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Research Progress on High-Efficiency Modified Biochar for Water Environment Remediation

Qiying Zhao; Kai Li; Haile Ma
School of Food and Biological Engineering, Jiangsu University
Zhenjiang 212013, Jiangsu, China

***Abstract* - Hindered by low adsorption capacity and poor selectivity, pristine biochar often struggles to meet the demands of advanced water remediation. This review highlights functionalization strategies designed to overcome these bottlenecks, systematically evaluating the preparation methods, process conditions, and trade-offs of modified biochars. We comprehensively summarize recent progress in deploying modified biochar as a standalone solution and within synergistic water treatment systems. Additionally, we critically examine key ongoing challenges, namely material regeneration hurdles, inadequate structural stability, and scale-up limitations. To propel the practical implementation of functionalized biochar, we propose future development directions centered on adopting green modification techniques, precisely engineering microstructures, and advancing integrated engineering applications.**

Keywords - biochar; functionalization; water treatment; adsorption

I. INTRODUCTION

Recently, rapid industrialization and urbanization have triggered an escalating water crisis, with excessive heavy metals, organic pollutants, and nutrients in industrial and domestic wastewater severely threatening ecosystems and public health. Conventional water treatment technologies (e.g., chemical precipitation, ion exchange, and membrane separation) are predominantly limited by high costs, complex operations, and potential secondary pollution. Specifically, chemical precipitation typically generates substantial hazardous effluent [1], ion-exchange resins face challenging regeneration processes [2], and membrane separation suffers from severe fouling and high maintenance costs [3]. In contrast, adsorption stands out for its operational simplicity and cost-effectiveness; however, traditional activated carbon faces bottlenecks such as poor selectivity and difficult regeneration. Additionally, despite the promising potential of advanced nanomaterials like nanoscale zero-valent iron (nZVI), graphene, and carbon nanotubes (CNTs), their large-scale engineering applications are severely hindered by high manufacturing costs and poor structural stability in real-world environments [4].

Biochar is a porous carbonaceous material derived from biomass precursors—such as crop residues, forestry waste, or livestock manure—through pyrolysis under oxygen-limited or anaerobic conditions [5]. Owing to its highly developed porous network, substantial specific surface area, and the renewability of its raw materials, biochar has demonstrated tremendous application potential in the field of environmental remediation [6]. Compared with conventional activated carbon, ion-exchange resins, and synthetic adsorbents such as metal-organic frameworks (MOFs), biochar exhibits significant advantages in terms of economic cost, environmental benignity, and surface customizability. It not only facilitates low-cost "waste-treats-waste" strategies and resource recycling, but its pyrolysis process also endows the material with remarkable carbon sequestration potential. More crucially, its abundant pore structure and versatile surface chemistry provide an ideal platform for subsequent functional modifications. This enables the targeted enhancement of its adsorption affinity, selectivity, and catalytic degradation efficiency for specific pollutants via physical, chemical, or biological approaches [7]-[9].

However, untreated pristine biochar still suffers from inherent drawbacks, including limited adsorption capacity, low recognition selectivity for target pollutants, and difficulties in cyclic regeneration, making it inadequate to meet the current challenges of complex and variable water environment remediation. Consequently, recent scholarly efforts have been dedicated to the structural and surface reconstruction of biochar through strategies such as physical activation, chemical modification, biological adaptation, and multi-component compounding. These interventions have substantially elevated its comprehensive adsorption performance, catalytic activity, and long-term stability [10]. The resultant functionalized biochar not only achieves highly efficient targeted removal of singular pollutant categories (e.g., heavy metals, organics, and nutrients), but also manifests broad prospects in the synergistic purification of multiple co-existing pollutants in complex water matrices [11],[12].

Based on a comprehensive review of the state-of-the-art literature, this paper focuses on three main aspects: (1) exploring the evolutionary modulation of core physicochemical properties (e.g., specific surface area, functional groups, and electronic structure) by various modification strategies, deeply revealing the structure-performance relationships in adsorption and catalysis; (2) clarifying the pathways and microscopic mechanisms of modified biochar for the highly efficient removal of heavy metals, organics, and nutrients from water; and (3) assessing the synergistic mechanisms and engineering potential of coupling modified biochar with technologies like advanced oxidation processes (AOPs), photocatalysis, and membrane separation. Oriented toward practical water treatment engineering, this review systematically summarizes the advantages and existing challenges of applying functionalized materials in complex water environments. It aims to offer theoretical guidance for the directional customization and large-scale application of advanced biochar materials.

II. PREPARATION METHODS OF BIOCHAR

The preparation processes intrinsically dictate the physicochemical properties and environmental efficacy of biochar. Depending on the underlying thermochemical conversion mechanisms, the prevailing synthesis methods for biochar currently encompass conventional pyrolysis, hydrothermal carbonization, and microwave-assisted pyrolysis.

A. Conventional Pyrolysis

Conventional pyrolysis is currently the most well-established biochar production technology. Its core lies in precisely controlling key parameters—such as pyrolysis temperature (300–900 °C), heating rate (typically 5–10 °C/min), and residence time (0.5–5.0 h)—to tailor the physicochemical properties of the material. During thermal conversion, moderately elevating the temperature facilitates the profound development of the pore network and promotes the graphitization of the carbon skeleton. However, once the temperature exceeds the 700 °C threshold, severe collapse of existing microporous structures is often induced [13]. Although high-temperature treatment endows biochar with enhanced structural stability, it inevitably causes the extensive thermal cleavage of surface oxygen-containing functional groups (e.g., carboxyl and phenolic hydroxyl groups), thereby drastically weakening the material's interfacial adsorption affinity for polar pollutants.

B. Hydrothermal Carbonization

Distinct from conventional dry pyrolysis, hydrothermal carbonization (HTC) primarily employs subcritical water (180–300 °C) as the reaction medium within a closed system to drive the thermochemical conversion of biomass. A notable advantage of this process lies in circumventing the energy-intensive feedstock drying pretreatment, thereby enabling the direct, in-situ conversion of high-moisture biomass. Governed by complex hydrolysis and dehydration mechanisms, the resulting hydrochar possesses highly abundant surface oxygen-containing functional groups [14]. Furthermore, this process generates minimal by-products and offers a more straightforward overall operation. However, constrained by the aqueous reaction environment, the pore structure of hydrochar is generally less developed than that of conventional pyrochar, typically necessitating subsequent surface modification or activation to further enhance its adsorption efficacy.

C. Microwave Pyrolysis

Microwave pyrolysis is a novel, energy-efficient, and highly effective thermochemical process. Its core mechanism utilizes the molecular polarization effect to convert microwave radiation directly into thermal energy, thereby achieving rapid heating. Overcoming the heat transfer limitations of conventional heating, this technology features rapid temperature elevation, low energy consumption, and uniform volumetric heating. Notably, it can endow materials with highly porous structural characteristics within a moderate temperature range of 300–600 °C [15], [16]. Furthermore, it demonstrates exceptional carbon sequestration performance and significantly reduces the yield of undesired by-products [17]. These advantages highlight its immense potential for synthesizing biochar with high porosity and superior surface activity. Nevertheless, it is crucial to acknowledge the existing technical bottlenecks of microwave pyrolysis, including poor feedstock universality (often necessitating the addition of microwave absorbers), susceptibility to localized uneven thermal distribution, and profound challenges in industrial scale-up.

In summary, the aforementioned processes exhibit significant variations in operating temperature, energy consumption, and product distribution. Therefore, in practical applications, targeted process selection strategies must be precisely tailored to the specific physicochemical properties of the target pollutants.

III. MODIFICATION OF BIOCHAR

To overcome the limitations of the intrinsic adsorption capacity of pristine biochar, targeted modification has emerged as a pivotal strategy to enhance its adsorption performance. Currently, the mainstream approaches in this field are primarily categorized into three methods: physical activation, chemical modification, and composite functionalization.

A. Physical Activation

Driven by high-intensity mechanical shearing and collision, ball milling effectively reduces the particle size of biochar and substantially improves its surface roughness and pore network interconnectivity, thereby profoundly enhancing the material's adsorption capacity for volatile organic compounds (VOCs) and heavy metals [18]. This mechanism was corroborated by the study of Xiang et al. [19], who demonstrated that ball-milled biochar achieved a remarkable leap in capture efficiency for VOCs. Conversely, microwave activation, utilizing high-frequency electromagnetic fields, facilitates the deep reconstruction of biochar's pore structure and the optimization of its surface chemical properties. Compared to conventional pyrolysis processes, this technology exhibits outstanding advantages, including rapid heating and high energy efficiency.

B. Chemical Modification

Chemical modification represents the most prevalent and extensively researched strategy for biochar performance enhancement. Treatment with chemical reagents facilitates the targeted introduction of novel surface functional groups, the modulation of surface charge profiles, and the refinement of pore structures. Consequently, both the adsorption capacity and the catalytic activity of the biochar are significantly elevated.

Acid modification utilizes inorganic acids to remove surface ash and impurities, simultaneously enriching the biochar with hydroxyl and carboxyl groups. This increase in acidic functional groups substantially improves the biochar's adsorption performance toward heavy metals and alkaline organic pollutants [20],[21]. For example, phosphoric acid modification can increase the specific surface area from 411 m^2/g to 1627 m^2/g and boost the adsorption capacity from 43.48 mg/g to 62.50 mg/g [22]. However, the resulting acidic wastewater requires appropriate complementary treatment to control environmental risks.

Alkali modification utilizes strong alkaline solutions, such as potassium hydroxide (KOH) or sodium hydroxide (NaOH), to activate biochar. This process neutralizes surface acidic functional groups (e.g., carboxyl and phenolic hydroxyl groups) and induces deprotonation, thereby increasing the negative charge density and substantially enhancing the adsorption capacity for cationic pollutants [23]. Furthermore, under elevated temperatures, the alkaline agents react with the carbon matrix to generate intermediates such as potassium carbonate (K_2CO_3), which further optimize the pore structure [24]. The scanning electron microscopy (SEM) morphology of potassium bicarbonate ($KHCO_3$)-modified biochar is depicted in Figure 1 [25]. As illustrated in Figure 1, a higher dosage of $KHCO_3$ corresponds to a more highly developed pore architecture in the modified biochar. Notably, Zhao et al. [26] found that after KOH modification, the specific surface area of the biochar surged to 965 m^2/g, leading to a more than 20-fold increase in its adsorption capacity for tetracycline compared to its pristine counterpart.

Metal modification serves as a fundamental strategy for enhancing the performance of biochar. Immobilizing metals or their compounds onto the biochar surface significantly increases the number of active sites, thereby substantially improving the catalytic and adsorptive capacities of the material. Current modification approaches are predominantly categorized into three paradigms: single metal doping, bimetallic synergy, and metal oxide compositing. Modifications using a single metal, such as the integration of Fe, Mn, or Cu, allow for the targeted manipulation of the specific surface area, pore architecture, and surface functionalization. For instance, iron modification provides the dual benefits of magnetic separability and performance reinforcement. In this context, Guo et al. [27] observed that the specific surface area of engineered biochar increased from 716 m^2/g to 2097 m^2/g. This structural expansion concurrently facilitated a marked improvement in both pollutant adsorption and catalytic degradation efficiencies.

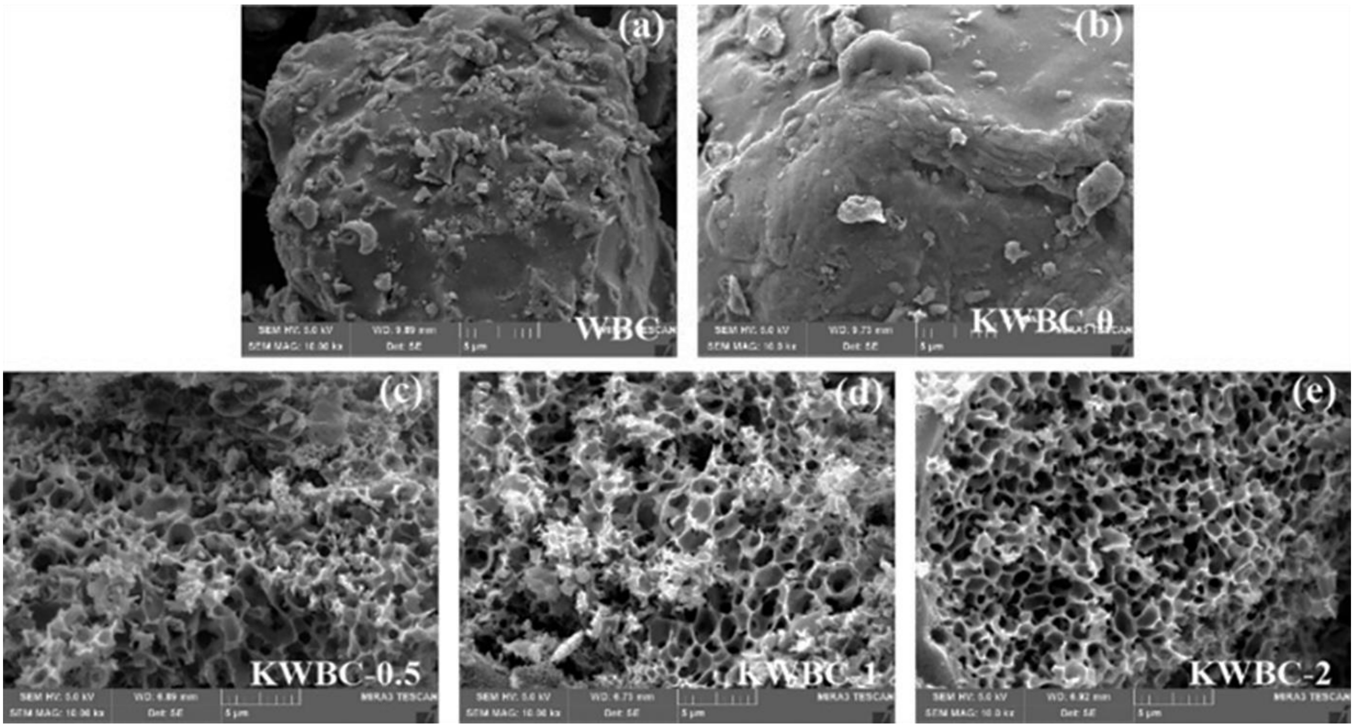

Fig. 1. SEM images of potassium bicarbonate-modified biochar: (a) WBC, (b) KWBC-0 (b), (c) KWBC-0.5 (c), (d) KWBC-1 and (e) KWBC-2[25].

Conversely, bimetallic modification capitalizes on the electronic synergistic effects between distinct metals to construct complex catalytic sites and robust electron transfer channels, thereby demonstrating pronounced superiority in pollutant abatement. The selection of a fabrication strategy is highly contingent on the inherent properties of the targeted metals. For example, biochars functionalized with metal oxides are conventionally synthesized via wet impregnation coupled with high temperature pyrolysis [28]. Driven by variations in intrinsic properties such as electronic configurations and oxidation states, different metals impart tailored functionalities to the biochar matrix. Specifically, titanium dioxide drives the photocatalytic decomposition of organics [29], whereas calcium carbonate intensifies adsorption through surface complexation. metal modification can promote the proliferation of surface hydroxyl and carboxyl groups, which enhances the overall remediation efficacy through various synergistic mechanisms [30]. Notably, oxygen functional groups derived from metal oxides elevate the anion exchange capacity, while the generation of cationic sites facilitates the electrostatic attraction and subsequent precipitation of anionic contaminants [31]. Ultimately, this precise engineering of surface chemistry solidifies the extensive application prospects of metal modified biochar in the field of environmental remediation.

C. *Composite Functionalization*

Composite functionalization couples biochar with two-dimensional nanomaterials to construct a hierarchical synergistic system via topological structural reconstruction and interfacial electronic effects, thereby remarkably surpassing the performance limits of individual pristine materials.

Current research hotspots are increasingly focused on the precise assembly of two-dimensional (2D) nanomaterials (e.g., graphene, carbon nanotubes, and MXenes) with biochar matrices. The unique interlayer confinement effects and interfacial charge transfer channels intrinsic to 2D nanomaterials can effectively circumvent the inherent limitations of conventional biochar, notably its restricted adsorption capacity and subdued catalytic activity. Upon the integration of graphene with biochar, the topological defect sites of graphene oxide can induce a substantial proliferation in the density of surface oxygen-containing functional groups, such as carboxyl and hydroxyl groups. Driven by the synergistic effects of π-π stacking and electrostatic interactions, the biochar-supported reduced graphene oxide composites exhibit enhanced adsorption capacities for Pb^{2+} and atrazine, achieving 1.24 and 1.23 times those of pristine biochar, respectively [32]. Similarly, the introduction of carbon nanotubes into the biochar matrix not only optimizes its hierarchical pore structure but also modulates the surface electronic configuration, thereby thermodynamically favoring the adsorption of targeted pollutants. For instance, Ma et al. [33] demonstrated that the incorporation of carbon nanotubes dramatically elevated the biochar's adsorption capacity for sulfamethoxazole from 5.43 mg/g to 23.50 mg/g. Conversely, MXene-modified biochars achieve superior adsorption performance via robust coordination interactions between their surface terminal oxygen groups and contaminant molecules. Research by Kumar et al. [34] revealed that doping biochar with MXenes boosted the adsorption efficiency for specific aqueous pollutants, such as NH_4^+, to an impressive 97.83%, while simultaneously enhancing the thermal stability of the composite material.

However, the practical implementation of composite modification technologies continues to encounter substantial hurdles. Primarily, insufficient thermodynamic compatibility at heterogeneous boundaries precipitates pronounced scale up complications during mass production. Furthermore, the inherent propensity of two dimensional nanomaterials to aggregate results in the detrimental shielding of active sites. Finally, dynamic interactions occurring at the solid liquid interface inherently compromise the cyclic stability of the material, which typically manifests as a diminished capacity for heavy metal adsorption following successive regeneration cycles. To circumvent these limitations, future paradigms must prioritize the fabrication of chemically bonded interfaces utilizing in situ growth methodologies. Concurrently, the synergistic integration of machine learning algorithms to precisely tailor the spatial architectures of two dimensional nanomaterials will be imperative for engineering smart responsive composite biochar platforms endowed with autonomous self healing capabilities.

Recently, integrating biochar with functional materials including clay minerals, metal organic frameworks (MOFs), and layered double hydroxides (LDHs) has emerged as a prominent research focus in water treatment and environmental remediation. This composite strategy not only achieves a synergistic integration of the structural and functional advantages inherent to each component but also significantly improves the adsorption capacity, catalytic activity, and long term stability of the resulting materials. Biochar provides a well developed porous network that serves as mass transfer channels and a supporting substrate. Furthermore, it acts in synergy with the ion exchange capacity of clay minerals, the selective adsorption sites of MOFs, and the interlayer anion capture ability of LDHs to establish a multifunctional interactive system, which substantially elevates the efficiency of the composite in removing aquatic pollutants. Arif et al. [35] reviewed the exceptional capacity of biochar and clay composites to adsorb aquatic contaminants through diverse mechanisms, including ion exchange, surface complexation, and pore filling. Their findings confirmed that the synergistic adsorption performance of the composite is markedly superior to that of individual components. Wang et al. [36] synthesized modified biochar composites based on Mg-MOF-74 via an in situ growth methodology. Utilizing density functional theory (DFT), they elucidated the mechanism by which multiple site coupling among oxygen vacancies, metal ions, and chemisorbed oxygen enhances carbon dioxide adsorption, thereby providing a robust theoretical foundation for the application of biochar composites in gas phase adsorption. The CaAl-LDH@biochar supported biochar prepared by Chi et al. [37] achieved the highly efficient and stable immobilization of lead and manganese ions through a synergistic combination of mechanisms, including interlayer anion exchange, chemical adsorption by surface functional groups, and electrostatic attraction. Consequently, the leaching concentrations of these metals were reduced by 59% and 39%, respectively, compared to the pure cement control group.

Nevertheless, current modified biochar composites continue to face significant challenges, including elevated preparation costs, ambiguous interfacial interaction mechanisms, and the critical need for comprehensive evaluations of long term environmental risks.

IV. MODIFIED BIOCHAR FOR WATER TREATMEENT

Propelled by rapid global industrialization and urbanization, water pollution has escalated into a severe environmental crisis. Conventional water treatment paradigms, including chemical precipitation, ion exchange, and membrane separation, are constrained by inherent bottlenecks such as elevated energy consumption and the persistent risk of secondary pollution. Consequently, developing ecologically sustainable and highly efficient alternative technologies is an urgent imperative. Owing to its hierarchical porous architecture, tunable surface chemistry, and ecologically benign attributes, biochar has emerged at the forefront of research on water purification materials. Employing cross scale functional modulation techniques enables the precise construction of a synergistically coupled system that integrates multilevel mass transfer channels with localized reactive sites within the biochar matrix. This sophisticated engineering significantly enhances the targeted capture and subsequent catalytic transformation of various aquatic contaminants.

A. Standalone Application

When deployed as an independent adsorbent, the performance advantages of modified biochar originate from the synergistic interactions within its multiscale architecture. Specifically, this synergy manifests across three distinct dimensions. First, at the macroscopic level, hierarchical porosity comprising macropores, mesopores, and micropores constructs highly efficient mass transfer channels. Second, at the mesoscopic level, an expanded specific surface area provides an abundance of active adsorption sites. Third, at the microscopic level, surface functional groups facilitate the specific capture of pollutants via mechanisms such as electrostatic interactions and coordination bonding. This integrated trinity of structure, interface, and activity endows modified biochar with an efficacy in removing heavy metals, organic contaminants, and nutrients that significantly surpasses that of pristine biochar (Fig. 2) [38]. Furthermore, customized regenerative designs enable the material to undergo multiple cycles of reuse while maintaining structural integrity and adsorption performance.

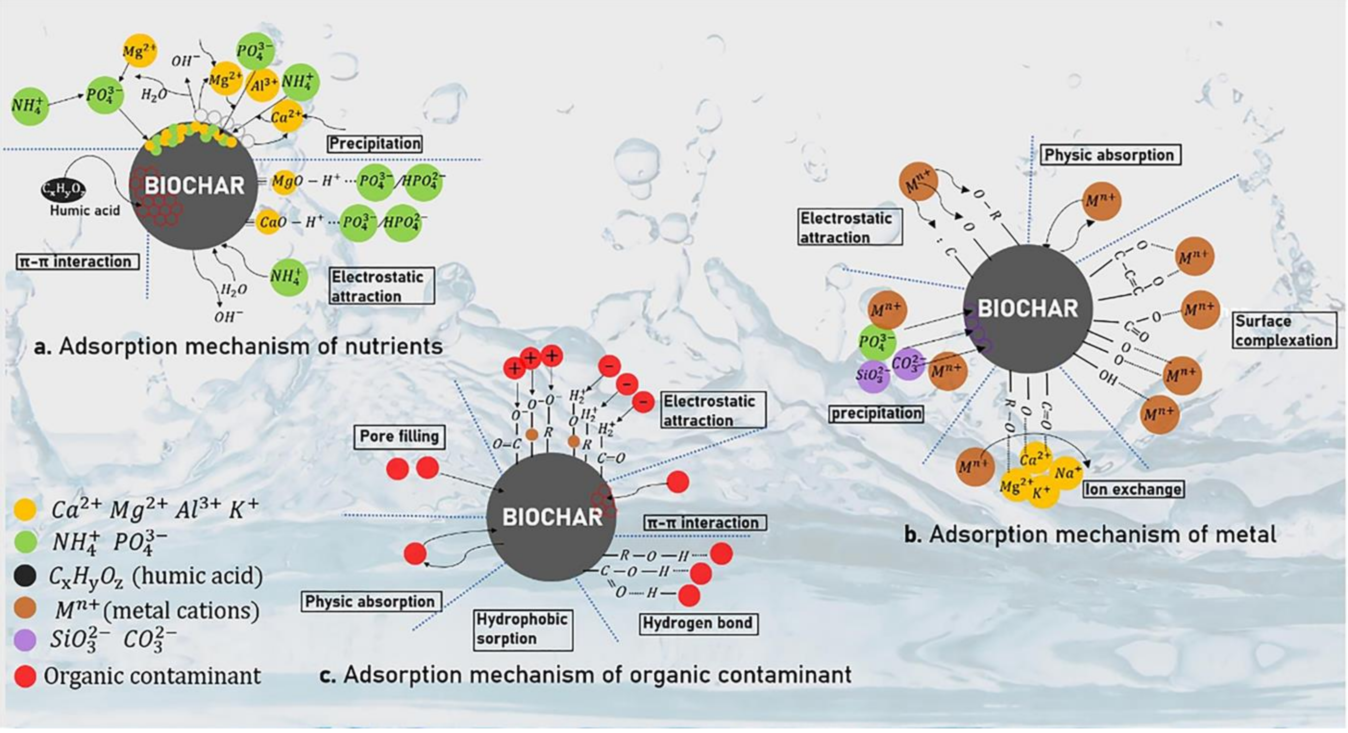

Fig. 2. Mechanisms of targeted pollutant removal from water by biochar adsorption[38].

1) Nutrient Removal

The efficient removal of phosphate and nitrate heavily relied on the tailored design of metal oxide active sites on the biochar surface (Fig. 2a). By modulating the type, loading capacity, and spatial distribution of metal oxides, the selective adsorption performance and reactivity of biochar toward diverse nutrients in aquatic environments were significantly enhanced, thereby providing a highly efficient technical pathway for the advanced treatment of eutrophic waters. Furthermore, Chen et al. [39] developed an Mg/La bimetallic-modified biochar. Through the synergistic action of La–O–P coordination precipitation and Mg^{2+} ion exchange, stable inner-sphere surface complexes were constructed to effectively adsorb phosphorus from wastewater. Concurrently, this modified biochar maintained high phosphorus removal efficiency even after multiple regeneration cycles, which revealed the critical regulatory role of strong metal-support interactions (SMSI) on the interfacial stability of the material.

2) Heavy Metal Ion Removal

Functionalized biochar achieved the multi-mechanism synergistic removal of heavy metal ions through surface coordination reconstruction and electron cloud modulation (Fig. 2b). The functionalization not only diversified and densified the adsorption sites but also intensified the selective interactions with target pollutants by tuning the interfacial electronic structures. Hao et al. [40] fabricated a magnesium oxide-loaded, sulfur-doped cotton straw biochar (MgO-S-BC) that removed Cd(II) and Pb(II) from aqueous solutions through precipitation, ion exchange, surface coordination complexation, and electrostatic attraction. The maximum adsorption capacities of MgO-S-BC were recorded at 630 mg/g for Cd(II) and 2022 mg/g for Pb(II). Furthermore, Yang et al. [41] innovatively developed a poly(m-phenylenediamine)-modified biochar (BC-PmPD) that triggered a coupled chemisorption-reduction process for Cr(VI) via the redox-active sites of its amine-quinone structure. Its maximum adsorption capacity reached 775 mg/g, exhibiting a 10.4-fold increase compared to the pristine material, which unveiled the synergistic enhancement mechanism of the interfacial coordination effect and electron transfer. Collectively, these studies demonstrated that tailoring the surface chemical environments and electronic properties of biochar through functionalization strategies provided novel paradigms for the precise remediation of complex heavy metal-contaminated water.

3) Organic Pollutant Removal

Functionalized biochar achieved the high-efficiency removal of organic pollutants through multiple synergistic mechanisms, including pore filling, electrostatic attraction, π-π interactions, hydrophobic adsorption, and hydrogen bonding (Fig. 2c). This material not only expanded the adsorption modes but also significantly enhanced mass transfer and immobilization efficiency via the coordinated design of surface chemistry and pore structures. Mei et al. [42] fabricated an Fe/N co-modified biochar using a one-step pyrolysis method, which exhibited a maximum adsorption capacity of 156 mg/g for tetracycline, representing a 5.4-fold increase over the pristine biochar. Concurrently, the magnetic components such as γ-Fe2O3, Fe3O4, and Fe3C within the material endowed it with superior magnetic separation performance. Furthermore, Yang et al. [43] developed a boron-modified biochar (BBC) that enhanced surface polarity through B—O and B—C bonds. Coupled with an 'aggregation-dissociation' mechanism—where imidacloprid molecules aggregated in macro/mesopores before being immobilized in micropores—the BBC reached a maximum adsorption capacity of 160.75 mg/g for imidacloprid. These findings indicated that precisely modulating the composition and hierarchical pore structure of biochar could improve its adsorption performance and engineering applicability, providing promising solutions for the efficient purification of complex organic-contaminated systems.

B. *Technology Integration*

The escalating complexity of water pollutants has driven treatment technologies toward a synergistic remediation paradigm. Although biochar excels in adsorption owing to its hierarchical porosity, tunable surface chemistry, and eco-compatibility, it remains constrained by dynamic capacity thresholds and regeneration bottlenecks. Systematically coupling biochar with technologies such as membrane separation and photocatalysis constructs a synergistic "adsorption-separation-degradation" system, effectively transcending the boundaries of standalone applications.

1) *Biochar-Membrane Separation Synergistic Systems*

Flux decline driven by membrane fouling is the primary bottleneck limiting the economic feasibility of membrane technologies. Biochar pretreatment units, leveraging dual mechanisms of pore sieving and chemical adsorption, selectively remove key foulants—such as macromolecular organics, colloidal particles, and heavy metal ions (Figure 3 [44]). Specifically, Yang et al. [45] integrated spherical biochar with polyvinylidene fluoride (PVDF) membranes to establish a gradient filtration interface. This configuration preferentially adsorbs macromolecular foulants and colloids, effectively mitigating their direct deposition on the membrane surface. Consequently, membrane flux increased by over 30%, service life was extended by 50%, and transmembrane pressure (TMP) remained stable while maintaining superior rejection efficiency.

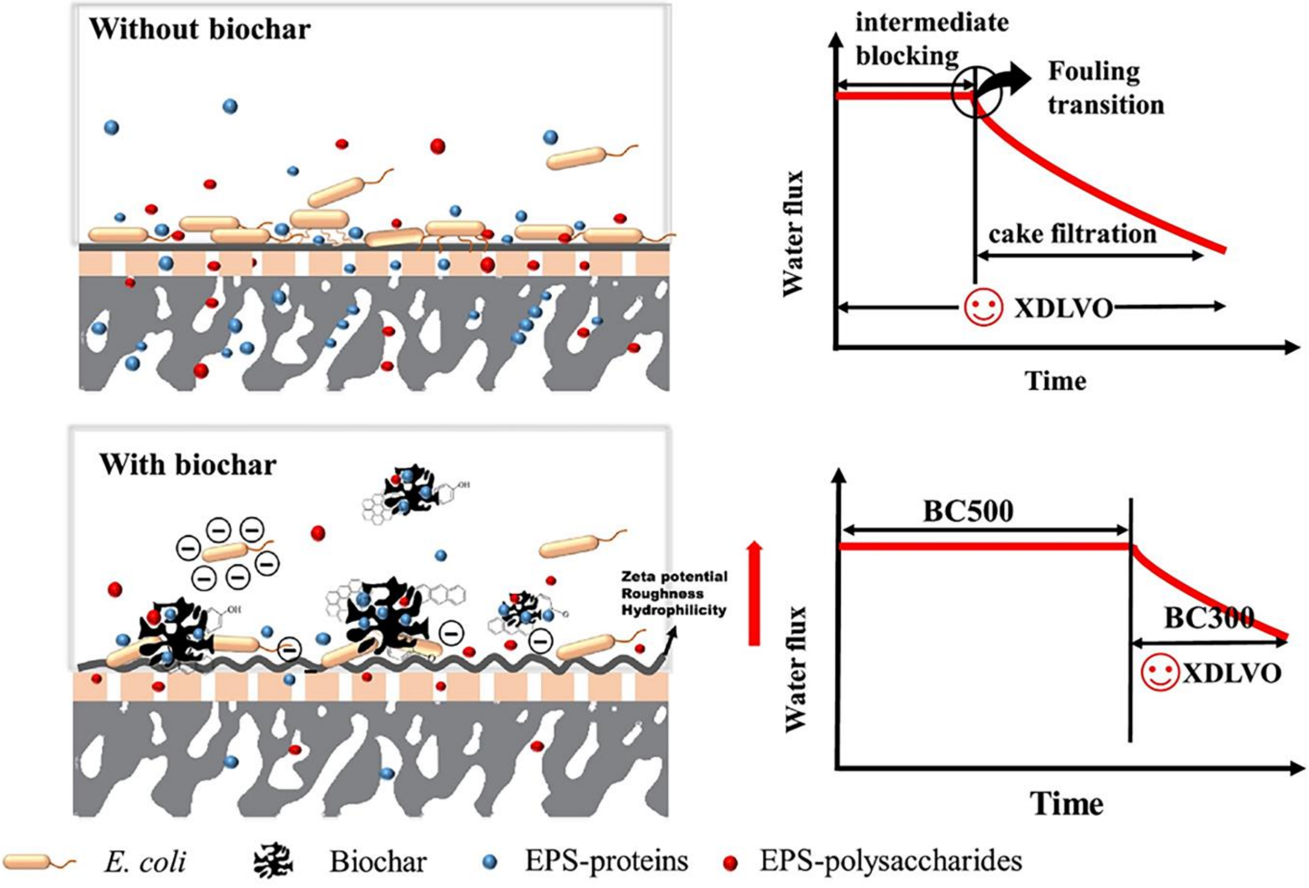

Fig.3. Schematic diagram of extended DLVO theory of membrane fouling process with and without biochar[44].

2) *Biochar-Photocatalysis Composite Systems*

To overcome the low quantum efficiency and narrow spectral response of traditional photocatalysts, biochar modulates their band structures to narrow the bandgap and constructs electron-transfer channels to facilitate charge carrier separation. Additionally, its high specific surface area maximizes active site exposure. For instance, Zhai et al. [46] designed a biochar@$CoFe_2O_4$/Ag_3PO_4 photocatalyst featuring a Z-scheme electron transfer pathway. Within 60 min, this composite achieved bisphenol A (BPA) degradation and mineralization rates of 91.12% and 80.23%, respectively—drastically outperforming pristine Ag3PO4 (35% and 25.98%) under identical conditions.

3) *Biochar-Advanced Oxidation Coupled Systems*

Advanced oxidation processes (e.g., Fenton, ozonation) degrade recalcitrant organics via reactive radicals but suffer from high energy consumption and secondary pollution risks. Coupling AOPs with biochar—acting as a catalyst or support—overcomes these hurdles. Biochar's abundant porosity and functional groups enable in-situ pollutant enrichment, establishing a synergistic adsorption-catalysis mechanism with profound application potential. For example, Wu et al. [47] engineered an Fe/N co-doped hierarchically porous carbon (Fe-N/C) where electron delocalization at Fe-N4 centers activates peroxymonosulfate (PMS) into high-valent iron-oxo species. This boosted the bisphenol F degradation rate constant 34-fold, confirming that micropore confinement and N-doping-optimized electron channels exponentially elevate catalysis. Similarly, Zhong et al. [49] synthesized an N/S co-doped biochar (NSBC) whose divacancies and topological defects accelerated electron transfer to adsorbed PMS. This promoted singlet oxygen ($^1O_2$) evolution, achieving 100% 2,4-dichlorophenol degradation within 5 min and an 88.7% total organic carbon (TOC) removal.

In summary, integrating modified biochar with complementary technologies capitalizes on their respective strengths to overcome standalone limitations, enabling the highly efficient remediation of complex water pollution. This synergy not only maximizes pollutant removal but also mitigates operation and maintenance costs and enhances overall system stability by optimizing reaction pathways and safeguarding key treatment units.

V. CONCLUSION AND PERSPECTIVES

Featuring hierarchical porosity and tunable surface chemistry, modified biochar demonstrates profound advantages in water treatment. Its integration with membrane, photocatalytic, and advanced oxidation technologies establishes an "adsorption-separation-degradation" synergistic paradigm that drastically improves treatment efficiency. Nevertheless, its industrialization is impeded by inherent bottlenecks: poor selectivity in complex water matrices, energy-intensive regeneration, batch-to-batch inconsistency, scale-up challenges, and high life-cycle costs.

Moving forward, research must pivot from the laboratory to engineering applications. Successful commercialization urgently demands a systematic trade-off analysis of various modification strategies: physical activation is eco-friendly and scalable but yields limited enhancements; chemical modification is highly efficacious but risks secondary pollution; biological modification proceeds under mild conditions but suffers from slow kinetics and instability; whereas composite functionalization delivers superior performance at the expense of prohibitive costs and intricate processes.

Therefore, future research must prioritize low-cost, high-throughput, and sustainable modification strategies, seeking breakthroughs in the following domains:

- Feedstock Optimization: Co-pyrolyzing high-carbon biomass (e.g., lignocellulose, manure) with heteroatom-rich (N/S) agricultural wastes minimizes exogenous modifier consumption, realizing a sustainable "waste-treats-waste" paradigm.
- Scalable Production: Developing continuous microwave-hydrothermal integrated equipment for ton-scale production demands overcoming engineering bottlenecks—such as thermal/flow field uniformity and mass/heat transfer efficiency—to ensure absolute batch-to-batch consistency in physicochemical properties.
- Precise Modification: Directional multi-component doping (e.g., N/S/metals) requires precisely tuning dopant states and spatial distributions. In-situ characterizations coupled with theoretical calculations are essential to elucidate precursor evolution, multi-element synergy/antagonism, and interfacial electronic modulation, ultimately guiding the "one-material-one-function" design for targeted pollutant capture.
- Efficient Regeneration: Exploring in-situ regeneration methods (e.g., non-thermal plasma, electrochemistry) and decoupling the mechanisms of structural decay are crucial. Concurrently, incorporating magnetic or density-gradient separation systems will facilitate the highly efficient recovery and cyclic utilization of biochar.

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CONFLICTS OF INTEREST

The authors assert that there are no conflicts of interest about the publishing of this work.

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