REVIEW ARTICLE

Study on the degradation of organic contaminants in water using biochar-based photocatalysts

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Photocatalysis is a recognized green and efficient method for treating organic pollutants in water, yet it faces challenges such as catalyst agglomeration, broad band gaps, and high carrier recombination rates. Biochar, a carbon-rich material with extensive surface functional groups and a porous structure, has been utilized to address these limitations. Its semiconductive and conductive properties significantly enhance photocatalytic performance. Despite the progress in the field of biochar-based photocatalysts, several challenges remain. This review focused on the degradation of organic substances in water using biochar-based photocatalysts. It explored the mechanisms through which biochar improved photocatalytic activity and identified existing gaps in the research of biochar-based materials. The insights aimed to inform and guide further applications and studies in this promising area.

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Introduction

As urbanization progresses, a diverse array of structurally complex organic compounds has been entering water bodies, posing severe threats to human health and ecological safety. The urgent need to manage organic pollutants in water has become apparent. Photocatalysis has attracted global attention due to its broad applicability, rapid reaction rate, mild operating conditions, and high efficiency in purification. In 2006, the term "biochar" first appeared in Nature [1], referring to a carbon-rich material produced by the thermal decomposition of organic matter in an oxygen-limited environment. Initially used as a soil amendment to enhance crop yields, deeper research into biochar has revealed its wide range of raw material sources, substantial surface area, complex surface functional groups, and rich porous structure. These features have continually unveiled its functional potential and expanding applications. Biochar has shown excellent performance in areas such as pollution remediation, carbon sequestration, photocatalytic degradation, and crop yield enhancement [2]. In the field of photocatalysis, many researchers investigated the inherent properties and structural advantages of biochar, using it as a photocatalyst, co-catalyst, or support for photocatalysts to degrade organic pollutants in water, achieving significant results [3, 4]. The number of publications has been increasing annually with researchers raising attention to biochar. Many investigations focused on the

adsorption capabilities of biochar and its modified materials when biochar was utilized for pollutants decontamination in water environment. Interestingly, the discovery of degradation products of organic pollutants during their adsorption by biochar has stimulated further research into biochar's pollutant degradation capabilities [5, 6]. Then, research focus turned to the photocatalysis capacity of biochar and biochar-based materials, leading to a rising trend in the number of publications and citations within the photocatalysis field in recent years. Notably, the citation frequency reached a significant number of 2,638 instances in 2023 using biochar and photo as the searching keywords in the Web of Science, which suggested that the use of biochar in photocatalysis has become a new focal point of interest.

Common photocatalysts often exhibit limitations, which include (1) catalyst agglomeration that electrostatic interactions between nanoparticles lead to agglomeration, inhibiting photocatalytic activity; (2) wide bandgap that some photocatalysts possess a wide band gap, only activatable by ultraviolet light, resulting in low light utilization efficiency; (3) high carrier recombination rate. These shortcomings restrict the practical applications of photocatalysts. Biochar-based photocatalysts offer potential solutions to these issues [7], primarily because (1) biochar contains abundant oxygen-rich functional groups, providing numerous binding sites for loading metal oxides, thereby theoretically enabling effective catalyst support; (2) biochar has a high specific surface area and adjustable porous structure. Its strong adsorption capacity for organic compounds facilitates the degradation of pollutants. Biochar-based photocatalysts can integrate the advantages of both adsorption and photocatalysis, enhancing the adsorption of target pollutants and providing adsorption sites for degrading intermediates; (3) biochar exhibits semiconductive and conductive properties. Upon loading, it can form H^+ ions, enhancing the stability of photocatalysts, reducing the band gap, and serving as an electron transfer channel

and electron acceptor that inhibits carrier recombination and increases the response to visible light [7-11]; (4) biochar helps prevent the agglomeration of photocatalysts, especially nanoscale photocatalysts, thereby reducing secondary pollution.

This review research integrated studies on the degradation of pollutants, introduced various biochar-based photocatalysts with a focus on the principles of photocatalytic degradation of organic substances by biochar and the mechanisms by which biochar enhances the photocatalytic activity of various catalysts, summarized the shortcomings of biochar-based photocatalysts in treating organic substances in water, and provided prospects for future research.

Photocatalytic properties of biochar

Historically, biochar has been widely utilized for the adsorption treatment of pollutants. However, adsorption alone does not eliminate pollutants from water, rather, it transfers them from the aqueous phase to the solid phase [12]. As a carbon-based material, biochar is endowed with abundant resources, an adjustable porous structure, a high surface area, and high conductivity. Its properties as a photocatalyst and co-catalyst are increasingly being recognized [13].

1. Raw biochar
Raw biochar is derived from its photocatalyst-like structure with its photocatalytic activity being influenced by the pyrolysis temperature [5]. Mu *et al*. demonstrated that biochar produced from high-temperature carbonization and hydrothermal carbonization of grapefruit peels exhibited photocatalytic degradation capabilities under visible light for Rhodamine B (RhB) with degradation rates of 39.8% and 50.1%, respectively, after 90 minutes [14]. The hydrothermally produced biochar showed enhanced photocatalytic performance due to its greater abundance of oxygen-containing groups.

Wu *et al*. found that biochar created through high-temperature pyrolysis could degrade RhB under UV light at a rate ten times greater than that in dark conditions, a capability closely linked to the graphite structure of the biochar and its surface oxygen groups (primarily C=O) [5]. Xiao *et al*. employed high-temperature pyrolysis and ball-milling techniques to produce nano-biochar, which contained a large number of oxygen-rich groups (O-C=O, -OH, C-O) and carbon defects [15]. Upon absorbing visible light, carbon defects in biochar could act as valence bands, while surface oxygen-containing groups served as conduction bands. Electrons generated at carbon defect sites transferred to the surface oxygen-containing groups, which produced H^+. The e^- reacted with O_2 to form $\cdot O_2^-$, and both $\cdot O_2^-$ and H^+ participated in the oxidation of enrofloxacin (EFA) in water. Notably, biochar produced at 300°C, which had a higher content of oxygen-containing groups (2.8 mmol/g), exhibited greater photocatalytic activity with an EFA degradation rate reaching 80.2%, significantly higher than that of biochar produced at other temperatures (33.3% at 370°C). Research by Fang *et al*. demonstrated that soluble organic matter (DOM) and oxygen-containing groups (especially carbonyl groups) in biochar could form $\cdot OH$ and $^1O_2$ under light excitation, further generating $\cdot O_2^-$, $H_2O_2\cdot$, and other radicals, which were the main active species in the degradation of phthalate esters [16].

2. Biochar from hyperaccumulator plants

Using hyperaccumulator plants to remediate soil pollution has become an effective and economical technique for managing heavy metal contamination in soils [17, 18]. However, the risk of secondary pollution such as leaching of heavy metals from hyperaccumulating plants during post-treatment severely limits the large-scale application of phytoremediation. Research has been conducted on converting plants enriched with heavy metals into biochar for pollutant treatment. Chen *et al*. utilized pyrolysis and hydrothermal carbonization to transform *Sedum alfredii*, a plant that accumulates cadmium, into CdS@C [19]. CdS@C exhibited a lower band gap

(2.01 eV) and higher H^+/e^- separation efficiency than pure CdS, resulting in improved light absorption capacity and photocatalytic efficiency. Upon illumination, it generated H^+, $\cdot O_2^-$, and $\cdot OH$, achieving a degradation rate of 99.8% for RhB in water after 120 minutes, significantly surpassing the 39.9% degradation rate of CdS alone. Cong *et al*. prepared CNT/ZnO from the zinc-accumulating plant *Physalis alkekengi* for the ultraviolet photocatalytic degradation of Bisphenol A (BPA), demonstrating a photocatalytic degradation rate of 86.5% for BPA [20]. Wang *et al*. treated *Sedum sarmentosum* with methanol and sulfuric acid to produce columnar nano-ZnO with a diameter of approximately 100 nm [21]. Photocatalytic experiments under a 30 W xenon lamp revealed the formation of $\cdot O_2^-$ and $\cdot OH$ with a degradation rate of 2-CP reaching 96.93% after 120 minutes of illumination. The use of hyperaccumulator plants to synthesize photocatalysts not only addresses the recycling issues of hyperaccumulator plants but also plays a positive role in reducing the production costs of photocatalysts.

3. Atomic doped biochar

By doping with heteroatoms to optimize the electronic and band gap structures, structural defects can be introduced, which lower the semiconductor band gap and enhance its optical, conductive, and luminescent properties, which includes both metal and non-metal doping. Metal atoms exhibit high catalytic activity and selectivity. Embedding single metal atoms can effectively adjust the band structure, electronic configuration, and surface structure, thereby influencing light response and photocatalytic activity. Biochar itself possesses a vast specific surface area and a rich array of functional groups, providing numerous surface sites for single atoms, which facilitates their integration. Dong *et al*. prepared Mn@N-Biochar using an impregnation calcination method, which demonstrated enhanced photocatalytic degradation of sulfonamides in water compared to raw biochar [22]. The enhancement was attributed to the Mn doping, where Mn atoms

served as active centers for photocatalysis. The interaction between Mn's d orbitals and N's p orbitals altered the electronic structure of the biochar. The electron-rich Mn atoms acted as electron pumps to transfer charge, inhibiting the recombination of electron-hole pairs and significantly boosting the photocatalytic capability of the biochar. Moreover, the abundant carbon defects and the lowered free energy barrier due to Mn modification in the biochar structure enhanced its adsorption capacity, light absorption capability, and electron separation efficiency. Upon photoexcitation, a large number of radicals (H^+, $\cdot O_2^-$, $\cdot OH$) were generated, increasing the removal rate of streptomycin from 52.44% before modification to 87.182% after modification. Compared to metal doping, non-metal doping with elements such as N, S, and I also effectively enhance the photocatalytic properties of biochar. Iodine doping involves complex surface charge transfers with a larger atomic radius than carbon and creates new micropores and mesopores in biochar, significantly increasing the surface area of the photocatalyst, which benefits the adsorption and degradation of pollutants. Additionally, the formation of I_3^- and I_5^- ions post-doping reduces the band gap of biochar, facilitates the generation of photoinduced carriers, decreases electron transfer resistance, and enhances the photocatalytic activity for degrading organic pollutants by over twenty orders of magnitude [23].

Biochar-based metal photocatalysts

1. Metal oxide biochar

Metal oxide semiconductors are noted for their excellent stability and have widespread applications in materials, energy storage, and catalysis. However, their wide band gaps generally only allow the utilization of ultraviolet light. Currently, the transition metal oxide semiconductors being extensively studied include TiO_2, ZnO, CuO, and others. TiO_2, one of the earliest and most widely researched photocatalysts, is favored for its non-toxicity, low cost, and high reactivity for degrading pollutants. However, TiO_2 also exhibits typical drawbacks such as a wide band gap, low light absorption rate, and high carrier recombination tendency. The rich oxygen-containing functional supports the loading of TiO_2 onto biochar. Additionally, the conductive nature of biochar plays a positive role in establishing electron transfer channels, improving electron-hole separation, and enhancing catalytic activity. Qu et al. loaded TiO_2 onto rice straw biochar and investigated its degradation of CIP under UV light exposure [10]. The results showed that, after binding to biochar through Ti-O, O-Ti-O, and Ti-O-C bonds, the catalyst exhibited good degradation performance within a wide pH range of 5 - 9 with an optimal degradation rate reaching 83.8%. Lu et al. found that the -OH, -COOH, and -CO oxygen-containing functional groups in rice husk biochar not only facilitated the adsorption of organic substances but also eased the loading of TiO_2 [24]. Furthermore, these groups acted as charge traps, significantly enhancing the charge transfer capabilities of TiO_2. Photocatalytic degradation experiments demonstrated that the loading of TiO_2 onto biochar significantly enhanced its utilization of visible light and stability. After five cycles, the removal capacity for methyl orange still reached 75.28 mg/g. Jiang et al. confirmed the presence of numerous Ti-O and Ti-C bonds in corn straw biochar-TiO_2 through characterizations such as Fourier transform infrared spectroscopy (FTIR), X-ray photoelectron microscopy (XPS), photoluminescence spectroscopy (PL), and electrochemical impedance spectra (EIS) [25]. The band gap of the loaded TiO_2 significantly decreased from 3.40 eV to 2.44 - 2.87 eV. A reduction in PL intensity and a decrease in the radius of the EIS spectrum indicated that biochar loading adjusted TiO_2 band gap, enhanced electron migration speed, inhibited photogenerated electrons and holes, and increased catalytic activity with an optimal degradation rate for methyl orange of 85.7%. ZnO is non-toxic, environmentally friendly, and possesses a high reduction potential at the conduction band edge and a high oxidation

potential at the valence band edge, which contribute to its high photocatalytic activity. However, its band gap of approximately 3.37 eV and absorption edge around 370 nm result in low solar energy utilization, and it exhibits poor stability in acidic and alkaline solutions, presenting significant limitations. The loading of ZnO onto biochar improves its light utilization and photocatalytic activity. Han et al. utilized a chemical precipitation method to load ZnO onto the surface and into the pore structure of hydrothermally produced biochar, resulting in the formation of biochar/ZnO [26]. This catalyst contained a large number of Zn-O and C-O-Zn bonds, indicating successful loading of ZnO onto biochar. Under the synergistic effects of biochar adsorption and ZnO catalysis, the degradation rate for methylene blue (MB) reached 98.2%, and even after four cycles, the degradation rate remained at 82.0%, demonstrating high stability. He et al. found that the addition of biochar significantly altered the structure and morphology of ZnO [27]. The composite featured numerous Zn-O-C bonds with ZnO presenting as hexagonal wurtzite phase and preferentially growing along the ZnO (002) diffraction peak. The morphology changed from the irregular cluster-like structure of pure ZnO to a more regular flower-like structure. The absorption edge shifted from the ultraviolet region at 396 nm to the visible light region at 407 nm, and the band gap decreased from 3.19 eV to 3.13 eV. These changes significantly enhanced the composite's adsorption and photocatalytic capabilities toward MB with the degradation rate increasing from 72.05% to 98.71%. CuO and Cu_2O particles are non-toxic, simple to produce, abundant in resources, cost-effective, and stable, which are their main advantages. They are extensively used across various fields. Unlike ZnO, they are narrow band gap p-type semiconductors with band gaps approximately ranging from 1.2 eV to 1.9 eV for CuO and from 1.8 eV to 2.17 eV for Cu_2O, which allows for a wide range of light absorption. However, they also face issues with the separation of photogenerated electron-hole pairs and aggregation. The conductive nature of biochar can accelerate electron transfer and

effectively inhibit aggregation, addressing the shortcomings of CuO and Cu_2O. The EIS arc radius of biochar-modified Cu_2O is significantly smaller than that of Cu_2O alone, and the transient photocurrent is considerably enhanced, indicating that the loading of biochar effectively delays [28]. Zheng's study also indicated that the abundant oxygen vacancies/hydroxyl groups on biochar could bond with Cu_2O, which resulted in the Cu_2O-loaded composite and improved visible light absorption properties. Under visible light irradiation, the generation of superoxide radicals ($\cdot O_2^-$) from Cu_2O/biochar was significantly higher than from Cu_2O alone, resulting in a noticeable enhancement in both the degradation rate and efficiency of dyes such as methylene blue when supported on biochar. Due to differing valence and conduction band positions of CuO and Cu_2O, the formation of a Cu_2O-CuO heterojunction facilitated the transfer of electrons from the conduction band of Cu_2O to that of CuO, while holes migrated from the valence band of CuO to that of Cu_2O. This heterostructure further improved the separation efficiency of the charge carriers. However, the transfer rate of photogenerated electrons of Cu_2O-CuO to the solution was slow, and the photocurrent density of Cu_2O-CuO was relatively limited. Biochar could capture electrons to accelerate the separation of electron-hole pairs. Using hydrothermal synthesis, Cu_2O-CuO was supported on biochar to produce Cu_2O-CuO@biochar. This composite exhibited a pseudo-first-order rate constant (k_{app}) of 2.1×10^{-2}/min, which was 3.5 times higher than that of Cu_2O-CuO alone, significantly enhancing the photocatalytic efficiency [29].

2. Metal sulfide biochar photocatalysts
Semiconductor metal sulfide photocatalysts have garnered significant to their light absorption properties in the visible spectrum, high specific surface area (SSA), and abundant. Tin SnS_2 is an n-type semiconductor and part of the two-dimensional, layered metal dichalcogenide family. Due to its strong anisotropic optical properties, it has recently garnered widespread attention. Gadore et al. found that, when SnS_2 was combined with biochar, the photocatalytic

activity was significantly enhanced although optimizing the biochar load was crucial for achieving the best catalytic performance of SnS_2/biochar [30]. Compared to SnS_2/biochar composited with 8% and 12% biochar, the addition of 10% biochar showed the most notable improvement in light absorption capacity and photogenerated carrier separation efficiency. Furthermore, the authors investigated the degradation of amoxicillin and Congo red in lake water, tap water, mineral water, and distilled water using SnS_2/biochar, discovering that the degradation was most effective in distilled water. They also examined the impact of common anions, cations, and organic substances on the degradation process. The results indicated that, aside from a slight promotion of degradation by Fe^{2+}, other ions (Na^+, Ca^{2+}, Al^{3+}, Cl^-, F^-, CO_3^{2-}, SO_4^{2-}) and HA generally inhibited the degradation to varying degrees. This inhibition was attributed to these ions and organic matter competing with target pollutants for adsorption sites and free radicals. Meanwhile, the presence of Fe^{2+} in water promoted the generation of free radicals through a Fenton-like reaction. Although the study designed experiments with actual water bodies and investigated the individual impacts of common ions and organic substances on photocatalysis, it did not address the presence of other ions such as K^+, Mg^{2+}, and HCO_3^- in the water, nor did it explore scenarios involving the coexistence of multiple ions and organic compounds. Further exploration of the underlying mechanisms remained necessary. The researchers also found that, after loading SnS_2 onto biochar, the photoluminescence spectrum intensity of SnS_2/biochar was significantly reduced, the absorption edge shifted to longer wavelengths, covering the entire visible light spectrum [30]. This indicated that biochar played a positive role in inhibiting carrier recombination and enhancing light absorption capabilities. The degradation rates of amoxicillin and Congo red by SnS_2/biochar reached 93.72% and 98.43%, respectively. Moreover, the authors discovered a synergistic effect between the adsorption capacity of biochar and the photocatalytic ability of SnS_2. The organic substances adsorbed by

biochar were degraded by SnS_2, which freed more active sites for continued adsorption and degradation. Consequently, the final degradation rate through direct photocatalysis was higher than that achieved by the combination of dark adsorption followed by photocatalysis.

3. Multimetallic hybrid biochar

To further enhance the performance of biochar-based photocatalysts, multimetallic compounds supported on biochar have also been employed in the degradation of organic substances. Characterization results of the photocatalysts indicated that, after loading $PbMoO_4$, a p-type semiconductor, onto biochar, the photoluminescence intensity was reduced and the photoresponse spectrum was elevated, suggesting a higher efficiency in the separation of photogenerated carriers [9]. The adsorption rate increased from 4.69% for unmodified $PbMoO_4$ to 38.36% for PBC-2. The degradation rate over 120 minutes (catalytic only) improved from 20.84% to 23.84%, and the total degradation rate (adsorption + photocatalysis) rose from 25.46% to 55.03%, representing a 1.6-fold increase. The pseudo-first-order rate constant for PBC-2 was higher than before compositing from 0.0018/min to 0.0047/min, and the specific surface area increased from 4 m²/g to 29 m²/g. Dey *et al*. had approached the adjustment of the bandgap width by doping Zn NPs, which had a relatively large particle size and narrower E_g, into CeO_2 to lower the bandgap [31]. Subsequently, Zn NPs-doped CeO_2 was supported on biochar to prevent photocatalyst sintering and agglomeration. Characterization of the photocatalytic performance revealed that, under the influence of biochar, Zn/CeO_2@BC extended the light absorption range of Zn/CeO_2 from the ultraviolet region (450 nm) to the visible light region (550 nm) with the bandgap decreasing from 2.8 eV to 2.1 eV, effectively enhancing the photocatalytic activity. Other studies utilized ball milling to produce Ag/TiO_2-biochar composites with varying Ag/Ti ratios and investigated their degradation effects. The results showed that, upon UV light excitation of TiO_2, electrons were rapidly transferred to the surface of Ag and

biochar, reacting with O_2 to form radicals. These radicals captured dye molecules absorbed on the surface, breaking molecular bonds such as C-S=C, aromatic rings, and C-N bonds. During the dye degradation process, the adsorptive and conductive properties of biochar, the low Fermi level of Ag, and the Schottky barrier enhanced the e-interfacial charge transfer and photocatalytic activity. The synergistic interaction among these components achieved complete degradation of methylene blue (MB) and Congo red (CR).

Other biochar-based photocatalysts

1. C_3N_4 biochar

As a non-metallic photocatalyst, graphitic carbon nitride (g-C_3N_4) is favored for its straightforward synthesis and stable properties. However, its high carrier recombination rate and limited light response range constrain its applications. Biochar can enhance the visible light absorption of g-C_3N_4, improve charge separation efficiency, reduce electrical conductivity, and enhance photocatalytic and peroxymonosulfate (PMS) activation capabilities [32]. When sulfur-doped g-C_3N_4 is combined with biochar, the bandgap of C_3N_4 is further reduced, and biochar also acts as an electron acceptor to attract electrons and inhibit electron-hole recombination [33]. After compositing with biochar, the degradation rate of methyl orange by g-C_3N_4/CdS reaches up to 99%. Ma *et al*. conducted focused studies on the mechanism behind the improved photocatalytic activity using UV-Vis spectroscopy, PL, EIS, and transient photocurrent responses (TPR) analyses [34]. It was found that biochar could rapidly transfer electrons at the heterojunction interface, reduce interface resistance, significantly lower the intensity of PL and the radius of EIS, and shift the absorption edge to 590 nm redshift. However, the amount of biochar added significantly affected the photocatalytic activity. Excessive biochar could create a masking effect that impeded the absorption of light by C_3N_4.

2. MOFs biochar

Metal-organic frameworks (MOFs) are porous crystalline structures composed of organic linkers and metal ions, known for their large specific surface area and adjustable pore sizes. Many MOF materials also exhibit semiconductor properties, but the displacement of binding ligands can compromise the structural integrity of MOFs, and competitive blocking by water at active sites may impact adsorption of target compounds. Thus, enhancing the stability of MOFs is crucial when used for water treatment. The photocatalyst MOF-MBC, a hybrid of MIL-53-Fe, Fe_3O_4, and biochar, demonstrated photocatalytic capabilities for the degradation of RhB [35]. Biochar served as a dispersant on the surface of MOFs, playing a significant role in reducing particle agglomeration, increasing mechanical strength, and improving the degradation of organic substances. MIL-125(Ti) was characterized by its crystal stability and high porosity, but its high bandgap of 3.6 eV limited its light utilization. After modification with biochar, the light absorption range was extended to 800 nm. The synergistic action of biochar and MOF materials enhanced the separation efficiency of electron-hole pairs and the degradation performance for TC, achieving a degradation rate of 94.62% and a TOC removal rate of 84.01%.

Challenges and research outlook

With researchers enhancing photocatalytic performance through structural improvements and performance tuning of biochar-based photocatalysts, numerous biochar-based photocatalysts have been employed for the efficient degradation of dyes, antibiotics, and persistent organic pollutants in water bodies. However, research on the degradation of organic substances using biochar-based photocatalysts still faces many challenges. Current research primarily focuses on photocatalysis of simulated wastewater with fewer studies applying these techniques to actual wastewater. Natural aquatic environments often contain multiple pollutants coexisting, making the environmental factors

affecting degradation highly complex. Conclusions and degradation mechanisms derived from simulated wastewater in laboratory settings need further exploration for application in actual water bodies. Most current studies use mercury lamps to simulate ultraviolet light or xenon lamps to simulate sunlight. However, these artificial light sources generally have a higher intensity than real sunlight. Studies using direct sunlight as the photocatalytic light source are comparatively rare. Therefore, when applying biochar-based photocatalysts to actual wastewater and natural water bodies, research urgently needs to be intensified on the impact of light intensity on the degradation of organic substances by biochar-based photocatalysts. The long-term stability of photocatalysts still requires extensive study. Current research on the stability of biochar-based photocatalysts typically involves cyclic photocatalytic experiments, where the photocatalyst, after completing one degradation cycle, is separated and entered the next photocatalytic reaction. After 5 - 10 cycles, studies assess whether there is a significant decline in photocatalytic capability. However, photocatalysts, especially in water with high concentrations, are at risk of loss, metal element leaching, and poisoning. A few cycles of testing do not adequately provide stability data, necessitating longer-term or more frequent stability experiments. In terms of economic and ecological assessment of biochar-based photocatalysts, the raw materials for biochar generally come from agricultural and forestry waste, which are low-cost resources. However, the addition of transition metals, precious metals, and other elements complicates the overall process and increases costs. Moreover, the production of biochar is associated with the emission of greenhouse gases, particulates, and other pollutants, leading to a lack of robust quantitative assessment of the full economic and ecological value of biochar-based photocatalysts. Recent research has primarily focused on enhancing the degradation performance of photocatalytic composite materials with numerous studies on the processes and mechanisms of photocatalytic reactions.

However, there is a lack of systematic research on the toxicity and ecological effects of biochar and its composite materials. There is minimal investigation into the toxic effects and damage mechanisms that biochar-based catalysts may cause to organisms and ecosystems under photonic excitation.

Acknowledgements

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