eng. J.* **2020**, *387*, 124094.
37. Li, Y.; Zimmerman, A.R.; He, F.; Chen, J.; Han, L.; Chen, H.; Hu, X.; Gao, B. Solvent-free synthesis of magnetic biochar and activated carbon through ball-mill ex-trusion with Fe_3O_4 nanoparticles for enhancing adsorption of methylene blue. *Sci. Total Environ.* **2020**, *722*, 137972.
38. Luo, J.; Bo, S.; Qin, Y.; An, Q.; Xiao, Z.; Zhai, S. Transforming goat manure into surface-loaded cobalt/biochar as PMS activator for highly efficient ciprofloxacin degradation. *Chem. Eng. J.* **2020**, *395*, 125063.
39. Zhang, J.; Zhou, H.; Gu, J.; Huang, F.; Yang, W.; Wang, S.; Yuan, T.; Liao, B. Effects of nano- Fe_3O_4 -modified biochar on iron plaque formation and Cd accumulation in rice (*Oryza sativa* L.). *Environ. Pollut.* **2020**, *260*, 113970. <https://doi.org/10.1016/j.envpol.2020.113970>.
40. Gong, H.; Huang, J.; Ding, Z.; Chi, J. A potential method using magnetically modified wheat straw biochars for soil Cd extraction. *Ecol. Eng.* **2021**, *166*, 106240.
41. Gu, P.; Zhang, Y.; Xie, H.; Wei, J.; Zhang, X.; Huang, X.; Wang, J.; Lou, X. Effect of cornstalk biochar on phytoremediation of Cd-contaminated soil by *Beta vulgaris* var. *cicla* L. *Ecotoxicol. Environ. Saf.* **2020**, *205*, 111144.
42. Rong, X.; Xie, M.; Kong, L.; Natarajan, V.; Ma, L.; Zhan, J. The magnetic biochar derived from banana peels as a persulfate activator for organic contaminants degradation. *Chem. Eng. J.* **2019**, *372*, 294–303.
43. Thines, K.R.; Abdullah, E.C.; Mubarak, N.M.; Ruthiraan, M. Synthesis of magnetic biochar from agricultural waste biomass to enhancing route for waste water and polymer application: A review. *Renew. Sustain. Energy Rev.* **2017**, *67*, 257–276. <https://doi.org/10.1016/j.rser.2016.09.057>.
44. Chaiyaraksa, C.; Lokham, N.; Kuikrong, R.; Artsanapaiboon, S. Immobilization of cadmium in soil using magnetic biochar derived from *Eichhornia crassipes*. *ScienceAsia* **2020**, *46*, 450–456.
45. Chen, B.; Chen, Z.; Lv, S. A novel magnetic biochar efficiently sorbs organic pollutants and phosphate. *Bioresour. Technol.* **2011**, *102*, 716–723.
46. Dong, J.; Shen, L.; Shan, S.; Liu, W.; Qi, Z.; Liu, C.; Gao, X. Optimizing magnetic functionalization conditions for efficient preparation of magnetic biochar and adsorption of Pb(II) from aqueous solution. *Science of the Total Environment* **2022**, *806*, 151442. DOI: 10.1016/j.scitotenv.2021.151442.
47. Wang, S.; Gao, B.; Zimmerman, A.R.; Li, Y.; Ma, L.; Harris, W.G.; Migliaccio, K.W. Removal of arsenic by magnetic biochar prepared from pinewood and natural hematite. *Bioresour. Technol.* **2015**, *175*, 391–395.
48. Oladipo, A.A.; Ifebajo, A.O.; Nisar, N.; Ajayi, O.A. High-performance magnetic chicken bone-based biochar for efficient removal of rhodamine-B dye and tetracycline: Competitive sorption analysis. *Water Sci. Technol.* **2017**, *76*, 373–385.
49. Shakoob, M.B.; Ali, S.; Rizwan, M.; Abbas, F.; Bibi, I.; Riaz, M.; Khalil, U.; Niazi, N.K.; Rinklebe, J. A review of biochar-based sorbents for separation of heavy metals from water. *Int. J. Phytoremediation* **2020**, *22*, 111–126.
50. Lu, H.P.; Li, Z.A.; Gasco, G.; Mendez, A.; Shen, Y.; Paz-Ferreiro, J. Use of magnetic biochars for the immobilization of heavy metals in a multi-contaminated soil. *Sci. Total Environ.* **2018**, *622*, 892–899.
51. Zhu, Y.; Yi, B.; Hu, H.; Zong, Z.; Chen, M.; Yuan, Q. The relationship of structure and organic matter adsorption characteristics by magnetic cattle manure biochar prepared at different pyrolysis temperatures. *J. Environ. Chem. Eng.* **2020**, *8*, 104112.
52. Dai, S.; Zhao, Y.; Niu, D.; Li, Q.; Chen, Y. Preparation and reactivation of magnetic biochar by molten salt method: Relevant performance for chlorine-containing pesticides abatement. *J. Air Waste Manag. Assoc.* **2019**, *69*, 58–70.
53. Luo, X.; Shen, M.; Liu, J.; Ma, Y.; Gong, B.; Liu, H.; Huang, Z. Resource utilization of piggery sludge to prepare recyclable magnetic biochar for highly efficient degradation of tetracycline through peroxymonosulfate activation. *J. Clean. Prod.* **2021**, *294*, 126372.
54. Tang, L.; Yu, J.; Pang, Y.; Zeng, G.; Deng, Y.; Wang, J.; Ren, X.; Ye, S.; Peng, B.; Feng, H. Sustainable efficient adsorbent: Alkali-acid modified magnetic biochar derived from sewage sludge for aqueous organic contaminant removal. *Chem. Eng. J.* **2018**, *336*, 160–169.
55. Jack, J.; Huggins, T.M.; Huang, Y.; Fang, Y.; Ren, Z.J. Production of magnetic biochar from waste-derived fungal biomass for phosphorus removal and recovery. *J. Clean. Prod.* **2019**, *224*, 100–106.
56. Luo, H.Q.; Zhang, Y.K.; Xie, Y.; Li, Y.L.; Qi, M.; Ma, R.Z.; Yang, S.H.; Wang, Y.B. Iron-rich microorganism-enabled synthesis of magnetic biocarbon for efficient adsorption of diclofenac from aqueous solution. *Bioresour. Technol.* **2019**, *282*, 310–317. <https://doi.org/10.1016/j.biortech.2019.03.028>.

57. Liang, S.; Shi, S.; Zhang, H.; Qiu, J.; Yu, W.; Li, M.; Gan, Q.; Yu, W.; Xiao, K.; Liu, B. One-pot solvothermal synthesis of magnetic biochar from waste biomass: Formation mechanism and efficient adsorption of Cr(VI) in an aqueous solution. *Sci. Total Environ.* **2019**, *695*, 133886.
58. Li, R.; Deng, H.; Zhang, X.; Wang, J.J.; Awasthi, M.K.; Wang, Q.; Xiao, R.; Zhou, B.; Du, J.; Zhang, Z. High-efficiency removal of Pb(II) and humate by a CeO₂–MoS₂ hybrid magnetic biochar. *Bioresour. Technol.* **2019**, *273*, 335–340. <https://doi.org/10.1016/j.biortech.2018.10.053>.
59. Zhang, H.; Xue, G.; Chen, H.; Li, X. Magnetic biochar catalyst derived from biological sludge and ferric sludge using hydrothermal carbonization: Preparation, characterization and its circulation in Fenton process for dyeing wastewater treatment. *Chemosphere* **2018**, *191*, 64–71.
60. Zhang, J.; Lu, W.; Zhan, S.; Qiu, J.; Wang, X.; Wu, Z.; Li, H.; Qiu, Z.; Peng, H. Adsorption and mechanistic study for humic acid removal by magnetic biochar derived from forestry wastes functionalized with Mg/Al-LDH. *Sep. Purif. Technol.* **2021**, *276*, 119296. <https://doi.org/10.1016/j.seppur.2021.119296>.
61. Duan, S.; Ma, W.; Pan, Y.; Meng, F.; Yu, S.; Wu, L. Synthesis of magnetic biochar from iron sludge for the enhancement of Cr(VI) removal from solution. *J. Taiwan Inst. Chem. Eng.* **2017**, *80*, 835–841.
62. Wang, F.; Zhao, B.; Zhang, F.; Gao, J.; Hao, H.; Zhang, S. A novel heavy metal chelating agent sixthio guanidine acid for in situ remediation of soils contaminated with multielements: Its synthesis, solidification, biodegradability, and leachability. *J. Soils Sediments* **2016**, *16*, 371–381.
63. Liu, J.; Jiang, J.; Aihemaiti, A.; Meng, Y.; Yang, M.; Xu, Y.; Gao, Y.; Zou, Q.; Chen, X. Removal of phosphate from aqueous solution using MgO-modified magnetic biochar derived from anaerobic digestion residue. *J. Environ. Manag.* **2019**, *250*, 109438.
64. Liu, Y.; Huang, J.; Xu, H.; Zhang, Y.; Hu, T.; Chen, W.; Hu, H.; Wu, J.; Li, Y.; Jiang, G. A magnetic macro-porous biochar sphere as vehicle for the activation and removal of heavy metals from contaminated agricultural soil. *Chem. Eng. J.* **2020**, *390*, 124638. <https://doi.org/10.1016/j.cej.2020.124638>.
65. Siddiqui, M.T.H.; Nizamuddin, S.; Baloch, H.A.; Mubarak, N.M.; Dumbre, D.K.; Asiri, A.M.; Bhutto, A.W.; Srinivasan, M.; Griffin, G.J. Synthesis of magnetic carbon nanocomposites by hydrothermal carbonization and pyrolysis. *Environ. Chem. Lett.* **2018**, *16*, 821–844.
66. Lovás, M.; Znamenáčková, I.; Zubrik, A.; Kováčová, M.; Dolinská, S. The application of microwave energy in mineral processing—a review. *Acta Montan. Slovaca* **2011**, *16*, 137.
67. Bai, X.; Tiwari, S.; Robinson, B.; Killmer, C.; Li, L.; Hu, J. Microwave catalytic synthesis of ammonia from methane and nitrogen. *Catal. Sci. Technol.* **2018**, *8*, 6302–6305.
68. Huang, Z.; Yi, Y.; Zhang, N.; Tsang, P.E.; Fang, Z. Removal of fluconazole from aqueous solution by magnetic biochar treated by ball milling: Adsorption performance and mechanism. *Environ. Sci. Pollut. Res.* **2022**, *29*, 33335–33344.
69. Shan, D.; Deng, S.; Zhao, T.; Wang, B.; Wang, Y.; Huang, J.; Yu, G.; Winglee, J.; Wiesner, M.R. Preparation of ultrafine magnetic biochar and activated carbon for pharmaceutical adsorption and subsequent degradation by ball milling. *J. Hazard. Mater.* **2016**, *305*, 156–163.
70. Li, J.; Zhang, Y.; Wang, F.; Wang, L.; Liu, J.; Hashimoto, Y.; Hosomi, M. Arsenic immobilization and removal in contaminated soil using zero-valent iron or magnetic biochar amendment followed by dry magnetic separation. *Sci. Total Environ.* **2021**, *768*, 144521.
71. Shepherd, B.J.; Ryan, J.; Adam, M.; Vallejo, D.B.; Castaño, P.; Kostas, E.T.; Robinson, J.P. Microwave pyrolysis of biomass within a liquid medium. *J. Anal. Appl. Pyrolysis* **2018**, *134*, 381–388.
72. Mubarak, N.M.; Sahu, J.N.; Abdullah, E.C.; Jayakumar, N.S. Plam oil empty fruit bunch based magnetic biochar composite comparison for synthesis by microwave-assisted and conventional heating. *J. Anal. Appl. Pyrolysis* **2016**, *120*, 521–528.
73. Mojiri, A.; Andasht Kazeroon, R.; Gholami, A. Cross-linked magnetic chitosan/activated biochar for removal of emerging micropollutants from water: Optimization by the artificial neural network. *Water* **2019**, *11*, 551.
74. Cui, Q.; Xu, J.; Wang, W.; Tan, L.; Cui, Y.; Wang, T.; Li, G.; She, D.; Zheng, J. Phosphorus recovery by core-shell γ -Al₂O₃/Fe₃O₄ biochar composite from aqueous phosphate solutions. *Sci. Total Environ.* **2020**, *729*, 138892. <https://doi.org/10.1016/j.scitotenv.2020.138892>.
75. Yang, J.; Zhao, Y.; Ma, S.; Zhu, B.; Zhang, J.; Zheng, C. Mercury removal by magnetic biochar derived from simultaneous activation and magnetization of sawdust. *Environ. Sci. Technol.* **2016**, *50*, 12040–12047.
76. Xiao, B.; Jia, J.; Wang, W.; Zhang, B.; Ming, H.; Ma, S.; Kang, Y.; Zhao, M. A review on magnetic biochar for the removal of heavy metals from contaminated soils: Preparation, application, and microbial response. *J. Hazard. Mater. Adv.* **2023**, *10*, 100254.

77. Yang, P.; Guo, D.; Chen, Z.; Cui, B.; Xiao, B.; Liu, S.; Hu, M. Removal of Cr (VI) from aqueous solution using magnetic biochar synthesized by a single step method. *J. Dispers. Sci. Technol.* **2017**, *38*, 1665–1674.
78. Li, H.; Mahyoub, S.A.A.; Liao, W.; Xia, S.; Zhao, H.; Guo, M.; Ma, P. Effect of pyrolysis temperature on characteristics and aromatic contaminants adsorption behavior of magnetic biochar derived from pyrolysis oil distillation residue. *Bioresour. Technol.* **2017**, *223*, 20–26.
79. Tu, Y.; Peng, Z.; Xu, P.; Lin, H.; Wu, X.; Yang, L.; Huang, J. Characterization and application of magnetic biochars from corn stalk by pyrolysis and hydrothermal treatment. *Bioresources* **2017**, *12*, 1077–1089.
80. Zhang, H.; Hay, A.G. Magnetic biochar derived from biosolids via hydrothermal carbonization: Enzyme immobilization, immobilized-enzyme kinetics, environmental toxicity. *J. Hazard. Mater.* **2020**, *384*, 121272.
81. Mohamed, B.A.; Liu, Z.; Bi, X.; Li, L.Y. Co-production of phenolic-rich bio-oil and magnetic biochar for phosphate removal via bauxite-residue-catalysed microwave pyrolysis of switchgrass. *J. Clean. Prod.* **2022**, *333*, 130090. <https://doi.org/10.1016/j.jclepro.2021.130090>.
82. Rocha, L.S.; Pereira, D.; Sousa, É.; Otero, M.; Esteves, V.I.; Calisto, V. Recent advances on the development and application of magnetic activated carbon and char for the removal of pharmaceutical compounds from waters: A review. *Sci. Total Environ.* **2020**, *718*, 137272.
83. Kumar, V.; Sharma, S.; Sharma, S.; Sharma, G. Electrochemical Properties of Biochar for Environmental Applications: Advances, Challenges, and Perspectives. *Biochar Environ. Remediat.* **2025**, 281–305. <https://doi.org/10.1016/b978-0-323-99889-5.00015-3>.
84. Kumar, A.; Bhattacharya, T. Biochar-Based Remediation of Heavy Metal Polluted Land. In *Environmental Contamination Remediation and Management*; Springer: Cham, Switzerland, 2023; pp. 317–352. https://doi.org/10.1007/978-3-031-04931-6_13.
85. Wibowo, Y.G. Carbon-Based Adsorbents for Heavy Metal Removal in Wastewater: Green Technology or Environmental Burden? *Environ. Nanotechnol. Monit. Manag.* **2025**, *23*, 101051. <https://doi.org/10.1016/j.enmm.2025.101051>.
86. Ouf, S.A.; El-Amriti, F.A.; El-Yasergy, K.F.; Abu-Elghait, M.; El-Hussein, A.; Mohamed, M.S.M. Enhancing *Zea mays* L. seedling growth with HeNe laser-irradiated *Alcaligenes* sp. E1 to mitigate salinity stress. *S. Afr. J. Bot.* **2024**, *173*, 208–216.
87. Chen, M.; Tao, X.; Wang, D.; Xu, Z.; Xu, X.; Hu, X.; Xu, N.; Cao, X. Facilitated transport of cadmium by biochar-Fe₃O₄ nanocomposites in water-saturated natural soils. *Sci. Total Environ.* **2019**, *684*, 265–275. <https://doi.org/10.1016/j.scitotenv.2019.05.326>.
88. Puga, A.P.; Abreu, C.A.; Melo, L.; Paz-Ferreiro, J.; Beesley, L. Cadmium, lead, and zinc mobility and plant uptake in a mine soil amended with sugarcane straw biochar. *Environ. Sci. Pollut. Res.* **2015**, *22*, 17606–17614.
89. Uchimiya, M.; Klasson, K.T.; Wartelle, L.H.; Lima, I.M. Influence of soil properties on heavy metal sequestration by biochar amendment: 1. Copper sorption isotherms and the release of cations. *Chemosphere* **2011**, *82*, 1431–1437.
90. Medyńska-Juraszek, A.; Ćwieląg-Piasecka, I.; Jerzykiewicz, M.; Trynda, J. Wheat straw biochar as a specific sorbent of cobalt in soil. *Materials* **2020**, *13*, 2462.
91. Ministry of Environmental Protection (MEP); Ministry of Land and Resources (MLR). National Soil Pollution Survey Bulletin. *China Environ. Prot. Ind.* **2014**, *5*, 10–11.
92. Yuan, S.; Zhao, L.; Meng, H.; Shen, Y. The main types of biochar and their properties and expectative researches. *J. Plant Nutr. Fertil.* **2016**, *22*, 1402–1417.
93. Wu, J.; Huang, R.; Zhou, Q.; Lu, H.; Li, F.; Wu, K.; Li, Z. Magnetic biochar reduces phosphorus uptake by *Phragmites australis* during heavy metal remediation. *Sci. Total Environ.* **2021**, *758*, 143643.
94. Zhao, L.; Cao, X.; Mašek, O.; Zimmerman, A. Heterogeneity of biochar properties as a function of feedstock sources and production temperatures. *J. Hazard. Mater.* **2013**, *256*, 1–9.
95. Li, X.; Thornton, I. Chemical partitioning of trace and major elements in soils contaminated by mining and smelting activities. *Appl. Geochem.* **2001**, *16*, 1693–1706.
96. Yao, Y.; Zhou, H.; Yan, X.; Yang, X.; Huang, K.; Liu, J.; Li, L.; Zhang, J.; Gu, J.; Zhou, Y. The Fe₃O₄-modified biochar reduces arsenic availability in soil and arsenic accumulation in indica rice (*Oryza sativa* L.). *Environ. Sci. Pollut. Res.* **2021**, *28*, 18050–18061.
97. Uchimiya, M.; Bannon, D.; Nakanishi, H.; McBride, M.B.; Williams, M.A.; Yoshihara, T. Chemical Speciation, Plant Uptake, and Toxicity of Heavy Metals in Agricultural Soils. *J. Agric. Food Chem.* **2020**, *68*, 12856–12869. <https://doi.org/10.1021/acs.jafc.0c00183>.
98. Marin, B.; Valladon, M.; Polve, M.; Monaco, A. Reproducibility testing of a sequential extraction scheme for the determination of trace metal speciation in a marine reference sediment by inductively coupled plasma-mass spectrometry. *Anal. Chim. Acta* **1997**, *342*, 91–112.

99. Rauret, G.; López-Sánchez, J.F.; Sahuquillo, A.; Rubio, R.; Davidson, C.; Ure, A.; Quevauviller, P. Improvement of the BCR three step sequential extraction procedure prior to the certification of new sediment and soil reference materials. *J. Environ. Monit.* **1999**, *1*, 57–61.
100. Reid, M.K.; Spencer, K.L.; Shotbolt, L. An appraisal of microwave-assisted Tessier and BCR sequential extraction methods for the analysis of metals in sediments and soils. *J. Soil. Sediments* **2011**, *11*, 518–528.
101. Haroon, B.; Ping, A.; Pervez, A.; Irshad, M. Characterization of heavy metal in soils as affected by long-term irrigation with industrial wastewater. *J. Water Reuse Desalination* **2019**, *9*, 47–56.
102. Tan, Z.X.; Wang, Y.H.; Zhang, L.M.; Huang, Q.Y. Study of the mechanism of remediation of Cd-contaminated soil by novel biochars. *Environ. Sci. Pollut. Res.* **2017**, *24*, 24844–24855. <https://doi.org/10.1007/s11356-017-0109-9>.
103. Huang, B.; Yuan, Z.; Li, D.; Zheng, M.; Nie, X.; Liao, Y. Effects of soil particle size on the adsorption, distribution, and migration behaviors of heavy metal (loid)s in soil: A review. *Environ. Sci. Process. Impact.* **2020**, *22*, 1596–1615.
104. Ruan, R.; Wu, H.; Yu, C.; Zhao, C.; Zhou, D.; Shi, X.; Cao, J.; Huang, B.; Luo, J. Impacts of magnetic biochar from reed straw on anaerobic digestion of pigment sludge: Biomethane production and the transformation of heavy metals speciation. *Process Biochem.* **2023**, *125*, 96–103.
105. Pu, S.; Yu, D.; Xiao, Y.; Shangguan, L. Study on the passivation and stabilization mechanism of calcium-based magnetic biochar on Cr (VI) polluted soil and its effect on soil microbes. *Acta Scie. Circumstantiae* **2022**, *42*, 390–402. <https://doi.org/10.13671/j.hjkb.2021.0332>.
106. Hao, Z.; Wang, C.; Yan, Z.; Jiang, H.; Xu, H. Magnetic particles modification of coconut shell-derived activated carbon and biochar for effective removal of phenol from water. *Chemosphere* **2018**, *211*, 962–969.
107. Gouma, V.; Tziassiou, C.; Pournara, A.D.; Giokas, D.L. A novel approach to sorbent-based remediation of soil impacted by organic micropollutants and heavy metals using granular biochar amendment and magnetic separation. *J. Environ. Chem. Eng.* **2022**, *10*, 107316. <https://doi.org/10.1016/j.jece.2022.107316>.
108. Hsu, C.; Cheng, Y.; Chung, A.; Huang, Y.; Ting, Y.; Hsi, H. Using recoverable sulfurized magnetic biochar for active capping to remediate multiple heavy metal contaminated sediment. *Environ. Pollut.* **2022**, *316*, 120555. <https://doi.org/10.1016/j.envpol.2022.120555>.
109. Fan, J.; Chen, X.; Xu, Z.; Xu, X.; Zhao, L.; Qiu, H.; Cao, X. One-pot synthesis of nZVI-embedded biochar for remediation of two mining arsenic-contaminated soils: Arsenic immobilization associated with iron transformation. *J. Hazard. Mater.* **2020**, *398*, 122901.
110. Wu, C.; Cui, M.; Xue, S.; Li, W.; Huang, L.; Jiang, X.; Qian, Z. Remediation of arsenic-contaminated paddy soil by iron-modified biochar. *Environ. Sci. Pollut. Res.* **2018**, *25*, 20792–20801.
111. Lei, C.; Sun, Y.; Tsang, D.C.W.; Lin, D. Environmental transformations and ecological effects of iron-based nanoparticles. *Environ. Pollut.* **2018**, *232*, 10–30. <https://doi.org/10.1016/j.envpol.2017.09.052>.
112. Allison, S.D.; Martiny, J.B. Resistance, resilience, and redundancy in microbial communities. *Proc. Natl. Acad. Sci. USA* **2008**, *105*, 11512–11519.
113. Sahu, N.; Vasu, D.; Sahu, A.; Lal, N.; Singh, S.K. *Strength of Microbes in Nutrient Cycling: A Key to Soil Health*; Springer: Berlin/Heidelberg, Germany, 2017; pp. 69–86.
114. Ameloot, N.; Graber, E.R.; Verheijen, F.G.; De Neve, S. Interactions between biochar stability and soil organisms: Review and research needs. *Eur. J. Soil Sci.* **2013**, *64*, 379–390.
115. Zhang, A.; Cui, L.; Pan, G.; Li, L.; Hussain, Q.; Zhang, X.; Zheng, J.; Crowley, D. Effect of biochar amendment on yield and methane and nitrous oxide emissions from a rice paddy from Tai Lake plain, China. *Agric. Ecosyst. Environ.* **2010**, *139*, 469–475.
116. Wu, C.; Shi, L.; Xue, S.; Li, W.; Jiang, X.; Rajendran, M.; Qian, Z. Effect of sulfur-iron modified biochar on the available cadmium and bacterial community structure in contaminated soils. *Sci. Total Environ.* **2019**, *647*, 1158–1168. <https://doi.org/10.1016/j.scitotenv.2018.08.087>.
117. Siedt, M.; Schäffer, A.; Smith, K.E.; Nabel, M.; Roß-Nickoll, M.; van Dongen, J.T. Comparing straw, compost, and biochar regarding their suitability as agricultural soil amendments to affect soil structure, nutrient leaching, microbial communities, and the fate of pesticides. *Sci. Total Environ.* **2021**, *751*, 141607.
118. Diao, Y.; Zhou, L.; Ji, M.; Wang, X.; Dan, Y.; Sang, W. Immobilization of Cd and Pb in soil facilitated by magnetic biochar: Metal speciation and microbial community evolution. *Environ. Sci. Pollut. Res. Int.* **2022**, *29*, 71871–71881. <https://doi.org/10.1007/s11356-022-20750-9>.
119. Lin, Y.; Ye, Y.; Hu, Y.; Shi, H. The variation in microbial community structure under different heavy metal contamination levels in paddy soils. *Ecotoxicol. Environ. Saf.* **2019**, *180*, 557–564.

120. Wang, L.; Chen, H.; Wu, J.; Huang, L.; Brookes, P.C.; Mazza Rodrigues, J.L.; Xu, J.; Liu, X. Effects of magnetic biochar microbe composite on Cd remediation and microbial responses in paddy soil. *J. Hazard. Mater.* **2021**, *414*, 125494. <https://doi.org/10.1016/j.jhazmat.2021.125494>.
121. Sahmoune, M.N. Performance of *Streptomyces rimosus* biomass in biosorption of heavy metals from aqueous solutions. *Microchem. J.* **2018**, *141*, 87–95.
122. Selvin, J.; Priya, S.S.; Kiran, G.S.; Thangavelu, T.; Bai, N.S. Sponge-associated marine bacteria as indicators of heavy metal pollution. *Microbiol. Res.* **2009**, *164*, 352–363.
123. Shariat, P.; Mitchell, W.J.; Boyd, A.; Priest, F.G. Anaerobic metabolism in *Bacillus licheniformis* NCIB 6346. *Microbiology* **1995**, *141*, 1117–1124.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.