



Research progress on biochar-based photocatalytic materials for pollutant treatment: Structural regulation, electronic mechanisms, and engineering challenges

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ABSTRACT

Biochar-based photocatalytic materials have shown broad application potential in environmental remediation, including the degradation of organic pollutants in aquatic systems, the reduction of heavy metal ions, and the purification of gaseous contaminants. These advantages stem from their high specific surface area, excellent electrical conductivity, and interfacial regulation capabilities. This review systematically summarizes the structural characteristics of biochar and its multiscale regulation strategies, with particular emphasis on its synergistic roles in the construction of Z-scheme and S-scheme heterojunctions, the regulation of photogenerated carrier dynamics, and the generation and transformation of reactive oxygen species (ROS). The practical performance of biochar-based composites in treating diverse pollutants is critically examined, followed by a comprehensive analysis of current challenges, including raw material variability, material stability, limited mechanistic understanding, insufficient engineering adaptability, and the absence of standardized performance evaluation frameworks. Based on these insights, this paper proposes a forward-looking development strategy centered on green synthesis and data-driven design optimization, offering theoretical guidance and technical pathways to accelerate the large-scale and sustainable application of biochar-based photocatalytic materials in complex environmental systems.

1. Introduction

As industrialization continues to accelerate and the global population keeps expanding, environmental pollution worldwide is intensifying, posing a serious threat to ecosystem stability and human health (Sharma et al., 2023). Various organic pollutants are widely present in environmental media such as water bodies, the atmosphere, and soil. Primary sources include industrial wastewater discharge, agricultural pesticide application, and improper treatment of domestic sewage (Ajiboye et al., 2021; Kilpinen et al., 2024; Wagner et al., 2021). These pollutants typically exhibit high stability, poor biodegradability, and bioaccumulation effects. They readily persist in the environment over extended periods and accumulate progressively through the food chain, ultimately posing potential hazards to human health, such as carcinogenicity, endocrine disruption, and neurotoxicity (Zhang et al., 2025).

At the same time, heavy metal pollution remains a significant concern. Pollutants represented by heavy metal ions such as mercury, cadmium, lead, and chromium originate extensively from metallurgical industries, mineral extraction, electronics manufacturing, and waste disposal. These substances exhibit remarkable environmental persistence and non-degradability, establishing them as prototypical sources of persistent pollution (Sheydaei, 2024). Additionally, a significant category of atmospheric pollutants, volatile organic compounds (VOCs), are primarily emitted during processes such as petrochemical production, coating and printing, pharmaceutical manufacturing, and motor vehicle exhaust. They not only contribute to the formation of photochemical smog, ozone, and fine particulate matter (PM_{2.5}), but may also cause respiratory irritation, pose carcinogenic risks, and lead to ecological toxicity issues (Liu et al., 2022; Wang et al., 2022).

In response to these multifaceted pollution challenges,

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photocatalytic technology has emerged as a promising solution due to its solar-driven nature, production of non-toxic byproducts, and ability to degrade a broad spectrum of pollutants (Mamaghani et al., 2017; Yang et al., 2022). Photocatalysis utilizes photogenerated electron-hole pairs in semiconductor materials upon light irradiation to initiate a series of redox reactions, thereby enabling the efficient degradation of contaminants. Owing to its mild reaction conditions and minimal environmental impact, photocatalysis is widely recognized as a green and sustainable technology. However, traditional inorganic semiconductor photocatalysts are still constrained by several critical limitations, including the rapid recombination of photogenerated carriers, limited responsiveness to visible light, and difficulties in catalyst separation and recovery. These limitations constrain their industrial-scale implementation.

In recent years, biochar has attracted increasing attention in environmental remediation due to its favorable physicochemical properties and its potential as a low-cost, sustainable carbon-based material (Yuan et al., 2023). Biochar, typically derived from the pyrolysis of biomass under oxygen-limited conditions, exhibits a high specific surface area, a well-developed porous structure, and abundant surface functional groups. Common biomass sources include agricultural residues, forestry by-products, and livestock waste (Allohverdi et al., 2021; Liang et al., 2021; Xie et al., 2022). These characteristics not only facilitate the high-value utilization of renewable biomass resources, but also contribute to carbon emission reduction and mitigation of secondary pollution associated with incineration practices (Goldaraz-Salamero et al., 2025). Moreover, key properties of biochar, including pore morphology, electrical conductivity, and surface reactivity, can be precisely controlled by adjusting the feedstock type, pyrolysis temperature, and post-treatment methods. These tunable features significantly enhance its efficiency in pollutant adsorption and catalytic degradation applications (Alsawy et al., 2022; Ouyang et al., 2020; Wang et al., 2023).

Despite considerable research into the adsorption capabilities of biochar, its synergistic roles within photocatalytic systems remain underexplored. A comprehensive, systematic evaluation of its enhancement mechanisms is still lacking. Therefore, this review aims to fill this knowledge gap by critically examining the multifaceted roles of biochar in photocatalytic processes, within a structured framework based on three interrelated research dimensions: (i) regulation of electron transfer, (ii) interface band structure coupling, and (iii) synergistic treatment of multiple pollutants. Specifically, the review focuses on how biochar contributes to: (i) Promoting the separation and migration efficiency of photogenerated electron-hole pairs and prolonging carrier lifetime; (ii) Modifying band structures and enhancing interfacial interactions through heterojunction formation or donor-acceptor interfaces with semiconductors; (iii) Improving photocatalytic activity and long-term stability in the simultaneous degradation of organic pollutants, heavy metals, and VOCs.

In conclusion, this study proposes an integrative analytical framework that systematically elucidates the critical role of biochar in enhancing photocatalytic performance. The framework is centered on three key aspects: electron transfer regulation, interface band coupling, and the synergistic treatment of multiple pollutants. Through a comprehensive review of current progress, critical analysis of scientific and engineering challenges, and exploration of future research directions, this study aims to provide theoretical foundations and technical insights for the development of efficient, low-carbon, and scalable pollution control technologies in line with global sustainability goals.

2. Structural characteristics of biochar and multi-scale regulation strategies

2.1. Raw material sources and structural foundations

The structure and physicochemical properties of biochar are

fundamentally governed by the nature of its precursor feedstocks and the associated pyrolysis conditions, which together define the initial framework for subsequent functional regulation in photocatalytic systems. Biochar can be derived from a wide range of renewable organic solid wastes, including agricultural residues (e.g., straw, rice husks), municipal sludge, and biomass-derived liquid wastes (Song et al., 2022). These diverse feedstocks exhibit substantial variability in organic composition, inorganic impurity content, and thermal degradation behavior, leading to pronounced differences in pore architecture, surface functional group distribution, and electrical conductivity, key parameters that critically determine photocatalytic performance.

Agricultural residues are predominantly composed of three structural biopolymers: cellulose, hemicellulose, and lignin. Among them, cellulose, with its high crystallinity and thermal stability, favors the formation of ordered carbon frameworks, whereas lignin, rich in aromatic structures, plays a crucial role in enhancing aromaticity and electrical conductivity in the resulting biochar (Chen et al., 2022; Sun et al., 2021; Wijitkosum, 2022; Zhang et al., 2021). For example, wheat straw typically contains a higher proportion of cellulose, while corn stalks are relatively lignin-rich (Serna-Loaiza et al., 2022; Zhang et al., 2021). These compositional differences significantly influence pyrolysis behavior, including the degree of carbonization, the formation of graphitic domains, and the nature and spatial distribution of surface functional groups, which in turn affect pollutant adsorption capacity and interfacial electron transfer characteristics in photocatalytic systems (Zhengyang et al., 2023).

Municipal sludge represents a more complex precursor matrix, containing proteins, polysaccharides, lipids, microbial metabolites, and inorganic salts. Biochar derived from sludge often exhibits high specific surface area and hierarchical pore structures. In addition, in situ retained metal oxides within the carbon matrix can introduce auxiliary catalytic functionalities, thereby promoting synergistic photocatalytic effects (Racek et al., 2020; Wu et al., 2021).

Biomass-derived liquid wastes, such as lignin extracts or biodiesel byproducts, also serve as promising biochar precursors. During high-temperature pyrolysis, these low-molecular-weight organics undergo polymerization and carbonization, forming relatively ordered carbon skeletons enriched with oxygen-containing functional groups. Such features are advantageous for constructing efficient charge transport pathways and modulating surface electronic properties in photocatalytic applications (Maaoui et al., 2023; Nguyen et al., 2024).

2.2. Influence of multiscale structural regulation on photocatalytic performance

The structural regulation of biochar can be strategically implemented across three distinct scales: microscale (atomic/molecular-level functional groups), mesoscale (lattice structure and electronic band configuration), and macroscale (particle size, pore architecture, and morphology). These multiscale structural parameters synergistically regulate key aspects of the photocatalytic process, including pollutant adsorption behavior, the separation and migration efficiency of photogenerated charge carriers, and interfacial reaction kinetics. Collectively, these factors constitute the structural foundation for enhanced photocatalytic performance.

- (1) Microscale regulation: carbon skeleton engineering and functional group configuration

The carbon-to-oxygen ratio (C/O) serves as a critical indicator for assessing the degree of graphitization and surface polarity in biochar. A higher C/O ratio typically reflects a more developed graphitic structure and improved electrical conductivity, whereas oxygen-containing functional groups (e.g., -COOH, -OH, -C=O) enhance polarity and contribute significantly to adsorption capacity. Liu et al. (2023) reported that biochar with a high C/O ratio exhibits superior electronic

conductivity, primarily due to the localization of oxygen in non-graphitized (sp^3 -hybridized) regions, which disrupts π -electron delocalization. In contrast, graphitized domains, composed predominantly of sp^2 -hybridized carbon atoms, enable the formation of a continuous π -conjugated network, thereby promoting efficient charge transport.

Aromaticity, another key structural feature, reflects the development level of the π -electron system within the carbon matrix and is commonly evaluated by the H/C ratio or the proportion of aromatic carbon. High aromaticity enhances π - π stacking interactions, facilitating both electron mobility and selective adsorption of aromatic pollutants. These characteristics contribute to synergistic effects in hybrid photocatalytic systems, especially when biochar is used as a support or electron mediator (Alves et al., 2022; Tang et al., 2018).

(2) Mesoscale regulation: heteroatom doping and band structure modulation

At the mesoscale, structural regulation of biochar is primarily achieved through heteroatom doping and heterojunction engineering. Incorporating heteroatoms such as nitrogen (N), phosphorus (P), sulfur (S), and boron (B) can effectively tailor the electronic band structure of biochar, introduce defect states, and create catalytically active sites, thereby enhancing its optoelectronic properties and photocatalytic performance (Lu et al., 2022).

Nitrogen doping, typically in the form of pyrrolic or graphitic nitrogen, has been demonstrated to enhance both the electrical conductivity and visible-light absorption capacity of carbon materials. These improvements are primarily attributed to modifications in the electronic structure and the introduction of localized energy states (Sun et al., 2023). Sulfur doping, on the other hand, introduces functional groups such as C-S and C=S bonds, which increase electron polarization and facilitate photogenerated charge separation under visible light irradiation (Liu et al., 2024). Phosphorus doping plays a crucial role in modulating the positions of band edges and strengthening intermolecular interactions through its electron-donating characteristics, thus improving charge carrier dynamics and interfacial activity (Liang et al., 2024). Meanwhile, boron doping can finely adjust the Fermi level and local density of electronic states, allowing for precise control over charge transport properties and redox reactivity (Khalil et al., 2024).

These doping strategies not only modify the intrinsic band structure and chemical reactivity of biochar, but also significantly enhance interfacial electron transfer efficiency, particularly when biochar is integrated into composite systems with semiconductor photocatalysts. Such mesoscale modifications provide a tunable platform for optimizing charge carrier dynamics, light absorption, and surface reactivity: key parameters in high-performance photocatalytic applications.

(3) Macroscale regulation: particle size, pore structure, and morphological optimization

At the macroscale, structural tuning focuses on controlling particle size distribution, pore architecture, and morphological features. Designing hierarchical porous structures, comprising micropores, mesopores, and macropores, enhances the mass transport of reactants and products, increases the availability of active sites, and improves light-harvesting efficiency. This facilitates an integrated structure-function synergy characterized by enhanced adsorption and photocatalysis (Alhawas et al., 2023).

Furthermore, particle morphology (e.g., spherical, flake-like, tubular) significantly influences light scattering behavior, surface wettability, and interfacial contact with co-catalysts or semiconductors. These parameters critically determine the stability, reactivity, and efficiency of biochar-based composite photocatalytic systems.

In addition to facilitating mass transport and light harvesting, the hierarchical pore architecture and morphological features of biochar

also serve as critical components of a nanoconfined catalytic environment. Recent studies have demonstrated that the micro- and mesoporous domains of biochar, in conjunction with structural defects and polar surface functionalities, create spatially restricted reaction zones that can concentrate reactants, stabilize transient intermediates, and localize charge carriers. This “nanoconfinement effect” modulates the local reaction microenvironment, alters activation energy barriers, and accelerates interfacial charge transfer. Compared with ordered carbon materials such as graphene or carbon nanotubes, biochar provides a uniquely disordered, multiscale porous network that simultaneously enables pollutant adsorption, photocatalytic transformation, and selective molecular recognition. As highlighted in a recent review on multi-dimensional nanoconfined catalysis in carbonaceous materials (Fang et al., 2025), such confined spaces can significantly enhance catalytic performance by tailoring local electronic structures, extending the residence time of reactive species, and facilitating directional charge transport.

This mechanistic perspective underscores that biochar’s role in photocatalytic systems extends far beyond that of a passive conductive support. It acts as an active and tunable scaffold whose hierarchical structure and spatial confinement capacity directly contribute to enhanced photocatalytic efficiency through synergistic control of charge transport and interfacial reaction dynamics.

Conceptually similar structure–energy relationships have also been reported in other functional carbon-based systems. For example, a recent study on bagasse-derived porous flower-like MoS_2 /carbon composites, designed for microwave absorption, demonstrated how tailored hierarchical architectures could trap and dissipate electromagnetic energy through multiscale pore networks and optimized surface features (Zhang et al., 2025). Although not a photocatalytic system, this work illustrates the broader design principle that well-engineered macro- and mesoporous frameworks can effectively confine energy, enhance interfacial interactions, and modulate local field effects. When translated to photocatalysis, this analogy reinforces the notion that morphology regulation should be understood not merely in terms of surface area or porosity, but as a powerful strategy for managing energy flow, charge confinement, and reactive site accessibility within biochar-based materials.

2.3. Characterization methods and mechanism validation approaches

To comprehensively understand how structural regulation of biochar governs its photocatalytic behavior, an integrated approach combining advanced characterization techniques and theoretical simulations is essential. These tools collectively enable multiscale analysis of material composition, electronic properties, and interfacial processes.

Representative techniques such as X-ray photoelectron spectroscopy (XPS), electron paramagnetic resonance (EPR), photoluminescence spectroscopy (PL), transient photocurrent (TPC) measurements, and electrochemical impedance spectroscopy (EIS) provide critical insight into surface chemical states, reactive species dynamics, and charge carrier behavior. Complementary theoretical methods, most notably density functional theory (DFT), enable atomistic-level interpretation of electronic structure, interfacial charge transfer, and reactive site distributions.

Importantly, the DFT calculations presented in this review are systematically correlated with experimental results, rather than used as isolated theoretical tools. For example, band structure simulations explain the bandgap modulation observed in UV–vis spectra; charge density and work function calculations align with trends in photocurrent and impedance measurements; and adsorption energy predictions support EPR and scavenging-based ROS identification. These correlations bridge theoretical modeling with experimental findings, offering a mechanistic framework to interpret charge transfer regulation and ROS formation in biochar-based systems.

To avoid redundancy, the major techniques, analysis targets, and

their application scenarios are systematically summarized in Table 1.

2.4. Frontier strategy expansion: carbon point modification and single-atom catalytic site integration

In recent years, the structural engineering of biochar has progressed beyond conventional physical or chemical modification toward more refined approaches involving high-dimensional confinement and atomic-level site regulation. Among these, carbon dot modification has emerged as a promising strategy to enhance both light-harvesting efficiency and interfacial reactivity. Carbon dots are characterized by excellent visible-light absorption, high electron mobility, and abundant surface functional groups. When integrated with biochar frameworks via π - π interactions, Carbon dots can significantly tailor the band structure and introduce highly active surface sites, thereby improving charge separation efficiency and catalytic activity (Sbacchi et al., 2023).

Simultaneously, the integration of single-atom catalysts (SACs) into biochar matrices represents a cutting-edge direction in catalyst design, offering superior atom utilization and catalytic specificity. Transition metal single atoms (such as Fe, Co, and Ni) are typically anchored within nitrogen-doped carbon matrices to form highly active and stable M-N-C coordination sites. These isolated catalytic centers not only demonstrate excellent selectivity and stability under photocatalytic conditions but also effectively facilitate the generation of ROS, which play a pivotal role in accelerating redox reactions and enhancing overall photocatalytic efficiency (Wang et al., 2025).

2.5. Summary

In conclusion, the multiscale structural regulation of biochar, ranging from the microscopic tailoring of surface functional groups, through mesoscale bandgap engineering and heteroatom doping, to macroscale control of pore architecture and morphology, collectively determines its physicochemical properties and functional performance in photocatalytic systems. These hierarchical modifications directly influence electron transfer behavior, pollutant adsorption capacity, and redox reaction pathways.

The integration of advanced characterization techniques (e.g., XPS, EPR, PL, TPC, EIS) and theoretical simulations (e.g., DFT) enables a comprehensive understanding of the structure-activity relationships, revealing the synergistic mechanisms that underlie enhanced photocatalytic performance.

Moreover, the deployment of frontier strategies such as carbon dot modification and single-atom catalytic site integration is further expanding the functional landscape of biochar in environmental photocatalysis. Through the coordinated design of multiscale structures and interfacial electronic properties, biochar is increasingly positioned as a highly versatile and sustainable platform for the efficient degradation of complex pollutants. These developments contribute significantly to the advancement of green and low-carbon photocatalytic material systems

Table 1

Functional classification of commonly used characterization and simulation techniques in biochar-based photocatalytic material research.

Technical category	Typical method	Analysis Object	Research objectives and application scenarios	Ref.
Surface element and functional group analysis	XPS (X-ray photoelectron spectroscopy)	Element type, valence state, functional group, doping behavior	Determine the type of impurity doping, confirm the functional group composition and bonding method.	(Wang et al., 2023)
Free radical and ROS analysis	EPR (electron paramagnetic resonance)	•OH, O ₂ ^{•-} , ¹ O ₂ and other reactive oxygen species	Identify degradation pathways and validate active species generation mechanisms	(Dou et al., 2025)
Photoelectric behavior analysis	PL (photoluminescence)	Photogenerated electron/hole recombination efficiency	Determine carrier recombination efficiency and evaluate electron transport behavior	(Liu et al., 2024)
Carrier dynamics analysis	TPC (transient photocurrent)	Photogenerated electron migration response	Reflects the charge response sensitivity of materials under light exposure	(Al Bacha et al., 2022)
Analysis of electrochemical interface behavior	EIS (electrochemical impedance spectroscopy)	Charge transfer impedance, interfacial reaction resistance	Evaluate charge transfer rates and determine interfacial electrochemical processes	(Khlifi et al., 2025)
Band and electronic structure simulations	DFT (density functional theory)	Electronic density, band structure, interface charge distribution	Simulate the effects of doping, structural defects, heterojunctions, etc. on electronic behavior, and assist in mechanical interpretation	(Wu et al., 2022)

with broad application prospects in environmental remediation.

3. Synergistic mechanisms between biochar and photocatalytic systems

3.1. Electron transfer regulation mechanism: heterojunction structures and interface engineering design

In photocatalytic systems, biochar not only provides structural support but also actively contributes in the regulation of charge carriers. Its high conductivity, extensive surface area, and favorable interfacial interactions support effective charge separation and transport. Graphitized carbon domains within biochar create continuous π -conjugated networks, which facilitate long-range electron migration and reduce recombination of photogenerated charge carriers, thus improving their overall utilization efficiency (Mian and Liu, 2018).

Building on this functionality, biochar has been increasingly integrated into advanced heterojunction architectures designed to steer directional charge transfer. Among the most widely adopted configurations are Z-scheme, S-scheme, and Schottky junctions, each distinguished by their energy band alignment, charge migration pathways, and underlying interfacial physics.

With the rapid evolution of interfacial engineering, various heterojunction architectures, namely Z-scheme, S-scheme, and Schottky junctions, have been developed to promote efficient spatial charge separation in photocatalytic systems. While all aim to enhance electron-hole separation and improve redox performance, their working principles and charge transfer pathways differ significantly. A brief comparative summary is provided below to facilitate conceptual clarity before discussing biochar's role in each structure. Table 2 outlines the fundamental mechanisms, energy band alignments, and electron

Table 2

Comparison of charge transfer mechanisms in Z-scheme, S-scheme, and Schottky-type heterojunction photocatalysts.

Type of Heterojunction	Charge Transfer Pathway	Energy Band Alignment	Key Characteristics
Z-scheme	Photogenerated e ⁻ from CB of PS I recombines with h ⁺ in VB of PS II	Staggered; resembles natural photosystem	Maintains strong redox ability on both ends; spatial charge separation
S-scheme	e ⁻ in CB of one semiconductor recombines with h ⁺ in VB of another via built-in electric field	Step-scheme with internal field	Selective preservation of high-energy e ⁻ and h ⁺ ; strong built-in field
Schottky junction	Metal captures electrons from semiconductor CB and inhibits recombination	Metal-semiconductor contact	Promotes charge separation via Schottky barrier; unidirectional transfer

migration directions of these heterojunctions.

(1) Z-scheme heterojunctions: electron bridge formation and spatial charge separation

Inspired by the Z-scheme of natural photosynthesis, this heterojunction involves recombination between low-energy electrons in the conduction band (CB) of one semiconductor and high-energy holes in the valence band (VB) of another. This leaves behind charge carriers with strong redox potentials on either side of the interface. When incorporated into such systems, biochar acts as a conductive electron mediator bridging the two semiconductors, lowering the interfacial energy barrier and supporting a spatially resolved charge separation pattern (Fig. 1).

For instance, the g-ZnO/2H-MoS₂ system reported by Ouyang et al. (2021) showed enhanced CO₂ reduction activity due to the presence of a biochar-like carbon mediator that improved interfacial conductivity and charge separation, as confirmed by DFT simulations. Similarly, in a BiOI/CdS composite (Zhang et al., 2020), radical quenching tests identified superoxide radicals ($\bullet\text{O}_2^-$) as the major active species, validating the Z-scheme charge migration route enhanced by biochar.

(2) S-scheme heterojunctions: interface band bending–induced selective charge migration

This heterostructure leverages differences in Fermi levels between two semiconductors, which induces band bending at the interface and generates an internal electric field. As a result, low-energy electrons and

holes recombine near the interface, while high-energy carriers are retained and spatially separated, thereby enhancing photocatalytic performance (Fig. 2).

Enesca and Andronic (2021) reported that in systems such as SnS₂/Bi₂S₃ and MoS₂/WO₃, efficient band alignment and interfacial architecture were key to pollutant degradation efficiency. Within such frameworks, biochar enhances electronic coupling, strengthens band bending effects, and introduces additional surface polarization. These modifications collectively improve charge mobility and reaction kinetics by promoting selective charge transfer.

(3) Schottky heterojunctions: interfacial potential barrier–induced unidirectional electron migration

When a semiconductor interfaces with a conductive material like biochar, a Schottky barrier forms due to work function mismatch. This potential barrier allows unidirectional electron migration while suppressing electron–hole recombination, which improves both carrier lifetime and photocatalytic efficiency (Fig. 3).

Xia et al. (2022) demonstrated that NiCoP/g-C₃N₄ structures with Schottky junctions achieved a 78 % NO removal rate due to enhanced carrier separation. In another case, Pd-modified g-C₃N₄ utilized plasmonic excitation of hot electrons to lower reaction barriers and accelerate catalytic processes (Wan et al., 2024). MXene-based Schottky interfaces have also shown great promise. Sun et al. (2025) fabricated a CAU-17/MXene heterojunction with oxygen vacancies, enabling nitrogen fixation at 56.34 $\mu\text{mol g}^{-1} \text{h}^{-1}$ without external co-catalysts. Furthermore, Ag-modified black phosphorus composites developed by

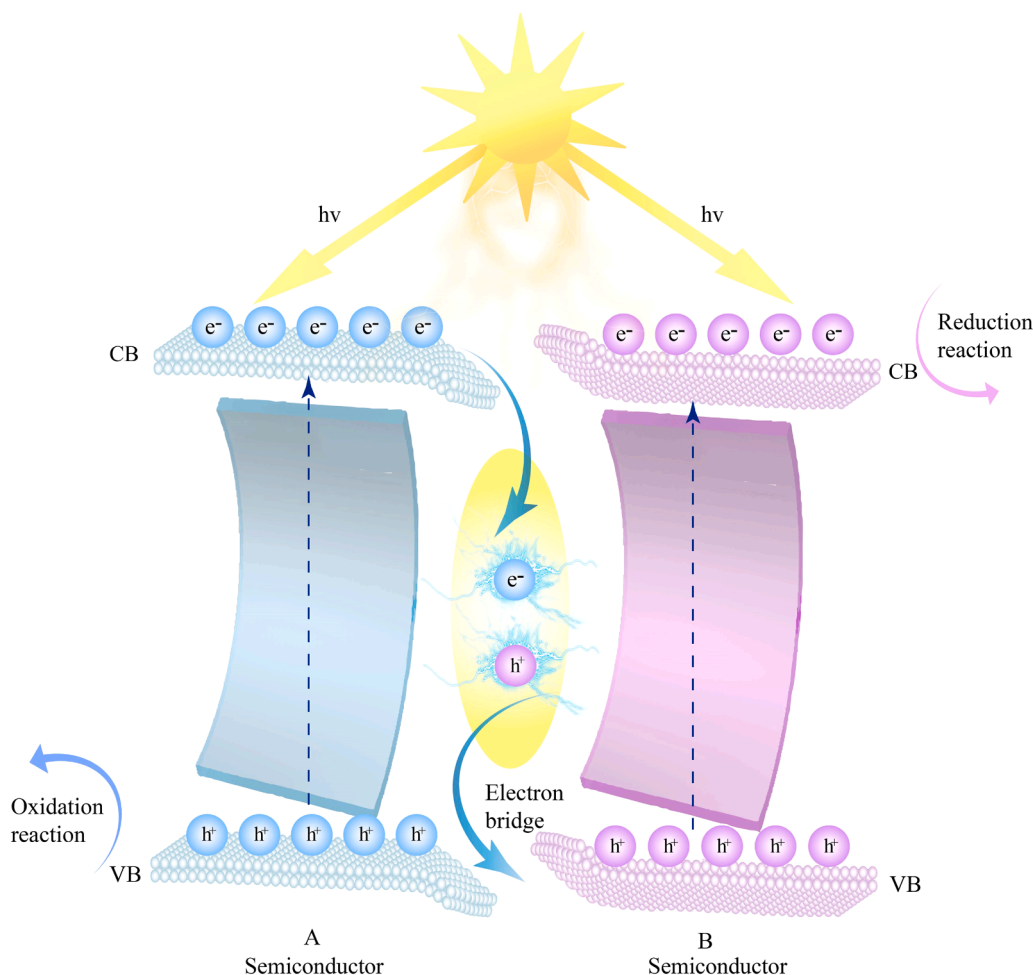


Fig. 1. Schematic illustration of charge carrier migration in a Z-scheme heterojunction with an electron mediator.

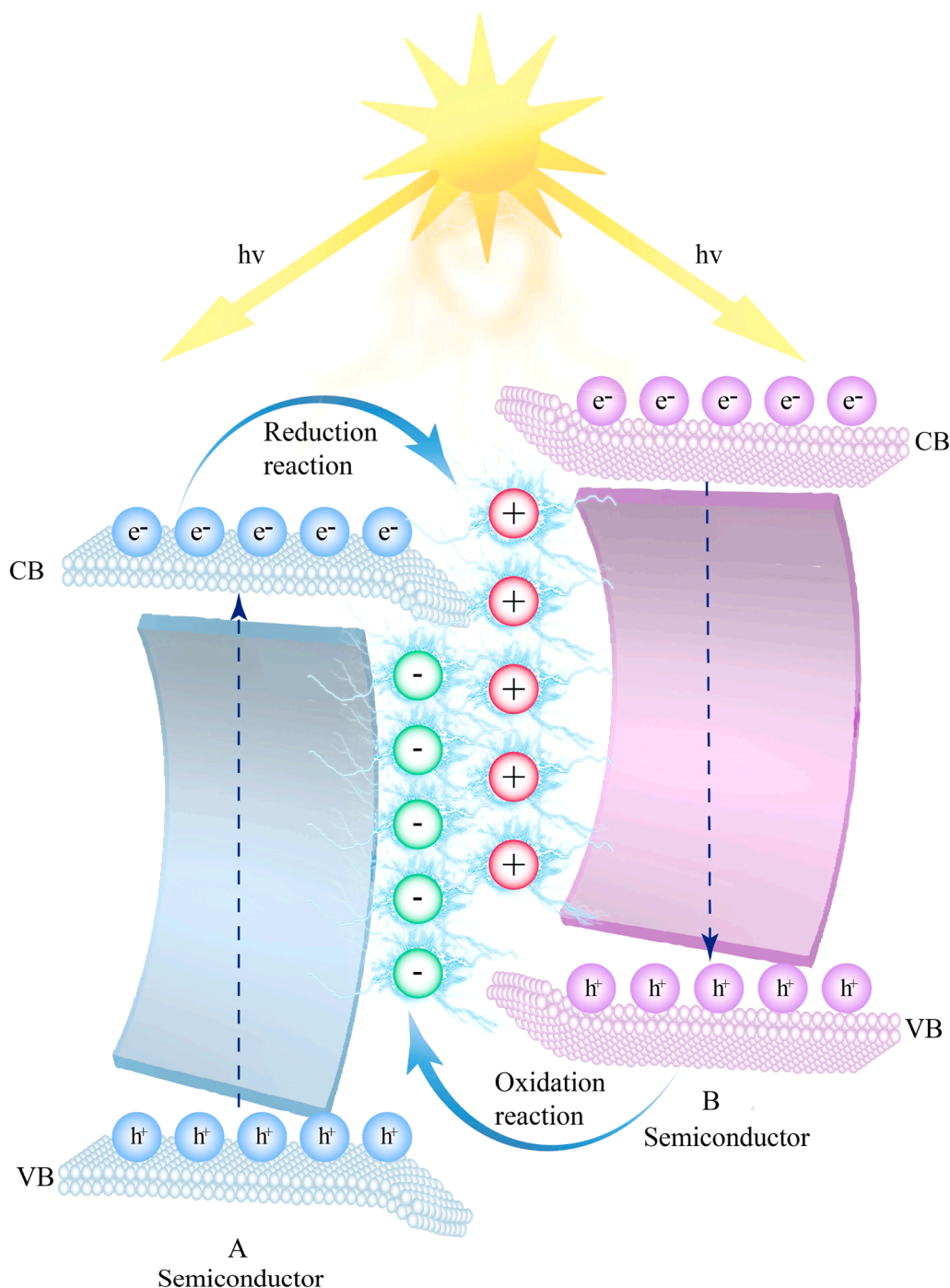


Fig. 2. Schematic illustration of charge transfer and selective carrier recombination in an S-scheme heterojunction.

Wang et al. (2024) exhibited a 1.87-fold improvement in dye degradation efficiency compared to pristine black phosphorus, attributed to accelerated interfacial electron transfer.

(4) Carbon skeleton conductivity and interface property optimization

The electrical properties of biochar are closely tied to its internal carbon structure, which is influenced by pyrolysis temperature and carbonization degree. According to Liu et al. (2023), increasing pyrolysis temperature reduces the H/C and O/C ratios, promoting the conversion from sp^3 -hybridized amorphous carbon to sp^2 -hybridized graphitic carbon. This transformation results in a more ordered

conductive framework that facilitates interfacial charge transport.

Such conductive structures also enhance surface interactions with O_2 molecules. Gasim et al. (2022) showed that biochar with graphitized skeletons promotes the formation of superoxide radicals ($\bullet O_2^-$), contributing to increased redox activity. The interplay between improved conductivity and reactive site density enables more efficient photocatalytic reactions, particularly under visible light conditions.

3.2. Synergistic mechanism of enhanced light absorption and pollutant adsorption

In addition to its role in regulating photogenerated charge dynamics, biochar significantly enhances photocatalytic efficiency through two

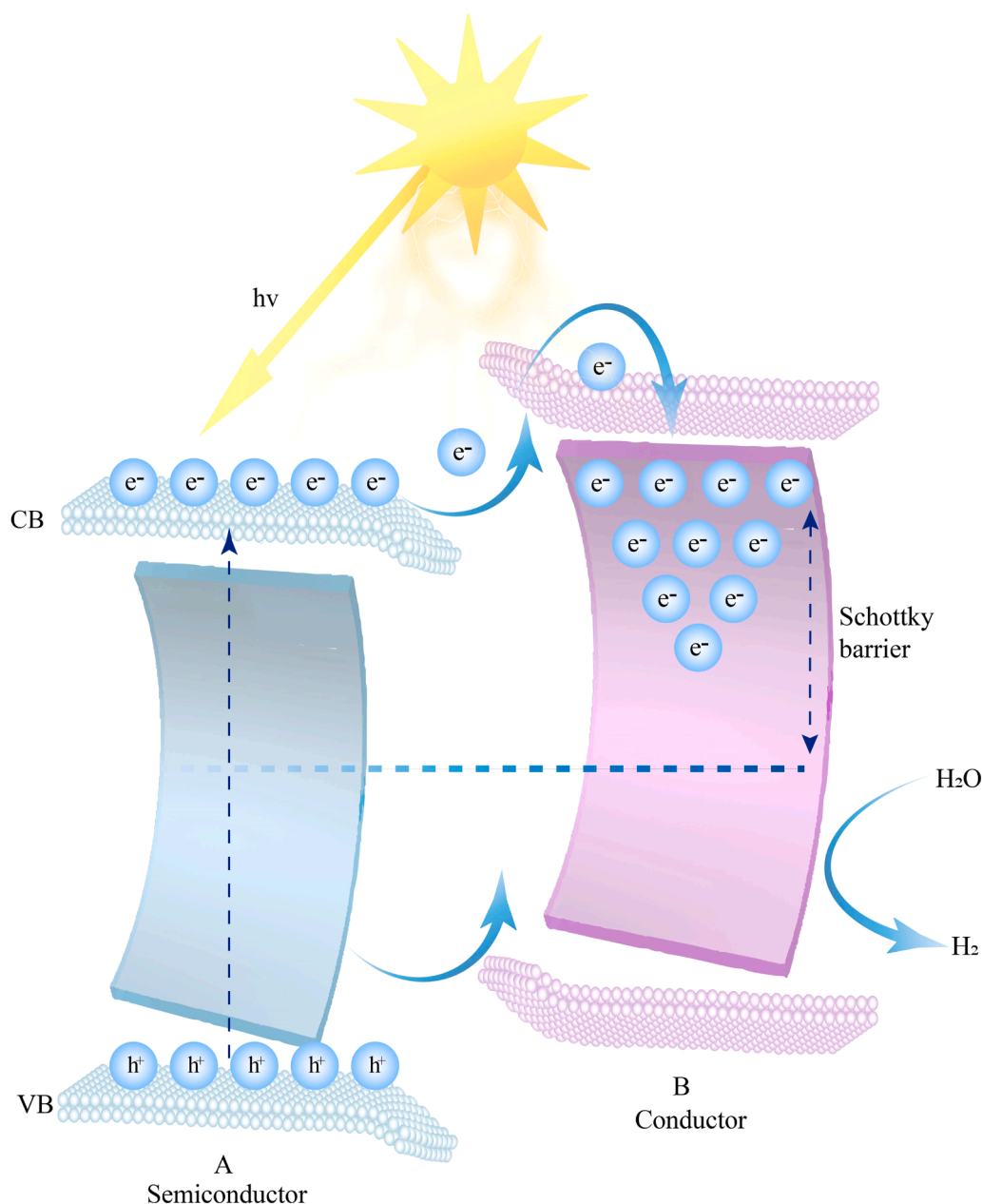


Fig. 3. Schematic illustration of unidirectional electron migration driven by interfacial potential barriers in Schottky heterojunctions.

complementary mechanisms: improving light harvesting and facilitating pollutant enrichment, as illustrated in Fig. 4. Owing to its unique band structure, abundant surface defects, and hierarchical porosity, biochar provides a robust and versatile platform for constructing high-performance photocatalytic systems.

3.2.1. Mechanisms for enhancing visible light responsiveness

Biochar prepared via high-temperature pyrolysis often exhibits semiconductive properties. Its surface contains abundant oxygen-containing functional groups, such as carbonyl ($C=O$) and hydroxyl ($-OH$), as well as various structural defects; both can serve as localized energy states. These features serve as active light-absorption centers, facilitating intra-band electronic transitions and extending the photocatalyst's absorption edge into the visible-light region.

When incorporated into composite systems, biochar not only broadens the spectral response but also improves interfacial charge transfer, thereby enhancing the utilization efficiency of photogenerated electrons through interfacial synergistic effects.

Moreover, non-metal doping (e.g., nitrogen, sulfur, phosphorus) can further tailor the band structure and density of states, optimizing optical response characteristics. For example, Pu et al. (2024) achieved a narrowed bandgap of 2.10 eV via sulfur doping in TiO_2 , significantly enhancing visible-light photocatalytic activity. Similar bandgap-engineering strategies are applicable to fine-tune interfacial compatibility between biochar and semiconductor components, promoting more efficient charge separation and light utilization.

3.2.2. Mechanisms for enhancing pollutant adsorption

Biochar is characterized by a high specific surface area and a multi-scale porous architecture, which together provide abundant adsorption sites for pollutant capture. Polar functional groups on its surface, such as carboxyl and phenolic hydroxyl groups, enhance the material's affinity for organic pollutants through hydrogen bonding, $\pi-\pi$ interactions, and electrostatic attraction. This enrichment effect increases the local concentration of pollutants at the photocatalytic interface, thereby accelerating surface reaction kinetics and improving degradation selectivity.

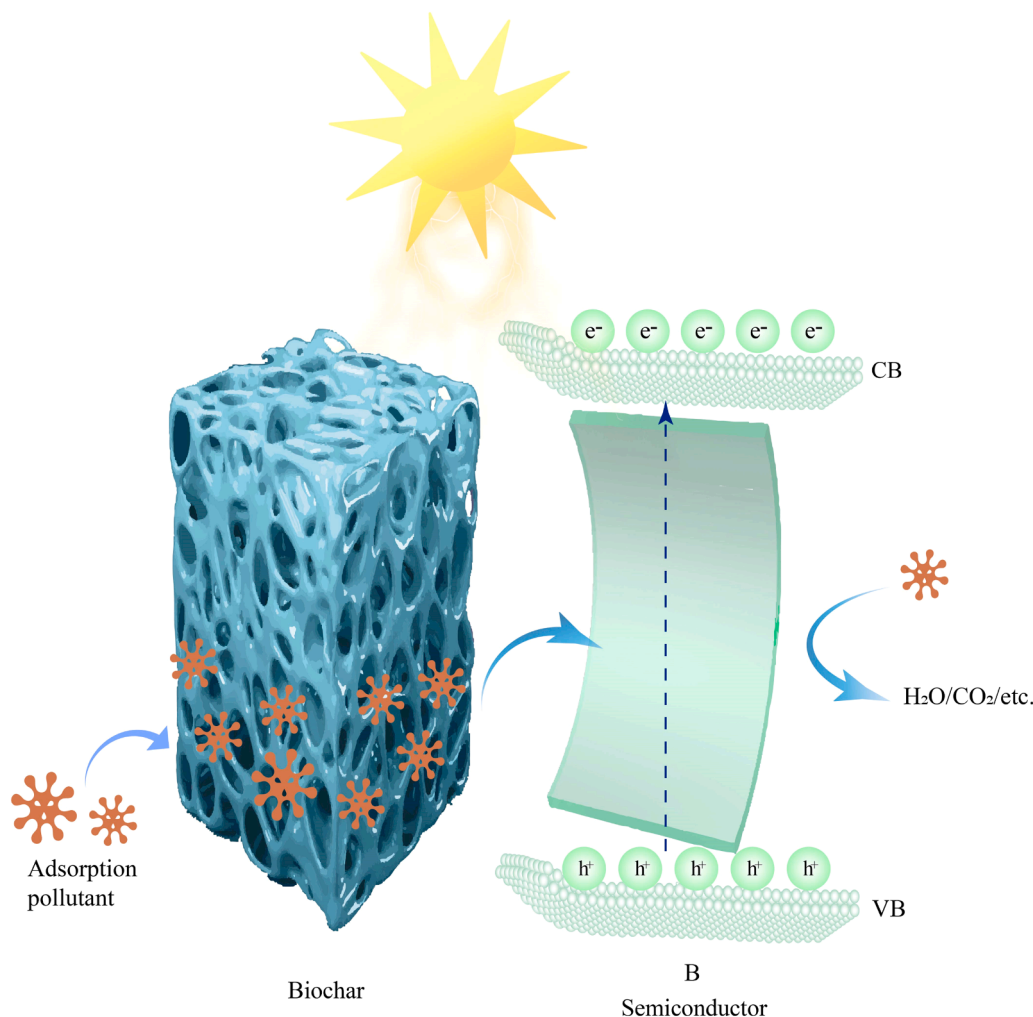


Fig. 4. Dual-role mechanism of biochar in pollutant removal: synergistic adsorption and photocatalytic degradation.

(Fig. 4) (Liu et al., 2024).

A notable example is the LC/ZnAl₂O₄/BiPO₄ composite developed by Li et al. (2024) where the addition of 1 wt% biochar enabled a 97.8 % removal efficiency for methylene blue within 2 h. This demonstrates the significant synergistic effect between pollutant adsorption and charge migration, highlighting biochar's dual-functionality in enhancing both mass transport and electronic processes in photocatalysis.

3.3. Synergistic regulatory mechanism of reactive oxygen species

In photocatalytic degradation processes, ROS including superoxide radicals ($\bullet\text{O}_2^-$), hydroxyl radicals ($\bullet\text{OH}$), and singlet oxygen ($^1\text{O}_2$), act as key oxidative agents responsible for the decomposition of organic pollutants. Through rational structural design, band structure modulation, and surface functional group engineering, biochar plays a multifaceted regulatory role in controlling both the generation efficiency and the reactive pathways of various ROS.

3.3.1. Regulatory mechanisms of free radical ROS

In conventional photocatalytic systems, $\bullet\text{O}_2^-$ and $\bullet\text{OH}$ are typically the dominant ROS involved in oxidation processes. The CeO/CA@GEL composite membrane developed by Karthik et al. (2024) demonstrated efficient degradation of dyes such as Crystal Violet and Rhodamine B (RhB) under visible light, with radical scavenging experiments confirming superoxide and hydroxyl radicals as the principal reactive species.

Biochar contributes significantly to the formation of these free radical species through two primary mechanisms: (i) its surface carboxyl and hydroxyl groups enhance the adsorption and activation of molecular oxygen, and (ii) its π -conjugated carbon structure facilitates rapid electron migration, enabling more efficient charge transfer to surface-bound oxygen molecules. These synergistic effects promote elevated ROS generation rates and improved degradation kinetics.

3.3.2. Regulatory mechanisms of non-radical ROS ($^1\text{O}_2$)

Unlike radical-based species, $^1\text{O}_2$ offers higher oxidative selectivity, making it particularly effective for degrading structurally specific or resistant pollutants. The generation of $^1\text{O}_2$ primarily involves energy transfer between photoexcited states (excitons) and ground-state molecular oxygen, mediated by spin-orbit coupling (SOC) and intersystem crossing (ISC) mechanisms.

Liu et al. (2024) demonstrated that introducing carbonyl functional groups into g-C₃N₄ significantly increased the triplet exciton population, thereby enhancing the yield of $^1\text{O}_2$. This work presents a promising strategy for activating non-radical oxidation pathways, which are especially useful in minimizing non-selective degradation and secondary pollution.

In such systems, biochar and photosensitizers exhibit strong synergistic interactions. While the photosensitizer is responsible for light absorption and energy transfer, biochar serves both as an energy mediator, facilitating exciton migration and ROS conversion, and as a pollutant concentrator, enriching target molecules at the reactive

interface.

As shown in Fig. 5, this dual-functionality enables biochar to guide the generation and transformation of ROS species under illumination.

By modulating the structural and interfacial properties of biochar, it is possible to finely control the distribution, reactivity, and selectivity of ROS. This facilitates multidimensional optimization of oxidation strength, reaction specificity, and pollutant compatibility, thereby expanding the functional potential of biochar in photocatalytic environmental remediation.

In addition to semiconductor band alignment and heterojunction design, insights from related catalytic systems further illustrate the importance of surface electronic environments in regulating charge transfer and ROS generation. For example, studies on non-noble metal catalysts used for levulinic acid conversion have shown that the nature of hydrogen donors can significantly affect surface electron density, intermediate stabilization, and the production of active oxygen species (e.g., H^+ , $\bullet OH$, $\bullet O_2^-$) under reaction conditions (Li et al., 2024). This suggests a mechanistic analogy: in biochar-based photocatalysis, surface functional groups, defect states, and electronic structures similarly modulate the local electron density and facilitate ROS formation and transformation pathways. Such cross-system comparisons underscore the broader principle that catalytic performance is intrinsically linked to how surface chemistry and electronic structure govern charge flow and reactive species dynamics, thereby enriching our understanding of electron transfer regulation and ROS synergy in biochar-photocatalyst composites.

DFT simulations further provide quantitative insights into the interfacial charge transfer processes and ROS generation pathways in biochar-based photocatalytic systems. Charge density difference calculations and work function analyses reveal spontaneous electron redistribution at the biochar–semiconductor interface, leading to the formation of an internal electric field that drives directional charge separation. This theoretical prediction is in good agreement with the reduced charge-transfer resistance observed in EIS and the enhanced TPC responses.

Furthermore, DFT-derived adsorption energies and spin density distributions of O_2 and H_2O molecules on defect-rich or doped biochar surfaces indicate preferential electron accumulation on adsorbed oxygen species, favoring the formation of $\bullet O_2^-$ and subsequent $\bullet OH$ radicals. These results provide direct theoretical support for ROS identification experiments, such as radical scavenging tests and EPR measurements, thereby linking electronic structure modulation to experimentally observed ROS-dominated degradation pathways.

3.4. Defect engineering and its role in photocatalytic processes

In addition to heteroatom doping, structural defects represent a critical dimension of mesoscale regulation in biochar-based photocatalysts. Defects such as carbon vacancies, edge sites, grain boundaries, and heteroatom-induced distortions significantly influence the material's optoelectronic behavior.

Carbon vacancies and surface vacancies can introduce mid-gap states

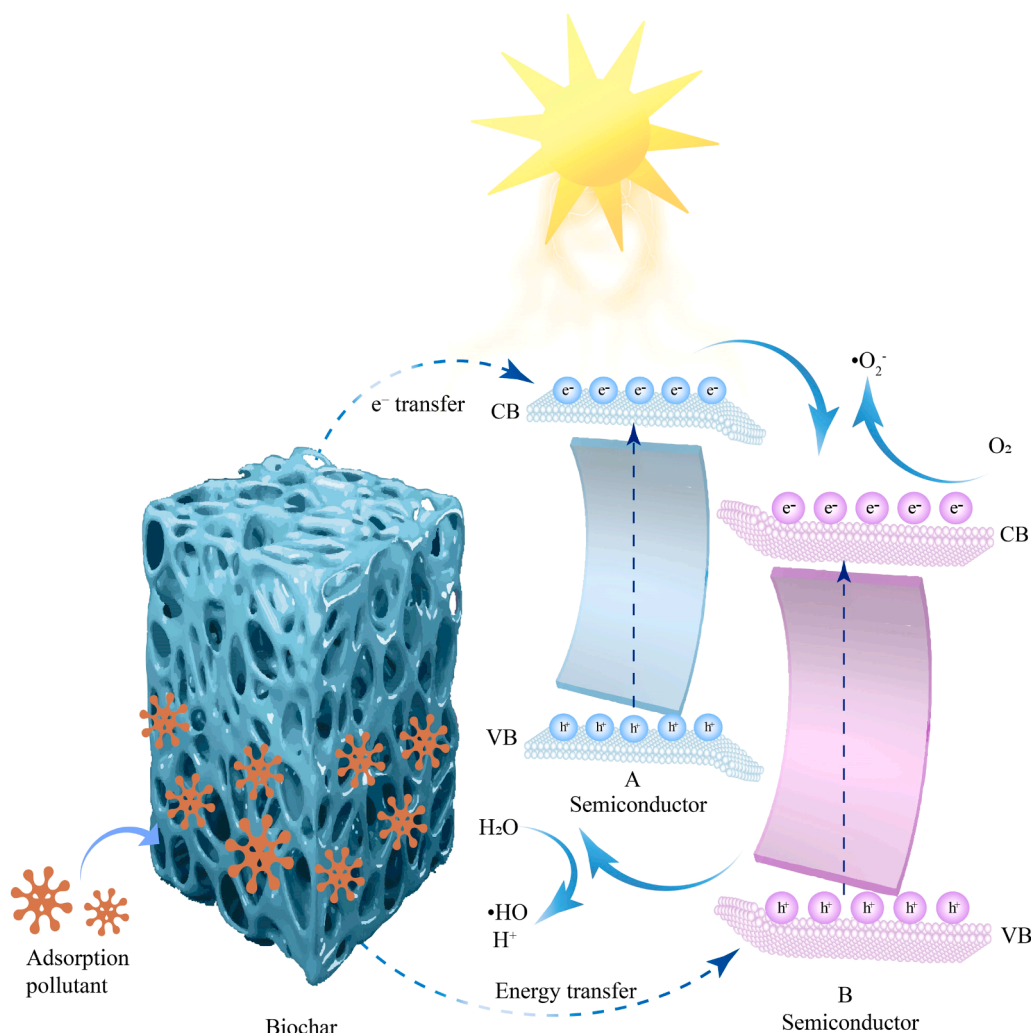


Fig. 5. Light-driven dual-function mechanism of biochar: adsorption and energy/electron transfer toward enhanced photocatalytic activity.

that enhance visible light absorption by narrowing the bandgap or facilitating sub-band transitions. These states can also serve as trap sites that prolong the lifetime of photogenerated charge carriers by suppressing fast recombination. Furthermore, edge defects and grain boundaries often exhibit localized charge accumulation, which promotes directional charge transfer and interfacial redox reactions.

Dopant-induced defects, especially when introduced through non-metal heteroatoms such as nitrogen, sulfur, or phosphorus, not only tune the band structure but also induce lattice distortions that modulate the local electron density. This facilitates more efficient interaction with O_2 and H_2O molecules, promoting the generation of ROS (e.g., $\bullet O_2^-$, $\bullet OH$, or even non-radical 1O_2).

Importantly, these different types of defects often function synergistically. For example, the coexistence of vacancies and heteroatom dopants may result in asymmetric charge distribution and internal electric fields, further enhancing charge separation. Recent studies have shown that optimized defect concentration and spatial distribution can significantly boost quantum efficiency and ROS production.

Therefore, defect engineering should be considered a fundamental design strategy, alongside doping and pore architecture, for tuning light absorption, charge migration, and interfacial reactivity in biochar-based

photocatalytic systems.

4. Application progress of biochar-based photocatalytic materials in the treatment of typical pollutants

In recent years, biochar-based composite photocatalytic materials have exhibited substantial potential in the remediation of both water and air pollution, as illustrated in Fig. 6 (E et al., 2024). This broad applicability is largely attributed to their unique combination of properties, including high specific surface area, superior charge transport capability, and selective adsorption affinity toward a wide range of pollutants. These synergistic characteristics endow biochar-based materials with the ability to effectively target and degrade various contaminants, such as organic dyes, antibiotics, heavy metal ions, and VOCs.

To comprehensively evaluate the environmental utility of these materials, this section categorizes and analyzes recent advancements in biochar-based photocatalysis according to the type of pollutant treated. This classification not only highlights the functional versatility of biochar-supported systems, but also provides insight into material design strategies that are specifically tailored to different pollution

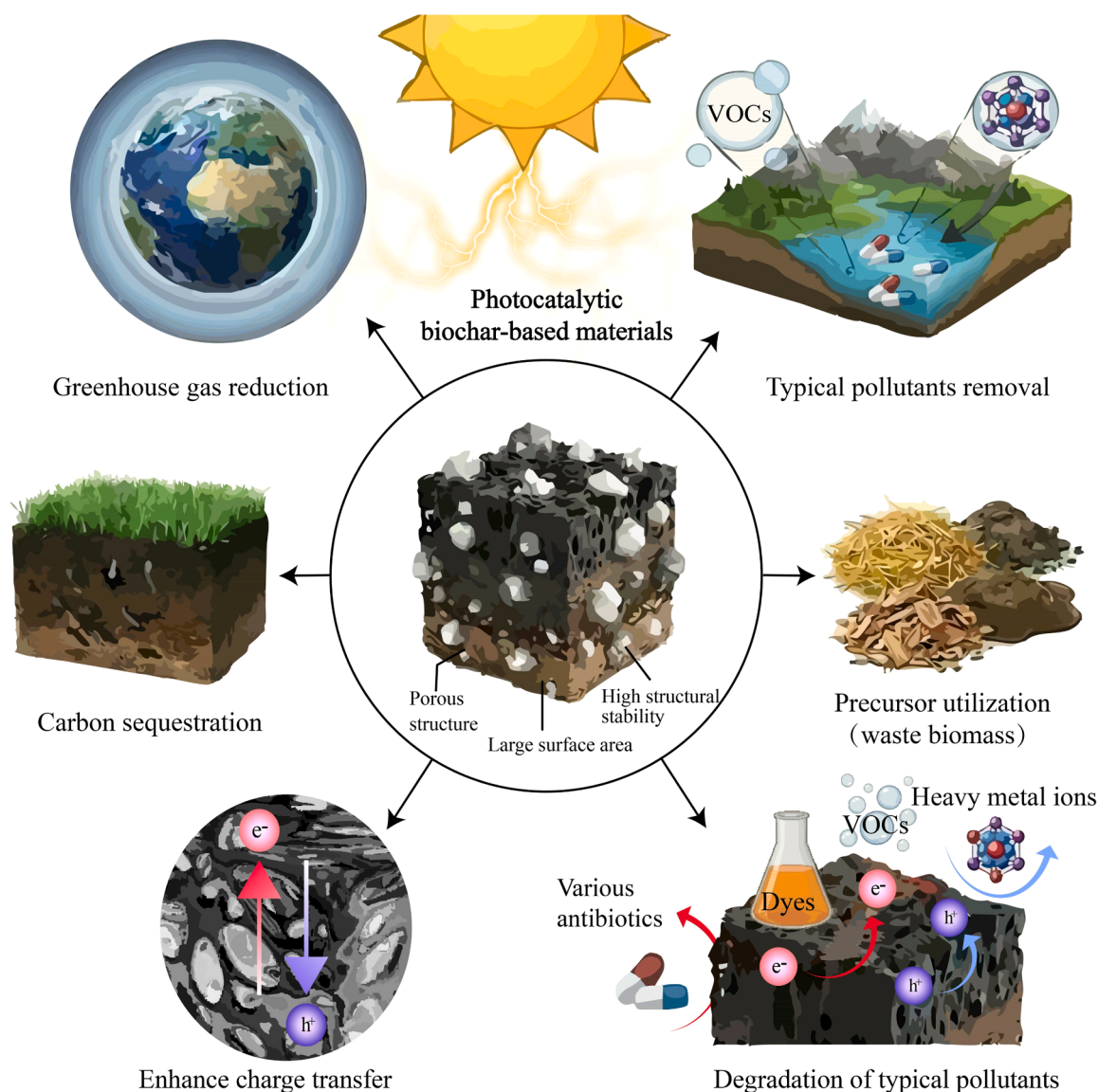


Fig. 6. Overview of the properties and environmental applications of biochar-based materials.

scenarios.

4.1. Organic pollutants: synergistic degradation mechanisms and applications of dyes and antibiotics

4.1.1. Dye degradation

Dye pollutants are prevalent in effluents from textile and printing industries, characterized by strong chromophoric structures, high chemical stability, and potential toxicity. Biochar-based photocatalytic materials have shown promising performance in dye degradation due to their high adsorption capacity, broad light absorption, and efficient charge transfer.

As summarized in Table 3, a variety of biochar-based composites, including Ru-TiO₂/PC, Z-scheme BC/ZIS/WO₃ systems, and heterostructures based on CdS, Ag₂S, or MnO₂, have achieved degradation efficiencies above 95 % under visible light for dyes such as RhB, MB, and CV. These systems exhibit synergistic mechanisms such as band modulation, ROS generation, and electron transfer enhancement. Depending on the coordination strategies (e.g., heterojunction design, doping, or interface engineering), different composites offer specific advantages in light harvesting, adsorption selectivity, or catalytic lifetime.

These results highlight the structural tunability and multifunctionality of biochar as both an active component and a support in photocatalytic dye degradation.

4.1.2. Antibiotic removal

Antibiotic pollutants are of growing environmental concern due to their high biological activity, chemical persistence, and potential to induce antibiotic resistance. These contaminants are widely detected in effluents from medical facilities, aquaculture operations, and municipal wastewater treatment plants. Even at trace concentrations, antibiotics can exert long-term ecological effects and contribute to the proliferation

of antibiotic-resistant genes (ARGs) in aquatic environments. Biochar-based photocatalytic materials have emerged as effective platforms for the adsorptive enrichment and photodegradation of antibiotics, owing to their porous structure, surface functionality, and tunable electronic properties.

For example, Zhang et al. (2023) prepared TiO₂/biochar (TiO₂/BC) composites by in situ anchoring TiO₂ nanoparticles onto grapefruit peel-derived biochar. The resulting material exhibited over 90 % degradation efficiency for tetracycline under visible light irradiation, highlighting the synergistic effect of biochar in improving light utilization and interfacial electron transfer.

Similarly, Feng et al. (2023) developed a NiCr-layered double hydroxide (LDH)/peanut shell biochar (PSB) composite catalyst, which showed excellent performance in the simultaneous removal of ofloxacin and tetracycline. The high adsorption capacity of PSB enhanced pollutant accumulation at the catalytic interface, thereby facilitating more effective interactions between reactants and active sites (see Table 4).

4.2. Heavy metal ions: adsorption - photoreduction synergistic mechanism represented by Cr(VI)

Hexavalent chromium (Cr(VI)) is one of the most hazardous heavy metal pollutants, known for its high solubility, strong oxidative potential, and tendency to bioaccumulate. Once released into aquatic environments, Cr(VI) poses severe ecological and human health risks due to its carcinogenic and mutagenic properties.

Biochar-based photocatalytic materials offer a dual-function strategy for Cr(VI) removal through a combination of surface adsorption and photoreduction. The abundant oxygen-containing functional groups (e.g., -COOH, -OH) on biochar surfaces promote electrostatic attraction and complexation with Cr(VI) species. Simultaneously, the conductive

Table 3
Performance comparison of various biochar-based photocatalytic materials for dye wastewater treatment.

Biochar-based photocatalytic materials	Biochar raw materials	Dye	Synthetic method	Coordination mechanism	Time	Degradation rate	Reusability	Ref.
Ru-TiO ₂ /PC	Grapefruit peel	RhB MB MO	In situ biomimetic method	Enhanced light absorption + electron transfer	1 h 1 h 2 h	99.12 % 100 % 99.06 %	5 cycles, retained its high photocatalytic activity	(Wu et al., 2025)
BC/2ZIS/WO ₃	Purple alfalfa	MB RhB	Hydrothermal method	Electron transfer (Z-path) + adsorption-catalysis	1 h 1 h	80.5 % 99 %	5 cycles, 75.8 % 95.07 %	(Cheng et al., 2022)
AC	Jasmine	MB	Hydrothermal method	Enhanced light absorption + electron transfer	2 h	94 %	5 cycles, 92 %	(Amalanathan et al., 2022)
Sn-QDs/CNO/BC	Peanut shells	MB	Pyrolysis method	Adsorption-catalysis + ROS synergy	1 h	99 %	5 cycles, above 90 % no significant decrease	(Zhang et al., 2025)
KOH/BC	Cannabis	CV	Activation and pyrolysis method	Band control + light absorption enhancement	75 min	98.2 %	No report	(Kanwal et al., 2025)
CIS-Mg/S-BC	Sugarcane bagasse	RhB	Pyrolysis method	Adsorption-catalysis + electron transfer (S-type heterostructure)	2 h	97.67 %	5 cycles, 95.62 %	(Peng et al., 2023)
ZnSm/Mg-BC	Sugarcane bagasse	RhB	Pyrolysis method	Electron transfer + ROS synergy	2 h	99.46 %	5 cycles, slightly deactivated	(Zhou et al., 2024)
Ag ₂ S-MgO/S-BC	Sugarcane bagasse	RhB	Activation and pyrolysis method	Enhanced light absorption + adsorption-catalysis	2 h	97.60 %	5 cycles, 91.87 %	(Zheng et al., 2023)
PO@ZIF-8/BC	Pea pod	CV VB	Precipitation method	Adsorption-catalysis + electron transfer	50 min 50 min	87 % 80 %	4 cycles, very little decrease	(Darabdhara et al., 2025)
MnO ₂ /P-MnO ₂ /AC	Potato peel	MB	Hydrothermal method	Band control + electron transfer	3 h	95.22 %	5 cycles, 92.45 %	(Manikandan et al., 2023)
PM6 : TPIC-4Cl/BC	Coconut shell	MB	impregnation method	Enhanced light absorption + adsorption-catalysis	3 min	98 %	10 cycles, above 90 %	(Cai et al., 2024)
Sr-ZnO/AC	Banana pseudostem	CV	Chemical precipitation method	Electron transfer + ROS synergy	2 h	98.92 %	5 cycles, 87.93 %	(Dhanabal and Priya, 2025)
Mn-Al-LDH/RHBC	Rice husk	TC	Co-precipitation method	Electron transfer + adsorption + energy band + ROS	90 min	90.10 %	4 cycles, 51.69 %	(Dou et al., 2025)
N-ZnO@LBC	Lantana camara leaf	MB	Microwave-assisted coprecipitation method	Electron transfer + adsorption + energy band + ROS	115 min	95.70 %	5 cycles, without a significant loss	(Demarema et al., 2024)

Table 4

Degradation performance of various biochar-based photocatalytic materials against different antibiotics.

Biochar-based photocatalytic materials	Biochar raw materials	Antibiotics	Synthetic method	Coordination mechanism	Time	Degradation rate	Reusability	Ref.
TiO ₂ /BC	Grapefruit peel	TC	Activation and pyrolysis method	Adsorption-catalysis + electron transfer	2 h	90 %	5 cycles, 80 %	(Zhang et al., 2023)
NiCr-LDH/BC	Peanut shells	OFX TC	Hydrothermal method	Electron transfer (S-scheme) + adsorption-catalysis	150 min 150 min	80 % 85 %	4 cycles, 80 %	(Feng et al., 2023)
ZnO/TiO ₂ /BC	Reed stem	DC	Pyrolysis method	Enhanced light absorption + bandgap control	2 h	92.45 %	4 cycles, no significant decrease	(Tuoi et al., 2024)
BiOBr/OPBC	Oil palm empty fruit	CIP	Precipitation method	Electronic transfer (Z-scheme) + ROS synergy	2 h	93.13 %	4 cycles, 77.53 %	(Daud et al., 2024)
TiO ₂ /BC	Straw	CIP	Sol-gel method	Adsorption-catalysis + electron transfer	3 h	83.8 %	No report	(Qu et al., 2023)
CN/BC	Crayfish shell	ENR	Pyrolysis method	Band control + adsorption-catalysis	8 h	90 %	4 cycles, no significant decrease	(Xiao et al., 2023)
Fe ₃ O ₄ /SnO ₂ /BC	Wheat straw	TC	Sol-gel method	Electron transfer (double Z-type) + ROS synergy	3 h	91.8 %	4 cycles, 82.33 %	(Zhang et al., 2025)
SCBW	Sugarcane bagasse	OTC	Hydrothermal method	Adsorption-catalysis	3 h	92.7 %	4 cycles, minimal loss	(Chauhan et al., 2025)
g-C ₃ N ₄ /BC	Grapefruit peel	TC	Calcination method	Electron transfer (Z-scheme) + enhanced light absorption	2 h	83 %	4 cycles, basically stable	(Guo et al., 2022)
FeOOH/BC	Pinus massoniana	TC	Carbonization-hydrothermal method	ROS Synergy + Adsorption-Catalysis	90 min	92 %	4 cycles, 86 %	(Xue et al., 2024)
CN/BC	Aloe vera leaf pulp	TC	Calcination method	Band control + ROS Synergy	1 h	95 %	4 cycles, no significant decrease	(Li et al., 2024)
TiO ₂ /BC	Corn stover	SMX	Sol-gel method	Adsorption-catalytic coupling + electron transfer	4 h	89 %	3 cycles, 49.38 %	(Dang et al., 2023)
BW/BC	Corn cob	TC	Hydrothermal method	Electron transfer (Z-scheme) + enhanced light absorption	1 h	99.8 %	5 cycles, no significant decrease	(Kang et al., 2023)
ZnO/BC	Cannabis stem	LFX	Hydrothermal method	Electron transfer + ROS synergy	2 h	95.8 %	5 cycles, 82.3 %	(Dong et al., 2023)

carbon matrix provides efficient electron transfer pathways, under the photocatalytic effect, Cr(VI) is reduced to the less toxic trivalent chromium (Cr(III)), as illustrated in Fig. 7.

This synergistic mechanism not only enhances the capture and conversion efficiency of Cr(VI) but also contributes to the overall sustainability of the photocatalytic process by reducing secondary pollution and minimizing energy input requirements.

Several biochar-based composites have demonstrated outstanding performance in the photocatalytic reduction of Cr(VI) under visible or simulated sunlight. For example, Hou et al. (2022) developed a TiO₂/biochar (TiO₂/BC) composite that achieved a Cr(VI) reduction efficiency exceeding 85 % under simulated solar irradiation. Deng et al. (2022) synthesized a thiourea-modified sodium alginate/biochar (T-BSA) composite, which exhibited a remarkable removal rate of 99.98 % within 180 min, along with excellent stability and reusability over multiple cycles. Similarly, Du et al. (2024) developed a high-efficiency composite, referred to as TBC-3, which achieved 99.9 % Cr(VI) removal within 25 min and retained 93 % of its efficiency after several reuse cycles. These results demonstrate strong potential for practical application (see Table 5).

Beyond material composition and heterojunction configuration, emerging hybrid systems further illustrate the importance of integrating multiple functional components to enhance stability and reactivity. For instance, a highly efficient and recyclable living biocatalyst composed of *Shewanella*@polydopamine@NH₂-doped carbon dot biohybrids and polypyrrole-immobilized melamine foam has been reported for microbial-photoreduction of Cr(VI), achieving robust reduction performance under repeated use Chen et al. (2024). Although distinct from classical semiconductor photocatalysis, this work exemplifies how

engineered interfaces combining catalytic centers, conductive matrices, and hierarchical structures can sustain electron transfer and redox activity over multiple cycles. It thereby reinforces the value of designing stable, multifunctional materials in photocatalytic heavy metal remediation.

4.3. VOCs: photocatalytic degradation and air purification applications

With increasing public awareness of indoor and urban air quality, the efficient removal of VOCs, such as formaldehyde, benzene, and toluene, has emerged as a key research focus for biochar-based photocatalytic materials. VOCs are characterized by their high volatility, chemical toxicity, and resistance to natural degradation, rendering conventional adsorption-based treatments insufficient for complete and sustained removal.

Recent advances in composite photocatalysts have demonstrated the promise of biochar in VOCs degradation. For instance, Yang et al. (2023) developed a Ru₂VO₆/V₂O₅ nanowire array capable of degrading 98 % of formaldehyde within 45 min under visible light irradiation. Similarly, Li et al. (2022) constructed a biochar/MnO₂/g-C₃N₄ heterojunction, achieving a formaldehyde removal efficiency of 91.78 % under ambient conditions. Notably, Chen et al. (2024) reported the effective degradation of formaldehyde in real-world indoor renovation scenarios using a CNx@HKUST-1 photocatalytic membrane, achieving a total removal rate of 86.9 %, with over 48 % of the removal attributable to photocatalytic processes.

Recent advances in the synthesis of biomass carbon-based porous nanostructures also provide valuable case studies for gas-phase pollutant treatment. In particular, electrospun biomass carbon-based

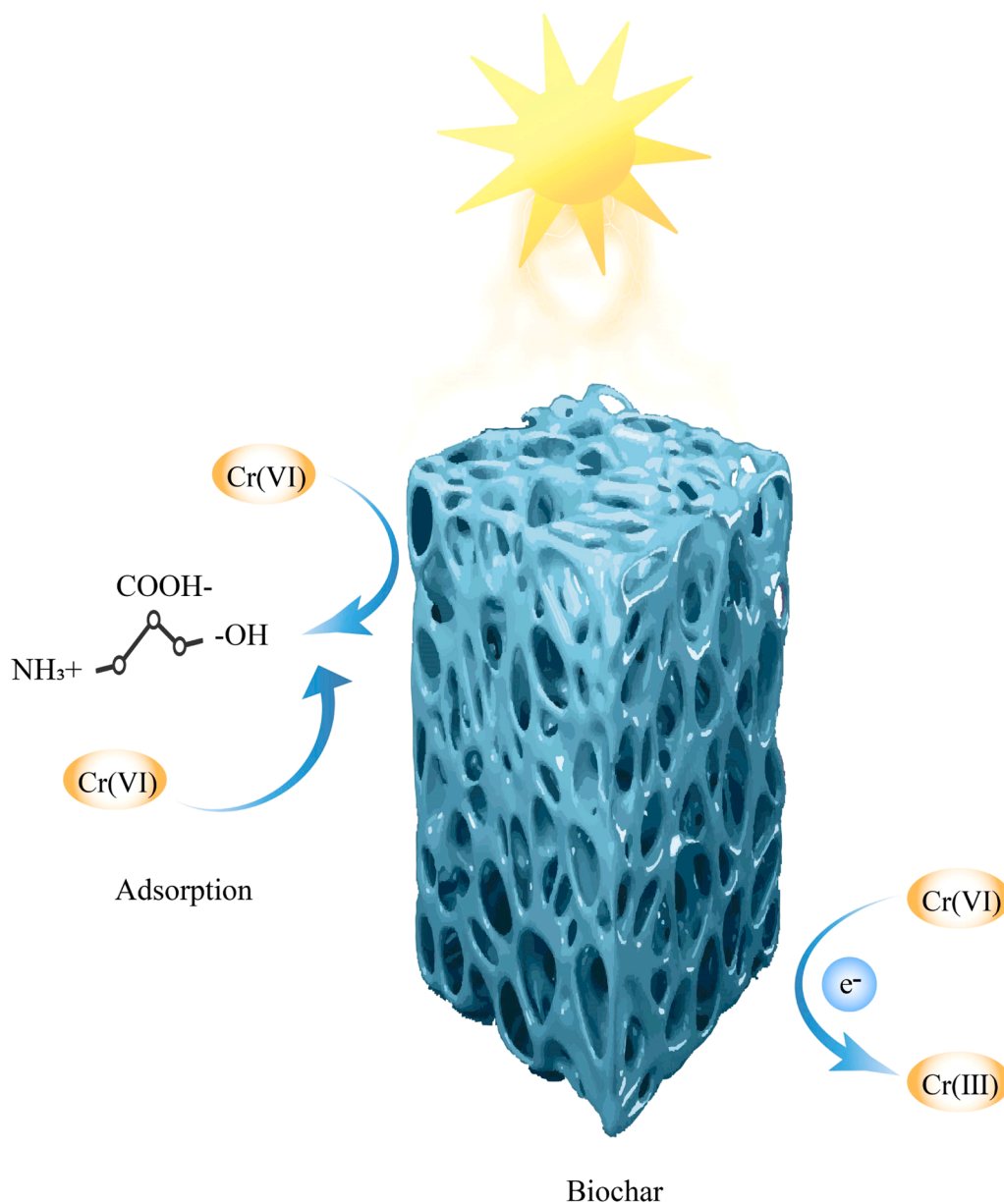


Fig. 7. Schematic illustration of the synergistic adsorption–reduction mechanism for Cr(VI) removal by photocatalytic materials.

porous nanofibers modified by green dry cold plasma have been shown to exhibit high formaldehyde adsorption capacity due to their well-developed pore networks and surface functionalities (Xiong et al., 2024). This work directly relates to VOCs remediation, demonstrating how controlled synthesis methods such as electrospinning and plasma activation can create hierarchical porous architectures that enhance both adsorption and subsequent photocatalytic degradation under irradiation. The inclusion of such advanced examples strengthens the discussion of VOCs applications and highlights the potential for process-engineered biochar structures to address air quality challenges.

These studies collectively underscore the excellent selectivity, visible-light responsiveness, and real-world applicability of biochar-based photocatalytic systems for gaseous pollutant treatment. Their application scope includes indoor air purification membranes, smart air filters, and VOCs abatement units in industrial or residential environments.

In these systems, biochar not only serves as a platform for the adsorption and enrichment of VOCs, capturing and concentrating molecules near catalytic sites, but also modulates the band structure and

enhances the composite's visible-light absorption. This dual role significantly contributes to improving the overall degradation efficiency and system responsiveness under real-world conditions.

To further elucidate the structure–function relationships governing the performance of these biochar-based photocatalytic systems, a comparative analysis of Tables 2–4 reveals several noteworthy trends. First, biochar derived from biomass with high porosity and oxygen-containing groups, such as sugarcane bagasse, fruit peels, or straw, tend to exhibit superior photocatalytic performance due to their strong adsorption capacity and effective charge transfer assistance. These precursors, when integrated with appropriate semiconductor components, promote spatial charge separation and redox reactions.

Second, the choice of synthetic method significantly influences catalytic outcomes. Hydrothermal, sol-gel, and multi-step pyrolysis–activation processes consistently outperform simpler one-step treatments, owing to their ability to generate hierarchical pore structures and active interfaces. For instance, materials constructed via hydrothermal assembly or plasma activation often show more uniform dispersion of nanoparticles and improved interfacial contact.

Table 5
Photocatalytic removal of heavy metal ions using biochar-based catalysts.

Biochar-based photocatalytic materials	Pollutants	Mechanism	Ref.
TiO ₂ /BC	Cr(VI)	Electron transfer + adsorption-catalysis	(Hou et al., 2022)
BC/T-BSA	Cr(VI)	Band control + adsorption-catalysis	(Deng et al., 2022)
TiO ₂ /BC	Cr(VI)	Electron transfer (Z-scheme) + adsorption-catalysis	(Du et al., 2024)
BW/NB	Cr(VI)	Electron transfer (Z-scheme) + enhanced light absorption	(Wang et al., 2020)
BW/NSBC	Cr(VI)	Electron transfer + ROS synergy	(Mao et al., 2021)
Bi/Fe ₃ O ₄ /BC	Cr(VI)	Enhanced light absorption + electron transfer	(Shen et al., 2021)
Fe ₂ TiO ₅ /BC	Cr(VI)	Electron transfer + adsorption-catalysis	(Herath et al., 2022)
ZnO/Cu ₂ O/BC	Cr(VI)	Band control + electronic transfer	(Soni et al., 2023)
nZVI/BC	Cr(VI)	Electron transfer + adsorption-catalysis	(Sun et al., 2022)
Fe ₂ O ₃ /CoFe ₂ O ₄ /BC	Cr(VI)	Electron transfer (S-scheme) + ROS synergy	(Yang et al., 2025)

Moreover, systems incorporating Z-scheme or S-scheme heterojunctions demonstrate notably higher degradation rates, particularly for complex pollutants such as antibiotics and Cr(VI), due to their ability to preserve high-energy charge carriers and suppress recombination. In contrast, Schottky-based structures enhance directional charge extraction, which is especially beneficial in heavy metal reduction and gas-phase photocatalysis.

Nevertheless, performance inconsistencies are observed across studies, partly due to variations in biomass sources and incomplete standardization of preparation protocols. In some cases, the photocatalytic efficiencies exceed 95 % within short reaction times, while others require extended irradiation or display limited reusability. These disparities underscore the need for a more systematic approach in correlating precursor characteristics, interfacial design, and pollutant-specific mechanisms.

4.4. Summary

Biochar-based photocatalytic materials exhibit remarkable synergistic effects and comprehensive performance advantages in the treatment of diverse environmental pollutants, positioning them as a promising direction in the development of next-generation functional materials for environmental remediation.

In the domain of water pollution treatment, biochar utilizes its high specific surface area and abundant surface polar functional groups to achieve selective adsorption of target contaminants. When integrated with semiconductor materials to form heterojunction structures, biochar significantly enhances the separation efficiency of photogenerated electron-hole pairs, thereby improving both photocatalytic degradation rates and pollutant enrichment at the reaction interface. This dual functionality leads to a notable improvement in overall purification efficiency.

In the removal of heavy metal ions, biochar offers numerous surface reduction sites and efficient electron transport pathways, facilitating the rapid photoreduction of highly toxic species such as Cr(VI). Moreover, several biochar-based composites exhibit excellent cycling stability and operational durability, underscoring their strong potential for practical engineering applications.

For atmospheric pollution control, especially in the treatment of low-concentration VOCs, biochar's adsorptive capability works synergistically with its light-responsive modulation properties. This enhances the photocatalytic degradation performance of the composite system,

making it well-suited for applications in indoor air purification, smart filtration membranes, and industrial gas-phase pollutant abatement.

In summary, biochar serves as a multifunctional platform that integrates selective adsorption, electron transfer regulation, and enhanced light harvesting. Through the synergistic coupling of its structural and electronic properties, biochar-based composites demonstrate high adaptability and efficiency across a wide range of pollution scenarios.

However, it should be emphasized that high pollutant removal efficiency does not necessarily equate to environmental safety. In practical applications, the photocatalytic degradation of dyes and antibiotics may generate intermediate products with unknown or even enhanced toxicity, while residual catalyst components or leached metal ions may pose additional ecological risks. Therefore, application-oriented studies should integrate ecotoxicological assessments of treated effluents, such as acute and chronic toxicity tests using aquatic organisms (e.g., *Daphnia magna*, algae, or zebrafish embryos), alongside conventional chemical analysis. Such bioassay-assisted evaluations are essential to verify whether photocatalytic treatment leads to a net reduction in ecological risk, thereby ensuring the environmental compatibility of biochar-based photocatalytic technologies (as shown in Fig. 8).

While current studies have demonstrated excellent initial removal efficiencies for a variety of pollutants, the long-term operational performance of biochar-based photocatalysts, such as structural stability, reusability over multiple cycles, and resistance to leaching or deactivation, remains insufficiently characterized. Only a limited number of reports provide systematic recyclability assessments, often without elucidating catalyst degradation mechanisms or surface evolution under realistic operational conditions. To advance real-world applicability, future research should prioritize standardized durability evaluation protocols and identify key factors governing long-term stability. Furthermore, comprehensive life-cycle assessments, including the monitoring of potential toxic by-products or metal ion release, are critical for ensuring the sustainable deployment of biochar-based photocatalytic materials.

These insights highlight the emerging emphasis on process-guided, structure-controlled strategies for efficient gas-phase pollutant remediation. In considering the broader landscape of carbonaceous materials for environmental applications, it is instructive to compare biochar with other widely used carbon supports. For example, activated carbon-based composites have been extensively reviewed for CO₂ capture, where their porosity, surface chemistry, and regeneration behavior are systematically analyzed (Kamran and Park, 2021). Such comparative frameworks can help elucidate the advantages and limitations of biochar relative to conventional activated carbons, particularly in terms of scalability, sustainability, and reusability. Integrating insights from CO₂ capture and other carbon material studies enhances the contextual understanding of biochar's role in photocatalysis, especially when evaluating long-term performance and life cycle considerations.

5. Current research challenges and development trends

Before analyzing the key technical and application challenges, it is important to clarify what sets biochar apart from other carbonaceous materials widely used in photocatalysis. The following comparative discussion aims to position biochar within this broader material landscape. In addition to its low cost and renewability, biochar exhibits a set of structural and chemical characteristics that distinguish it from other common conductive carbon materials such as graphene, carbon nanotubes, and conventional activated carbon. Unlike highly ordered carbon allotropes (e.g., graphene and carbon nanotubes), which primarily derive their conductivity from extended π -conjugated networks, biochar's carbon framework is inherently "disordered" and rich in heterogeneous domains, defect sites, and oxygen-containing functional groups. These features contribute not only to electrical conductivity but also to multifunctional interfacial behavior, including strong adsorption of reactants, enhanced pollutant preconcentration, and activation of

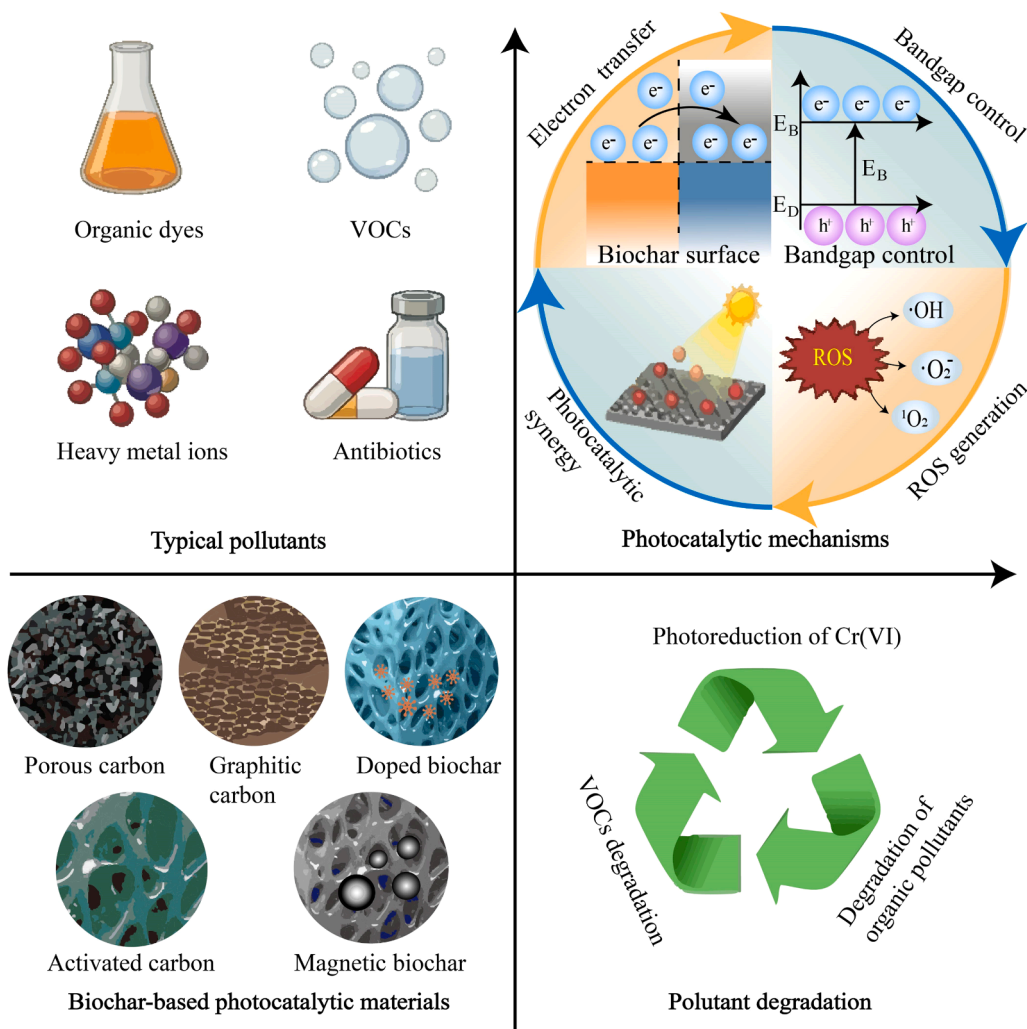


Fig. 8. Classification of mechanisms and performance comparison of biochar-based photocatalytic materials for typical pollutant treatment.

molecular oxygen, thereby facilitating synergistic coupling between adsorption and photocatalysis.

Specifically, the surface functional groups and defect sites in biochar (e.g., $-\text{OH}$, $-\text{COOH}$, edge defects) can act as localized electron reservoirs and trap sites for photogenerated carriers, effectively modulating surface charge density and promoting interfacial charge separation. This behavior contrasts with graphene or carbon nanotubes, which, although having excellent intrinsic conductivity, often require extensive functionalization to achieve comparable surface reactivity and pollutant affinity.

Compared with conventional activated carbon, whose porosity and surface area are often engineered primarily for adsorption, biochar typically retains in situ heteroatom dopants (e.g., N, S, P) and residual inorganic species derived from the biomass precursor. These intrinsic dopants can modulate the electronic structure, create mid-gap states, and promote redox activity without the need for further chemical modification. For example, recent work on nitrate and biochar@birnessite composite microspheres demonstrates the ability of a biochar matrix to support mixed metal oxide phases and to suppress adverse processes through strong interfacial interactions (Zhao et al., 2025). Although this study focuses on soil remediation rather than photocatalysis per se, it highlights how biochar's morphology, functional group landscape, and hybrid composite formation capacity can yield performance advantages beyond simple conductivity.

Taken together, these differences imply that biochar is not merely a cheap conductive support, but rather a tunable, multifunctional scaffold

whose hierarchical structure, surface chemistry, and intrinsic heterogeneity can be leveraged to enhance adsorption, charge separation, and ROS generation in photocatalytic systems. This comparison framework may also serve as a foundation for future systematic benchmarking of biochar against other carbon material classes under standardized photocatalytic conditions.

Despite the promising photocatalytic performance and wide application potential demonstrated by biochar-based composite materials in laboratory studies, their real-world deployment in environmental remediation remains hindered by several critical challenges. These issues primarily include: (i) variability in raw material sources, (ii) insufficient material stability, (iii) limited understanding of photocatalytic mechanisms, (iv) poor engineering adaptability, and (v) lack of comprehensive performance evaluation systems.

Addressing these obstacles is essential for accelerating the transition of biochar-based materials from experimental success to practical application. This section identifies and analyzes key barriers and proposes future development pathways to enable the sustainable and scalable utilization of biochar in environmental technologies.

Beyond application-driven challenges, it is also important to acknowledge several inherent material-level limitations of biochar-based photocatalysts to provide a balanced and realistic assessment. Compared with advanced carbon materials such as graphene, carbon nanotubes, or MXenes, pristine biochar generally exhibits lower intrinsic electrical conductivity due to its partially disordered carbon framework and limited graphitization degree. This can restrict long-range charge

transport and, in some cases, constrain photocatalytic efficiency.

In addition, biochar typically shows lower mechanical robustness and structural integrity, particularly under prolonged irradiation, fluid shear, or cyclic operation conditions. More importantly, the intrinsic variability arising from heterogeneous biomass feedstocks and sensitive pyrolysis conditions leads to batch-to-batch inconsistency in physicochemical properties, which poses a fundamental challenge for reproducibility, standardization, and engineering-scale deployment.

These inherent limitations do not undermine the unique advantages of biochar but underscore the importance of targeted structural regulation, composite design, and process standardization, which are discussed in the following sections.

5.1. Controllability of raw material sources and reproducibility of preparation

The structural and functional properties of biochar are intrinsically linked to the characteristics of its precursor biomass, as well as to the pyrolysis conditions and post-treatment protocols applied during synthesis. Commonly used feedstocks - such as crop residues, fruit shells, forestry biomass, and municipal sludge - exhibit wide variations in organic composition, ash content, and cellulose-to-lignin ratios. These compositional differences directly affect the resulting pore structure, surface functional groups, and electrochemical behavior, posing a major challenge to the standardization and scalability of biochar production.

More critically, even with identical feedstock types, variations in batch processing, including differences in pyrolysis temperature, atmospheric conditions, and heat transfer efficiency, can result in significant variations in carbon structure, heteroatom doping, and surface chemistry of the final product. These inconsistencies undermine the reproducibility, performance predictability, and quality control of biochar-based photocatalytic materials.

To overcome these limitations, future research should prioritize the establishment of a systematic structure–composition–process relationship, forming a clear mapping between biomass composition, pyrolysis parameters, and resulting material properties. This foundational understanding would support the development of controllable synthesis strategies and standardized production protocols.

Technologically, approaches such as multi-stage pyrolysis, controlled-atmosphere carbonization, catalytic activation with multi-phase agents, and uniform feedstock pretreatment hold great promise in enhancing material consistency. These methods can provide a solid technical basis for the stable, high-quality, and large-scale preparation of functional biochar materials, thereby facilitating their broader application in photocatalytic environmental remediation.

Representative studies have demonstrated that the integration of multiple synthesis and activation strategies can effectively regulate the pore architecture and surface chemistry of biochar. For example, eco-friendly porous bamboo-derived carbon microfibers prepared via steam explosion pretreatment, followed by carbonization and plasma activation, exhibited well-developed hierarchical porosity and enriched surface functional groups, leading to significantly enhanced gaseous formaldehyde adsorption performance (Su et al., 2023).

This multi-step synthesis route exemplifies a typical multi-scale tuning strategy, in which physical pretreatment, thermal conversion, and post-activation collectively determine the microstructural features and functional properties of biochar. Such approaches provide valuable insights into how advanced pretreatment and activation technologies can be leveraged to achieve more controllable and reproducible biochar materials for environmental applications.

This need for systematic correlation is further supported by previous studies on biomass-derived carbons for CO₂ adsorption, which demonstrate that variations in feedstock composition can lead to significant differences in pore structure and adsorption behavior, even under comparable synthesis conditions (Pu et al., 2021).

5.2. Material stability and potential environmental risks

Although biochar-based photocatalytic materials often demonstrate excellent initial activity under controlled laboratory conditions, issues related to structural stability and potential environmental risks present major obstacles to their practical application.

Over extended operation, these materials may suffer from declining adsorption capacity and impaired charge transfer efficiency. Such degradation can result from the loss of surface functional groups, pore structure blockage, or agglomeration of active components, all of which collectively lead to the attenuation of photocatalytic performance over time.

Certain metal-containing composites, such as those incorporating Ag, Cu, or Fe, are prone to metal ion leaching under acidic or oxidative conditions. This not only compromises the stability and efficiency of the photocatalyst but also poses the risk of introducing secondary pollution into the treated environment, potentially offsetting the environmental benefits of the treatment process.

Furthermore, while widely adopted strategies such as non-metal doping, defect engineering, and heterojunction construction can significantly enhance catalytic activity, insufficient interfacial bonding strength or lack of structural integrity may still lead to problems such as lattice distortion, interfacial delamination, and even catalyst deactivation under harsh operational conditions.

Therefore, chemical stability, mechanical robustness, interfacial durability, and long-term reusability should be regarded as critical evaluation criteria for assessing the environmental adaptability and engineering feasibility of biochar-based photocatalytic materials.

Future research should prioritize the design and development of structurally reinforced biochar composites with improved resistance to photocorrosion, enhanced interfacial stability, and, ideally, self-healing capabilities. These improvements will be essential for extending material lifespan, reducing secondary environmental risks, and promoting the safe and scalable application of photocatalytic technologies in real-world environmental remediation.

In addition to structural instability and metal ion leaching, the ecotoxicity of degradation intermediates represents a critical but often underestimated risk in real-world applications. Incomplete mineralization of antibiotics, dyes, and other complex organic pollutants may lead to the accumulation of transformation products that exert chronic toxicity on aquatic organisms or disrupt microbial community structures.

To enable a realistic assessment of environmental safety, quantitative ecotoxicity endpoints, such as LC₅₀, EC₅₀, or no observed effect concentration (NOEC) values obtained from standardized bioassays, should be incorporated into long-term stability and safety evaluations. The integration of such measurable biological indicators provides a scientific basis for identifying secondary pollution risks and guiding the design of safer biochar-based photocatalytic systems.

5.3. Quantitative analysis and dynamic tracking of catalytic mechanisms

Current investigations into the photocatalytic mechanisms of biochar-based materials remain largely qualitative, with limited efforts directed toward the quantitative characterization of key processes such as charge carrier dynamics, interfacial reactions, and the real-time evolution of reactive species. While conventional characterization techniques can provide valuable static data, such as elemental composition, surface functional groups, and surface area, they are often inadequate for elucidating electron transfer pathways, active site dynamics, and intermediate species behavior during photocatalytic reactions.

Zhao et al. (2024) successfully constructed a multi-objective optimized MoS₂/Cd-ZnIn₂S₄/CdS composite through in situ structural engineering. This highlights the synergistic effects between multiple modulations and the complexity involved in creating efficient charge transport pathways—a principle equally instructive for biochar-based

systems.

To achieve a deeper and more comprehensive understanding of the underlying catalytic mechanisms, it is essential to integrate advanced in situ and time-resolved analytical techniques. Methods such as time-resolved photoluminescence (TRPL), in situ Fourier-transform infrared spectroscopy (FTIR), and EPR can capture transient intermediates and monitor real-time charge transfer processes. These tools provide critical insights into dynamic reaction pathways, particularly the behavior of short-lived species and intermediate states under illumination.

In parallel, DFT calculations offer a powerful theoretical framework for probing electronic structure-level phenomena. This includes modeling doping configurations, energy level alignment at hetero-junction interfaces, and reaction energy barriers. Such simulations can help validate experimental findings and reveal atomic-scale mechanisms that are otherwise inaccessible through conventional methods.

Looking forward, the integration of machine learning algorithms with high-throughput computational modeling presents a promising direction for mechanism-driven material design. By constructing a three-dimensional coupling model of structure–mechanism–performance, researchers can systematically investigate nonlinear correlations among parameters such as the carbon-to-oxygen ratio, electrical conductivity, and pore structure distribution with respect to photocatalytic efficiency. This data-driven approach not only accelerates the discovery of high-performance materials but also enables predictive modeling and intelligent optimization based on fundamental mechanistic insights.

5.4. Barriers to translating laboratory findings into practical applications

Although biochar-based photocatalytic materials have shown promising pollutant removal efficiency in laboratory-scale studies, their real-world applicability remains significantly constrained by a series of practical and systemic challenges.

In environmental settings, natural water bodies and atmospheric systems typically contain complex pollutant mixtures, including organic contaminants, heavy metals, inorganic ions, and natural organic matter (NOM). These coexisting substances often induce competitive adsorption, catalytic site passivation, or interfacial fouling, thereby compromising the photocatalyst's reactivity and selectivity. However, current research is still predominantly focused on single-pollutant model systems, with limited studies addressing the co-degradation behaviors and competitive interactions among multiple pollutants in complex matrices.

Moreover, under continuous operational conditions, biochar-based materials are prone to structural deterioration, including pore collapse, surface active site loss, and metal ion leaching. These degradation phenomena contribute to performance attenuation or even complete deactivation. Existing stability assessments, often limited to 3–5 reuse cycles, fall short of representing the material's behavior under prolonged real-life use.

From a production standpoint, the large-scale synthesis of biochar-based composites currently lacks standardized protocols. Key synthesis parameters, such as pyrolysis temperature, atmosphere composition, doping techniques, and metal loading strategies, exhibit significant variability across studies, often leading to inconsistent material performance. In addition, critical engineering challenges, including material immobilization, reactor configuration, light source optimization, and continuous flow operation, have yet to be systematically resolved. These technological gaps severely hinder the scalability and industrial translation of laboratory findings.

To bridge the divide between experimental success and practical deployment, it is imperative to adopt a life cycle assessment (LCA) approach for a holistic evaluation of resource consumption, energy input, carbon footprint, and environmental impacts throughout the entire life span of the material - from raw material sourcing, synthesis, and operational use, to end-of-life disposal.

Simultaneously, techno-economic comparisons with existing commercial technologies, such as ozone oxidation, Fenton systems, and membrane filtration, should be carried out to evaluate performance–cost trade-offs, assess scalability, and identify the sustainability benefits of biochar-based photocatalysts. Only through such integrated assessments can these materials be positioned as viable alternatives for large-scale environmental remediation in the future.

In addition to technical and environmental challenges, economic feasibility remains a critical barrier to the large-scale deployment of biochar-based photocatalysts. Although biochar is derived from inexpensive and renewable biomass, the overall production cost is often increased by energy-intensive processes such as high-temperature pyrolysis, precise heteroatom doping, and complex composite formation. The lack of standardized synthesis protocols further contributes to batch-to-batch variability and increased costs associated with quality control and post-synthesis adjustment.

Moreover, the integration of biochar-based materials into functional photocatalytic systems typically requires additional processing steps, such as immobilization, shaping, or surface modification, which add to both material and operational costs. Compared to established technologies like ozonation, Fenton oxidation, and membrane filtration, biochar composites still face challenges in demonstrating clear cost advantages, especially under industrial-scale conditions that demand high throughput, long-term stability, and regulatory compliance.

To overcome these barriers, future research should focus on developing low-energy, scalable, and modular synthesis strategies, along with simplified composite integration processes. Parallel techno-economic assessments, benchmarking biochar-based systems against conventional treatment technologies, are essential for identifying application niches where biochar provides a distinct performance-to-cost advantage. These efforts are vital for positioning biochar not only as a sustainable material but also as a cost-effective solution for large-scale environmental remediation.

5.5. Requirements for establishing a comprehensive performance evaluation system

Current assessments of photocatalytic performance primarily rely on pollutant removal rates as the core metric. However, this single-dimensional indicator is insufficient to comprehensively reflect a material's purification capacity, reaction selectivity, and environmental compatibility. In practical applications, additional factors such as the degree of pollutant mineralization, degradation pathways, byproduct toxicity, and system stability must be holistically considered. For example, relying solely on concentration–time curves may confirm pollutant reduction, but fails to determine whether complete mineralization has occurred or if toxic intermediates remain, potentially leading to secondary pollution.

In real-world environments, pollutants rarely exist in isolation. The shift from single-pollutant degradation to synergistic removal of multiple pollutants has become a key frontier in addressing complex environmental contamination (Abdipour et al., 2024). This synergistic effect is not a simple summation but achieves efficient purification of multiple pollutants through mechanisms such as electron transfer, reactive species competition, or interfacial coupling.

Moreover, substantial methodological variability across existing studies, including differences in light source (e.g., visible vs. UV), irradiation intensity, pollutant type and concentration, reactor design (batch vs. continuous flow), and testing duration, further complicates result comparison. These inconsistencies hinder data integration, meta-analysis, and the establishment of reliable structure–activity correlations.

Therefore, there is an urgent need to establish a systematic and multidimensional performance evaluation framework. At the fundamental level, parameters such as apparent quantum efficiency (AQE) and total organic carbon (TOC) removal can be employed to evaluate

both photon utilization and mineralization depth. From a mechanistic perspective, techniques including quantitative analysis of ROS, pathway tracing of intermediates, and reaction kinetics modeling can clarify degradation pathways and rate-limiting steps.

In terms of environmental sustainability, metrics such as the Green Chemistry Metric (GCM), E-factor, specific energy consumption, and carbon footprint should be integrated to assess life-cycle impacts. Importantly, ecotoxicological safety should also be treated as a core evaluation dimension. Post-treatment toxicity assessments using bioassay models, such as *Daphnia magna* immobilization, algal growth inhibition, zebrafish embryo toxicity, or *Vibrio fischeri* luminescence inhibition, can provide quantitative biological endpoints (e.g., LC₅₀ and EC₅₀) to assess the potential hazards of degradation products. In addition to acute toxicity endpoints (e.g., LC₅₀), chronic toxicity indicators such as NOEC (No Observed Effect Concentration) or LOEC (Lowest Observed Effect Concentration) should also be incorporated, particularly for materials intended for long-term or continuous operation in aquatic environments. These multi-tiered assessments provide a more comprehensive picture of both immediate and cumulative ecological risks, particularly in long-term exposure scenarios, where sub-lethal effects may dominate ecological responses.

This multidimensional evaluation strategy is essential not only for aligning laboratory-scale development with regulatory and environmental safety expectations but also for promoting the safe and scalable application of biochar-based photocatalysts.

Finally, to improve comparability and reproducibility across studies, standardized experimental protocols and reporting guidelines are urgently needed. Harmonizing critical parameters, such as light intensity (e.g., mW cm⁻²), pollutant concentration, and reactor configuration, would enable robust benchmarking and predictive modeling, thereby facilitating more coherent and collaborative progress in this field.

Moreover, aligning performance metrics with international ecotoxicity evaluation frameworks, such as OECD guidelines, EU REACH, or USEPA protocols, can greatly enhance the regulatory readiness and public trust in biochar-based photocatalysts, facilitating their acceptance in real-world environmental remediation.

5.6. Integration of green synthesis and data-driven optimization in future design

In addition to addressing current technical limitations, the future development of biochar-based photocatalysts should actively incorporate green synthesis principles and data-driven optimization strategies to enhance environmental sustainability and accelerate material discovery.

Green synthesis approaches emphasize the use of environmentally benign, low-energy, and waste-minimizing processes. In the context of biochar, this includes the use of agricultural or food waste as renewable carbon sources, which not only reduce feedstock costs but also close material cycles. Thermochemical methods such as hydrothermal carbonization or low-temperature pyrolysis under inert or self-generated atmospheres offer scalable, energy-efficient routes to produce functionalized carbon materials. Furthermore, in situ heteroatom doping (e.g., nitrogen from protein-rich biomass, phosphorus from phytate-containing feedstocks) eliminates the need for post-synthetic modification and reduces the use of chemical reagents. Solvent-free, template-free, and one-pot composite formation strategies can also reduce environmental burdens associated with synthesis.

Parallel to green design, data-driven optimization offers a powerful framework to guide rational material development. Key tunable parameters such as bandgap energy, C/O ratio, specific surface area, pore volume, and defect density can be systematically linked to photocatalytic performance using machine learning models trained on experimental datasets or literature-mined data. Regression models, decision trees, and random forest algorithms can predict pollutant degradation efficiency or ROS yield from structural descriptors, while

clustering algorithms may reveal hidden structure–activity patterns. Additionally, Bayesian optimization or genetic algorithms can be employed to design multi-variable experimental workflows that converge toward optimal material configurations with fewer iterations.

Combining these two strategies, green synthesis and machine learning-guided optimization can lead to a more sustainable and efficient discovery pipeline for next-generation biochar-based photocatalysts. Looking ahead, establishing open-access databases and standardized reporting protocols for photocatalytic metrics would greatly facilitate the development of robust predictive models and accelerate material innovation in this field.

These future-oriented strategies not only offer a path toward more sustainable material development but also provide a practical roadmap for bridging the gap between laboratory-scale innovation and scalable environmental technologies. By integrating green chemistry principles with artificial intelligence-assisted design, the next generation of biochar-based photocatalysts can achieve higher performance, lower environmental burden, and faster transition from experimental proof-of-concept to real-world deployment.

6. Conclusions and outlook

Biochar-based photocatalytic materials exhibit great promise in environmental remediation, including the degradation of organic pollutants, heavy metal reduction, and gaseous contaminant removal. These capabilities are attributed to their high specific surface area, abundant functional groups, tunable pore structure, and excellent electron transport properties. Through the regulation of precursor composition, optimization of pyrolysis conditions, heteroatom doping, and interface engineering, the photocatalytic properties of biochar, such as light absorption, charge separation, and redox performance, can be significantly enhanced.

Biochar plays multiple roles within photocatalytic systems: as a pollutant adsorbent that promotes interfacial concentration, an electron mediator in heterojunction configurations (e.g., Z-scheme, S-scheme and Schottky), and a regulator of ROS generation through surface chemistry and defect engineering.

To further advance the field, the following research directions are suggested:

- (1) **Functional Design:** Develop multi-responsive biochar-based photocatalysts capable of adapting to environmental fluctuations such as pH, temperature, and light intensity. Nanoarchitectural design and interfacial modulation should be applied to tailor electronic properties and catalytic selectivity.
- (2) **Mechanistic Understanding:** Integrate advanced in-situ and time-resolved characterization techniques (e.g., TRPL, in-situ FTIR, EPR) with theoretical simulations (e.g., DFT) to gain insight into charge carrier behavior, surface reaction kinetics, and intermediate species evolution. Employ machine learning and high-throughput screening to establish structure–activity relationships and guide predictive material optimization.
- (3) **Engineering Translation and Safety Evaluation:** Promote the greening and decarbonization of biochar production by adopting standardized feedstocks and scalable, low-energy synthesis protocols. Emphasize improvements in long-term structural stability, material immobilization, and reactor engineering. Crucially, establish a comprehensive evaluation framework that incorporates not only technical performance and operational durability but also quantitative ecotoxicity endpoints (e.g., LC₅₀, EC₅₀, NOEC, LOEC) and life-cycle environmental impacts. This integrated approach will help ensure that photocatalytic treatments offer true environmental benefits without introducing secondary ecological risks.
- (4) **Cross-Disciplinary Applications:** Investigate the potential of biochar in terrestrial photoreactive environments, particularly

within illuminated surface soils and the rhizosphere, where biochar-microbe-light interfaces may provide a promising frontier for the development of photo responsive soil systems. Under natural sunlight, photosynthetically derived organic exudates could act as electron donors to support anaerobic respiration pathways in bacteria colonizing biochar surfaces. These microbial redox processes, when coupled with light-induced electron flow within the carbon matrix, may further modulate the catalytic behavior of biochar materials. Exploring such biochar-microbe-light interactions in terrestrial environments, especially within the rhizosphere, may open new opportunities for low-input, passive photocatalysis in agricultural pollution control and sustainable land management.

CRedit authorship contribution statement

Zhen Wang: Writing – original draft, Formal analysis, Data curation. **Qing Xiang:** Writing – review & editing, Methodology, Investigation, Funding acquisition. **Daixiong Zhang:** Software, Methodology, Funding acquisition. **An Xue:** Methodology, Conceptualization. **Yu Fang:** Software, Methodology, Visualization, Funding acquisition. **Shanshan Hu:** Methodology, Conceptualization.

Compliance with ethics requirements

This article does not contain any studies with human participants or animals performed by any of the authors.

Declaration of Competing Interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled.

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Data availability

No data was used for the research described in the article.

References

- Abdipour, H., Asgari, G., Seid-Mohammadi, A., Rahmani, A., Shokoohi, R., 2024. Investigating the efficiency of fixed bed colu6d nitrate from water. *Ecotoxicol. Environ. Saf.* 288, 117359. <https://doi.org/10.1016/j.ecoenv.2024.117359>.
- Ajiboye, T.O., Oyewo, O.A., Onwudiwe, D.C., 2021. Simultaneous removal of organics and heavy metals from industrial wastewater: a review. *Chemosphere* 262, 128379. <https://doi.org/10.1016/j.chemosphere.2020.128379>.
- Al Bacha, S., Saitzek, S., McCabe, E.E., Kabbour, H., 2022. Photocatalytic and photocurrent responses to visible light of the lone-pair-based oxysulfide Sr₆Cd₂Sb₆S₁₀O₇. *Inorg. Chem.* 61, 18611–18621. <https://doi.org/10.1021/acs.inorgchem.2c03040>.
- Alhawas, M.S., Rafique, M.I., Ahmad, M., Al-Wabel, M.I., Usman, A.R.A., Al-Swadi, H.A., Al-Farraj, A.S., 2023. Ball mill, humic acid, and rock phosphate-modified concarpus biochar for efficient removal of heavy metals from contaminated water. *Sustainability* 15 (14), 11474. <https://doi.org/10.3390/su151411474>.
- Allohverdi, T., Mohanty, A.K., Roy, P., Misra, M., 2021. A review on current status of biochar uses in agriculture. *Molecules* 26 (18), 5584. <https://doi.org/10.3390/molecules26185584>.
- Alsawy, T., Rashad, E., El-Qelish, M., Mohammed, R.H., 2022. A comprehensive review on the chemical regeneration of biochar adsorbent for sustainable wastewater

- treatment. *NPJ Clean. Water* 5 (1), 29. <https://doi.org/10.1038/s41545-022-00172-3>.
- Alves, Z., Ferreira, N.M., Figueiredo, G., Mendo, S., Nunes, C., Ferreira, P., 2022. Electrically conductive and antimicrobial agro-food waste biochar functionalized with zinc oxide particles. *Int. J. Mol. Sci.* 23 (14), 8022. <https://doi.org/10.3390/ijms23148022>.
- Amalanathan, M., Aravind, M., Ahmed, N., Mary, M.S.M., Velusamy, P., Kumaresubitha, T., Noreen, R., Ali, S., 2022. The influence of activated carbon annealing temperature on sunlight-driven photocatalytic dye degradation and biological activity. *Inorg. Chem. Commun.* 146, 110149. <https://doi.org/10.1016/j.inoche.2022.110149>.
- Cai, S., Huang, C., Wang, C., Zhang, L., Huang, K., Dong, H., Luo, H., Chen, K., Yao, S., Zhu, H., Sun, K., Li, G., Yang, T., Tang, B., Zou, B., Liu, T., 2024. New breakthrough in dye removal: ultrafast removal of high concentration MB with biochar-based organic photocatalysts under indoor light (30 W/m²) drive. *J. Clean. Prod.* 449, 141539. <https://doi.org/10.1016/j.jclepro.2024.141539>.
- Chauhan, S., Bhar, R., Ray, K., Chowdhury, S., Ghangrekar, M.M., Dubey, B.K., 2025. Enhanced visible light photocatalytic degradation of oxytetracycline through sugarcane bagasse biochar supported layered WS₂ type-II staggered heterojunction: towards performance, degradation pathway, toxicity, and life cycle assessment. *Environ. Res.* 271, 121100. <https://doi.org/10.1016/j.envres.2025.121100>.
- Chen, D., Cen, K., Zhuang, X., Gan, Z., Zhou, B., Zhang, Y., Zhang, H., 2022. Insight into biomass pyrolysis mechanism based on cellulose, hemicellulose, and lignin: evolution of volatiles and kinetics, elucidation of reaction pathways, and characterization of gas, biochar and bio-oil. *Combust. Flame* 242, 112142. <https://doi.org/10.1016/j.combustflame.2022.112142>.
- Chen, Zheng, Li, J., Zhang, J., Wang, H., Zeng, Y., Wang, F., Huang, P., Chen, X., Ge, L., Dahlgren, R.A., Gao, H., Huang, X., 2024. A highly efficient and recyclable living biocatalyst using Shewanella@polydopamine@NH₂-doped carbon dot biohybrids and polypyrrole immobilized melamine foam for microbial-photoreduction of Cr (VI). *J. Clean. Prod.* 435, 140497. <https://doi.org/10.1016/j.jclepro.2023.140497>.
- Chen, Zicheng, Zhang, X., Xu, K., He, X., Li, J., Zhang, L., Wang, G., 2024. Facile fabrication of nanocellulose-supported membrane composited with modified carbon nitride and HKUST-1 for efficient photocatalytic degradation of formaldehyde. *Int. J. Biol. Macromol.* 268, 131937. <https://doi.org/10.1016/j.ijbiomac.2024.131937>.
- Cheng, L., Zhang, Y., Fan, W., Ji, Y., 2022. Synergistic adsorption-photocatalysis for dyes removal by a novel biochar-based Z-scheme heterojunction BC/ZnS/WO₃: mechanistic investigation and degradation pathways. *Chem. Eng. J.* 445, 136677. <https://doi.org/10.1016/j.cej.2022.136677>.
- Dang, J., Pei, W., Hu, F., Yu, Z., Zhao, S., Hu, J., Liu, J., Zhang, D., Jing, Z., Lei, X., 2023. Photocatalytic degradation and toxicity analysis of sulfamethoxazole using TiO₂/BC. *Toxics* 11 (10), 818. <https://doi.org/10.3390/toxics11100818>.
- Darabdhara, J., Roy, S., Ahmaruzzaman, M., 2025. Pea pod-derived biochar-zeolitic imidazolate framework composite for the photocatalytic degradation of two organic dyes crystal violet and victoria blue. *Appl. Organomet. Chem.* 39 (2), e7833. <https://doi.org/10.1002/aoc.7833>.
- Daud, N.A., Rithwan, A.F., Sagadevan, S., Salaeh, S., Adnan, R., Imam, S.S., Kaus, N.H. M., 2024. Synergistic effect from integrated palm oil biomass biochar enhanced nanoplate bismuth oxybromide for fluoroquinolone photodegradation under xenon light irradiation. *J. Mater. Sci. Mater. Electron* 35 (24), 1653. <https://doi.org/10.1007/s10854-024-13361-2>.
- Demarema, S., Nasr, M., Ookawara, S., Abdelhaleem, A., 2024. Enhanced synergistic system for the persulfate activation under visible light using novel N–ZnO photocatalyst supported on Lantana camara-based biochar. *Chemosphere* 349, 140840. <https://doi.org/10.1016/j.chemosphere.2023.140840>.
- Deng, A., Wu, S., Hao, J., Pan, H., Li, M., Gao, X., 2022. Photocatalytic removal of Cr(VI) by thiourea modified sodium alginate/biochar composite gel. *Gels* 8 (5), 293. <https://doi.org/10.3390/gels8050293>.
- Dhanabal, R., Priya, P.G., 2025. Optimization and photocatalytic degradation of crystal violet dye using Sr-ZnO/activated carbon nanoneedles. *Mater. Sci. Semicond. Process* 192, 109481. <https://doi.org/10.1016/j.mssp.2025.109481>.
- Dong, G., Chi, W., Chai, D., Zhang, Z., Li, J., Zhao, M., Zhang, W., Lv, J., Chen, S., 2023. A novel Ag₃BiO₃/ZnO/BC composite with abundant defects and utilizing hemp BC as charge transfer mediator for photocatalytic degradation of levofloxacin. *Appl. Surf. Sci.* 619, 156732. <https://doi.org/10.1016/j.apsusc.2023.156732>.
- Dou, Z., Li, C., Ji, X., Lai, J., Fu, Q., Liu, H., Gong, S., Wu, J., 2025. Efficient degradation of tetracycline in wastewater by novel biochar-based photocatalytic materials: performance, photocatalytic mechanism and degradation pathways. *Res. Chem. Inter.* 51, 111–134. <https://doi.org/10.1007/s11164-024-05451-x>.
- Du, Y., Ye, X., Hui, Z., Jiao, D., Xie, Y., Chen, S., Ding, J., 2024. Synergistic effect of adsorption-photocatalytic reduction of Cr(VI) in wastewater with biochar/TiO₂ composite under simulated sunlight illumination. *Phys. Chem. Chem. Phys.* 26, 15891–15901. <https://doi.org/10.1039/d4cp01226g>.
- E, Z., Liang, J., Li, P., Qiang, S., Fan, Q., 2024. A review on photocatalytic attribution and process of pyrolytic biochar in environment. *Water Res* 251, 120994. <https://doi.org/10.1016/j.watres.2023.120994>.
- Enesca, A., Andronic, L., 2021. Photocatalytic activity of S-Scheme heterostructure for hydrogen production and organic pollutant removal: a mini-review. *Nanomaterials* 11 (4), 871. <https://doi.org/10.3390/nano11040871>.
- Fang, Q., Sun, Q., Ge, J., Wang, H., Qi, J., 2025. Multidimensional engineering of nanoconfined catalysis: frontiers in carbon-based energy conversion and utilization. *Catalysts* 15, 477. <https://doi.org/10.3390/catal15050477>.
- Feng, X., Li, X., Su, B., 2023. Photocatalytic degradation performance of antibiotics by peanut shell biochar anchored NiCr-LDH nanocomposites fabricated by one-pot hydrothermal protocol. *Colloid Surf. A Physicochem. Eng. Asp.* 666, 131337. <https://doi.org/10.1016/j.colsurfa.2023.131337>.

- Gasim, M.F., Choong, Z.-Y., Koo, P.-L., Low, S.-C., Abdurahman, M.-H., Ho, Y.-C., Mohamad, M., Suryawan, I.W.K., Lim, J.-W., Oh, W.-D., 2022. Application of biochar as functional material for remediation of organic pollutants in water: an overview. *Catalysts* 12 (2), 210. <https://doi.org/10.3390/catal12020210>.
- Goldaraz-Salamero, N., Baima, L., Moles, S., Sierra-Perez, J., Martinez, I., Murillo, R., Brun, F., Blanc, S., 2025. Opportunities for biomass valorisation through sorption-enhanced gasification: assessing environmental and economic aspects on biochar production. *Bioresour. Technol.* 434, 132772. <https://doi.org/10.1016/j.biortech.2025.132772>.
- Guo, F., Shi, C., Sun, W., Liu, Y., Lin, X., Shi, W., 2022. Pomelo biochar as an electron acceptor to modify graphitic carbon nitride for boosting visible-light-driven photocatalytic degradation of tetracycline. *Chin. J. Chem. Eng.* 48, 1–11. <https://doi.org/10.1016/j.cjche.2021.06.027>.
- Herath, A., Navarathna, C., Warren, S., Perez, F., Pittman, C.U., Mlsna, T.E., 2022. Iron/titanium oxide-biochar (Fe₂TiO₅/BC): a versatile adsorbent/photocatalyst for aqueous Cr(VI), Pb²⁺, F⁻ and methylene blue. *J. Colloid Interface Sci.* 614, 603–616. <https://doi.org/10.1016/j.jcis.2022.01.067>.
- Hou, N., Li, X., Jiang, X., Zhang, N., Wang, R., Li, D., 2022. The role of biochar in the photocatalytic treatment of a mixture of Cr(VI) and phenol pollutants: biochar as a carrier for transferring and storing electrons. *Sci. Total Environ.* 844, 157145. <https://doi.org/10.1016/j.scitotenv.2022.157145>.
- Kamran, U., Park, S.-J., 2021. Chemically modified carbonaceous adsorbents for enhanced CO₂ capture: a review. *J. Clean. Prod.* 290, 125776. <https://doi.org/10.1016/j.jclepro.2020.125776>.
- Kang, F., Jiang, X., Wang, Y., Ren, J., Xu, B.B., Gao, G., Huang, Z., Guo, Z., 2023. Electron-rich biochar enhanced Z-scheme heterojunctioned bismuth tungstate/bismuth oxyiodide removing tetracycline. *Inorg. Chem. Front* 10, 6045–6057. <https://doi.org/10.1039/d3qj01283b>.
- Kanwal, H., Khoja, A.H., Hajji, Y., Shakir, S., Anwar, M., Liaquat, R., Din, I.U., Bahadar, A., Hleili, M., 2025. Photocatalytic performance of dual-function selenium-enriched biomass-derived activated carbon as a catalyst for dye degradation and hydrogen production. *Int. J. Hydrog. Energy* 101, 1288–1303. <https://doi.org/10.1016/j.ijhydene.2024.12.509>.
- Karthik, P., Rajesh, J., Ravichandran, S., 2024. Enhancement photocatalytic activity of CeO₂ infused CA@Gelatin nanocomposites for the degradation of organic dyes under UV-light irradiation. *Surf. Interfaces* 50, 104474. <https://doi.org/10.1016/j.surfint.2024.104474>.
- Khalil, I.E., Das, P., Kucukkececi, H., Dippold, V., Rabeah, J., Tahir, W., Roeser, J., Schmidt, J., Thomas, A., 2024. Hierarchical porous covalent organic frameworks: the influence of additional macropores on photocatalytic hydrogen evolution and hydrogen peroxide production. *Chem. Mat.* 36, 8330–8337. <https://doi.org/10.1021/acs.chemmater.4c01298>.
- Khlifi, M.A., Hassan, W.H., Kadhum, A.A.H., Boujelbene, M., Almezhia, A.A., Diab, M.A., El-Sabban, H.A., Atamurotov, F., Abdvokhidov, A., 2025. Construction of a novel S-scheme CaIn₂S₄-ZnO/pine cone-derived biochar for enhanced visible-light-induced photocatalytic H₂O₂ production and antibiotic degradation. *J. Water Process. Eng.* 71, 107111. <https://doi.org/10.1016/j.jwpe.2025.107111>.
- Kilpinen, K., Tisler, S., Jørgensen, M.B., Mortensen, P., Christensen, J.H., 2024. Temporal trends and sources of organic micropollutants in wastewater. *Sci. Total Environ.* 957, 177555. <https://doi.org/10.1016/j.scitotenv.2024.177555>.
- Li, X., Fang, G., Qian, X., Tian, Q., 2022. Z-scheme heterojunction of low conduction band potential MnO₂ and biochar-based g-C₃N₄ for efficient formaldehyde degradation. *Chem. Eng. J.* 428, 131052. <https://doi.org/10.1016/j.cej.2021.131052>.
- Li, Xiang, Pan, A., Liang, F., Wang, J., Tian, Q., Yang, Q., Zhu, Y., Guo, W., Zhang, J., Fang, G., 2024. Enhanced organic pollutant and AOX degradation of lignin-biochar/ZnAl₂O₄/BiPO₄ with adsorption-photocatalysis synergy: roles of lignin-biochar. *J. Mol. Struct.* 1303, 137574. <https://doi.org/10.1016/j.molstruc.2024.137574>.
- Li, Xiaojian, Shi, X.-L., Wang, J., Shi, K., Wang, Q., 2024. Effect of different hydrogen donors on the catalytic conversion of levulinic acid to γ -valerolactone over non-noble metal catalysts. *J. Ind. Eng. Chem.* 138, 17–33. <https://doi.org/10.1016/j.jiec.2024.04.008>.
- Li, Yayaao, Zhang, A., Liu, Z., Yao, S., Zhou, R., Fu, Y., Zhou, Q., 2024. A study on the role of high-energy holes and reactive oxygen species in photocatalytic degradation using oxygen-doped/biochar-modified 2D carbon nitride. *J. Water Process. Eng.* 65, 105808. <https://doi.org/10.1016/j.jwpe.2024.105808>.
- Liang, L., Xi, F., Tan, W., Meng, X., Hu, B., Wang, X., 2021. Review of organic and inorganic pollutants removal by biochar and biochar-based composites. *Biochar* 3 (3), 255–281. <https://doi.org/10.1007/s42773-021-00101-6>.
- Liang, X., Zhao, Y., Liu, B., Li, J., Cui, L., Wang, C., Yang, Q., 2024. Phosphorus doped magnetic biochar activated PMS for effective degradation of pesticide in water: targeted regulation of interfacial charge transfer by phosphorus doping. *Sep. Purif. Technol.* 340, 126739. <https://doi.org/10.1016/j.seppur.2024.126739>.
- Liu, Wei, Che, H., Liu, B., Ao, Y., 2024. Unveiling the mechanism on photocatalytic singlet oxygen generation over rationally designed carbonylated carbon nitride. *J. Mater. Chem. A* 12 (22), 13427–13434. <https://doi.org/10.1039/d4ta00835a>.
- Liu, Yunfang, Dai, X., Li, J., Cheng, S., Zhang, J., Ma, Y., 2024. Recent progress in TiO₂-biochar-based photocatalysts for water contaminants treatment: strategies to improve photocatalytic performance. *RSC Adv.* 14 (1), 478–491. <https://doi.org/10.1039/d3ra06910a>.
- Liu, Xinkai, Liu, T., Zhou, Y., Wen, J., Dong, J., Chang, C., Zheng, W., 2024. Synergic effect of CuS and MgO for boosting adsorption-photocatalytic activity of S-doped biochar. *J. Phys. Chem. Solids* 185, 111781. <https://doi.org/10.1016/j.jpcs.2023.111781>.
- Liu, R., Wu, H., Shi, J., Xu, X., Zhao, D., Ng, Y.H., Zhang, M., Liu, S., Ding, H., 2022. Recent progress on catalysts for catalytic oxidation of volatile organic compounds: a review. *Catal. Sci. Technol.* 12 (23), 6945–6991. <https://doi.org/10.1039/d2cy01181f>.
- Liu, Y., Yu, X., Kamali, M., Zhang, X., Feijoo, S., Al-Salem, S.M., Dewil, R., Appels, L., 2023. Biochar in hydroxyl radical-based electrochemical advanced oxidation processes (eAOPs)-Mechanisms and prospects. *Chem. Eng. J.* 467, 143291. <https://doi.org/10.1016/j.cej.2023.143291>.
- Liu, Xinyu, Zhu, Y., Gao, S., Ren, Y., 2024. Synthesis and visible light catalytic activity of HC/BiOCl/BiOBr microspheres. *Appl. Phys. AMater. Sci. Process* 130 (10), 706. <https://doi.org/10.1007/s00339-024-07875-z>.
- Lu, Y., Cai, Y., Zhang, S., Zhuang, L., Hu, B., Wang, S., Chen, J., Wang, X., 2022. Application of biochar-based photocatalysts for adsorption-(photo)degradation/reduction of environmental contaminants: mechanism, challenges and perspective. *Biochar* 4 (1), 45. <https://doi.org/10.1007/s42773-022-00173-y>.
- Maaoui, A., Trabelsi, A.B.H., Ben Abdallah, A., Chagtm, R., Lopez, G., Cortazar, M., Olazar, M., 2023. Assessment of pine wood biomass wastes valorization by pyrolysis with focus on fast pyrolysis biochar production. *J. Energy Inst.* 108, 101242. <https://doi.org/10.1016/j.joei.2023.101242>.
- Mamaghani, A.H., Haghghat, F., Lee, C.-S., 2017. Photocatalytic oxidation technology for indoor environment air purification: The state-of-the-art. *Appl. Catal. B Environ.* 203, 247–269. <https://doi.org/10.1016/j.apcatb.2016.10.037>.
- Manikandan, S., Sasikumar, D., Rameshkumar, K.A., Thangappan, R., Kumar, R., Dhinesh, S., 2023. Bifunctional activities of phosphorus doped MnO₂ with activated carbon from Manilkara zapota peel bio-waste for supercapacitor and photocatalytic degradation of organic dye. *Ionics* 29 (2), 769–792. <https://doi.org/10.1007/s11581-022-04850-7>.
- Mao, W., Zhang, L., Liu, Y., Wang, T., Bai, Y., Guan, Y., 2021. Facile assembled N, S-codoped corn straw biochar loaded Bi₂WO₆ with the enhanced electron-rich feature for the efficient photocatalytic removal of ciprofloxacin and Cr(VI). *Chemosphere* 263, 127988. <https://doi.org/10.1016/j.chemosphere.2020.127988>.
- Mian, M.M., Liu, G., 2018. Recent progress in biochar-supported photocatalysts: synthesis, role of biochar, and applications. *RSC Adv.* 8 (26), 14237–14248. <https://doi.org/10.1039/c8ra02258e>.
- Nguyen, V.N., Sharma, P., Rowinski, L., Le, H.C., Le, D.T.N., Osman, S.M., Le, H.S., Truong, T.H., Nguyen, P.Q.P., Cao, D.N., 2024. Biochar-based catalysts derived from biomass waste: production, characterization, and application for liquid biofuel synthesis. *Biofuels Bioprod. Bioref.* 18 (2), 594–616. <https://doi.org/10.1002/bbb.2593>.
- Ouyang, T., Guo, J., Shen, H., Mu, M., Shen, Y., Yin, X., 2021. The Z-scheme transfer of photogenerated electrons for CO₂ photocatalytic reduction over g-ZnO/2H-MoS₂ heterostructure. *Nanoscale* 13 (43), 18192–18200. <https://doi.org/10.1039/d1nr05889d>.
- Ouyang, J., Zhou, L., Liu, Z., Heng, J.Y.Y., Chen, W., 2020. Biomass-derived activated carbons for the removal of pharmaceutical micropollutants from wastewater: A review. *Sep. Purif. Technol.* 253, 117536. <https://doi.org/10.1016/j.seppur.2020.117536>.
- Peng, H., Li, H., Li, B., Zhou, Y., Wen, J., Zheng, X., 2023. CuInS₂-MgO/S-doped biochar heterojunction for the efficient adsorption-photocatalytic elimination of cationic dye. *Chem. Phys. Lett.* 832, 140862. <https://doi.org/10.1016/j.cplett.2023.140862>.
- Pu, H., Tian, C., Zhang, H., 2024. Preparation of red TiO₂ with excellent visible light absorption from industrial TiOSO₄ solution for photocatalytic degradation of dyes. *ACS Omega* 9 (52), 51611–51622. <https://doi.org/10.1021/acsomega.4c09262>.
- Pu, Q., Zou, J., Wang, J., Lu, S., Ning, P., Huang, L., Wang, Q., 2021. Systematic study of dynamic CO₂ adsorption on activated carbons derived from different biomass. *J. Alloy. Compd.* 887, 161406. <https://doi.org/10.1016/j.jallcom.2021.161406>.
- Qu, K., Huang, L., Hu, S., Liu, C., Yang, Q., Liu, L., Li, K., Zhao, Z., Wang, Z., 2023. TiO₂ supported on rice straw biochar as an adsorptive and photocatalytic composite for the efficient removal of ciprofloxacin in aqueous matrices. *J. Environ. Chem. Eng.* 11 (2), 109430. <https://doi.org/10.1016/j.jece.2023.109430>.
- Racek, J., Sevcik, J., Chorazy, T., Kucerik, J., Hlavinek, P., 2020. Biochar - recovery material from pyrolysis of sewage sludge: A review. *Waste Biomass. Valoriz.* 11 (7), 3677–3709. <https://doi.org/10.1007/s12649-019-00679-w>.
- Sbacchi, M., Mamone, M., Morbiato, L., Gobbo, P., Filippini, G., Prato, M., 2023. Shining light on carbon dots: New opportunities in photocatalysis. *ChemCatChem* 15 (16), e202300667. <https://doi.org/10.1002/cctc.202300667>.
- Serna-Loaiza, S., Adamczyk, J., Beisl, S., Miltner, M., Friedl, A., 2022. Sequential pretreatment of wheat straw: Liquid hot water followed by organosolv for the production of hemicellulose sugars, lignin, and a cellulose-enriched pulp. *Waste Biomass. Valoriz.* 13 (12), 4771–4784. <https://doi.org/10.1007/s12649-022-01824-8>.
- Sharma, Amit Kumar, Sharma, Munish, Sharma, Arvind Kumar, Sharma, Munit, Sharma, Munish, 2023. Mapping the impact of environmental pollutants on human health and environment: A systematic review and meta-analysis. *J. Geochem. Explor.* 255, 107325. <https://doi.org/10.1016/j.gexplo.2023.107325>.
- Shen, X., Yang, Y., Song, B., Chen, F., Xue, Q., Shan, S., Li, S., 2021. Magnetically recyclable and remarkably efficient visible-light-driven photocatalytic hexavalent chromium removal based on plasmonic biochar/bismuth/ferroferric oxide heterojunction. *J. Colloid Interface Sci.* 590, 424–435. <https://doi.org/10.1016/j.jcis.2021.01.095>.
- Sheydaei, M., 2024. Investigation of heavy metals pollution and their removal methods: A review. *Geomicrobiol. J.* 41 (3), 213–230. <https://doi.org/10.1080/01490451.2024.2318227>.
- Song, G., Qin, F., Yu, J., Tang, L., Pang, Y., Zhang, C., Wang, J., Deng, L., 2022. Tailoring biochar for persulfate-based environmental catalysis: Impact of biomass feedstocks. *J. Hazard. Mater.* 424, 127663. <https://doi.org/10.1016/j.jhazmat.2021.127663>.
- Soni, V., Sonu, Singh, P., Thakur, S., Thakur, P., Ahamad, T., Nguyen, V.-H., Van Le, Q., Hussain, C.M., Raizada, P., 2023. Fabricating cattle dung-derived nitrogen-doped

- biochar supported oxygen-deficient ZnO and Cu₂O-based novel step-scheme photocatalytic system for aqueous doxycycline hydrochloride mitigation and Cr (VI) reduction. *J. Environ. Chem. Eng.* 11 (5), 110856. <https://doi.org/10.1016/j.jece.2023.110856>.
- Su, G., Xiong, J., Li, Q., Luo, S., Zhang, Y., Zhong, T., Harper, D.P., Tang, Z., Xie, L., Chai, X., Zhang, L., Wu, C., Du, G., Wang, S., Xu, K., 2023. Gaseous formaldehyde adsorption by eco-friendly, porous bamboo carbon microfibers obtained by steam explosion, carbonization, and plasma activation. *Chem. Eng. J.* 455, 140686. <https://doi.org/10.1016/j.cej.2022.140686>.
- Sun, A., Sun, M., Zhang, R., Zhu, H., Xing, Y., 2025. Surface and interface engineering of CAU-17/MXene Schottky heterojunction for efficient photocatalytic nitrogen fixation. *Sep. Purif. Technol.* 362, 131939. <https://doi.org/10.1016/j.seppur.2025.131939>.
- Sun, P., Wang, Z., An, S., Zhao, J., Yan, Y., Zhang, D., Wu, Z., Shen, B., Lyu, H., 2022. Biochar-supported nZVI for the removal of Cr(VI) from soil and water: Advances in experimental research and engineering applications. *J. Environ. Manag.* 316, 115211. <https://doi.org/10.1016/j.jenvman.2022.115211>.
- Sun, Y., Wang, T., Sun, X., Bai, L., Han, C., Zhang, P., 2021. The potential of biochar and lignin-based adsorbents for wastewater treatment: Comparison, mechanism, and application-A review. *Ind. Crop. Prod.* 166, 113473. <https://doi.org/10.1016/j.indcrop.2021.113473>.
- Sun, J., Zhang, B., Chen, W., Tao, Z., Liu, J., Wang, L., 2023. Biochar doped carbon nitride to enhance the photocatalytic hydrogen evolution through synergy of nitrogen vacancies and bridging carbon structure: Nanoarchitectonics and first-principles calculation. *Carbon* 209, 117988. <https://doi.org/10.1016/j.carbon.2023.03.063>.
- Tang, J.X., Jin, Y.T., He, Z.L., Hou, Q.Y., Zhao, C.T., 2018. A review of researches on biochar adsorbing organic pollutants and its mechanism and influence factors. *IOP Conf. Ser. Mater. Sci. Eng.* 392, 052030. <https://doi.org/10.1088/1757-899X/392/5/052030>.
- Tuoi, N.T., Nguyen, B.T.M., Tuyen, T.N., Lieu, P.K., Khieu, D.Q., Hung, N.V., 2024. Dispersion of ZnO or TiO₂ nanoparticles onto *P. australis* stem-derived biochar for highly efficient photocatalytic removal of doxycycline antibiotic under visible light irradiation. *Mater. Res. Express* 11 (9), 095601. <https://doi.org/10.1088/2053-1591/ad7448>.
- Wagner, M., Lin, K.-Y.A., Oh, W.-D., Lisak, G., 2021. Metal-organic frameworks for pesticidal persistent organic pollutants detection and adsorption - A mini review. *J. Hazard. Mater.* 413, 125325. <https://doi.org/10.1016/j.jhazmat.2021.125325>.
- Wan, Y., Liu, Q., Xu, Z., Li, J., Wang, Huijie, Xu, M., Yan, C., Song, X., Liu, X., Wang, Huiqin, Zhou, W., Huo, P., 2024. Interface engineering enhanced g-C₃N₄/rGO/Pd composites synergistic localized surface plasmon resonance effect for boosting photocatalytic CO₂ reduction. *Carbon Lett.* 34 (4), 1143–1154. <https://doi.org/10.1007/s42823-023-00683-0>.
- Wang, Y., Jia, G., Yang, P., Zhang, L., Wong, K.-Y., 2025. Bioinspired design of heterogeneous single-atomic-site catalysts for electrocatalysis and photocatalysis. *Adv. Mater.* 37, 2502131. <https://doi.org/10.1002/adma.202502131>.
- Wang, B., Lan, J., Bo, C., Gong, B., Ou, J., 2023. Adsorption of heavy metal onto biomass-derived activated carbon: review. *RSC Adv.* 13 (7), 4275–4302. <https://doi.org/10.1039/d2ra07911a>.
- Wang, T., Liu, S., Mao, W., Bai, Y., Chiang, K., Shah, K., Paz-Ferreiro, J., 2020. Novel Bi₂WO₆ loaded N-biochar composites with enhanced photocatalytic degradation of rhodamine B and Cr(VI). *J. Hazard. Mater.* 389, 121827. <https://doi.org/10.1016/j.jhazmat.2019.121827>.
- Wang, J., Wang, G., Yu, T., Ding, N., Wang, M., Chen, Y., 2023. Photocatalytic performance of biochar-modified TiO₂ (C/TiO₂) for ammonia–nitrogen removal. *RSC Adv.* 13 (35), 24237–24249. <https://doi.org/10.1039/d3ra03789d>.
- Wang, S., Yuan, B., Wu, C., Wang, C., Li, T., He, X., Huangfu, Y., Qi, J., Li, X.-B., Sha, Q., Zhu, M., Lou, S., Wang, H., Karl, T., Graus, M., Yuan, Z., Shao, M., 2022. Oxygenated volatile organic compounds (VOCs) as significant but varied contributors to VOC emissions from vehicles. *Atmos. Chem. Phys.* 2022, 1–36. <https://doi.org/10.5194/acp-22-9703-2022>.
- Wang, J., Zhang, S., Ma, S., Hao, X., Li, X., Xu, B., 2024. Silver nanoparticle-modified black phosphorus for photocatalytic properties. *ACS Appl. Nano Mater.* 7 (6), 6178–6184. <https://doi.org/10.1021/acsnan.3c05290>.
- Wijitkosum, S., 2022. Biochar derived from agricultural wastes and wood residues for sustainable agricultural and environmental applications. *Int. Soil Water Conserv. Res.* 10, 335–341. <https://doi.org/10.1016/j.iswcr.2021.09.006>.
- Wu, H., Miao, T., Deng, Q., Xu, Y., Shi, H., Huang, Y., Fu, X., 2022. Accelerating nickel-based molecular construction via DFT guidance for advanced photocatalytic hydrogen production. *ACS Appl. Mater. Interfaces* 14, 17486–17499. <https://doi.org/10.1021/acsnan.2c02107>.
- Wu, R., Zhang, H., Liu, W., Bai, R., Zheng, D., Tian, X., Lin, W., Li, L., Ke, Q., 2025. In-situ biomimetic synthesis of Ru-TiO₂/PC composite for photocatalytic dye degradation of wastewater under simulated sunlight. *J. Alloy. Compd.* 1011, 178418. <https://doi.org/10.1016/j.jallcom.2024.178418>.
- Wu, W., Zhu, S., Huang, X., Wei, W., Ni, B.-J., 2021. Mechanisms of persulfate activation on biochar derived from two different sludges: Dominance of their intrinsic compositions. *J. Hazard. Mater.* 408, 124454. <https://doi.org/10.1016/j.jhazmat.2020.124454>.
- Xia, X., Xu, B., Zhang, H., Ji, K., Ji, X., Wang, D., Yang, P., 2022. NiCoP/g-C₃N₄ Schottky heterojunctions towards efficient photocatalytic NO oxidation. *J. Alloy. Compd.* 928, 167207. <https://doi.org/10.1016/j.jallcom.2022.167207>.
- Xiao, L., Zhang, S., Chen, B., Wu, P., Feng, N., Deng, F., Wang, Z., 2023. Visible-light photocatalysis degradation of enrofloxacin by crawfish shell biochar combined with g-C₃N₄: Effects and mechanisms. *J. Environ. Chem. Eng.* 11 (3), 109693. <https://doi.org/10.1016/j.jece.2023.109693>.
- Xie, Y., Wang, L., Li, H., Westholm, L.J., Carvalho, L., Thorin, E., Yu, Z., Yu, X., Skreibeberg, O., 2022. A critical review on production, modification and utilization of biochar. *J. Anal. Appl. Pyrolysis* 161, 105405. <https://doi.org/10.1016/j.jaap.2021.105405>.
- Xiong, J., Wang, Y., Wang, H., Xie, L., Chai, X., Zhang, L., Peng, W., Wang, S., Du, G., Xu, K., 2024. Electrospun biomass carbon-based porous nanofibers modified by green-dry cold plasma for gaseous formaldehyde adsorption. *Ind. Crops Prod.* 222, 119769. <https://doi.org/10.1016/j.indcrop.2024.119769>.
- Xue, Q., Song, B., Feng, Q., Yu, Z., Hu, K., Yang, Y., Shen, X., 2024. Efficiently removal of tetracycline via synergistic photocatalysis with Fenton reaction with biochar/FeOOH. *Appl. Surf. Sci.* 645, 158869. <https://doi.org/10.1016/j.apsusc.2023.158869>.
- Yang, L., Fan, D., Li, Z., Cheng, Y., Yang, X., Zhang, T., 2022. A Review on the bioinspired photocatalysts and photocatalytic systems. *Adv. Sustain. Syst.* 6, 202100477. <https://doi.org/10.1002/adsu.202100477>.
- Yang, D., Wang, M., Xie, M., Peng, S., Lu, X., Chang, S., Fang, D., Yi, J., Wang, X., 2023. Photocatalytic degradation of formaldehyde by ruthenium vanadate quantum dots-V₂O₅ nanowires array. *Thin Solid Films* 775, 139863. <https://doi.org/10.1016/j.tsf.2023.139863>.
- Yang, Y., Yu, Z., Yang, S., Liu, W., Beldean-Galea, M.-S., Sean, G.P., Shan, S., Shen, X., Xue, Q., 2025. Construction of CoFe₂O₄/Fe₂O₃ S-type heterojunctions on biochar for activating peroxymonosulfate towards simultaneous removal of TC and Cr (VI). *Sep. Purif. Technol.* 354, 129157. <https://doi.org/10.1016/j.seppur.2024.129157>.
- Yuan, X., Cao, Y., Li, J., Patel, A.K., Dong, C.-D., Jin, X., Gu, C., Yip, A.C.K., Tsang, D.C.W., Ok, Y.S., 2023. Recent advancements and challenges in emerging applications of biochar-based catalysts. *Biotechnol. Adv.* 67, 108181. <https://doi.org/10.1016/j.biotechadv.2023.108181>.
- Zhang, C., Cha, L., Zhang, Z., Zhang, L., Li, Q., Fan, H., Zhang, S., Liu, Q., Qiao, Y., Tian, Y., Wang, Y., Hu, X., 2021. Pyrolysis of cellulose: evolution of functionalities and structure of bio-char versus temperature. *Renew. Sust. Energ. Rev.* 135, 110416. <https://doi.org/10.1016/j.rser.2020.110416>.
- Zhang, Y., Chen, K., Zhang, J., Huang, K., Liang, Y., Hu, H., Xu, X., Chen, D., Chang, M., Wang, Y., 2023. Dense and uniform growth of TiO₂ nanoparticles on the pomelo-peel-derived biochar surface for efficient photocatalytic antibiotic degradation. *J. Environ. Chem. Eng.* 11 (2), 109358. <https://doi.org/10.1016/j.jece.2023.109358>.
- Zhang, T., Wang, X., Sun, Z., Liang, Q., Zhou, M., Xu, S., Li, Z., Sun, D., 2020. Constructing Z-scheme based BiOI/CdS heterojunction with efficient visible-light photocatalytic dye degradation. *Solid State Sci.* 107, 106350. <https://doi.org/10.1016/j.solidstsci.2020.106350>.
- Zhang, Y., Wang, H., Sun, X., Wang, Y., Liu, Z., 2021. Separation and characterization of biomass components (cellulose, hemicellulose, and lignin) from corn stalk. *Bioresources* 16 (4), 7205. <https://doi.org/10.15376/biores.16.4.7205-7219>.
- Zhang, Q., Xing, S., Han, J., Feng, L., Li, J., Qian, Z., Zhou, J., 2025. Organic pollutant sensing for human health based on carbon dots. *Chin. Chem. Lett.* 36 (1), 0117. <https://doi.org/10.1016/j.ccl.2024.110117>.
- Zhang, Y., Xu, L., Wang, J., Pan, H., Dou, M., Teng, Y., Fu, X., Liu, Z., Huang, X., Wang, M., 2025. Bagasse-based porous flower-like MoS₂/carbon composites for efficient microwave absorption. *Carbon Lett.* 35, 145–160. <https://doi.org/10.1007/s42823-024-00832-z>.
- Zhang, H., Zhang, M., Gao, W., Liu, Y., Chen, J., Zhong, M., Li, W., Su, B., Lei, Z., 2025. Adsorptive-photocatalytic removal of organic dyes via biomass-derived nitrogen, oxygen-containing biochar-embedded Tin quantum dots catalyst. *J. Environ. Chem. Eng.* 13 (3), 116331. <https://doi.org/10.1016/j.jece.2025.116331>.
- Zhang, C., Zhao, S., Huang, Q., Liu, J., Zhang, Q., 2025. Adsorptive-photocatalytic removal of tetracycline from wastewater by Fe₃O₄- and SnO₂-containing biochar nanocomposites. *Biochar* 7 (1), 38. <https://doi.org/10.1007/s42773-024-00420-4>.
- Zhao, X., Chen, Y., Hu, J., Wang, H., Ye, Z., Zhang, J., Meng, J., Li, J., Dahlgren, R.A., Zhang, S., Gao, H., Chen, Z., 2025. Efficacy of nitrate and biochar/birnessite composite microspheres for simultaneous suppression of As(III) mobilization and greenhouse gas emissions in flooded paddy soils. *Environ. Res.* 279, 121757. <https://doi.org/10.1016/j.envres.2025.121757>.
- Zhao, W., Yan, A., Su, Z., Huang, F., Wang, Q., Li, S., Lu, S., Wang, C., Zhang, T., Zhang, J., Gao, Y., Yuan, H., 2024. Multiobjective-optimization MoS₂/Cd-ZnIn₂S₄/CdS composites prepared by in situ structure-tailored technique for high-efficiency hydrogen generation. *Small Struct.* 5 (7), 2300569. <https://doi.org/10.1002/sstr.202300569>.
- Zheng, X., Shen, Y., Li, B., Zhou, Y., Zheng, W., Dong, J., Chang, C., Wen, J., 2023. Bi-functional adsorption-photocatalysis activity of Ag₂S-MgO/S-doped biochar heterojunction for cationic dye removal. *Chem. Phys. Lett.* 833, 149098. <https://doi.org/10.1016/j.cplett.2023.149098>.
- Zhengyang, E., Liang, J., Dong, Y., Chao, Q., Li, P., Fan, Q., 2023. Different photoreduction processes of Cr(VI) on cellulose-rich and lignin-rich biochar. *Environ. Res.* 236 (2), 116819. <https://doi.org/10.1016/j.envres.2023.116819>.
- Zhou, Y., Wen, J., Dong, J., Zheng, W., Chang, C., Liu, T., Zheng, X., 2024. Efficient adsorption-photocatalysis activity of ternary ZnO-Sm₂O₃-MgO co-modified biochar for dye removal. *Appl. Organomet. Chem.* 38 (3), e7349. <https://doi.org/10.1002/aoc.7349>.