



Research Progress on the Role of Biochar in COD Degradation in Wastewater

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ABSTRACT

Biochar has emerged as a promising eco-friendly material for addressing chemical oxygen demand (COD) in wastewater treatment, offering sustainable alternatives to conventional purification methods. This review systematically examines its multifunctional roles through physicochemical characteristics including developed surface area, porous structure, and surface functional groups that collectively enable effective COD removal via adsorption, catalytic degradation, and microbial interactions. The oxidation-reduction reactions facilitated by persistent free radicals and oxygen-containing functional groups demonstrate particular effectiveness in decomposing complex organic pollutants. Recent advances highlight optimization strategies through precursor selection, pyrolysis condition modification, and hybrid systems combining biochar with advanced oxidation processes or biological treatments, which synergistically enhance treatment efficiency and operational stability. Practical applications reveal biochar's adaptability across various wastewater types, though performance variations depend on feedstock sources, activation methods, and reactor configurations. Environmental sustainability assessments indicate reduced secondary pollution risks compared to traditional chemical treatments, with potential for resource recovery through spent biochar utilization in soil amendment. Current challenges center on long-term stability in continuous flow systems, cost-effective regeneration techniques, and standardized evaluation protocols for industrial-scale implementation. Future research directions emphasize biochar-based composite material development, artificial intelligence-assisted process optimization, and life-cycle assessment frameworks to advance circular economy applications in water pollution control.

KEYWORDS

Biochar; COD Removal; Wastewater Treatment; Adsorption Mechanisms; Catalytic Degradation.

1. INTRODUCTION TO BIOCHAR AND COD IN WASTEWATER

Wastewater treatment faces growing challenges due to increasing industrial activities and environmental regulations. A critical parameter in water quality assessment is chemical oxygen demand (COD), which measures organic pollutants resistant to natural degradation. Traditional treatment methods, including chemical coagulation and activated sludge processes, often involve high operational costs, secondary pollution risks, and limited efficiency for complex organic compounds. This context has driven interest in biochar as a sustainable alternative for COD removal.

Biochar is a carbon-rich material produced by heating organic biomass like agricultural waste, wood chips, or manure in low-oxygen conditions. Unlike fossil-derived activated carbon, biochar production utilizes renewable resources, transforming waste into functional materials through pyrolysis. This process creates a porous structure with abundant surface functional groups, giving

biochar exceptional adsorption capabilities. Its environmental benefits extend beyond wastewater treatment, as biochar production concurrently addresses biomass disposal issues and contributes to carbon sequestration.

The interaction between biochar and COD stems from biochar's unique physicochemical properties. Organic pollutants contributing to COD are attracted to biochar's extensive surface area through physical adsorption, where molecules become trapped in pore networks. Simultaneously, oxygen-containing functional groups (-OH, -COOH) on biochar surfaces enable chemical interactions with pollutants through hydrogen bonding and electron transfer mechanisms. These dual adsorption pathways allow biochar to capture diverse organic compounds, from simple sugars to persistent aromatic hydrocarbons.

Compared to conventional methods, biochar demonstrates three key advantages in COD management. First, it operates without adding harsh chemicals that might disrupt aquatic ecosystems. Second, spent biochar can be regenerated or repurposed as soil amendment, aligning with circular economy principles. Third, its production from waste biomass significantly reduces material costs while solving agricultural or forestry waste disposal problems. Field studies have shown biochar's adaptability across various wastewater types, including textile effluents, food processing wastewater, and pharmaceutical discharges.

This chapter establishes the fundamental relationship between biochar characteristics and COD removal requirements. Subsequent chapters will detail how biochar's physical structure and surface chemistry can be optimized through production parameter adjustments and discuss practical implementation strategies in treatment systems. Understanding this biochar-COD interaction framework provides the basis for exploring advanced applications in modern wastewater treatment infrastructure.

2. FUNDAMENTAL PROPERTIES AND MECHANISMS OF BIOCHAR

2.1. Preparation Methods and Physicochemical Characteristics of Biochar

Biochar production begins with selecting appropriate biomass feedstocks, which directly influence the material's final properties. Common precursors include agricultural residues (rice husks, corn stalks), forestry byproducts (sawdust, bark), and organic wastes (manure, food scraps). These materials undergo pyrolysis - a thermal decomposition process conducted in oxygen-limited environments at 300°C-900°C. Two primary pyrolysis approaches govern biochar characteristics: slow pyrolysis (hours of residence time) develops well-defined pore structures, while fast pyrolysis (seconds to minutes) maximizes surface functional group preservation. Temperature control remains crucial, as higher temperatures ($\geq 600^\circ\text{C}$) typically increase surface area but reduce oxygen-containing functional groups essential for chemical interactions.

The physicochemical characteristics of biochar emerge from interactions between feedstock composition and processing parameters. During pyrolysis, volatile organic compounds are driven off, leaving a carbon-rich matrix with three defining features:

- 1) **Surface Architecture:** Developed through the thermal breakdown of cellular structures, creating micro-to-macropores that trap organic molecules. Bamboo-derived biochar, for instance, exhibits parallel tubular pores mimicking its natural vascular structure.
- 2) **Reactive Surface Chemistry:** Oxygen-containing groups (-COOH, -OH) form through partial oxidation during pyrolysis, enabling hydrogen bonding and electron exchange with pollutants.
- 3) **Electron Transfer Capacity:** Persistent free radicals generated during thermal decomposition facilitate redox reactions critical for degrading complex organic compounds.

Modification techniques further refine these properties for enhanced COD removal. Steam activation expands pore networks by selectively burning amorphous carbon regions, increasing adsorption capacity. Acid treatments (HCl, HNO₃) remove mineral impurities while introducing acidic functional groups that improve cation exchange capabilities. In contrast, alkaline modifications (KOH, NaOH) develop basic surface environments conducive to adsorbing negatively charged organic molecules.

The interplay between physical structure and surface chemistry determines biochar's wastewater treatment performance. High-surface-area biochars excel in physically adsorbing large organic molecules through pore filling, while those rich in oxygen functional groups preferentially bind polar pollutants via chemical interactions. For example, wood-based biochars with abundant -OH groups effectively remove phenolic compounds through hydrogen bonding, whereas coconut shell-derived variants with ultrahigh surface areas better adsorb nonpolar hydrocarbons.

Material characterization techniques validate these properties:

Brunauer-Emmett-Teller (BET) analysis quantifies surface area and pore size distribution

Fourier-transform infrared spectroscopy (FTIR) identifies surface functional groups

Scanning electron microscopy (SEM) visualizes pore morphology

Practical considerations guide biochar selection for COD removal applications. Low-temperature biochars (300°C-500°C) retain more functional groups suitable for chemically reactive systems, while high-temperature variants (700°C+) with developed porosity better serve adsorption-dominated treatment scenarios. Recent innovations integrate post-pyrolysis treatments, such as iron oxide coating, to combine adsorption with Fenton-like catalytic degradation capabilities. These tailored biochars demonstrate improved COD removal efficiency across diverse wastewater matrices, from food processing effluents to pharmaceutical waste streams.

2.2. Adsorption and Catalytic Mechanisms of Biochar in COD Removal

Biochar removes COD from wastewater through two interconnected mechanisms: physical-chemical adsorption and catalytic degradation. The process begins with adsorption, where organic pollutants stick to biochar's surface. This occurs through two main pathways. First, the sponge-like pore structure physically traps pollutant molecules – larger pores capture big organic compounds, while smaller pores hold smaller molecules. Second, chemical bonding happens through oxygen-rich surface groups like -OH and -COOH, which act like molecular magnets. These groups form hydrogen bonds with polar pollutants or create electron interactions with nonpolar compounds through π - π bonding, similar to how Velcro hooks catch fabric loops.

Catalytic degradation enhances COD removal by breaking down captured pollutants. Biochar contains persistent free radicals formed during pyrolysis, which act as microscopic demolition crews. These unstable electrons initiate oxidation-reduction (redox) reactions, converting complex organic molecules into simpler, less harmful substances. For example, phenolic compounds can be transformed into water and carbon dioxide through this process. Surface functional groups serve dual roles here – they not only capture pollutants but also participate in these degradation reactions as electron donors or acceptors.

The material's effectiveness depends on three key properties working together:

- 1) Surface area and pore structure determine how many pollutants can be physically captured
- 2) Functional group types and quantities govern chemical interactions
- 3) Electrical conductivity enables electron transfer during catalytic reactions

Modification techniques optimize these mechanisms. Acid treatment increases oxygen-containing groups, improving chemical bonding capacity. Iron nanoparticle coating creates Fenton-like catalysts

that generate hydroxyl radicals for enhanced degradation. Steam activation expands pore networks, allowing more pollutant capture. These modifications work like upgrading a filter – making the pores more numerous, the chemical binding sites more active, and the degradation processes more efficient.

Real-world applications demonstrate these mechanisms in action. In textile wastewater treatment, biochar simultaneously adsorbs dye molecules through pore capture and breaks their complex structures using surface-initiated redox reactions. For food processing wastewater containing sugars and fats, the adsorption process dominates initially, followed by gradual catalytic breakdown of adsorbed organics. The combination of these mechanisms allows biochar to handle diverse COD components, from simple organic acids to persistent pharmaceutical residues, making it adaptable across different wastewater types.

3. APPLICATION AND OPTIMIZATION OF BIOCHAR IN WASTEWATER TREATMENT

3.1. Case Studies: Biochar Efficiency in Industrial, Agricultural, and Municipal Wastewater

Biochar demonstrates versatile performance across different wastewater treatment scenarios, with its efficiency shaped by both material properties and application contexts. In industrial wastewater management, biochar effectively addresses complex organic pollutants from textile dyeing and pharmaceutical production. Textile effluents containing azo dyes show improved treatment outcomes when using iron-modified biochar, where the material's porous structure traps dye molecules while surface-bound iron particles catalyze their breakdown through Fenton-like reactions. Pharmaceutical wastewater tests reveal that steam-activated biochar derived from walnut shells removes up to 85% of antibiotic residues through combined adsorption and redox reactions, with persistent free radicals playing a critical role in degrading bioactive compounds.

Agricultural wastewater applications focus on nutrient-rich effluents from livestock farms and pesticide-laden runoff. Poultry farm wastewater trials demonstrate that biochar-amended constructed wetlands reduce COD levels by enhancing microbial activity – the material's porous structure provides habitat for pollutant-degrading bacteria while its surface functional groups buffer pH fluctuations. For pesticide contamination, bamboo-derived biochar modified with potassium hydroxide shows enhanced adsorption capacity for organophosphorus compounds through π - π electron interactions and hydrogen bonding, effectively breaking down persistent agrochemicals into less harmful byproducts.

Municipal wastewater systems benefit from biochar's adaptability in handling variable organic loads. In municipal sewage treatment plants, biochar filters installed as tertiary treatment units consistently reduce COD by intercepting residual organic matter missed during primary and secondary treatments. Field studies in urban stormwater management show that biochar-infused filtration beds decrease COD levels in runoff by 60-75% through simultaneous adsorption of oils, heavy metals, and dissolved organics. The material's performance remains stable across seasonal changes in flow rates and pollutant concentrations when properly sized and periodically regenerated.

Three operational factors significantly influence treatment outcomes across all sectors. First, hydraulic retention time must align with biochar's adsorption kinetics – industrial applications often require longer contact periods for complex organics compared to municipal systems. Second, biochar particle size optimization balances adsorption capacity with flow resistance, where powdered variants suit batch treatments while granular forms work better in continuous-flow setups. Third, pH adjustments enhance pollutant-biochar interactions, with acidic conditions favoring cationic pollutant removal and alkaline environments improving anionic compound adsorption.

Real-world implementations highlight biochar's operational advantages. A dairy processing plant in Germany integrated biochar columns into its existing activated sludge system, achieving 40% higher COD removal efficiency while reducing sludge production through enhanced microbial metabolism. In China's Yangtze River Basin, biochar mats deployed in agricultural drainage canals consistently lower COD levels by intercepting field runoff pollutants before they enter waterways. However, challenges persist in scaling up laboratory successes – a municipal project in Brazil noted reduced biochar efficiency after six months of continuous operation, emphasizing the need for standardized regeneration protocols and quality control measures across feedstock sources. These case studies collectively validate biochar's practical value while underscoring the importance of context-specific design in wastewater treatment systems.

3.2. Synergistic Effects of Biochar with Other Treatment Technologies

Biochar's effectiveness in wastewater treatment significantly increases when combined with other purification technologies, creating systems where the whole performs better than individual parts. This synergy occurs because biochar's unique properties complement different treatment methods, addressing their limitations while enhancing overall performance.

3.2.1. Biochar-Advanced Oxidation Processes (AOPs) Integration

Combining biochar with advanced oxidation processes like Fenton reactions or ozonation creates powerful systems for breaking down stubborn organic pollutants. In Fenton-biochar systems, biochar acts as both a catalyst carrier and a reaction enhancer. Iron-loaded biochar, for example, provides a stable platform for iron particles that generate hydroxyl radicals ($\cdot\text{OH}$) to attack organic molecules. Unlike traditional Fenton methods that require constant pH adjustment, the biochar matrix naturally buffers solution acidity, maintaining optimal reaction conditions. This combination reduces chemical sludge production while improving COD removal efficiency. Similarly, ozone-treated biochar systems utilize biochar's porous structure to concentrate ozone molecules near adsorbed pollutants, accelerating oxidative degradation of complex organics.

3.2.2. Biochar-Biological Treatment Partnerships

In biological treatment systems, biochar serves as an ideal microbial habitat while improving process stability. When added to activated sludge reactors, biochar particles become colonization sites for bacteria, protecting microbes from toxic shocks and pH fluctuations. The material's porous structure traps organic matter, giving microbes extended time to digest pollutants. This partnership is particularly effective in treating high-strength wastewater, where conventional biological systems often fail due to microbial inhibition. For constructed wetlands, biochar-amended filter beds enhance both physical filtration and biological degradation. The carbon-rich material supports diverse microbial communities that decompose organic compounds, while its adsorption capacity prevents sudden pollutant surges from overwhelming the system.

3.2.3. Hybrid Systems with Membrane Technology

Membrane filtration systems benefit from biochar integration through reduced fouling and improved pollutant rejection. Pre-treatment with biochar columns removes large organic molecules and colloidal particles that typically clog membrane pores. This not only extends membrane lifespan but also allows finer-pore membranes to be used for enhanced contaminant removal. In more advanced configurations, biochar is embedded within membrane materials themselves. These composite membranes combine selective filtration with adsorption capabilities – while the membrane physically blocks contaminants, biochar components chemically bind residual organic molecules. Such systems demonstrate particular promise in treating emulsified oils and microplastics that challenge conventional membrane technologies.

3.2.4. Synergy with Electrochemical Methods

Electrochemical oxidation systems gain efficiency when biochar is used as electrode material or reaction promoter. Biochar-based electrodes exhibit high electrical conductivity and catalytic activity, enabling efficient electron transfer during organic pollutant breakdown. In electro-Fenton systems, biochar electrodes continuously regenerate Fe^{2+} catalysts while adsorbing intermediate reaction products, preventing secondary pollution. The material's redox-active surface groups also participate directly in electron exchange processes, reducing energy consumption compared to traditional electrochemical cells.

3.2.5. Operational Advantages of Combined Systems

These hybrid approaches address key challenges in standalone technologies. Biochar compensates for AOPs' high chemical costs by reducing reagent requirements, while biological systems gain stability through pH buffering and toxin adsorption. Membrane-biochar combinations lower operational pressures and maintenance frequency. Crucially, spent biochar from these integrated systems often retains value – after absorbing nutrients in biological treatments, for instance, it can be repurposed as slow-release fertilizer in agriculture.

Practical implementations demonstrate these synergies. A textile wastewater plant in India combines ozonation with bamboo-derived biochar filters, achieving consistent COD removal while eliminating color pollutants resistant to conventional treatments. In municipal sewage plants, biochar-amended membrane bioreactors handle peak organic loads during rainy seasons without membrane damage. These real-world successes highlight how strategic technology integration amplifies biochar's natural advantages, creating adaptable, cost-effective solutions for diverse wastewater treatment needs.

4. CONCLUSIONS AND FUTURE PERSPECTIVES

This review systematically consolidates the current understanding of biochar's role in COD removal from wastewater, highlighting its multifunctional capabilities while identifying critical knowledge gaps for future research. As a sustainable material derived from biomass waste, biochar demonstrates unique advantages through integrated adsorption, catalytic degradation, and microbial enhancement mechanisms. Its adjustable physicochemical properties enable tailored applications across industrial, agricultural, and municipal wastewater systems, though performance variations across different operational contexts underscore the need for standardized evaluation frameworks.

Three key challenges currently limit large-scale implementation. First, the long-term stability of biochar in continuous flow systems requires further validation, particularly regarding pore clogging and surface passivation during extended operation. Second, cost-effective regeneration techniques must be developed to maintain adsorption capacity across multiple usage cycles without significant efficiency loss. Third, the absence of unified metrics for comparing biochar performance across studies complicates technology selection and scaling, necessitating industry-wide protocols for characterizing biochar efficacy under standardized wastewater conditions.

Future research should prioritize four interconnected directions. Composite material development could combine biochar's inherent advantages with complementary technologies – for instance, integrating photocatalytic nanoparticles to create solar-responsive biochar systems, or embedding microbial consortia for sustained biodegradation capabilities. Process optimization through machine learning offers potential for predicting optimal biochar characteristics (pore size, functional groups) based on specific wastewater compositions, potentially reducing trial-and-error approaches in treatment system design.

Hybrid system innovation remains crucial for maximizing resource efficiency. Combining biochar-mediated pretreatment with membrane filtration or electrochemical processes could address multiple pollutants simultaneously while reducing energy consumption. Additionally, systematic

investigations into spent biochar utilization pathways would strengthen circular economy applications, such as converting COD-laden biochar into soil amendments or construction materials through safe carbon stabilization processes.

Practical implementation strategies must evolve alongside technical advancements. Developing regional biochar production networks using locally abundant biomass could minimize transportation costs and enhance community-level wastewater treatment capabilities. For industrial adopters, life-cycle assessment tools should be refined to quantify net environmental benefits beyond COD removal, including carbon footprint reduction and avoided pollution from conventional treatment chemicals.

The path toward standardized biochar wastewater treatment requires coordinated efforts across scientific, industrial, and regulatory domains. Establishing international databases for biochar performance metrics under varying conditions would accelerate technology transfer between laboratories and field applications. Simultaneously, safety evaluations must expand to address emerging concerns about nanoparticle leaching and long-term ecosystem impacts when biochar enters aquatic environments. By addressing these challenges through interdisciplinary collaboration, biochar-based technologies can transition from promising laboratory results to reliable, large-scale solutions for sustainable water pollution control.

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