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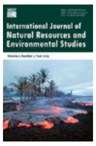

Environmental Applications and Future Prospects of Biochar

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ABSTRACT

Biochar, a porous carbon-rich material produced through high-temperature pyrolysis of biomass, has shown great potential in environmental remediation and sustainable development. This article systematically reviews the development trajectory of biochar technology. Firstly, it elaborates on the structure-activity relationship between its preparation parameters and physicochemical properties. Secondly, it focuses on its application mechanisms and efficacy in three major environmental media: as a soil amendment and long-term carbon sequestration carrier in soil; as an efficient adsorption/catalytic material for pollutants in water; and its production process itself also contributes to greenhouse gas reduction. Despite its promising prospects, the large-scale application of biochar still faces challenges such as unclear long-term environmental behavior, incomplete ecological effect assessment, and the absence of standards. Finally, suggesting that long-term research and interdisciplinary collaboration are needed to quantify its long-term ecological safety and carbon sequestration potential, and to establish engineering standards and a life-cycle assessment system, in order to promote its transformation from a potential material to a reliable environmental solution.

KEYWORDS

Biochar; Soil; Environmental remediation; Carbon sequestration.

1. INTRODUCTION

Biochar is a black, carbon-rich, porous solid material generated via the thermochemical conversion of biomass under oxygen-limited or anaerobic conditions[1]. The feedstock for biochar production is highly diverse, encompassing agricultural residues (e.g., crop straw, rice husks, and fruit shells) [2], forestry byproducts (e.g., sawdust and bark) [3, 4], livestock and poultry manure, municipal sewage sludge, and food processing waste. Converting these waste materials into biochar not only facilitates resource recycling and mitigates greenhouse gas emissions associated with their natural decomposition or open burning but also offers a promising strategy for addressing environmental pollution challenges. The chemical composition of various feedstocks, specifically the content of cellulose, hemicellulose, and lignin, significantly influences the physicochemical properties of the resulting biochar. For example, lignin-rich woody materials tend to yield biochar with higher carbon content and enhanced structural stability, whereas nutrient-dense feedstocks such as animal manure produce biochar enriched in essential nutrients, including nitrogen, phosphorus, and potassium[5, 6]. Owing to its low production cost, environmental sustainability, and distinctive physical architecture, chemical makeup, and surface functionality, biochar has emerged as a multifunctional material with considerable application potential across diverse domains, including environmental remediation, renewable energy, and sustainable agriculture[7, 8]. In recent years, biochar has attracted considerable attention due to its great potential in addressing climate change, improving soil health, and environmental remediation[9]. This review aims to systematically elaborate on the preparation and property regulation of biochar, its diverse applications in the environment, and to deeply explore

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its potential environmental impacts and risks, with the expectation of providing a comprehensive reference for the scientific research and sustainable application of biochar.

2. PREPARATION AND REGULATION OF BIOCHAR PROPERTIES

2.1. Preparation of Biochar

The production of biochar primarily depends on thermochemical conversion of biomass, with pyrolysis being the most widely employed method. Based on heating rate and residence time, pyrolysis can be categorized into slow and fast pyrolysis[10]. Slow pyrolysis favors higher biochar yields and enhanced structural stability, whereas fast pyrolysis is optimized for the production of bio-oil and syngas. In addition to pyrolysis, gasification and hydrothermal carbonization represent other significant pathways for biochar synthesis[11, 12]. Pyrolysis is typically conducted within a temperature range of 300–700 °C under an inert gas atmosphere. This process is particularly suitable for dry biomass feedstocks and produces biochar characterized by high carbon content, extensive aromaticity, superior stability, and significant potential for long-term carbon sequestration. Hydrothermal carbonization is particularly suitable for feedstocks with high moisture content, such as sewage sludge and animal manure. This process is carried out in a closed system at temperatures ranging from 180 to 260 °C, yielding a carbonaceous material known as hydrochar. Hydrochar is characterized by an abundance of surface oxygen-containing functional groups and high polarity, which enhance its suitability for applications in soil amendment and environmental remediation through pollutant adsorption[13].

2.2. Regulation of Properties of Biochar

The physicochemical properties of biochar can be adjusted through the systematic control of key process parameters, including pyrolysis temperature, heating rate, residence time, and feedstock composition. [14] Pyrolysis temperature is a critical parameter: as temperature increases, biochar yield decreases due to thermal decomposition of organic matter, whereas carbon content, aromaticity, and structural stability are enhanced. Concurrently, the H/C and O/C atomic ratios decline significantly, indicating a higher degree of carbon condensation and graphitization, which contributes to improved long-term carbon sequestration potential[15, 16]. The specific surface area and pore structure undergo significant development within the temperature range of 500–700 °C, driven by progressive carbonization and volatile release. However, at excessively high temperatures (>800 °C), structural degradation may occur, leading to pore collapse and a reduction in surface area[17]. Surface functional groups, such as -OH and -COOH, diminish with increasing pyrolysis temperature, leading to reduced material polarity and diminished cation exchange capacity[18]. Moreover, the formation of polycyclic aromatic hydrocarbons (PAHs) is governed by a complex temperature-dependent mechanism: while elevated temperatures can promote the thermal decomposition of certain PAHs, incomplete volatilization or high-pressure conditions may favor their accumulation, particularly in confined reaction environments. In addition, rapid heating rates combined with extended residence times promote the development of more ordered carbon structures and increase fixed carbon content through enhanced carbonization efficiency. However, rapid heating alone can lead to intensified secondary reactions, resulting in higher volatile yields and distinct pore morphology development.

To further enhance biochar performance, numerous researchers have employed physical and chemical modification strategies. These include CO_2 activation to increase specific surface area and porosity; acid or base treatments and metal impregnation to tailor surface chemistry; and co-pyrolysis (such as sludge and straw) methods to achieve raw material synergy and performance optimization [19, 20]. In recent years, post-treatment modification (such as metal oxide loading, redox treatment, etc.) has also become an important means to enhance adsorption, catalytic performance, and stability. The property regulation of biochar is a systematic process from raw material selection to preparation technology, and the specific regulation methods depend on the target application in life.

3. APPLICATIONS OF BIOCHAR

3.1. Soil improvement and remediation applications

Biochar, as a widely recognized soil amendment, not only improves soil water retention and regulates nutrient cycling via its porous architecture, but also enhances the soil's internal ecological environment by promoting microbial activity and stabilizing organic matter. This dual functionality provides critical support for increasing agricultural productivity and advancing sustainable agriculture[21, 22]. [23] further clarified the mechanism of this process: biochar not only can adsorb and retain water in low water potential environments through internal pores, but also can actively regulate the overall water-holding characteristics of the soil by changing the pore structure between soil particles. In sandy soils, biochar can significantly enhance the effective water holding capacity; in other soil types, however, its impact is strongly dependent on the physical and chemical characteristics of the biochar itself[24]. In contrast, biochar with a high specific surface area and rich in oxygen functional groups can more effectively adsorb water and regulate water release under different soil water potential conditions, thereby optimizing the range of plant available water[25]. In addition, biochar plays a significant role in regulating soil pH and enhancing cation exchange capacity. Its inherent alkalinity effectively neutralizes acidic soils, while surface functional groups enhance the soil's buffering capacity against pH changes through protonation-deprotonation processes. [24] Biochar can also enhance nitrogen use efficiency and soil fertility by adsorbing nitrogen, delaying urea hydrolysis and nitrification, and reducing ammonia volatilization and nitrate leaching[26]. Moreover, the mineral elements it carries and its combination with fertilizers further extend the nutrient release cycle and improve nutrient use efficiency[21, 27].

Biochar has demonstrated highly efficient adsorption and fixation capabilities in the remediation of soil heavy metal pollution, with its performance significantly influenced by raw materials, pyrolysis conditions, and chemical modification[28]. For instance, Zhou et al. (2019) reported that rice straw biochar achieved a removal rate of over 90% for Cr(VI) under strong acidic conditions[29]. The mechanism involved surface protonation, increased specific surface area, and reduction of Cr(VI) to Cr(III), which was then stably fixed through surface complexation and precipitation. Natural or simulated aging can enhance the long-term immobilization capacity of biochar for heavy metals. Chen et al. (2022) demonstrated that aging increases the specific surface area and the abundance of oxygen-containing functional groups (–COOH, –OH) in biochar, thereby enhancing its ability to transform acid-extractable lead into stable residual forms through mechanisms including surface complexation, co-precipitation, and ion exchange[30]. Liu et al. (2023) compared the adsorption of Zn^{2+} by biochar from different raw materials and found that fruit shell biochar achieved a removal rate of 98.87% and an adsorption capacity of 46.71 mg/g at pH 3–7, with aging further enhancing its adsorption performance[31]. In summary, by optimizing raw materials, preparation and modification conditions, and leveraging the aging effect, the remediation potential of biochar for soil heavy metals can be significantly enhanced.

3.2. Remove Organic And Inorganic Pollutants From Water

The presence of both organic and inorganic pollutants in wastewater has attracted significant scientific and environmental concern[32]. Among organic contaminants, dyes, phenols, pesticides, and antibiotics are particularly problematic due to their complex aromatic structures, high toxicity, and recalcitrance to biodegradation. Biochar has emerged as a promising adsorbent owing to its high specific surface area (up to 1500 m^2/g), well-developed porous structure, and abundant surface functional groups, enabling effective removal of diverse organic pollutants such as dyes, phenols, pesticides, and antibiotics. For example, rice straw-derived biochar exhibits an adsorption capacity of 620.3 mg/g for crystal violet, while seaweed-derived biochar achieves an exceptionally high adsorption capacity of 5306.2 mg/g for malachite green[33]. Chemical modifications—such as nitrogen doping, magnetic functionalization, or metal loading—can further enhance both adsorption performance and regeneration potential[34]. For persistent organic pollutants including polycyclic aromatic hydrocarbons (PAHs) and pesticides, biochar-mediated removal efficiencies frequently exceed 90%, driven by mechanisms such as hydrophobic interactions, π–π electron donor–acceptor interactions, pore filling, hydrogen bonding, and electrostatic attraction[32]. Despite these advantages, practical implementation faces challenges related to variable environmental conditions (e.g., pH fluctuations, coexisting ions, and competitive effects from natural organic matter), scalability, long-term stability, and regeneration efficiency. Future research should prioritize the rational design of tailored biochar materials, multifunctional modification strategies, and the integration of biochar with advanced oxidation processes or microbial degradation technologies to achieve synergistic pollutant removal.

Regarding inorganic pollutants, biochar and its composite materials demonstrate high adsorption efficiency toward heavy metal ions such as Pb(II), Cu(II), Cr(VI), and Cd(II), with removal mechanisms encompassing electrostatic adsorption, ion exchange, surface complexation, precipitation, and redox reactions—including the reduction of Cr(VI) to Cr(III). For example, Artemisia argyi stem-derived biochar exhibits adsorption capacities of 161.9 mg/g for Cr(VI) and 156.0 mg/g for Cu(II). Advanced modification strategies, such as MnO_2 deposition, magnetic functionalization, or incorporation of nanoscale zero-valent iron, can significantly enhance both adsorption capacity and selectivity. Notably, MnO_2-biochar composites achieve an adsorption capacity of up to 904 mg/g for U(VI)37. These engineered modifications not only strengthen the material's affinity for target metal species but also improve its recyclability and adaptability under varying environmental conditions.

3.3. Gas Adsorption and Atmospheric Pollution Control

Biochar has shown considerable promise in the adsorption of gaseous pollutants and the control of atmospheric emissions. Studies indicate that its capacity to adsorb typical flue gas contaminants—such as CO_2, SO_2, and NO_x—is primarily governed by its well-developed pore architecture and tailored surface chemistry. Pyrolysis within the mesothermal range (500–700 °C) promotes the formation of an extensive porous network and high specific surface area, making it an optimal condition for achieving superior adsorption performance. Furthermore, the gas adsorption properties of biochar can be significantly enhanced through activation techniques and heteroatom doping. Physical activation using agents such as CO_2, steam, or NH_3, as well as chemical activation with KOH or H_3PO_4, effectively increases both specific surface area and pore volume. For example, KOH-activated biochar derived from corn cobs exhibits a specific surface area of up to 3708 m^2/g. Additionally, the incorporation of heteroatoms (e.g., nitrogen, sulfur, phosphorus) or the loading of metal oxides (e.g., CeO_2, MnO_2, CuO) introduces functional groups or catalytically active sites that enhance the chemical adsorption and catalytic transformation of acidic gases. Specifically, NH_3 treatment increases the nitrogen content of biochar and generates basic nitrogen functionalities—including pyridinic and quaternary nitrogen—that strengthen CO_2 chemisorption. Meanwhile, the deposition of MnO_2 and similar metal oxides enables catalytic oxidation of SO_2 to sulfate species, thereby markedly improving desulfurization efficiency[35].

In practical applications, biochar-based adsorbents have demonstrated the capability for synergistic removal of multi-component pollutants—such as SO_2, NO_x, and chlorobenzene mixtures—highlighting their considerable potential in the purification of complex flue gas streams. Notably, real flue gases typically contain multiple coexisting species; for example, CO is commonly emitted alongside CO_2. According to Ghanbarpour Mamaghani et al. (2024)[36], cork shavings-derived biochar exhibits a significantly higher adsorption capacity for CO_2 (2.325 mmol/g) compared to CO

(0.700 mmol/g). In competitive adsorption scenarios, CO_2 demonstrates a distinct thermodynamic advantage and can displace pre-adsorbed CO molecules via a "roll-up" effect. Furthermore, temperature exerts a pronounced influence on adsorption behavior: the adsorption capacity for CO_2 decreases by 43.5% when the temperature increases from 20 °C to 100 °C, whereas CO adsorption remains largely unaffected, resulting in a relatively higher uptake proportion of CO under elevated temperatures. Molecular simulations conducted in the study further reveal that the binding energies between CO_2 and various surface functional groups on biochar are consistently higher than those for CO. Additionally, the heterogeneous adsorption process is well described by the dual-site Langmuir model and the Avrami kinetic model, indicating that both physical and chemical interactions jointly govern the adsorption mechanisms of CO_2 and CO.

4. CONCLUSION AND PROSPECTS

4.1. Conclusion

Biochar, a carbon-rich material derived from the pyrolysis of biomass, exhibits considerable application potential in environmental remediation and sustainable agriculture owing to its distinctive porous structure, abundant surface functional groups, high chemical stability, and strong adsorption capacity. This review highlights that the multidimensional environmental benefits of biochar are manifested across multiple domains. Guided by the circular principle of "waste valorization and carbon sequestration with emission reduction," biochar enables the transformation of agricultural residues and organic solid wastes into high-value functional materials for environmental applications. The synergistic effects of biochar in enhancing soil quality, mitigating pollution, and alleviating climate change underscore its pivotal role in advancing sustainable environmental management systems.

4.2. Prospects

Despite substantial advances in biochar research and its practical applications, the transition to large-scale, standardized deployment remains hindered by technical, economic, and regulatory challenges. To bridge the gap between scientific understanding and real-world implementation, future research must prioritize two key directions: deepening mechanistic insights into biochar’s long-term environmental behavior and accelerating the development of scalable, context-specific application technologies.

Most current research is limited to short-term indoor experiments or small-scale field trials, lacking a systematic understanding of the long-term behavior and fate of biochar in complex real-world environments. By conducting long-term field experiments, we can systematically study the impact of the aging process of biochar in soil (such as chemical oxidation and biological degradation) on its properties, functions, and stability, and quantify the carbon sequestration efficiency and environmental risks over a timescale of a century or even longer.

In addition, beyond the research on a single medium (soil, water) or target pollutants, a comprehensive assessment of the integrated impact of biochar addition on the soil-water-biological continuum should be conducted. Clarify its potential negative impacts and positive benefits on ecosystem functions such as nutrient cycling, biodiversity, and food webs, and establish a comprehensive ecological safety evaluation system. Carry out systematic life cycle assessment to comprehensively calculate the environmental footprint and economic costs of each link from raw material collection, transportation, production to application. Based on the assessment results, promote the establishment of market-based policy tools such as carbon trading and ecological compensation, and convert the carbon sequestration and environmental benefits of biochar into economic incentives, thereby promoting the large-scale and commercial application of this technology.

In conclusion, the future development of the biochar field requires a synergy between deepening basic scientific understanding and promoting engineering practice and policy innovation. Through interdisciplinary collaboration and systematic long-term research, biochar is expected to transform from a promising material into a measurable, reportable, and verifiable mature environmental solution, making substantive contributions to global ecological environment security and agricultural green transformation.

CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

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