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Biochar-Based Materials for Environmental Remediation: Recent Advances and Applications

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Abstract

Environmental pollution resulting from industrialization, urbanization, intensive agriculture, and unsustainable waste disposal has become a major global challenge affecting ecosystems and human health. Contamination of soil, water, and air by heavy metals, organic pollutants, pharmaceuticals, pesticides, dyes, microplastics, and emerging contaminants necessitates the development of efficient, sustainable, and environmentally friendly remediation technologies. Among various materials investigated for pollution control, biochar has emerged as a promising carbon-rich material due to its high surface area, porous structure, abundant functional groups, low production cost, and excellent adsorption capacity. Biochar is produced through the thermochemical conversion of biomass under oxygen-limited conditions and can be further modified with metals, metal oxides, polymers, and nanomaterials to enhance its physicochemical properties and environmental performance. Biochar-based materials have demonstrated remarkable effectiveness in wastewater treatment, heavy metal immobilization, soil remediation, carbon sequestration, greenhouse gas mitigation, nutrient recovery, catalytic degradation of pollutants, and environmental restoration. Recent advances in nanotechnology and material engineering have further expanded the applications of biochar composites in sustainable environmental management. This review discusses biochar production technologies, physicochemical properties, modification strategies, mechanisms of pollutant removal, recent environmental applications, current challenges, and future perspectives for biochar-based materials.

Keywords: *Biochar, Environmental remediation, Heavy metals, Wastewater treatment, Adsorption, Sustainable materials, Biochar composites, Pollution control.*

1. Introduction

Rapid industrial growth, expanding urban populations, and intensive agricultural activities have significantly increased environmental pollution worldwide. Large quantities of heavy metals, synthetic dyes, pesticides, pharmaceutical residues, antibiotics, petroleum hydrocarbons, endocrine-disrupting chemicals, and other hazardous pollutants are continuously released into aquatic and terrestrial ecosystems. These contaminants threaten biodiversity, reduce agricultural productivity, contaminate drinking water, and pose serious risks to human health through bioaccumulation and biomagnification. Conventional remediation technologies, including chemical precipitation, membrane filtration, ion exchange, advanced oxidation, and incineration, often suffer from high operational costs, energy requirements, secondary pollution, and limited long-term sustainability [1].
Biochar has gained considerable attention as an environmentally friendly material capable of addressing these challenges. Produced through the pyrolysis of biomass under oxygen-limited conditions, biochar possesses a highly porous carbonaceous structure, large specific surface area, abundant oxygen-containing functional groups, excellent chemical stability, and high adsorption capacity. These characteristics make biochar highly suitable for capturing a wide variety of environmental pollutants [2]. The feedstocks used for biochar production include agricultural residues, forestry wastes, municipal organic waste, animal manure, food processing residues, sewage sludge, and other renewable biomass resources. Utilizing these waste materials not only reduces environmental pollution but also supports circular economy principles through waste valorization and resource recovery.
Recent research has focused on enhancing biochar performance by incorporating nanoparticles, metal oxides, polymers, magnetic materials, and other functional modifiers. These engineered biochar composites exhibit superior adsorption efficiency, catalytic activity, mechanical stability, and regeneration capacity compared with pristine biochar. Consequently, biochar-based materials have found extensive applications in wastewater treatment, contaminated soil remediation, greenhouse gas mitigation, nutrient management, carbon sequestration, environmental catalysis, and sustainable agriculture [3-4]. This review summarizes recent advances in biochar production technologies, physicochemical properties,

modification techniques, pollutant removal mechanisms, environmental applications, current limitations, and future research opportunities.

2. Biochar Production Technologies and Physicochemical Properties

Biochar is produced through the thermochemical decomposition of biomass under limited or oxygen-free conditions. The production process significantly influences the physical structure, chemical composition, surface chemistry, and adsorption performance of the resulting biochar. Several thermochemical conversion methods have been developed, each producing biochar with distinct characteristics suitable for specific environmental applications [5]. Slow pyrolysis is the most commonly employed technique for biochar production. It involves heating biomass at temperatures ranging from 300–700°C for relatively long residence times under oxygen-deficient conditions. Slow pyrolysis generally produces higher biochar yields with well-developed pore structures and stable carbon frameworks suitable for long-term environmental applications [6]. Fast pyrolysis utilizes rapid heating rates and short residence times to maximize bio-oil production while generating moderate quantities of biochar. Gasification, conducted at higher temperatures with limited oxygen or steam, primarily produces synthesis gas while yielding smaller amounts of highly porous biochar. Hydrothermal carbonization offers an alternative approach by converting wet biomass into hydrochar under moderate temperatures and high-pressure aqueous environments without requiring extensive drying [7]. The physicochemical properties of biochar depend on biomass feedstock, production temperature, heating rate, residence time, and post-treatment processes. High-temperature biochars generally exhibit larger surface areas, higher aromaticity, increased carbon content, and improved electrical conductivity. Conversely, low-temperature biochars retain greater quantities of oxygen-containing functional groups such as hydroxyl, carboxyl, and carbonyl groups, enhancing their affinity toward metal ions and polar contaminants [8]. The porous structure of biochar provides numerous adsorption sites for pollutants, while its negatively charged surface facilitates electrostatic interactions with positively charged contaminants. These combined structural and chemical properties contribute to the excellent environmental performance of biochar-based materials.

Table 1: Major Biochar Production Technologies

Production Method	Operating Conditions	Major Characteristics	Environmental Applications
Slow Pyrolysis	300–700°C, long residence time	High biochar yield	Soil remediation, adsorption
Fast Pyrolysis	Rapid heating	Moderate biochar production	Waste utilization
Gasification	>700°C	Highly porous biochar	Catalysis and adsorption
Hydrothermal Carbonization	180–250°C, aqueous environment	Hydrochar production	Wet biomass treatment

3. Modification Strategies for Biochar-Based Materials

Although pristine biochar possesses excellent adsorption properties, its performance can be substantially improved through physical, chemical, and nanotechnological modification techniques. Surface modification increases surface area, pore volume, functional group density, catalytic activity, and selectivity toward specific pollutants [9]. Chemical activation using acids, alkalis, hydrogen peroxide, or oxidizing agents introduces additional oxygen-containing functional groups that enhance adsorption capacity. Metal impregnation with iron, manganese, zinc, magnesium, aluminum, titanium, calcium, and copper produces composite materials capable of removing heavy metals through precipitation, ion exchange, and complexation mechanisms [10]. Magnetic biochar has emerged as an important advancement in environmental remediation. Incorporation of iron oxide nanoparticles enables rapid magnetic separation after pollutant adsorption, facilitating material recovery and reuse. Similarly, biochar-supported photocatalysts containing titanium dioxide, zinc oxide, or other semiconductor nanoparticles exhibit excellent photocatalytic degradation of organic pollutants under visible or ultraviolet light [11]. Nanocomposite biochars prepared by integrating carbon nanotubes, graphene oxide, metal-organic frameworks, or polymeric materials provide enhanced adsorption efficiency, catalytic performance, and mechanical stability. These multifunctional composites have expanded biochar applications beyond conventional adsorption toward advanced oxidation processes, electrochemical remediation, and environmental sensing.

4. Mechanisms of Pollutant Removal by Biochar-Based Materials

The remarkable environmental remediation performance of biochar-based materials arises from multiple physicochemical mechanisms that enable the efficient removal of inorganic and organic contaminants. Unlike conventional adsorbents that often rely on a single removal pathway, biochar exhibits a combination of adsorption, ion exchange, electrostatic attraction, surface complexation, precipitation, pore filling, hydrogen bonding, π–π interactions, and catalytic degradation. These complementary mechanisms make biochar an effective material for treating complex environmental pollutants [12]. Adsorption is the primary mechanism responsible for contaminant removal. The highly porous structure and large specific surface area of biochar provide abundant adsorption sites for heavy metals, dyes, pesticides, antibiotics, pharmaceuticals, and other organic pollutants. The adsorption efficiency is influenced by pore size distribution, surface functional groups, solution pH, pollutant concentration, temperature, and the physicochemical characteristics of both the biochar and contaminants.

Ion exchange plays a significant role in removing positively charged metal ions from contaminated water and soils. Functional groups such as carboxyl, hydroxyl, and phenolic groups present on the biochar surface exchange naturally occurring ions with toxic heavy metals including lead, cadmium, copper, zinc, chromium, mercury, and arsenic. Surface complexation further enhances pollutant removal through the formation of stable coordination bonds between metal ions and oxygen-containing functional groups [13]. Electrostatic interactions contribute substantially to contaminant adsorption. Negatively charged biochar surfaces attract positively charged contaminants, whereas appropriate surface modifications allow efficient adsorption of negatively charged pollutants.

Organic contaminants containing aromatic structures are removed through π–π electron donor–acceptor interactions with the aromatic carbon framework of biochar. Hydrophobic interactions and hydrogen bonding also facilitate the adsorption of pharmaceuticals, pesticides, endocrine-disrupting chemicals, and persistent organic pollutants [14]. Modified biochar materials containing metal oxides or photocatalytic nanoparticles exhibit catalytic degradation of organic pollutants. These composites generate reactive oxygen species capable of oxidizing complex contaminants into less toxic or biodegradable compounds. Consequently, biochar functions not only as an adsorbent but also as an efficient catalyst for advanced environmental remediation.

Table 2: Major Pollutant Removal Mechanisms of Biochar-Based Materials

Removal Mechanism	Target Pollutants	Primary Function
Physical adsorption	Organic pollutants, dyes	Surface adsorption and pore filling
Ion exchange	Heavy metals	Replacement of exchangeable ions
Surface complexation	Metal ions	Formation of stable coordination complexes
Electrostatic attraction	Charged pollutants	Electrostatic adsorption
Hydrogen bonding	Pharmaceuticals, pesticides	Molecular interaction
π–π interactions	Aromatic compounds	Adsorption of organic pollutants
Catalytic oxidation	Persistent organic contaminants	Pollutant degradation
Precipitation	Heavy metals	Formation of insoluble compounds

5. Environmental Applications of Biochar-Based Materials

Biochar-based materials have demonstrated exceptional versatility across numerous environmental remediation applications. One of the most important applications is wastewater treatment, where biochar efficiently removes heavy metals, synthetic dyes, pharmaceuticals, antibiotics, pesticides, phenolic compounds, petroleum hydrocarbons, and other emerging contaminants from industrial and municipal wastewater. Engineered biochar composites often exhibit adsorption capacities comparable to or exceeding those of commercial activated carbon while offering lower production costs and greater sustainability [15]. In soil remediation, biochar immobilizes toxic metals, reduces contaminant bioavailability, improves soil structure, increases water retention, and enhances microbial diversity. Biochar amendments reduce the mobility of cadmium, lead, arsenic, chromium, mercury, and nickel while simultaneously improving soil fertility and supporting sustainable crop production. These properties make biochar an important component of sustainable land restoration strategies.

Biochar also contributes significantly to carbon sequestration and climate change mitigation. Owing to its highly stable aromatic carbon structure, biochar remains in soil for decades or even centuries, effectively storing atmospheric carbon captured by plants during photosynthesis. This long-term carbon storage reduces greenhouse gas emissions while improving soil quality. Additionally, biochar decreases methane and nitrous oxide emissions from agricultural soils, contributing further to climate change mitigation [16]. In agricultural systems, biochar enhances nutrient retention by reducing nitrogen and phosphorus leaching, thereby improving fertilizer use efficiency and crop productivity. Its porous structure provides favorable habitats for beneficial soil microorganisms that promote nutrient cycling and plant health. Modified biochars have also been investigated as slow-release fertilizer carriers capable of improving nutrient availability while minimizing environmental losses [17]. Recent studies have extended biochar applications to air pollution control, catalytic degradation of volatile organic compounds, oil spill remediation, microplastic removal, environmental sensors, and renewable energy storage. These diverse applications demonstrate the growing importance of biochar as a multifunctional material for sustainable environmental management.

Table 3: Environmental Applications of Biochar-Based Materials

Application Area	Target Pollutants/Problems	Major Benefits
Wastewater treatment	Heavy metals, dyes, pharmaceuticals	Efficient pollutant removal
Soil remediation	Metal contamination, pesticides	Reduced bioavailability and improved soil health
Carbon sequestration	Atmospheric CO_2	Long-term carbon storage
Sustainable agriculture	Nutrient loss, poor soil fertility	Enhanced crop productivity
Air pollution control	Volatile organic compounds	Adsorption and catalytic degradation
Oil spill remediation	Petroleum hydrocarbons	Rapid contaminant adsorption
Microplastic removal	Plastic particles	Improved water purification

6. Challenges and Future Perspectives

The significant progress, several challenges continue to limit the large-scale implementation of biochar-based materials. One major limitation is the variability in biochar properties resulting from differences in biomass feedstock, pyrolysis conditions, and post-treatment processes. This variability affects adsorption capacity, chemical stability, and environmental performance, making standardization difficult. Another important concern involves regeneration and long-term reuse. Although many biochar materials can be regenerated through thermal or chemical treatments, repeated regeneration may reduce adsorption efficiency and alter structural properties. The safe disposal or recycling of pollutant-saturated biochar also requires careful consideration to prevent secondary environmental contamination. Economic factors influence commercial adoption. While agricultural residues provide inexpensive feedstocks, the costs associated with large-scale production, modification, transportation, and quality control remain significant. Further optimization of production technologies is necessary to improve cost-effectiveness and industrial scalability. Future research should emphasize the development of standardized production protocols, engineered multifunctional biochar composites, and environmentally benign modification techniques. Integration of nanotechnology, artificial intelligence, machine learning, and computational modeling will facilitate the rational design of highly efficient biochar materials tailored for specific contaminants. Hybrid systems combining biochar with photocatalysis, membrane filtration, electrochemical technologies, and biological treatment processes are expected to provide next-generation remediation solutions with superior efficiency and sustainability.

7. Conclusion

Biochar-based materials have emerged as versatile, sustainable, and environmentally friendly technologies for addressing a wide range of environmental pollution challenges. Produced from renewable biomass resources through thermochemical conversion, biochar possesses unique physicochemical properties, including high surface area, porous architecture, abundant functional groups, and excellent chemical stability, which enable the efficient removal of heavy metals, organic pollutants, pharmaceuticals, pesticides, dyes, and emerging contaminants from water, soil, and air. Recent advances in material engineering have significantly expanded the capabilities of biochar through chemical activation, metal oxide incorporation, magnetic modification, nanotechnology, and composite fabrication. These engineered biochar materials exhibit enhanced adsorption capacities, catalytic activity, regeneration potential, and multifunctionality, making them suitable for wastewater treatment, contaminated soil remediation, carbon sequestration, greenhouse gas mitigation, nutrient recovery, sustainable agriculture, and environmental restoration.

The integration of biochar with advanced oxidation processes, photocatalysis, and nanomaterials has further broadened its applications in modern environmental technologies. Despite these advances, challenges related to feedstock variability, production standardization, regeneration efficiency, long-term environmental safety, and commercial scalability remain important areas for future investigation. Continued interdisciplinary research combining environmental chemistry, materials science, nanotechnology, computational modeling, and sustainable engineering will facilitate the development of high-performance biochar-based materials with improved efficiency and broader practical applications, biochar-based materials represent a promising platform for sustainable environmental remediation and circular bioeconomy initiatives.

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