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Research Progress on Biochar Adsorption of Sewage Pollutants

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ABSTRACT

This article aims to systematically review the research advancements of biochar in the field of wastewater pollutant adsorption and explore its application potential and challenges as an environmentally friendly adsorbent material. With the acceleration of industrialization and urbanization, the massive discharge of various organic and inorganic pollutants into water bodies poses severe threats to both ecosystems and human health, making the development of efficient, cost-effective, and sustainable water treatment technologies a critical focus in environmental engineering. Biochar, a porous carbon material produced through pyrolysis of biomass under oxygen-deficient conditions, demonstrates significant advantages in adsorbing and removing pollutants such as heavy metal ions, organic dyes, drug residues, and nutrients due to its extensive pore structure, large specific surface area, and surface-modifiable functional groups. Starting from theoretical foundations, this paper elucidates how raw materials and pyrolysis conditions critically influence biochar's physicochemical properties, as well as the key mechanisms involved in adsorption—including pore filling, electrostatic attraction, surface complexation, ion exchange, and π-π interactions. Subsequently, it reviews current domestic and international research on biochar's performance in adsorbing various pollutants, analyzes the relationships between raw material selection, modification methods (e.g., acid/alkali treatment, metal loading, composite construction), and adsorption efficiency, and evaluates the effects of adsorption parameters such as pH, temperature, initial pollutant concentration, and contact duration. Although studies confirm biochar's ability to significantly reduce pollutant concentrations, its practical applications face challenges including limited adsorption capacity, insufficient selectivity, unstable regeneration performance, and potential ecological risks. This paper provides a comprehensive review of existing research and emphasizes that future studies should focus on optimizing biochar performance through green modification strategies, investigating its synergistic adsorption mechanisms in complex wastewater systems, evaluating its long-term environmental safety, and facilitating its transition from laboratory research to large-scale water treatment applications, thereby providing more practical technical references for wastewater treatment.

KEYWORDS

Biochar; Adsorption; Sewage Pollutants; Wastewater Treatment; Environmental Remediation.

1. BACKGROUND

The rapid pace of global industrialization and urbanization has led to a severe and persistent crisis of water pollution, posing a significant threat to ecosystems and human health worldwide. Sewage and wastewater from diverse sources, including industrial effluents, agricultural runoff laden with fertilizers and pesticides, and domestic discharges containing pharmaceuticals and personal care products, collectively introduce a complex mixture of contaminants into aquatic environments. These pollutants encompass heavy metals, organic dyes, persistent organic compounds, and excessive nutrients such as nitrogen and phosphorus, which can cause eutrophication, toxicity to aquatic life, and pose long-term risks to human health. The need for effective, affordable, and environmentally sustainable water treatment technologies has therefore become an urgent priority for environmental science and engineering.

Traditional water treatment methods, while effective for certain conventional pollutants, often face limitations such as high operational costs, generation of secondary waste, and inefficiency in removing emerging contaminants. This has driven the search for alternative materials and processes. In this context, biochar has emerged as a highly promising candidate. Biochar is a carbon-rich, porous material produced through the thermal decomposition of biomass—such as agricultural residues, forestry waste, or municipal sludge—under oxygen-limited conditions. This process, known as pyrolysis, transforms waste biomass into a valuable resource, aligning with the principles of a circular economy. The appeal of biochar lies in its multifaceted advantages: it is typically low-cost due to abundant and often undervalued feedstocks, possesses a substantial surface area and porous structure ideal for trapping pollutants, and carries a variety of surface chemical groups that can interact with different contaminants. Furthermore, its production represents a form of waste valorization, turning potential environmental liabilities into functional materials for environmental remediation.

The purpose of this literature review is to systematically gather, synthesize, and critically evaluate the vast and growing body of research on the application of biochar for adsorbing pollutants from sewage. By examining the fundamental properties of biochar, its interactions with various pollutant types, the factors influencing its performance, and the challenges in its application, this review aims to provide a clear and comprehensive overview of the field's current state. It seeks to move beyond isolated studies to identify overarching trends, key mechanisms, and knowledge gaps.

The significance of this research topic is multi-layered and profound. Scientifically, it advances our understanding of the complex interfacial processes between a heterogeneous carbon material and diverse aqueous pollutants. Technologically, it contributes to the development of next-generation, green adsorption materials that can be tailored for specific water treatment challenges. From an environmental and societal perspective, the research promotes sustainable solutions by addressing two critical issues simultaneously: managing organic waste streams and purifying contaminated water. Successful implementation of biochar-based technologies could lead to more decentralized, cost-effective, and eco-friendly water treatment options, particularly beneficial for developing regions or for treating specific industrial wastewaters. Ultimately, this line of inquiry supports the broader goals of sustainable development, resource conservation, and the protection of vital water resources for future generations.

2. THEORETICAL FRAMEWORK

The process by which biochar removes pollutants from water is governed by a well-established theoretical framework, which provides essential tools for understanding, analyzing, and predicting its performance. At the heart of this framework are two key concepts: adsorption isotherms and adsorption kinetics. Adsorption isotherms describe the equilibrium relationship between the amount of pollutant adsorbed onto the biochar surface and its concentration remaining in the solution at a constant temperature. The Langmuir isotherm model is frequently applied, assuming that adsorption occurs on a homogeneous surface with a finite number of identical sites, leading to monolayer coverage. It is particularly useful for estimating the maximum adsorption capacity of a biochar material. In contrast, the Freundlich isotherm model is an empirical equation often used for heterogeneous surfaces, suggesting that adsorption energy decreases logarithmically as surface coverage increases. These models help researchers quantify the affinity and capacity of biochar for a specific pollutant under equilibrium conditions.

To understand the speed and pathway of the adsorption process, kinetic models are employed. The pseudo-first-order kinetic model assumes that the rate of adsorption is proportional to the number of unoccupied adsorption sites, often describing the initial rapid phase of adsorption. However, the pseudo-second-order kinetic model is more commonly used and found to better fit experimental data for many biochar-pollutant systems. This model assumes that the rate-limiting step is a chemical interaction, such as sharing or exchange of electrons between the pollutant and the biochar surface. Analyzing kinetic data with these models helps determine whether the adsorption process is controlled primarily by physical diffusion of the pollutant to the biochar surface or by chemical reaction at the surface.

The removal of pollutants by biochar is not achieved through a single mechanism but rather through a combination of simultaneous physical and chemical processes. Physical adsorption, also known as physisorption, involves weaker intermolecular forces. The highly porous structure of biochar provides a vast internal surface area and pore volume, allowing pollutants to be trapped within these pores—a mechanism known as pore filling. Additionally, van der Waals forces, which are weak attractive forces between molecules, play a significant role, especially for non-polar organic pollutants like certain dyes or hydrocarbons. These physical processes are generally reversible and are highly dependent on the biochar's specific surface area and pore size distribution.

Chemical adsorption, or chemisorption, involves stronger chemical bonds and is often more specific. One of the most important mechanisms is surface complexation, where functional groups on the biochar surface (such as carboxyl, hydroxyl, and phenolic groups) form coordinate bonds with metal ions like lead or cadmium. Ion exchange is another crucial mechanism, where positively charged metal ions in the water swap places with other cations (like potassium, calcium, or magnesium) that are naturally present on the biochar's surface or within its ash content. In some cases, under specific pH conditions, biochar can induce the precipitation of pollutants, such as forming insoluble metal hydroxides or phosphates that are then physically trapped. For organic pollutants containing aromatic rings, such as certain antibiotics or dyes, π-π interactions between the electron-rich aromatic systems on the biochar surface and the pollutant molecule can be a dominant removal pathway. Finally, electrostatic attraction occurs when the biochar surface carries a net charge opposite to that of the pollutant ion. For instance, at higher pH values, biochar surfaces tend to become more negatively charged, enhancing their attraction to positively charged metal ions.

This theoretical framework—encompassing isotherm and kinetic models alongside the detailed mechanisms of interaction—serves as the essential foundation for interpreting experimental results. It allows researchers to move beyond simply observing that a pollutant is removed, to understanding *how much* can be removed (capacity), *how fast* it happens (kinetics), and *by what means* it is retained on the biochar (mechanism). This understanding is critical for tailoring biochar production and modification strategies to target specific pollutants in complex sewage environments effectively.

3. CURRENT RESEARCH STATUS

3.1. Adsorption Mechanisms and Efficacy for Heavy Metal Pollutants

The removal of heavy metal ions from sewage represents a major challenge due to their persistence, toxicity, and bioaccumulation potential. Biochar has garnered significant attention as a sustainable adsorbent for this purpose, with its efficacy largely dependent on the interplay between its inherent properties and the specific metal targeted. The primary mechanisms governing heavy metal adsorption onto biochar are surface complexation, ion exchange, precipitation, and, in some cases, reduction. Surface complexation is often the dominant pathway, where oxygen-containing functional groups on the biochar surface, such as carboxyl, hydroxyl, and phenolic groups, form strong coordinate bonds with metal cations like Pb(II), Cd(II), and Cu(II). As Gao et al. demonstrated in their study on copper adsorption, modification with phosphate groups via a facile one-step process significantly enhanced complexation, leading to a dramatic increase in adsorption capacity [1]. Ion exchange involves the replacement of naturally occurring cations (e.g., K^+, Ca^{2+}, Mg^{2+}) present in the biochar's ash or on its surface with the target heavy metal ions from solution. This mechanism is particularly prominent in biochars derived from mineral-rich feedstocks. Under alkaline conditions, biochar can also facilitate the precipitation of metals as hydroxides or phosphates, effectively immobilizing them. For redox-sensitive metals like Cr(VI), biochar's reducing functional groups can convert the highly toxic and mobile Cr(VI) to the less toxic and more easily adsorbed Cr(III).

The adsorption performance for heavy metals is profoundly influenced by biochar's self-properties, which are dictated by feedstock and production conditions. Biochars from agricultural residues like rice husk or straw often possess a balanced profile of porosity and functional groups, while those from nutrient-rich wastes like sewage sludge or animal manure may have higher ash and mineral content, favoring ion exchange and precipitation mechanisms. However, as noted by Tanwar, sewage sludge-derived biochar can suffer from poor surface area and functional group scarcity, limiting its native adsorption capacity [2]. This has spurred extensive research into post-production modification strategies aimed at tailoring biochar for enhanced metal uptake. Chemical activation with agents like KOH or H_3PO_4 is commonly used to increase porosity and surface area, thereby improving physical adsorption via pore filling. Doping with metals (e.g., Fe, Mn) or impregnation with sulfur or phosphate compounds can introduce new active sites specifically for complexation or precipitation. For instance, magnetic modification with iron oxides not only improves separation efficiency but can also enhance adsorption through added surface sites. The dissolved organic matter released from biochar (BCDOM) can also play a synergistic role; the protein-like components within BCDOM can complex with heavy metals, promoting their subsequent adsorption and immobilization onto the solid biochar matrix [3].

Comparative studies consistently show that modified biochars outperform their pristine counterparts. Modification strategies are often designed to target a specific metal or a group of metals with similar chemistries. For example, phosphate-modified biochars show exceptional affinity for lead and copper due to the formation of stable metal-phosphate complexes [1]. The integration of biochar into composite materials, such as with metal-organic frameworks (MOFs), represents another advanced frontier, leveraging the high surface area and tunable chemistry of MOFs for potentially superior capture efficiency [4]. While research has historically emphasized organic pollutants, there is a growing and critical focus on emerging inorganic pollutants (EIPs), including less common heavy metals and metalloids, recognizing the unique threats they pose [5]. Overall, the body of research confirms that through strategic selection of feedstock, controlled pyrolysis, and targeted modification, biochar can be engineered into a highly effective and versatile adsorbent for a wide spectrum of heavy metal pollutants in sewage.

3.2. Removal of Organic Contaminants by Biochar Adsorption

The removal of organic contaminants from sewage is a complex challenge due to the vast diversity of these pollutants, which range from industrial dyes to pharmaceuticals and pesticides. Biochar has demonstrated considerable promise in this domain, with its adsorption efficacy primarily governed by its structural and chemical attributes. For non-polar organic pollutants, such as many polycyclic aromatic hydrocarbons (PAHs) and certain pesticides, the hydrophobic nature and aromatic carbon matrix of biochar facilitate adsorption primarily through pore filling and van der Waals forces. The high specific surface area and well-developed microporous structure of many biochars provide ample sites for these non-specific, physical adsorption processes. Conversely, for polar and ionic organic compounds, such as many pharmaceuticals, personal care products (PPCPs), and organic dyes, specific chemical interactions become paramount. The oxygen- and nitrogen-containing functional groups on biochar surfaces can engage in hydrogen bonding with polar molecules, while the aromatic sheets of biochar can participate in π–π electron donor-acceptor interactions with compounds containing aromatic rings, a mechanism crucial for adsorbing antibiotics like tetracycline and sulfonamides [3]. Electrostatic attraction also plays a role, particularly for ionic dyes whose charge varies with solution pH.

The choice of feedstock and pyrolysis conditions critically determines biochar's suitability for targeting specific organic pollutant classes. High-temperature pyrolysis tends to produce biochar with higher aromaticity and surface area, which is beneficial for adsorbing non-polar contaminants via partitioning and pore diffusion. In contrast, biochar produced at lower temperatures or via hydrothermal carbonization often retains more polar oxygenated functional groups, enhancing its affinity for hydrophilic organic pollutants through hydrogen bonding and specific interactions. For instance, biochar derived from nutrient-rich sources like sewage sludge, while often having limited surface area, can possess unique surface chemistries that are effective for certain organic molecules. However, as noted in reviews, the native adsorption capacity of sewage sludge-derived biochar for pollutants is often suboptimal due to poor surface area and functional group scarcity, necessitating pretreatment or modification to unlock its full potential [2]. Modification strategies are thus widely employed to tailor biochar for enhanced organic contaminant removal. Chemical activation with agents like KOH or H_3PO_4 is common to expand pore volume and surface area, directly boosting physical adsorption capacity. Impregnation with metals or the creation of magnetic biochar composites can introduce new catalytic or adsorption sites, and also facilitate easy separation from treated water, a significant practical advantage for continuous-flow systems.

Research has progressively moved from studying simple model compounds like methylene blue to more complex and environmentally relevant emerging organic contaminants. The adsorption of antibiotics, endocrine disruptors, and various PPCPs has been a focal point, revealing that successful removal often relies on a combination of the aforementioned mechanisms. The dissolved organic matter released from biochar (BCDOM) can also play a synergistic role in this process; studies indicate that BCDOM can enhance the adsorption of organic pollutants onto the solid biochar through π–π interactions and hydrogen bonding [3]. Furthermore, the integration of biochar into hybrid systems represents a significant research trend. For example, coupling biochar with biological processes, as seen in systems integrating magnetic biochar with microbial electrolysis cells, can create synergistic effects where biochar not only adsorbs pollutants but also supports microbial communities that degrade them, leading to more robust and sustainable treatment outcomes [6]. While much attention has historically been on organic pollutants, there is a parallel and growing recognition of the threats posed by emerging inorganic pollutants, underscoring the need for multifunctional adsorbents [5]. Overall, the current research status confirms that biochar, through strategic design and modification, can be engineered as a versatile and effective adsorbent for a wide spectrum of organic contaminants in sewage, with performance highly dependent on achieving a match between the biochar's properties and the chemical nature of the target pollutant.

3.3. Biochar Application for Nutrient (Nitrogen and Phosphorus) Recovery and Removal

In the context of sewage treatment, the management of nutrient pollutants, specifically nitrogen and phosphorus, is critical to prevent eutrophication and maintain water quality. Biochar has emerged as a promising material not only for the removal of these nutrients but also for their potential recovery and reuse, aligning with principles of circular economy. The mechanisms through which biochar interacts with different nutrient species vary significantly. For ammonium (NH_4^+), electrostatic attraction is a primary mechanism. Many biochars, particularly those produced at lower temperatures or from feedstocks rich in acidic oxygen-containing groups, develop a net negative surface charge under typical sewage pH conditions. This facilitates the electrostatic attraction and retention of positively charged NH_4^+ ions [7]. Additionally, the porous structure of biochar can physically trap ammonium ions, and cation exchange with inherent minerals like K^+, Ca^{2+}, or Mg^{2+} present in the biochar ash further contributes to its removal from the aqueous phase.

Phosphate (PO_4^{3-}) removal, however, relies on distinct mechanisms. Due to its anionic nature, phosphate is not effectively removed by electrostatic attraction to most pristine biochars, which tend to be negatively charged. Instead, the key pathways involve ligand exchange and precipitation. Biochars derived from feedstocks inherently rich in metals (e.g., sewage sludge, manure) or those modified by impregnation with metal oxides (such as those of magnesium, iron, aluminum, or calcium) exhibit a strong affinity for phosphate. On these modified surfaces, phosphate can form inner-sphere complexes through ligand exchange with surface hydroxyl groups or precipitate as insoluble metal phosphates (e.g., struvite, hydroxyapatite). Research has shown that even simple modifications can drastically enhance this capacity. For instance, Yuan Gao et al. pointed out that biochar modified with ammonium phosphate displayed excellent adsorption performance toward copper ions, with the main removal mechanism involving complexation between surface phosphate groups and the metal [1]. This principle of surface functionalization with phosphate-containing groups or metal ions is directly applicable to enhancing phosphate adsorption from sewage. The review by Vijendra Singh Tanwar also highlights that sewage sludge-derived biochar, despite its often suboptimal native properties, can be engineered through various pretreatment and modification methods for applications such as phosphate recycling [2].

In contrast, the direct adsorption of nitrate (NO_3^-) onto most biochars is generally limited due to electrostatic repulsion from negatively charged surfaces and the high mobility of the nitrate anion. Therefore, biochar's role in nitrogen cycling often extends beyond simple adsorption. When integrated into biological treatment systems like constructed wetlands or biofilters, biochar serves as an excellent substrate for microbial colonization. The porous structure provides a protected habitat for microbial communities involved in nitrification (converting NH_4^+ to NO_3^-) and denitrification (converting NO_3^- to N_2 gas). Biochar can facilitate these processes by acting as an electron shuttle, enhancing microbial metabolic activity, and potentially adsorbing inhibitory compounds, thereby indirectly promoting the biological removal of nitrogen species. This synergistic abiotic-biotic functionality underscores biochar's value in complex treatment systems.

A significant advancement in this field is the shift from viewing nutrient-laden biochar merely as a spent adsorbent to recognizing it as a valuable resource. After adsorbing nutrients from sewage, the biochar itself becomes enriched with nitrogen and phosphorus. This nutrient-rich material can be directly applied to soil as a slow-release fertilizer, thereby closing the nutrient loop. As noted in research on reed biochar, such materials can adsorb components like ammonium, nitrate, and phosphorus from sources like pig urine and subsequently be used for crop cultivation, such as watermelon, in polluted regions [7]. This approach transforms a waste treatment problem into a resource recovery opportunity, contributing to sustainable agriculture. However, challenges remain, including the need to optimize biochar production and modification for targeted nutrient recovery, ensure the stability of captured nutrients to prevent rapid leaching, and assess the long-term agronomic and environmental impacts of applying nutrient-loaded biochar to soils. Future research should focus on developing standardized, cost-effective modification techniques to enhance biochar's selectivity and capacity for specific nutrients, and on conducting more field-scale trials to validate the performance and economic viability of biochar-based nutrient recovery systems within integrated wastewater management frameworks.

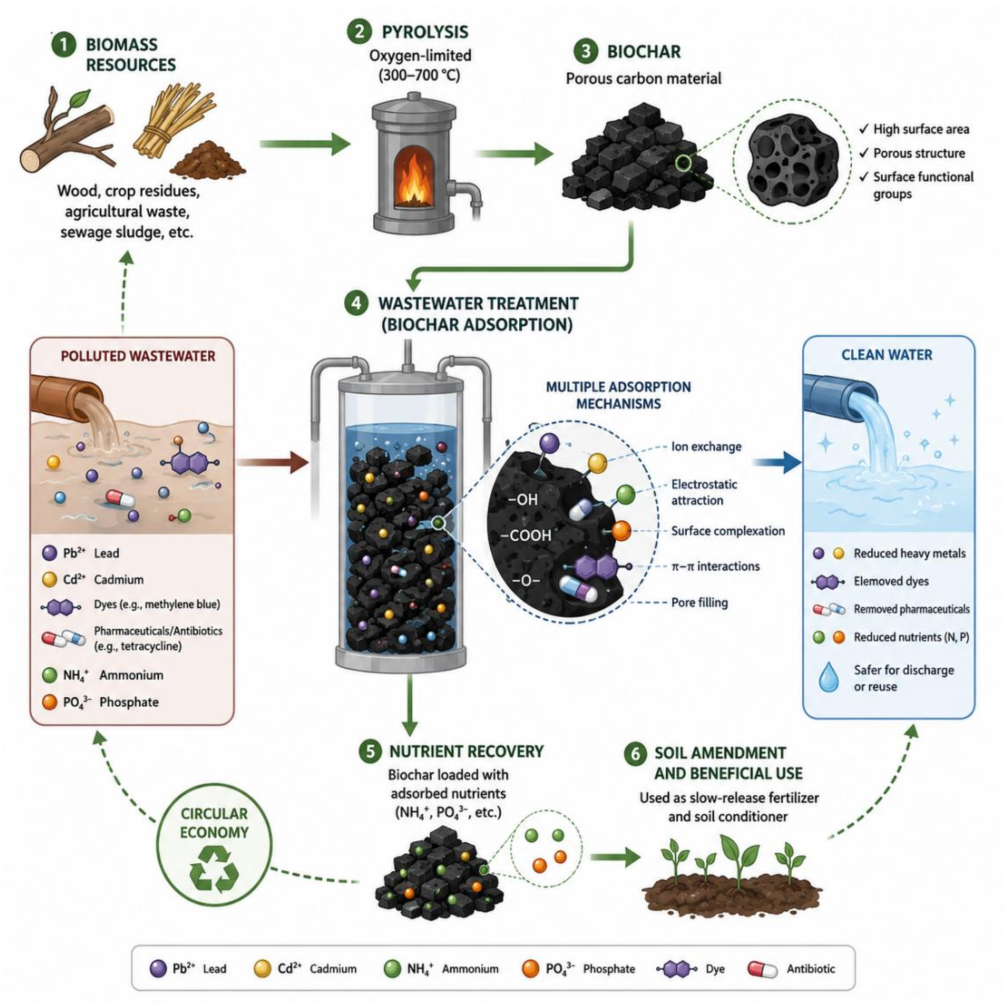

Figure 1. Schematic Illustration of Biochar-Mediated Wastewater Purification and Resource Recovery

4. SYNTHESIS AND CRITICAL COMMENTARY

The extensive body of research reviewed in preceding chapters provides compelling evidence of biochar's versatility and potential as a sustainable adsorbent for sewage pollutants. From heavy metals and organic compounds to nutrients, studies have successfully demonstrated that biochar, often through strategic modification, can achieve significant removal efficiencies. The underlying mechanisms—spanning physical pore-filling, electrostatic interactions, surface complexation, and ion exchange—are reasonably well understood for single-pollutant systems. This foundational work has been crucial in establishing biochar as a material of significant interest within the environmental remediation community. However, a critical synthesis of this literature reveals a pronounced disconnect between controlled laboratory investigations and the multifaceted realities of actual sewage treatment. The prevailing research paradigm has largely focused on proving efficacy under idealized conditions, which, while necessary, is insufficient for guiding practical implementation.

A primary limitation lies in the overwhelming focus on batch adsorption experiments using synthetic wastewater containing a single target pollutant. Real sewage is a complex matrix containing a diverse mixture of inorganic ions, organic matter, suspended solids, and microorganisms, all of which can interact competitively or synergistically with the biochar surface. The adsorption capacity and selectivity for a specific contaminant, such as lead or tetracycline, can be dramatically altered in the presence of co-existing substances like natural organic matter or competing cations. For instance, humic acids may block adsorption sites or form complexes with metal ions, changing their removal pathway. Yet, systematic studies on these competitive adsorption dynamics in multi-pollutant systems are relatively scarce. Future research must urgently shift towards investigating these complex interactions to predict biochar performance in real-world scenarios accurately. This requires designing experiments that mimic the typical composition of domestic or industrial sewage, moving beyond simplified single-solute models.

Furthermore, the long-term performance and practical feasibility of biochar in continuous-flow treatment systems represent another significant research gap. Most studies conclude with a batch isotherm or kinetics plot, but few extend to column studies or pilot-scale trials that assess operational parameters like hydraulic retention time, flow rate, clogging potential, and pressure drop. The stability of the adsorbed pollutants is also a critical concern; there is a need to evaluate whether contaminants are permanently immobilized or if they can leach out over time, especially under changing environmental conditions like pH fluctuations. Linked to this is the challenge of regeneration and reuse. While some studies explore desorption using chemical eluents, the effectiveness of multiple adsorption-desorption cycles and the consequent changes in biochar's structural and chemical properties are not thoroughly documented. The development of robust, cost-effective regeneration protocols is essential for the economic viability of biochar-based treatment, particularly for recovering valuable resources like adsorbed nutrients or metals.

From a broader perspective, a comprehensive assessment of biochar's lifecycle environmental and economic impacts is conspicuously absent from much of the current literature. The sustainability claim of biochar hinges not only on its adsorption performance but also on the net environmental benefit of its entire production and application chain. This includes the energy input and emissions from pyrolysis, the potential ecological risks associated with the disposal or land application of spent biochar (which may contain concentrated pollutants), and a comparative cost-benefit analysis against conventional adsorbents like activated carbon. Without such holistic evaluations, it is difficult to advocate for the large-scale adoption of biochar technology in municipal or industrial wastewater treatment plants. Research must therefore integrate technical performance studies with lifecycle assessment and techno-economic analysis to provide a complete picture of its feasibility and sustainability.

In synthesizing these points, it becomes clear that the next critical phase of research must bridge the gap between promising laboratory results and practical application. The proposed novel direction involves a systems-based approach that treats biochar not merely as an isolated adsorbent but as an integrated component within a wastewater treatment process. This entails focused investigations into: 1) the competitive and synergistic adsorption behaviors in complex, multi-pollutant sewage matrices; 2) the long-term hydraulic and chemical stability of biochar in continuous-flow configurations, including its regeneration potential; and 3) a full lifecycle analysis to quantify the true environmental footprint and economic cost. By addressing these interconnected challenges, future work can transition biochar from a material of demonstrated potential to a reliable, optimized, and sustainably engineered solution for modern sewage pollution control, ultimately contributing a more holistic and applicable framework to the field of water treatment technology.

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