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Techniques and applications of advanced oxidation processes for degrading pollutants in wastewater using biochar-based catalysts: a critical review

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Abstract

Proper waste disposal is crucial for sustainable development. However, human activities have contributed to environmental pollution, particularly in water, through the discharge of untreated wastewater. An effective and environmentally friendly wastewater treatment solution is the use of biochar derived from carbonaceous materials or biomass. This review critically examines the synthesis of biochar-based (BC-based) catalysts, the mechanisms underlying their catalytic performance, the synergistic effects of combined BC-based systems, and their applications in wastewater treatment using advanced oxidation processes (AOPs). Reports from various studies indicate that combining biochar with graphitic carbon nitride (g-C_3N_4) enhances water splitting, hydrogen production, and pollutant degradation. Findings also reveal that under visible-light irradiation, numerous reactive oxygen species are generated for the photocatalytic degradation of organic pollutants in wastewater. Fe-Cu-doped hollow biochar sphere-supported TiO_2 exhibited remarkable removal of rhodamine B (99.2%), thereby revealing the significance of reactive radicals and the high surface area of the

functionalized biochar. Additionally, findings reveal that little attention has been given to microbial inactivation in wastewater, with most research focusing on *Escherichia coli* among other microorganisms. Future studies should focus on developing multifunctional and eco-friendly BC-based composites with validated performance in real-world wastewater treatment to ensure scalability, practical applicability, and environmental safety.

Keywords: Biochar; Adsorption; Environmental remediation; Photocatalysis; Wastewater treatment

1. Introduction

Wastewater, comprising both domestic and industrial waste, greatly affects the environment and public health (Teodosiu et al., 2018). The vast majority of wastewater discharged from diverse activities contains numerous harmful pollutants (e.g., heavy metals, polycyclic aromatic hydrocarbons, organic dyes, phenols, pesticides, pharmaceuticals) that are released into the environment untreated. These pollutants in untreated wastewater may pollute soil, water, and air (Dhamorikar et al., 2024). Many of these pollutants are persistent and resistant to degradation, enabling their accumulation in ecosystems and entry into the food chain. As a result, humans at higher

trophic levels are particularly susceptible to exposure via contaminated food and water (Nambowa et al., 2024). Among these pollutants, heavy metals are highlighted briefly for their unique biological relevance. Although certain essential metals (e.g., iron, zinc, and copper) are required at trace levels for normal cellular function, both their dysregulation and exposure to toxic heavy metals (such as lead, cadmium, and mercury) can disrupt metal homeostasis and impair fundamental biological processes, including glycosylation (Durin et al., 2023). Such disruptions can contribute to the development of severe and potentially deadly diseases (Adeleke et al., 2025). These challenges are further exacerbated by the inadequate removal efficiency of conventional wastewater treatment methods, which have resulted in the continuous discharge of these pollutants into aquatic environments, thereby posing significant environmental and public health risks (Afzal et al., 2024; Balali-Mood et al., 2021; Gworek et al., 2019; Sanusi et al., 2023). Therefore, the development of alternative, cost-effective wastewater treatment strategies capable of efficiently removing these harmful contaminants is essential to support sustainable development and protect ecosystems.

Biochar (BC), produced by carbonizing cellulosic or non-cellulosic biomass under anaerobic or low-oxygen conditions (Moreira et al., 2017), offers lower production costs and improved availability as a precursor material (Dong et al., 2021). Biomass comprises living organisms such as plants, animals, and microbes (Chavan et al., 2022). BC-based adsorbents and catalysts have gained significant attention in recent years as environmental cleanup agents.

Nonetheless, adsorptive separation alone cannot completely remove contaminants from solutions, as it involves transporting pollutants through a medium from one phase to another (Gupta et al., 2022). Contaminant adsorption onto BC can occur through mechanisms such as pore filling, complexation, precipitation, ion exchange, hydrogen bonding, π–π electron-donor–acceptor interactions, and electrostatic attraction. Removal efficiency can be further enhanced through biochar activation, surface modification, material impregnation, or integration with complementary treatment strategies (Gupta et al., 2022). In contrast, advanced oxidation processes (AOPs) are sustainable techniques for degrading various organic contaminants without secondary pollution (Sikandaier et al., 2024; Y. Yang et al., 2021). In particular, photo-Fenton, an advanced oxidation process that combines photolysis with Fenton processes, uses Fe^{2+} and H_2O_2 to generate highly reactive hydroxyl radicals (•OH). These reactive species rapidly degrade organic contaminants into smaller molecules or mineralize them into water and carbon dioxide (Qi et al., 2023; Zhu et al., 2023). However, the Fenton degradation process has significant drawbacks that limit its practical applicability. Because BC-based composites have been shown to display photocatalytic properties, combining biochar with photocatalytic materials could advance the photo-Fenton process (Hao et al., 2021; S. Li et al., 2025), thereby enhancing the degradation of contaminants in wastewater.

BC can prevent the agglomeration of TiO_2 particles (a successful photocatalyst) and increase the number of light-absorption sites, thereby

increasing the number of photocatalytic active sites on the catalyst (Liu et al., 2020). Because TiO_2 exhibits satisfactory photocatalytic efficiency without further contamination (Gopinath et al., 2020; Irshad et al., 2021; Lettieri et al., 2021), combining it with BC will help improve the degradation of contaminants, particularly pharmaceuticals, in wastewater. Metal-organic frameworks (MOFs) have also been applied in various wastewater cleanup investigations, notably AOPs, owing to their adaptable internal frameworks, large surface areas, and catalytic characteristics. These qualities have led to their widening use in energy storage, separation, and wastewater cleanup (H. Li et al., 2022; Shi et al., 2024; X. Yang & Xu, 2017; C. Zhang et al., 2022). However, the structural instability of MOF derivatives, which leads to degradation at elevated temperatures, restricts their applicability in various AOPs, such as the Fenton reaction, sulfate radical-based oxidation, and photocatalysis. Therefore, integrating biochar with MOFs or MOF membranes to form a stable and effective material would not only promote pollutant degradation but also enhance water treatment efficiency. The present study examines recent advances in wastewater remediation strategies, including BC-metal oxide composites, MOF-functionalized biochar, and heterojunction photocatalysts across diverse AOPs.

Several literature reviews have examined the use of BC and BC-based catalysts in wastewater treatment (He et al., 2021; R. Huang et al., 2025; Nidheesh et al., 2021; L. Wang et al., 2025), peroxide activation with a deep understanding of reactive oxygen species formation (J. Wang et al., 2022),

and biochar-catalyzed peroxides for water decontamination (Y. Wu et al., 2024). Additionally, Huang & Zhai conducted a comprehensive systematic review and bibliometric analysis of black gold catalysts, focusing on wastewater remediation via BC catalysis (C. Huang & Zhai, 2024). However, a clear correspondence between BC and BC-based composites as supports in advanced oxidation and photocatalytic processes remains elusive. To address this knowledge gap, this study examines the synthesis, properties, and functionalization of advanced biochar composites (BC-based AOPs) for photocatalytic removal of contaminants in wastewater. This review also examines the role and synergistic interactions of BC-supported systems in the catalytic enhancement of AOPs. Finally, this study presents a comprehensive review of the application of BC-based AOP systems in wastewater treatment, their limitations, and research opportunities.

2. Review Methodology

To identify relevant literature for this study, a thorough search was conducted across reputable scientific databases, including Springer, Elsevier, Google Scholar, MDPI, Web of Science, Science Direct, and PubMed. These platforms were chosen for their broad representation of scholarly journals in environmental science, materials chemistry, chemical engineering, and nanotechnology, thereby ensuring a diverse and high-quality pool of academic sources. A structured article screening technique from Sanusi et al. (2023) was used to meet the purpose of this study. In addition, the Boolean operators “AND” and “OR” were used to combine

keywords such as biochar-based materials, water pollution, wastewater treatment, photocatalytic processes, adsorption, and photodegradation. Modifications were made to tailor the approach to the literature on biochar-based photocatalysts, the synergistic effects of biochar-based systems, advanced oxidation processes, and pollutant remediation in water published in the previous 10 years. The outline of the screening process employed in this review is shown in Figure 1.

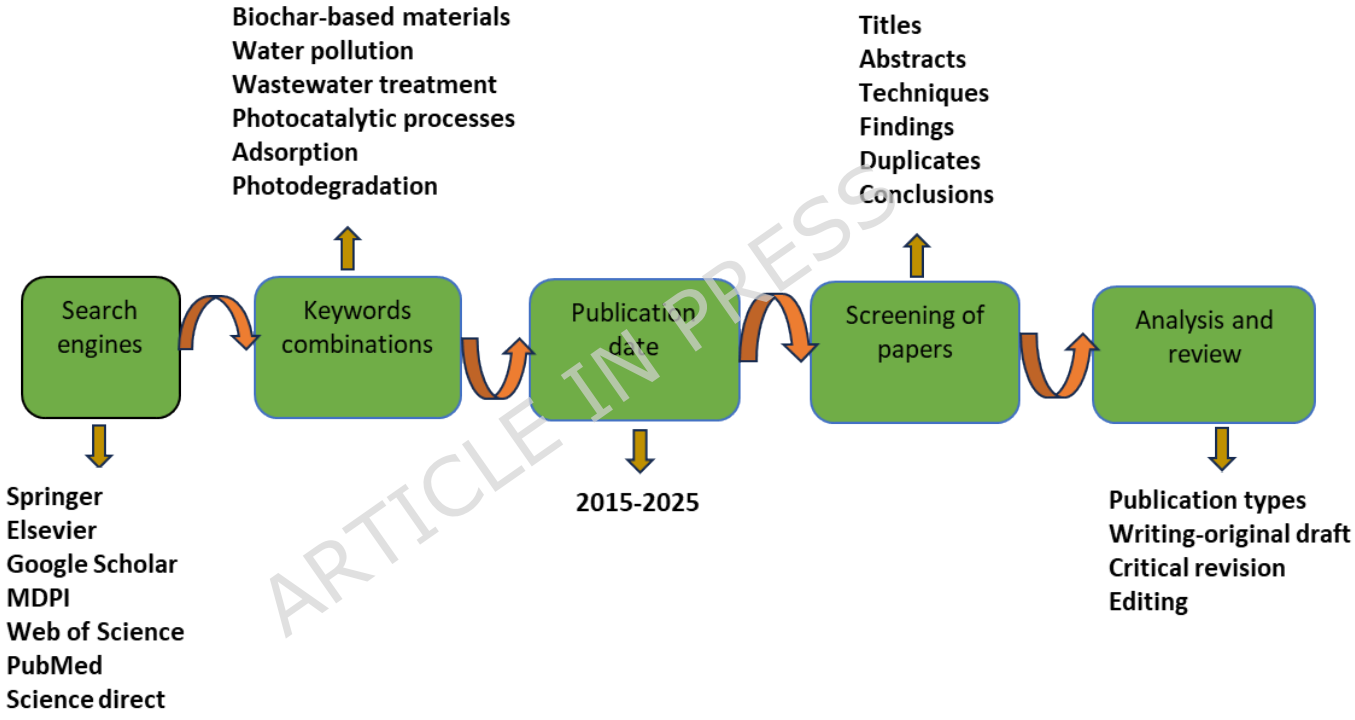

Figure 1. Methodology employed in screening articles. Adapted from Sanusi et al. (2025).

3. Fundamental Mechanisms of AOPs

The primary mechanism of AOPs involves the in-situ generation of reactive oxygen species, particularly hydroxyl radicals, which react with organic

pollutants through hydrogen abstraction, electrophilic addition, or electron transfer, leading to bond cleavage and degradation. Other reactive species, such as sulfate radicals, complement hydroxyl radicals in specific processes. These radicals are generated via various physical and chemical methods, including photochemical activation, electrochemical reactions, cavitation, ozonation, and catalytic processes.

Hydroxyl radicals are the cornerstone of most AOPs due to their high reactivity. The mechanism enhances the efficiency of radical generation for pollutant degradation (Lupu et al., 2023). In the Fenton process, hydroxyl radicals are produced via the reaction of hydrogen peroxide (H_2O_2) with ferrous iron (Fe^{2+}) under acidic conditions (pH approximately 3):

$$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + HO^- + {}^{\bullet}OH \quad (1)$$

In Photo-Fenton, light (UV or solar) regenerates Fe^{2+} from Fe^{3+}, and finally, the conversion of the organic pollutant to the degraded product. The following simple equations explain the reactions (Haber and Willstätter, 1931):

$$Fe^{3+} + H_2O + h\nu \rightarrow Fe^{2+} + {}^{\bullet}OH + H^+ \quad (2)$$

$$H_2O_2 + {}^{\bullet}OH \rightarrow H_2O + HO_2{}^{\bullet} \quad (3)$$

$$Fe^{2+} + {}^{\bullet}OH \rightarrow Fe^{3+} + HO^- \quad (4)$$

$$Fe^{3+} + HO_2{}^{\bullet} \rightarrow Fe^{2+} + O_2 + H^+ \quad (5)$$

$$^{\bullet}OH + {}^{\bullet}OH \rightarrow H_2O_2 \quad (6)$$

Furthermore, sulfate radical-based AOPs (SR-AOPs) generate sulfate radicals ($SO_4^{\bullet-}$, E_0 = 2.5–3.1 V) by activating persulfate (PS, $S_2O_8^{2-}$) or peroxymonosulfate (PMS) using UV light, heat, ultrasound, or transition metal catalysts (e.g., Fe^{2+}, Co^{2+}). Sulfate radicals selectively attack aromatic or unsaturated bonds in organic pollutants (e.g., antibiotics), thereby facilitating their degradation. The reaction of persulfate with UV light is shown below:

$$S_2O_8^{2-} + h\nu \rightarrow 2SO_4^{\bullet -} \quad (7)$$

Additionally, some AOPs generate reactive species. In heterogeneous photocatalysis (TiO_2/UV), semiconductors absorb UV light to produce electron-hole pairs, leading to hydroxyl and superoxide radicals ($O_2^{\bullet-}$). These radicals mineralize organic pollutants to CO_2 and H_2O (Lupu et al., 2023). Plasma-assisted AOPs also generate •OH, O•, and H_2O_2 through electrical discharges, enhancing degradation (Allabakshi et al., 2022).

$$TiO_2 + h\nu \rightarrow e^- + h^+ \quad (8)$$

$$h^+ + H_2O \rightarrow {}^{\bullet}OH + H^+ \quad (9)$$

$$e^- + O_2 \rightarrow O_2^{\bullet-} \quad (10)$$

4. Classification of AOPs

Advanced Oxidation Processes (AOPs) are classified by the mechanisms that generate reactive oxygen species, primarily hydroxyl radicals (•OH), for degrading organic pollutants. Key types include Fenton and photo-Fenton processes, ozone-based processes, photocatalytic and photochemical processes, cavitation-based processes, and sonolysis AOPs. Table 1 summarizes the different types of AOPs.

4.1. Fenton and Fenton-like AOPs

Fenton-based AOPs rely on the catalytic reaction of Fe^{2+} with H_2O_2 to produce hydroxyl radicals, as shown in the Fenton reaction above. Fenton-like processes use other transition metals, such as Cu^{2+}, or heterogeneous catalysts to generate OH radicals. Photo-Fenton enhances this process by using light to regenerate Fe^{2+}, thereby increasing the radical yield (Lupu et al., 2023; Ma et al., 2021). Photoelectro-Fenton combines light and an electric current to activate Fe^{2+} and H_2O_2, thereby generating •OH radicals for efficient pollutant mineralization (Ding et al., 2014). The primary advantage of the Fenton process is that contaminants are completely degraded into nontoxic substances, such as CO_2, H_2O, and inorganic salts. Furthermore, Fenton and Fenton-like reactions exploit the advantages of both UV light and the Fe reagent. Pandis et al. (2022) claimed that the ability of Fe ions to react with a variety of active pollutants, particularly during water purification processes, benefits organic pollutants. Recent studies reporting the use of Fenton and Fenton-like processes with BC as a catalyst will be discussed later in this review.

4.2. Ozone-based AOPs

Ozone (O_3) acts as a strong oxidant, directly oxidizing pollutants or decomposing to form hydroxyl radicals, particularly in peroxone systems (O_3/H_2O_2):

$$O_3 + H_2O_2 \rightarrow {}^{\bullet}OH + O_2 + HO_2^{\bullet} \quad (11)$$

Ozone is typically used to cleave C=C bonds in organic compounds. In its indirect reactions, it generates different radicals depending on the pH.

$$O_3 + HO^- \rightarrow HO_2^{\bullet} + O_2^{\bullet -} \qquad (1 < pH < 7) \quad (12)$$

$$O_3 + HO^- \rightarrow HO_2^{\bullet} + O_2 \ (8 < pH < 14)$$

$$O_3 + HO_2^{\bullet} \rightarrow HO_2^{\bullet} + O_3^{\bullet -} \quad (13)$$

Catalytic ozonation or UV enhancement increases •OH production and improves degradation efficiency. According to Almomani et al. (2016), ozone/hydrogen peroxide has been used in the pharmaceutical industry to treat wastewater. Additionally, the oxidation of medications such as estrogens and antibiotics has been observed, and the levels that directly increase the rates of these oxidation processes are the primary factors for higher yields (Pandis et al., 2022).

4.3. Photocatalytic and Photochemical AOPs

Photocatalytic AOPs use semiconductors (TiO_2) to generate electron-hole pairs under UV light, producing $^{\bullet}OH$ and $O_2^{\bullet -}$ radicals, as described above. Photochemical AOPs, such as H_2O_2/UV and O_3/UV, rely on photolysis to generate hydroxyl radicals:

$$H_2O_2 + h\nu \rightarrow 2^{\bullet}OH \quad (14)$$

$$O_3 + H_2O + h\nu \rightarrow 2^{\bullet}OH + O_2 \quad (15)$$

The photochemical AOP involving O_3/UV is reported to be more efficient due to higher light absorption. Solar-driven photocatalysis uses solar photons to activate catalysts, leading to sustainable radical generation. The most common applications of these AOPs involve metal oxides, with TiO_2, ZnO, and other binary metal oxides being the most widely utilized (Chan et al., 2011; H. Wang et al., 2014). Moreover, photocatalysis is used in wastewater treatment, using the catalyst's surface to eliminate contaminants as effectively as possible. According to Pandis et al. (2022), photocatalysis is the most widely used AOP for the degradation of water pollutants because of its low operating costs, high efficiency, and environmentally benign approach. Based on valence bond theory, Figure 2 shows a commonly used method for pollutant degradation via photocatalysis on TiO_2.

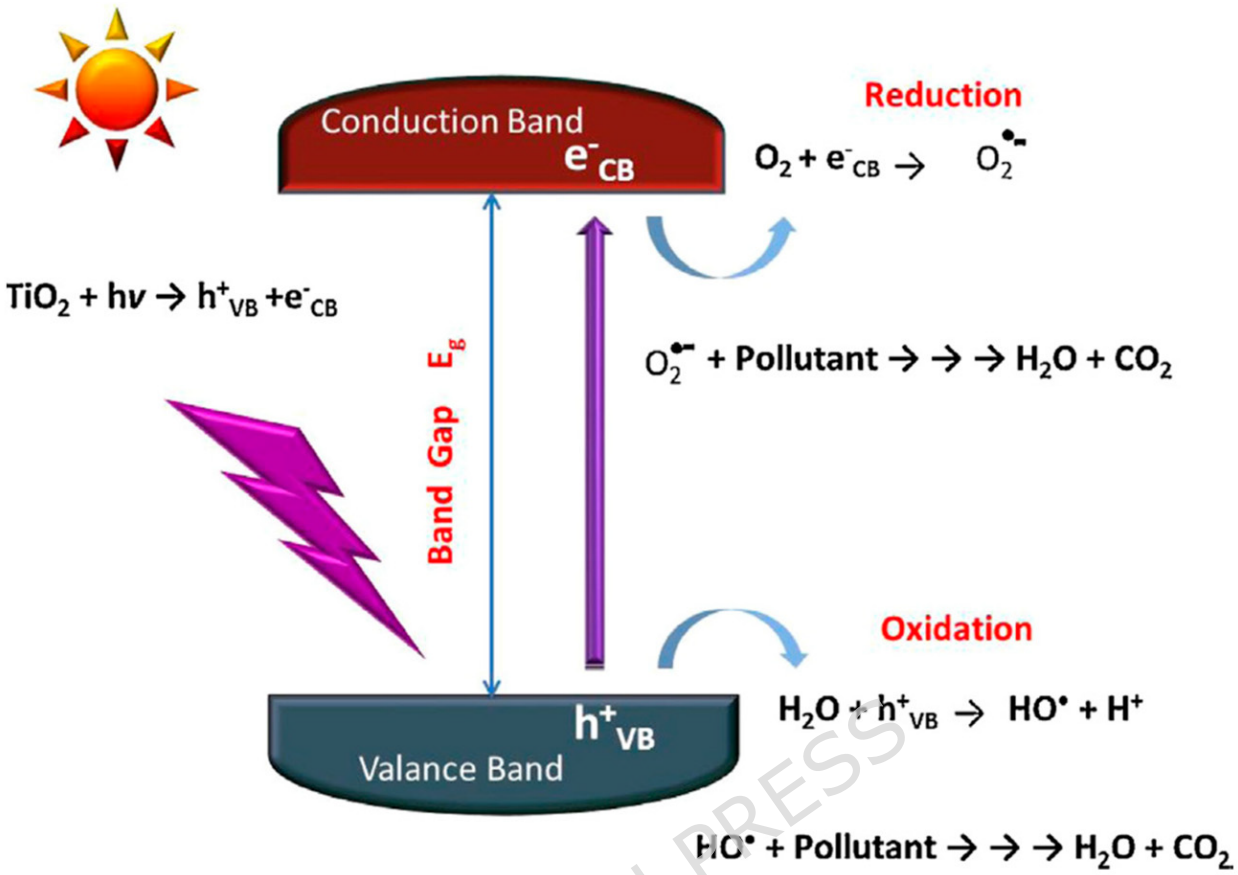

Figure 2. Indicative mechanism of photocatalysis on TiO_2 (Etacheri et al., 2015).

4.4. Cavitation-based AOPs

Cavitation-based AOPs, including acoustic cavitation (ultrasonication) and hydrodynamic cavitation, generate OH radicals through the collapse of microbubbles formed under high pressure or ultrasonic waves, thereby creating localized high temperatures (5000 K) and pressures (1000 atm). The reaction is shown below:

$$H_2O \rightarrow {}^\bullet OH + {}^\bullet H \quad (16)$$

The produced ROS and/or sulfate radical (Equation 7) subsequently react, decompose organic contaminants in the water, and then transform them into less hazardous chemicals. The synergy between cavitation-based AOPs and photocatalysts or other AOPs has been reported to enhance radical production (Hayati et al., 2020; Ma et al., 2021).

4.5. Sonolysis

Sonolysis, a recent AOP approach, employs ultrasonic irradiation to degrade organic compounds in water, thereby generating hydroxyl radicals (Dhamorikar et al., 2024). Sonolysis is the process of molecular decomposition by the formation, expansion, and implosion of a bubble in a liquid via sonic cavitation. Energy is also required to generate acoustic cavities in bubbles via ultrasonic irradiation. This leads to cavitation, characterized by the rapid formation, explosion, and collapse of bubbles within a liquid medium, thereby transforming substantial quantities of energy into chemical energy (Dhamorikar et al., 2024). In research reported by Yin et al. (2018), the authors adopted the sonolysis approach, applying ultrasonic irradiation to activate PMS and subsequently to degrade sulfamethazine (SMT). They reported that the degradation efficiency of SMT over 30 min was 99.6% with the ultrasound/PMS method, whereas PMS alone achieved 54.3% elimination. In addition, they discovered that ultrasound (US) could greatly increase PMS activation for SMT degradation, thereby accelerating PMS breakdown by releasing more ROS and improving the mass transfer owing to the cavitation and thermolytic effects of US irradiation. The process of

activation of PMS and the breakdown route for SMT are depicted in **Figure 3**.

Table 1: Summary table of advanced oxidation processes.

S/No	AOP Category	Type of AOP	References
1.	Cavitation-based AOPs	Acoustic Cavitation/Ultrasonication	(Hayati et al., 2020)
		Hydrodynamic Cavitation/Photocatalytic	(Ma et al., 2021)
		Sonochemical Oxidation	(Ma et al., 2021)
		Catalytic AOPs	(Hübner et al., 2024)
		Catalytic Wet Air Oxidation	(Ma et al., 2021)
		Fenton and Fenton-like Oxidation	(Ma et al., 2021)
		Fenton and Photo-Fenton Oxidation	(Lupu et al., 2023)
		Fenton-based AOP	(Allabakshi et al., 2022)
		Photo-electro-Fenton	(Ding et al., 2014)
2.	Electrochemical AOPs	Electrochemical AOPs	(Lupu et al., 2023)
		Electrochemical Oxidation	(Ma et al., 2021)
3.	Ozone-based AOPs	Ozone Oxidation	(Ma et al., 2021)
		Ozone-based AOP	(Hübner et al., 2024)
		Ozone-based AOPs	(Hübner et al., 2024)

4.	Photocatalytic and Photochemical AOPs	Heterogeneous Photocatalysis (TiO_2/UV)	(Lupu et al., 2023)
		Photocatalytic Oxidation	(Ma et al., 2021)
		Photochemical AOPs (H_2O_2/UV, O_3/UV)	(Lupu et al., 2023)
		Radiation-driven AOPs (UV/H_2O_2, UV/O_3, UV/Cl_2, photo-Fenton, heterogeneous photocatalysis)	(Hübner et al., 2024)
		Sustainable AOPs (Solar-driven)	(Lupu et al., 2023)
5.	Sulfate Radical-based AOPs	Sulfate Radical-based AOP	(Ma et al., 2021)
		Sulphate Radical-based AOP (SR-AOP)	(Hayati et al., 2020; Yang et al., 2019)
	Other AOPs	Combined AOPs (UV/H_2O_2/O_3)	(Lupu et al., 2023)
		Plasma-assisted AOP	(Allabakshi et al., 2022)
		Other AOPs (electrochemical, ultrasound, plasma, thermal, SCWO)	(Hübner et al., 2024)

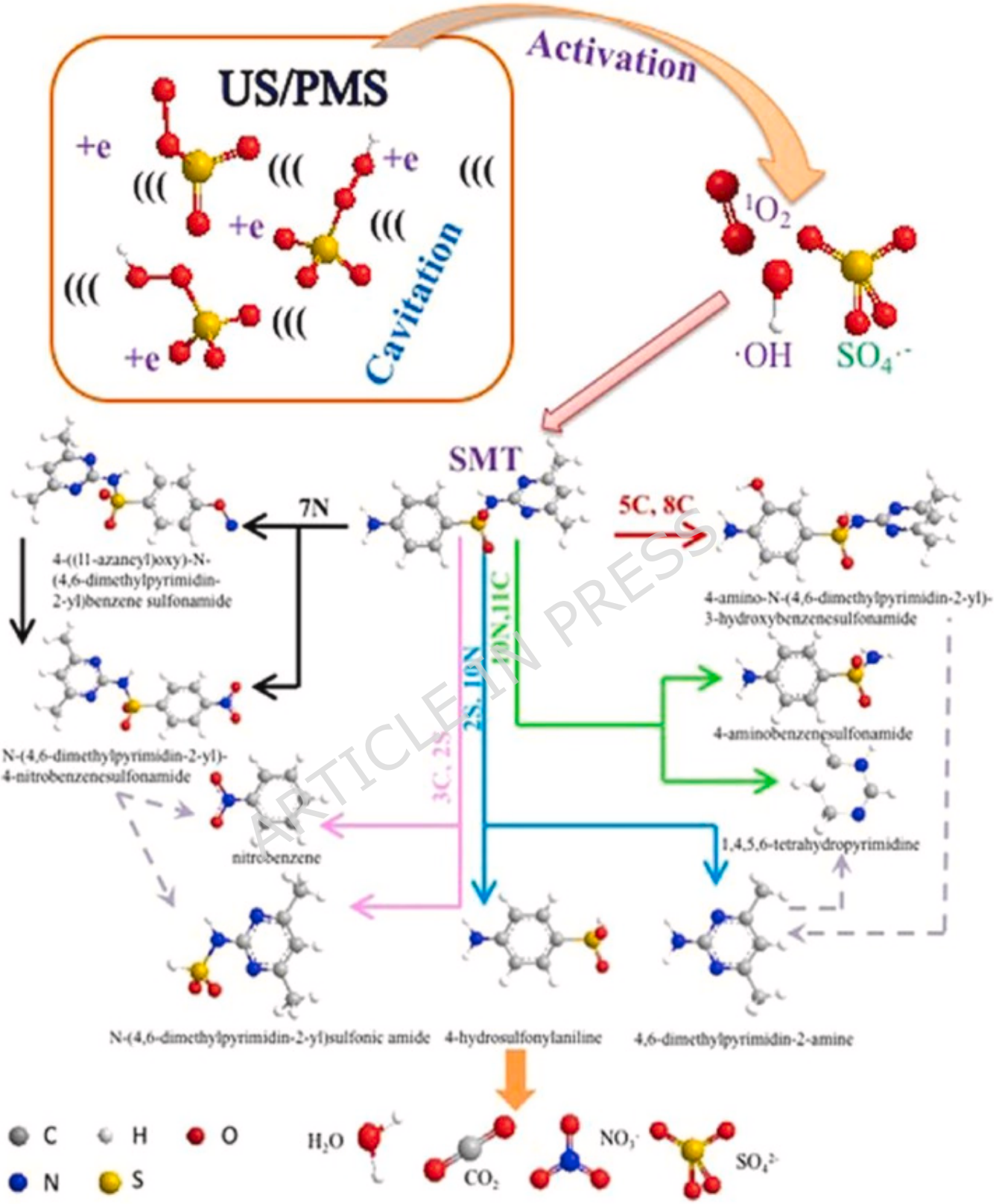

Figure 3. The mechanism of activation PMS by ultrasound for the degradation of sulfamethazine (Yin et al., 2018).

5. Production and Functionalization Strategies of Biochar

Biochar production primarily uses thermochemical conversion techniques such as pyrolysis and hydrothermal carbonization (HTC). Pyrolysis decomposes organic biomass under an inert atmosphere, typically at temperatures between 400 and 800°C, and is categorized into slow, fast, intermediate, and flash modes based on residence time and heating rate. Slow pyrolysis yields more char, whereas fast and flash pyrolysis favor bio-oil production (A. Khan et al., 2022; A. A. Khan et al., 2022; Naveed et al., 2024; Vuppaladadiyam et al., 2022). Recent pyrolysis methods, such as catalytic pyrolysis, hydropyrolysis, co-pyrolysis, and microwave-assisted pyrolysis (MAP), enhance energy efficiency and product specificity (Potnuri et al., 2023; Robinson et al., 2022). However, limitations such as feedstock conditions, energy demands, and a lack of standardization affect the reproducibility and scalability of pyrolysis (Vuppaladadiyam et al., 2022). Figure 4 illustrates how biochar-based products are prepared for wastewater treatment.

Hydrothermal carbonization (HTC) operates at lower temperatures (180–250 °C) and moderate pressures (<6.0 MPa) in water, allowing for wet biomass processing without prior drying. It involves hydrolysis, dehydration, condensation, and aromatization to produce hydrochar (HC). The carbon content and calorific value of HC increase with temperature (Liang et al., 2022; Świątek et al., 2020). Advanced HTC variants like microwave-assisted HTC (MHTC) improve the textural properties of HC, while integration with anaerobic digestion supports resource recovery (Cavali et al., 2023; Mannarino et al.,

2022; Scrinzi et al., 2022). Despite its energy efficiency, HTC faces constraints such as slow kinetics and high-pressure reactor requirements (Yameen et al., 2024; Yang et al., 2022).

Gasification is another method for preparing biomass-derived carbon-based nanomaterials. This method is conducted at temperatures between 600 and 1200°C and uses various gasification agents, such as pure oxygen, air, or air mixed with steam, to convert biomass into a gas rather than solid products (Hou et al., 2020). The four key phases of gasification are drying, pyrolysis, partial oxidation, and reduction (Loha et al., 2014). Compared to other strategies, gasification typically yields low amounts but can be justified because it is practical and environmentally friendly (Priya et al., 2024). A drawback of this cycle is that increased oxygen demand can reduce production, compromise biochar cohesiveness, and increase waste products (L. Wang et al., 2020).

Various functionalization strategies have been employed to improve the physicochemical properties of BC for specific applications. These strategies include ball milling, which enhances surface area and introduces structural defects, thereby improving adsorptive and reactive performance (Yameen et al. 2024). Templating methods have been used to remove templates such as silica to create ordered porous structures for catalysis (Yameen et al. 2024). X. Yang et al. (2022) reported that a simple, efficient process that uses little energy to produce absorbent biochar from hickory wood via mild acid treatment was developed. The schematic diagram for the synthesis of the biochar using the ball milling method is shown in Figure 5.

Molten salt activation is another technique employed in BC functionalization with salts like KCl or $ZnCl_2$, which yields highly porous structures by promoting dehydration and aromatization (Yameen et al. 2024). Chemical activation involves the use of activating agents like KOH and H_3PO_4 that add oxygenated functional groups to the BC, thereby increasing its surface area and adsorption capacity (Yameen et al. 2024; Naqvi et al. 2023). The method employed by researchers to improve the catalytic properties of BC is through functionalizing or impregnating the BC with transition metals (Yameen et al. 2024), while boosting of the conductivity and active site density of the BC is done via heteroatom doping (e.g., N, S, P) (Yameen et al. 2024). Electrospraying enables the formation of uniform, porous carbon structures with improved electrochemical behavior (Guo et al. 2023; Yameen et al. 2024). These strategies of functionalizing BC have increased its versatility in fields such as energy storage, environmental remediation, and catalysis.

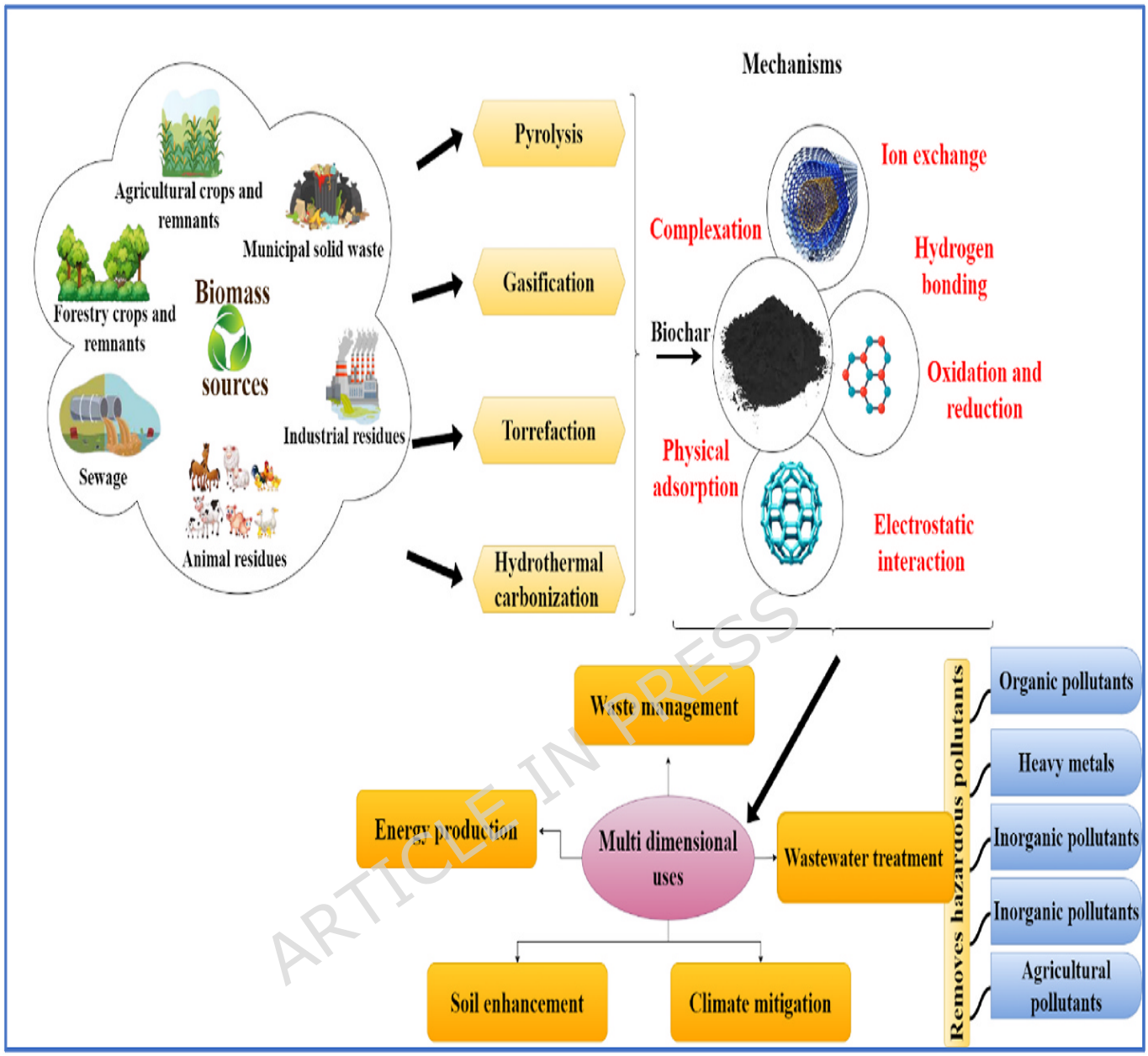

Figure 4. Preparation of biochar-based materials for wastewater treatment (Priya et al., 2024).

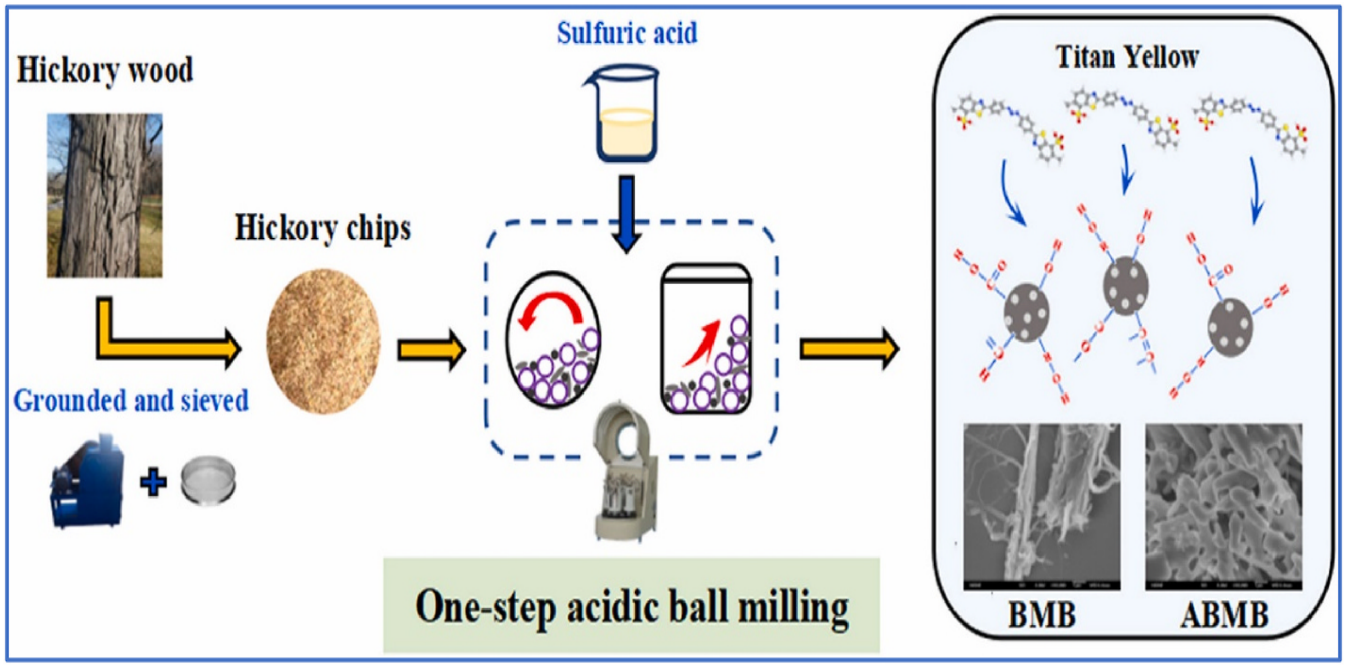

Figure 5. Synthesis of hickory biochar via one-step acidic ball milling for titan yellow adsorption (X. Yang et al., 2022).

6. Role of BC in Catalytic Enhancement of AOPs

The use of AOPs alone to remove pollutants from wastewater has not been effective in many conditions owing to constraints such as pH effects, oxidant activation, and the release of secondary pollutants after treatment. However, incorporating BC as a catalyst or support in AOPs has been shown to enhance photocatalytic efficiency in wastewater treatment, particularly for antibiotics (one of the most frequently used pharmaceuticals). This section presents a comprehensive review of current research on the function of biochar as a catalyst in different AOPs and on the synergistic interactions in BC-supported systems.

6.1. Catalytic AOPs

H. Chen et al. developed a novel catalyst system (CoZn@LDO-BC2) for tetracycline degradation by synergistically combining a biochar (corncob) with layered double hydroxide (LDH) and zeolitic imidazolate framework (H. Chen et al., 2025). The catalyst achieved a remarkable 95.68% removal of tetracycline within 7 min, driven by synergistic interactions between free and non-free radicals, with singlet oxygen ($^1O_2$) and sulfate radicals ($SO_4^{\cdot -}$) as the primary reactive oxygen species. The authors also found that tetracycline removal was higher at pH 5.0–9.0 when the catalyst was coupled with peroxymonosulfate (oxidant); however, excessively acidic and strongly alkaline conditions hampered the breakdown process (H. Chen et al., 2025). Similarly, J. Chen et al. created a composite (TiO_2/Fe-Cu-HBS) using Fe-Cu-doped hollow biochar sphere (HBS)-supported TiO_2 for the degradation of tetracycline hydrochloride, rhodamine B, and carbamazepine (J. Chen et al., 2023). The authors reported that the HBS shell of the composite exhibited superior adsorption for organic pollutants and light-harvesting abilities, thereby enhancing light trapping and photorefractive performance. Under visible light, the composite generated numerous reactive radicals, resulting in effective photocatalytic degradation of tetracycline hydrochloride, rhodamine B, and carbamazepine, with removal rates of 95.4%, 99.2%, and 67.5%, respectively. The presence of oxygen vacancies (Ov) and a high surface area in the composite increased active sites, promoting free radical generation and greatly enhancing photocatalytic effectiveness (J. Chen et al., 2023). The studies above demonstrated that

modifying BC with transition metals (Fe, Co, Cu) further enhances its ability to activate oxidants and increase degradation efficiencies.

Sludge-derived biochar (SDB) has also attracted interest as a catalyst in advanced oxidation processes to eliminate refractory organic pollutants (N. Li et al., 2023; Zhou et al., 2024). Wu et al. developed an iron-enriched SDB and used it to degrade triclosan via Fenton-like reactions (L. Wu et al., 2022). The research demonstrated that H_2O_2 activation was largely driven by iron species (80.3%), with a minor but considerable contribution from persistent free radicals (PFRs), thereby improving the efficiency of pollutant breakdown. Additionally, Miao et al. found that SDB effectively activated peracetic acid (PAA) for the degradation of 4-chlorophenol, achieving a rate constant of 0.051 $M^{-1}min^{-1}$ (Miao et al., 2024). The key mechanism discovered in the research indicates that the activation of PAA by SDB is largely regulated by quinone/hydroquinone groups and residual metals on the SDB. These components play a critical role in the creation of PFRs, which enhance the activation process. These findings suggest that SDB is a notable material that could potentially be employed as a support system in accomplishing effective wastewater treatment. Table 2 presents current research on the utilization of BC as a catalyst/support in wastewater treatment.

Biochar modification plays a decisive role in determining its catalytic performance in advanced oxidation processes by tailoring its physicochemical and electronic properties (Faheem et al., 2020). Chemical

activation and surface functionalization introduce abundant oxygenated functional groups (e.g., –OH, –COOH, and C=O) and enlarge pore structures, enhancing pollutant adsorption and promoting intimate contact between contaminants and reactive sites. Heteroatom doping (N, S, or P) modifies biochar's electronic structure by creating defects and improving electrical conductivity, thereby facilitating electron transfer and accelerating oxidant activation pathways (Yameen et al., 2024). These effects are experimentally identified through a combination of selective scavenging experiments and EPR spectroscopy. Metal impregnation or in situ incorporation of transition metals (e.g., Fe, Co, Cu, Mn) introduces redox-active centers that catalyze the decomposition of oxidants such as H_2O_2, PMS, or PDS, leading to increased generation of reactive oxygen species, including •OH, $SO_4^{\bullet -}$, and $^1O_2$ (H. Chen et al., 2025). Furthermore, integrating biochar with semiconductors or MOFs forms heterojunction interfaces that suppress charge-carrier recombination, extend light absorption into the visible region, and enhance photocatalytic efficiency. These synergistic effects collectively translate into faster degradation kinetics, higher removal efficiencies, improved pH tolerance, and superior reusability of modified biochar-based catalysts compared to pristine biochar (X. Zhang et al., 2024). In real wastewater systems, BC-based catalysts demonstrate favorable reusability and structural stability across multiple cycles, with performance losses mainly attributed to surface fouling rather than catalyst framework degradation.

6.2. Synergistic Interactions in BC-Supported System

The synergistic effects of the BC-supported system in the composite have led to improved pollutant removal, stability, reusability over several cycles, and enhanced charge transfer. Xue et al. demonstrated the synergistic interaction of a photocatalysis-Fenton system using a BC-supported system (S-type heterojunction) for the degradation of tetracycline (Xue et al., 2025). The biochar/iron hydroxide oxide/bismuth molybdate (BC/FeOOH/Bi2MoO6) catalyst achieved a 97% removal rate of tetracycline after 40 minutes, surpassing the performance of BC/FeOOH (65%) and BC/Bi2MoO6 (59%). The authors attributed the elevated removal rate to the synergistic interaction between photocatalysis and the Fenton reaction; hence, there is a need to develop more bifunctional S-type heterojunction photocatalysts for a wide range of pharmaceutical removals (Xue et al., 2025). Additionally, Yao et al. (2023) reported the synergistic adsorption and oxidation of trivalent antimony (Sb(III)) from groundwater using a BC-supported magnesium ferrite (BC@MF). They observed that the functional groups and metal species present in the functionalized BC enhanced Sb(III) capture, resulting in a maximal adsorption capacity of 77.44 mg/g. Among the calcined samples, BC@MF300 (300°C) emerged as a potential adsorbent and demonstrated the capability to mitigate Sb(III) toxicity by oxidizing Sb(III) to Sb(V) (Yao et al., 2023). These findings suggest that combining BC with suitable metal species could help increase the removal efficiency of contaminants in wastewater.

Table 2: Recent studies on the utilization of BC as a catalyst/support in wastewater treatment.

Catalyst	Pollutant	Oxidant	Reaction time	Removal efficiency	Key findings	References
Sludge-derived biochar	Methylene blue (50 mg/L)	H_2O_2	2 h	43.84%	The desirability curve indicated that improved variables did not substantially improve the rate of removal of methylene blue	(Porto et al., 2024)
Sewage sludge biochar	Ciprofloxacin (10 mM)	H_2O_2	4 h	95%	An inexpensive catalyst that has the potential to remove ciprofloxacin from aquatic environments—a crucial step in the final disposal of Sewage sludge	(J. Li et al., 2019)
Shrimp shell biochar	2,4-dichlorophenol (100 mg/L)	PDS	2 h	100%	Results revealed that hierarchical pores and carbon configuration were two key impact factors of biochar in AOP	(Yu et al., 2020)
Sludge-derived biochar	Carbamazepine (5 mg/L)	PMS	90 min	~ 95%	Organic pollutants could affect the kinetics of PMS activation by competing for adsorption sites with PMS	(S. Wang & Wang, 2020)
Cobalt-impregnated biochar (CoIB)	Acetaminophen (5 mg/L)	PMS	1 h	95%	CoIB is recyclable for the activation of PMS to efficiently break down acetaminophen across numerous cycles	(M.-T. Yang et al., 2019)
Bimetallic metal-organic framework impregnated	Tetracycline (20 mg/L)	PDS	2 h	97.70%	The biochar-supported system exhibits outstanding catalytic activity and has promising applications in wastewater treatment	(Ling et al., 2024)

biochar
(BC@CoFe)

PDS = peroxydisulfate; PMS = peroxymonosulfate

7. Advanced Biochar Composites for Photocatalytic Applications

BC is a carbon-rich material produced from biomass through a thermochemical conversion process known as pyrolysis. Researchers are exploring the possibility of incorporating BC into diverse modern materials to overcome the limitations of conventional photocatalysts, such as low light absorption and fast recombination of photogenerated charge carriers. These include metal oxides, MOFs, covalent organic frameworks (COFs), and heterojunction semiconductors. These hybrid composites are more photocatalytic because of BC's adsorption and conductivity properties. This illustrates that the active components can collect light and act as catalysts.

7.1. Biochar-Metal Oxide Composites and MOF-Functionalized Biochars

Metal-biochar composites are promising materials for the efficient sequestration of noxious contaminants from environmental compartments such as soil and water (Dzoujo et al. 2024). They are promising photocatalysts because of their unprecedented synergy of adsorption capacity, surface area, and catalytic activity (Dzoujo et al. 2024). MOFs are materials with ultra-high surface area, tunable pore size, and chemical versatility that complement the innate merits of BC (Mane et al. 2024). BC–metal oxide composites often outperform MOF–biochar systems in advanced oxidation processes because of their higher structural stability, stronger metal–support interactions, and superior resistance to hydrolysis under harsh reaction conditions. Metal oxides (e.g., TiO_2, Fe_3O_4, CuO) anchored on biochar provide robust redox-

active sites and maintain catalytic activity across wider pH ranges, while biochar enhances conductivity, adsorption, and charge transfer (Adamu et al., 2024; Bhavani et al., 2022). In contrast, MOF–biochar composites, although offering ultra-high surface area and tunable porosity, can suffer from framework instability, metal leaching, and partial collapse under acidic, oxidative, or high-temperature AOP conditions (C. Yang et al., 2024). Consequently, BC–metal oxide systems generally exhibit greater durability, reusability, and practical applicability in real wastewater matrices, whereas MOF–biochar composites excel in selectivity and light-harvesting efficiency but remain more sensitive to operational constraints (Dzoujo et al. 2024; Mane et al. 2024). By enhancing the stereochemistry of biochars with MOFs, these composites become hybrid catalysts that provide a light trap and active sites, thereby creating a conducive environment and a stable structure in the BC (Tan et al., 2023). Composites of this kind have found successful applications in the photocatalytic degradation of dyes, pharmaceuticals, antibiotics, and emerging contaminants, with enhanced reusability and efficiency compared to conventional photocatalysts. Their combination with MOFs also provides additional functionality, such as gas storage, pollutant adsorption, and selectivity for certain pollutants, further broadening their applications in environmental and energy fields. In research reported by Z. Liu et al. (2022), the authors devised an MOF-derived biochar composite synthesized by a one-step hydrothermal technique to build the MOF MIL-125(Ti) onto a nitrogen- and sulfur-co-doped bio-carbon (NSCDBC). The

successful linkage of the biochar with MIL-125(Ti) was verified by SEM, TEM, and XPS investigations prior to degradation of tetracycline hydrochloride (TC). The authors concluded that the primary oxidizing agents responsible for TC degradation were photogenerated holes and superoxide radicals, thereby providing a plausible justification for the photocatalytic degradation process (Z. Liu et al., 2022). The study's findings, which include details on the composite's stability, degradation rates, and photocatalytic degradation efficiency of TC under specific conditions, are shown in Figure 6.

7.2. COF-Modified BC and Heterojunction Photocatalysts

Recently, COFs have emerged as novel photocatalysts for BC modification. COF-modified biochars are highly chemically stable, regularly porous, and light-responsive. By covalently linking COFs to BC scaffolds, a synergy can be achieved to enhance light harvesting, charge mobility, and photocatalytic CO_2 reduction. BC also enhances electron conductivity and pollutant adsorption (Ge et al., 2024). This simultaneously facilitates the degradation of organic pollutants under visible light and inhibits the recombination of photogenerated electrons and holes. Accordingly, light-sensitive COF-modified biochars are also useful in degrading persistent organic pollutants (POPs), including pharmaceuticals and endocrine-disrupting chemicals (Chauhan et al., 2023; Kasonga et al., 2021). The rationale for heterojunction photocatalysts, when linked to different semiconductors and BC, is to create an efficient charge-separating interface (Liang et al., 2024). Such

heterojunctions are classified as Z-scheme, S-scheme, and type-II heterojunctions (Balapure et al., 2024). These heterojunctions are highly valuable for achieving optimal redox potentials and enhancing photocatalytic activity. For instance, the combination of BC and graphitic carbon nitride (g-C_3N_4) has demonstrated greater efficiency in water splitting, hydrogen production, and pollutant degradation (Idrees et al., 2025; Z. Li et al., 2025; Sharma et al., 2022; Xiao et al., 2021; Yadav et al., 2024; Zheng et al., 2019). The BC catalyst not only serves as a conductive bridge but also stores electrons, thereby reducing charge recombination and enhancing system stability. Additionally, the use of a broader range of light wavelengths, including those in the visible and near-infrared regions, makes it feasible to efficiently convert light into solar energy via heterojunctions.

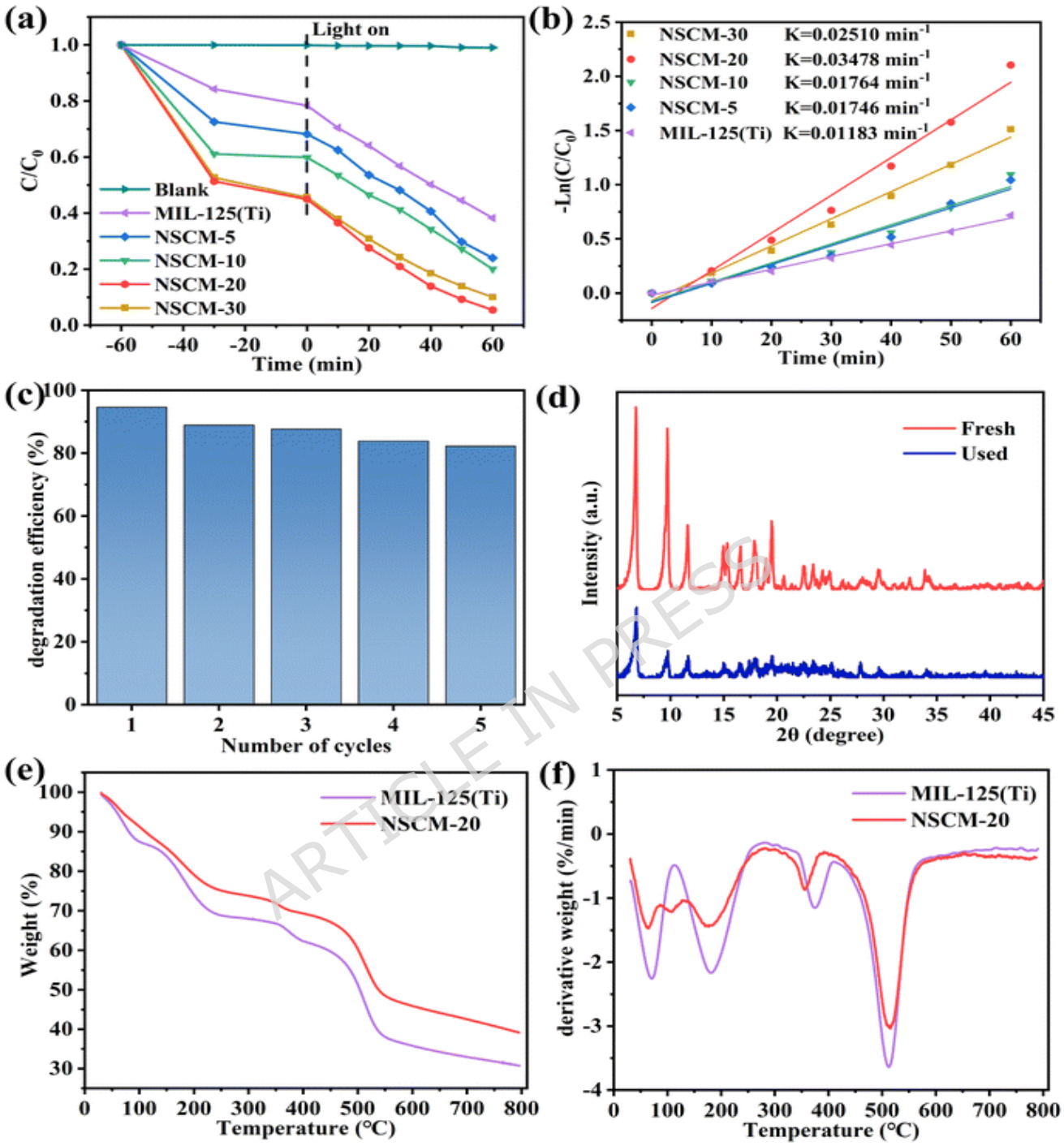

Figure 6 (a) Full-spectra light irradiation (λ > 365 nm) photocatalytic degradation of TC with various samples; (b) corresponding pseudo-first-order kinetic plots; (c) photocatalytic degradation efficiency of NSCM-20 with 5 cycles; (d) XRD analysis of new and used NSCM-20; TGA (e) and DTG (f) of MIL-125(Ti) and NSCM-20 (Z. Liu et al., 2022).

7.3. Mechanistic Insights into Composite Performance

Multiple synergistic processes contribute to the high photocatalytic performance of the advanced BC composites. The first mechanism is increased light absorption, achieved by integrating the dark-colored BC with photoactive elements, thereby broadening the light-harvesting range. Secondly, the BC hetero-structural interface with photocatalysts results in efficient charge separation and transfer. The high-speed shuttling of electrons in the conductive matrix of biochar reduces recombination with holes, enabling long-term redox reactions to degrade pollutants and produce hydrogen. Moreover, the high surface functional groups in BC (carboxyl, hydroxyl, and carbonyl) serve as adsorption sites for pollutants and enable redox reactions on the surface. These reactions are also catalyzed by metals or MOF/COF, which provide catalytic ROS sites that produce •OH, $\bullet O_2^-$, and $^1O_2$. The integration of biochar also enhances the mechanical strength, chemical stability, and stability under working conditions, promoting the durability and reusability of composite photocatalysts. promotes the durability and reusability of composite photocatalysts (Bhavani et al. 2022). Emerging studies have also highlighted the importance of heteroatom species produced by the heteroatom doping step of BC (nitrogen, sulfur, or phosphorus) to refine the electronic structure and enhance catalytic properties (Hassaan et al., 2023; Wu et al., 2024). Several changes, such as the creation of defects, distortion of the band structure, and improved

electron mobility, are results of the doping approach and can lead to greater photocatalytic output (Wu et al., 2024). Furthermore, multidimensional spectroscopic methods such as electron paramagnetic resonance (EPR), X-ray photoelectron spectroscopy (XPS), and in situ diffuse reflectance infrared Fourier transform spectroscopy (DRIFTS) are widely used to elucidate the underlying photocatalytic mechanism and guide rational material design (Baer & Sherwood, 2025; Bowman & Maryasov, 2021).

In China, biochar-based photocatalysts are used in wastewater treatment facilities, where titanium dioxide-biochar (TiO_2-BC) composites have been employed to remove a wide range of heavy metals and antibiotics (Liu et al. 2024). Additionally, BC-based catalysts can be integrated into solar-driven systems by serving as conductive supports for photocatalysts, enhancing visible-light absorption, and facilitating charge transport. Coupling BC-based photocatalytic AOPs with solar irradiation reduces energy demand and improves sustainability, particularly in decentralized wastewater treatment systems. The concept of solar-powered BC composite reactors is under consideration and could be used in rural areas of India and sub-Saharan Africa to obtain clean water in a cost-effective and sustainable way (Onwuemezie, 2024). In conclusion, these mechanistic insights highlight the disruptive potential of BC-based photocatalytic composites in environmental remediation, green energy generation, and carbon-neutral technologies. Future developments to improve interface engineering, band structure modulation, material wearability, and real-world applicability will further

make the above applications more viable and commercially feasible in the future.

8. Application of BC-Based AOPs for Wastewater Pollutant Removal

In a society contending with escalating pollution and diminishing clean water resources, the removal of hazardous pollutants from wastewater has become increasingly important (Tella et al., 2024). Contaminants such as heavy metals, pharmaceuticals, and persistent organic chemicals endanger both ecosystems and population health (Gomes, 2025). This section reports current research on the use of BC-based advanced oxidation processes (AOPs) for pollutant removal from wastewater.

Pharmaceuticals, heavy metals, dyes, microplastics, and pathogens have contributed significantly to the pollution of aquatic ecosystems, making their removal a major global concern and an area of increasing research interest (Almeida-Naranjo et al., 2023; Kang et al., 2022). Compared with other conventional AOPs, BC-based AOPs offer significant advantages in treating pharmaceuticals and other pollutants in wastewater (Gwenzi et al., 2017; Nand et al., 2025). Owing to their low cost, high efficiency, renewability, and sustainability, BC-based AOPs are widely explored as a sustainable solution for both drinking water and wastewater treatment (Olugbenga et al., 2024). Some pharmaceuticals are considered "Contaminants of Emerging Concern" (CECs) because of their persistence in the environment, driven by their use, manufacturing, and improper disposal (Akinyeye et al., 2021; Almeida-Naranjo et al., 2023). Their persistence has been implicated in endocrine

disruption, antimicrobial resistance, and toxicity (Ahmed et al., 2024; Benotti et al., 2009; Sanusi et al., 2023). Tables 3 and 4 present recent studies on the removal of pollutants from wastewater using BC-based AOPs. Findings reveal that pharmaceuticals, among other pollutants, are the most frequently reported in wastewater treatment using BC-based AOPs. This review also shows that there are limited studies on the inactivation of various types of microbes in wastewater, with *Escherichia coli* (*E. coli*) accounting for the majority of reported studies. Therefore, there is a need for more studies on the inactivation of several microbes in wastewater using BC-based AOP systems.

Table 3: Biochar and biochar-based enhanced AOP for the removal of pharmaceuticals in wastewater.

Drug residue (Target water Pollutant)	Biochar precursor(s)	Mechanism of purification	AOPs	Adsorption Removal Efficiency	AOPs Removal Efficiency	Key Findings	Reference(s)
Acetaminophen	Microalgae Based biochar,	Adsorption (physical and chemical interactions) /AOPs	$SO_4^{\bullet-}$ $^{\bullet}OH^-$ $^1O_2$	90%	100%	Increasing dosage mass (mg) enhances acetaminophen removal	(González-Hourcade et al., 2022)
	Palm - derived biochar	Adsorption (physical and chemical interactions) /AOP	$SO_4^{\bullet-}$ $^{\bullet}OH^-$	90%	96%	Doping with nitrogen enhances catalytic performance and multiple use advantage	(Badiger & Nidheesh, 2023; Grisales-Cifuentes et al., 2022)
	Pulp mill sludge,	Adsorption (physical and chemical interactions) /AOPs	$SO_4^{\bullet-}$ $^{\bullet}OH^-$	98%	95%	High adsorption rate with dual efficiency, including mineralization, when doped with metal (Fe).	(Kanakaraju et al., 2025; Masud et al., 2025; Simões dos Reis et al., 2022)
	Cotton gin waste	Adsorption (physical and chemical interactions) /AOPs	$SO_4^{\bullet-}$ $^{\bullet}OH^-$	68%	NA	Increased degradation through radical generation when the surface is engineered and used as a catalyst.	(Chauhan et al., 2023; Ndoun et al., 2023)

Ibuprofen	Sunflower seed husk	AOPs	$SO_4^{\bullet-}$ $^{\bullet}OH^-$	NA		89%	6 cycles reusable ability with low-cost recovery, enabling rapid mineralisation at low phenyl urea, urea, Fe(II), and Fe(III) salts content	(Ramirez et al., 2025)
	Biochar composites (PANI/H-BC)	Adsorption (physical and chemical interactions)/ AOPs	$SO_4^{\bullet-}$ $^{\bullet}OH^-$	35.58mg/g	NA		Modification enabled biochar hydrophilicity. This increase contact area with ibuprofen, resulting in higher efficiency	(Zhou et al., 2025)
Sulfamethoxazole	Walnut green peel waste	AOP	OH^-	NA		92.25%	Enhanced redox cycling of catalyst through combined transition of Fe^{3+}/Fe^{2+} and Cu^{2+}/Cu^{+}. Cost-effective with dual usage.	(S. Zhang et al., 2025)

	Lemon stalks	AOPs	$SO_4^{\bullet-}$ $^{\bullet}OH^-$ $^1O_2$	NA	0.5 mg/L	Follows radical and non-radical pathways for PDS. The presence of chloride accelerates the oxidation process.	(Giannakopoulos et al., 2023)
	Bermudagrass	Adsorption (physical and chemical interactions)/AOP	OH^-	NA	89.58%	FeCl3-mediated pyrolysis up to 3 times reusability with increased removal efficiency at higher reaction temperature	(Zeng & Kan, 2022)
Tetracycline	Maize straw	AOPs	$SO_4^{\bullet-}$ $^{\bullet}OH^-$ $^1O_2$	NA	86.55%	Carbonization of urea mixed with maize straw shows better removal efficiency when compared to urea mixed with pristine obtained from maize straw	(X. Zhang et al., 2024)
Caffeine	Tea waste	Adsorption (physical and chemical interactions)/ AOP	NA	17.6 mg/g	NA	Engineered tea waste exhibited high aromaticity, thereby enhancing	(Keerthanan et al., 2020)

						adsorption efficiency.	
Ciprofloxacin	Corn cob	AOP	OH^-	NA	93.60%	Biochar demonstrated high catalytic activity and structural stability	(Liu et al., 2022)
Carbamazepine	Dried Soya beans	AOPs	$SO_4^{\bullet-}$ $^{\bullet}OH^-$ $^1O_2$	NA	99%	Modification of soya bean biochar by Fe, Mn and FE@Mn results to an optimal degradation effect. The stalactite-like morphology of FE@Mn enables fast degradation.	(He et al., 2024)

Table 4: Biochar and biochar-based enhanced AOP for the removal of dyes, microplastics, and microbial inactivation in wastewater.

Pollutant	Catalyst	Oxidant	Operation condition	Removal efficiency	Key findings	References
Dye						
Methylene blue (MB)	Peach skin-derived fibrous biochar impregnated with zerovalent iron nanoparticles (nZVI-FBC)	H_2O_2	pH of MB = 4.5, conc = 20 mg/L, temp = 25 °C, H_2O_2 conc = 7 mM, R.T = 40 min	99.80%	The BC-based system exhibited superior catalytic performance, excellent stability, and reusability over multiple cycles	(Bashir et al. 2022)
Azo dye orange (AO7)	Heavy metals-enriched hyperaccumulator (*Sedum alfredii*) residues	PMS	AO7 (50 mg/L), R.T = 30 min	99.70%	The BC/PMS system exhibited superior environmental performance	(Pan et al., 2
Reactive Red 218 (RR218)	CuO-modified loofah BC (Cu@LSC)	PMS	0.125 g/L (catalyst), temp = 25°C, pH = 9, R.T = 30 min	98.20%	Promising for rapid treatment and reusability	(B. Wang et a 2025)
MB	Bamboo-derived BC (BBC)	H_2O_2	BC pyrolysis @400 °C, H_2O_2 conc = 15 mM, R.T = 30 min	90%	The efficacy of MB removal was significantly influenced by the concentration of carbon-centered PFRs and their temporal stability.	(Zanardi et a 2024)
Acid orange 7	Magnetic sludge-derived biochar (MSDBC)	PS	BC pyrolysis @ 400 °C, AO7 conc = 0.06 mM, R.T = 20 min, temp = 25 °C, pH = 5.22	98.10%	Lower pH value enhanced AO7 elimination by the MSDBC/PS system.	(J. Wang et a 2017)
Methyl orange (MO), and tartrazine (TZ)	$CuFe_2O_4$ impregnated BC	H_2O_2	BC pyrolysis @ 350 °C, MO & TZ conc (10 mg/L), pH = 3, catalyst conc = 1 g/L	~ 100% for MO & TZ	$CuFe_2O_4$/BC is an effective photocatalyst composite for removing dyes from wastewater	(Monitoring al., 2022)
AO7 and MB	Iron-doped biochar (Fe@BC)	H_2O_2	BC pyrolysis @ 900 °C, Fe@BC (2.0 g/L) and H_2O_2 (4.0 mmol/L), temp = 30 °C	NA	The Fe@BC/H_2O_2 system effectively degraded the dyes.	(C. Wang et a 2021)

Congo red (CR)	Metal salt impregnated biochar ($AlCl_3$@BC)	NA	BC pyrolysis @ 500 °C, CR conc = 50 mg/L, catalyst = 2 g/L, temp = 35 °C	96.80%	The efficacy of CR removal decreased as the solution pH increased, whereas it improved with a higher biochar dose.	(Le et al., 20
MB	Food waste-derived BC	H_2O_2	BC pyrolysis @ 300 °C, 2 g/L catalyst, 200-mM H_2O_2, temp = 25 °C	84%	The BC-based system exhibited synergistic effects and effectively removed organic dyes from water	(Chu et al., 2
Microbe inactivation						
$FeCl_3$ - activated bermudagrass-derived BC (FA-BC)	*Escherichia coli (E. coli)*	PS	1000 mg/L FA-BC, 3000 mg/L PS, pH 7, and 20 °C, R.T = 180 min	99.2% (real stormwater)	The BC-based system is a promising and efficient technique for water disinfection.	(Zeng & Kan 2023)
$FeCl_3$ - activated biochar (Fe-BC)	*E. coli*	PMS	BC conc = 1 g/L, PMS dose = 300 mg/L, pH = 7.8,	NA	As PMS and Fe-BC concentrations increased, the bacterial inactivation efficacy of the Fe-BC/PMS treatment also improved	(Adeel et al., 2024)
Spirulina-derived biochar (SDBC)	*E. coli*	PDS	BC pyrolysis @ 900 °C, 6mM PDS, R.T = 90 min, temp = 37 °C	NA	The biochar-based nonradical system achieved outstanding performance in real water matrices.	(Ho et al., 20
Anaerobic digestion sludge biochar (ADSBC)	*E. coli*	PDS	BC pyrolysis @1000 °C, 0.2 g/L catalyst, 10 mMPDS, pH = 6, R.T = 90 min	NA	The BC based system (ADSBC 1000) was highly reactive for the inactivation of diverse microbial communities in real water	(Y. Chen et a 2019)
Microplastics (MPs)						
Fe-modified biochar (FeBC)	Polystyrene microplastics (PS-MPs)	NA	3 g/L catalyst, 20 mg/L PS-MPs	72.39% (tap water) 78.33% (lake water)	Metal-modified biochar had a potential application in purifying MP-contaminated tap and lake waters	(L. Zhang et 2023)
PAHs						

Fe-Mn binary oxides modified biochar (Fe-Mn/BC)	Naphthalene	H_2O_2	BC pyrolysis @ 500 °C, 30 mg/L naphthalene, 100 mg/L catalyst, R.T = 60 min	75.80%	The improvement of catalytic activity was significantly impacted by the synergistic effects of biochar and Fe-Mn binary oxides.	(L. Li et al., 2019)

9. Limitations and Future Suggestions

BC-based systems integrated with AOPs have proven efficient for wastewater remediation. However, there are limitations that warrant serious attention to improve stability, safety, reusability, and operational scalability. These limitations are outlined below;

i. pH effect: Several studies have shown that not all BC-based activators can effectively degrade contaminants across a wide pH range, particularly the initial solution pH (Cao et al., 2025; Mai et al., 2025; S. Wang & Wang, 2019; S. Zhu et al., 2019). Most BC-based systems do not support efficient removal of organic pollutants under extremely alkaline or acidic pH conditions. Certain photocatalytic reactions, such as heterogeneous Fenton-like and catalytic ozonation, are particularly sensitive to pH because the formation of reactive oxidizing species varies with solution pH (X. Chen et al., 2021). Therefore, there is a need for more studies on BC-based composites that can activate oxidants and operate over a wider pH range with a relatively high removal efficiency.

ii. Practical application in wastewater treatment: Majority of the study focused more on simulated pollutants in aqueous environment e.g. metal, pharmaceutical, dye solutions etc. without real time application. Therefore, there is a need for more studies on the removal of these pollutants in wastewater.

iii. Stability of BC/metal composites: The physicochemical interactions between BC/metal nanocomposites during AOPs are unclear; therefore,

more studies are needed to elucidate the reaction mechanism and the generation of radicals for activation of the oxidant.

iv. Toxicity of BC/metal composites: One of the disadvantages of BC/metal composites used in AOPs is the emission of metal nanoparticles during preparation and application. The release of these pollutants could pose a threat to human health and ecosystems; therefore, future research is needed to develop more environmentally friendly nanocomposites. To the best of the authors' knowledge, there are limited studies reported on the ecotoxicity of BC and BC-based catalysts after use. Additional efforts are required to evaluate the ecotoxicity of used BC or BC-based catalysts in pollutant degradation.

v. Limited studies on microbial inactivation: This study reveal that little attention has been given to microbial inactivation in general, with most research focusing on *E. coli* inactivation in wastewater. Therefore, there is a need for more studies on the inactivation of multiple microorganisms in wastewater treatment. Additionally, other essential limitations include catalyst fouling in real wastewater, gradual activity loss over repeated cycles, potential metal leaching, variability in biochar feedstocks, challenges in reactor design, and catalyst recovery.

Conclusion

The findings highlight the significant potential of biochar and its composites as effective, economically viable, and environmentally sustainable catalysts across a wide range of AOP systems. BC-based materials demonstrated high

efficacy in removing a broad spectrum of contaminants, including pharmaceuticals, dyes, heavy metals, microplastics, and microbial pathogens, achieving removal efficiencies exceeding 99% in several instances, particularly for pharmaceutical pollutants. The enhanced performance of BC-based AOPs is attributed to synergistic interactions between BC and functional components such as metal oxides, metal-organic frameworks (MOFs), covalent organic frameworks (COFs), and heterojunction semiconductors. These combinations significantly improve photocatalytic activity, reactive oxygen species (ROS) generation, charge separation, and pollutant adsorption. Moreover, BC's physicochemical properties, including high surface area, electrical conductivity, and surface functional groups, facilitate radical generation and contaminant interaction, thereby enhancing overall degradation efficiency. Despite these promising outcomes, several challenges persist. Notably, the application of BC-based systems in real wastewater matrices remains limited, with most studies conducted under controlled laboratory conditions using simulated pollutants. The stability of BC-metal composites across varying pH conditions, the potential ecotoxicity of the catalysts, and the lack of comprehensive microbial inactivation studies beyond *E. coli* highlight critical research gaps. In light of these limitations, future research should focus on developing scalable, eco-friendly, and multifunctional BC-based composites that can work in a wider pH range and are validated for real-world wastewater treatment scenarios. Additionally, comprehensive mechanistic studies and life cycle assessments

are essential to ensure the environmental safety, scalability, and practical applicability of these emerging technologies.

Authors' contributions

IOS: Conceptualization, Writing—original draft, Investigation, Visualization. RSD: Writing—original draft, Writing—review & editing. MBO: Writing—original draft, Writing—review & editing. KMM: Writing—original draft, Writing—review & editing. AAA: Writing—original draft, Writing—review & editing. BDA: Writing—original draft, Writing—review & editing. ABA: Writing—review & editing. KAL: Writing—original draft, Supervision, Writing—review & editing.

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