

## ORIGINAL RESEARCH ARTICLE

Water treatment using silver-iron-modified  
biochar for enhanced disinfection and  
sustainability

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**Abstract**

The contamination of water resources by pathogenic microorganisms remains a critical global challenge, predominantly in low- and middle-income countries. Conventional water treatment technologies, such as chlorination and filtration, often face drawbacks, including the formation of harmful byproducts and high operational costs. The increasing demand for efficient, sustainable, and scalable solutions necessitates the exploration of advanced materials for water disinfection. This study investigates the potential of silver-iron (Ag-Fe)-modified biochar as a photocatalyst under visible light to achieve high microbial inactivation. The material demonstrates dual functionality through the antibacterial effects of Ag and the photocatalytic activity of Fe, integrated within a renewable biochar. Elemental composition analysis shows that a composition of 4.3 wt% Ag and 30.0 wt% Fe enhances antimicrobial performance. Experimental results indicate bacterial inactivation under visible light conditions. Ag-Fe-modified biochar presents a potential alternative to conventional disinfection methods.

**Keywords:** Photocatalysis; Biochar; Water disinfection; Silver; Iron catalysis

**1. Introduction**

The contamination of water resources by pathogenic bacteria, including *Escherichia coli*, *Salmonella*, and *Vibrio cholerae*, represents a significant challenge to public health

worldwide. These microorganisms are introduced into water supplies through agricultural runoff, untreated sewage, and stormwater, contributing to an estimated 1.2 million deaths annually from waterborne diseases, particularly in low- and middle-income regions.<sup>1,2</sup> Traditional water treatment technologies, such as chlorination, sand filtration, and boiling, have been widely employed to manage microbial contamination.<sup>3</sup> However, these methods present limitations that reduce their suitability for large-scale or resource-constrained applications. Chlorination, for example, produces potentially carcinogenic byproducts, such as trihalomethanes, while sand filtration is often ineffective at removing certain microbial contaminants, and boiling is energy-intensive and impractical for widespread use in energy-limited settings.<sup>3,4</sup> These shortcomings necessitate the development of advanced technologies capable of providing safe and sustainable water treatment solutions.

Advanced oxidation processes (AOPs), ultraviolet (UV) irradiation, and membrane filtration systems have been proposed as alternatives to conventional methods.<sup>5-7</sup> AOPs generate reactive radicals that degrade pollutants and inactivate microorganisms, while UV irradiation provides non-chemical disinfection without producing harmful byproducts, and membrane filtration effectively separates contaminants through physical barriers. However, the widespread adoption of these advanced methods is constrained by high operational costs, significant infrastructure requirements, and challenges associated with scalability. Membrane fouling increases operational costs by 30%, while the initial capital investment for UV and AOP systems limits their feasibility in resource-limited settings.<sup>8</sup> Furthermore, the emergence of antimicrobial resistance introduces additional challenges to ensuring reliable disinfection performance.

In this context, biochar, a porous carbonaceous material produced through the pyrolysis of biomass, has attracted considerable interest as a platform for environmental remediation due to its high surface area, tunable surface chemistry, and renewable origin. Recent research has focused on enhancing biochar properties through the incorporation of metals, such as silver (Ag) and iron (Fe), creating multifunctional photocatalysts with superior antibacterial and photocatalytic activities.<sup>9,10</sup> Ag exhibits antimicrobial properties through mechanisms that disrupt bacterial cell membranes and interfere with intracellular processes, while Fe enhances photocatalytic performance by facilitating the production of reactive oxygen species (ROS) under visible light conditions. The integration of Ag and Fe within a biochar matrix produces a composite material with dual functionality, where the antibacterial

effects of Ag are complemented by the photocatalytic properties of Fe.<sup>11,12</sup> This approach not only improves the efficiency of water disinfection but also reduces energy demands by utilizing solar energy, making it a potentially sustainable and cost-effective solution for microbial water contamination.

Recent studies increasingly treat metal-modified biochar as a multifunctional disinfection material rather than a purely adsorptive carbon. Ag-modified biochar is synthesized by immobilizing Ag on porous biochar and incorporating it into beads or hydrogels intended for drinking-water purification, where the antibacterial performance is typically attributed to contact-mediated effects and controlled Ag species release. A chitosan-coated biochar-nanoAg composite reported sustained antibacterial activity and reusability in a drinking-water context, highlighting the practicality of immobilizing Ag onto a recoverable scaffold.<sup>13</sup> Similarly, porous Ag-loaded biochar was embedded into polymer gel beads to suppress bacteria, a strategy that improves handling and reduces direct nanoparticle dispersion while still achieving strong antibacterial outcomes in laboratory tests.<sup>14</sup> For Fe-modified biochar, the emphasis was on the redox/photochemical routes, frequently involving oxidant activation or visible light assistance, which can yield strong disinfection but also introduce condition-dependence. Maghemite-impregnated biochar with visible light-assisted disinfection of *E. coli* has been investigated, where the Fe-bearing phases can participate in photo-assisted inactivation rather than purely contact killing.<sup>15</sup> Fe<sub>3</sub>O<sub>4</sub>-loaded magnetic hydrochar with bacterial inactivation reported that iron-carbon composites can support radical-driven disinfection under visible light. The FeCl<sub>3</sub>-activated biochar/peroxymonosulfate system was evaluated for *E. coli* inactivation in real secondary-treated urban wastewater, and the interference effects of microplastics on disinfection performance were explicitly examined.<sup>16</sup> Meanwhile, Ag-Fe hybrid concepts have also been explored in photocatalytic/radical frameworks, where Ag<sub>3</sub>PO<sub>4</sub>/Fe<sub>3</sub>O<sub>4</sub>-activated biochar was used under visible light, emphasizing that dual-metal systems can be designed for recoverability and enhanced photo-redox performance.<sup>17</sup> Ag-biochar has been tested in sand filtration columns and reported >90% *E. coli* removal from wastewater samples, demonstrating that deployment-like configurations can yield measurable microbial reductions.<sup>18</sup>

This research investigates the antibacterial and photocatalytic properties of Ag-Fe-modified biochar and assesses its application in realistic conditions of pond water. The preparation of Ag and Fe within the biochar matrix represents an alternative approach to

achieving dual functionality, combining antimicrobial and photocatalytic properties. The dual-action nature of this material not only enhances disinfection efficiency but also reduces reliance on synthetic materials and minimizes environmental impact, offering a practical and sustainable solution for water treatment.<sup>19</sup> The current development of Ag-Fe-modified biochar as a photocatalyst for water disinfection has been carried out as proof-of-concept through lab-scale validation. This study also aims to address limitations in existing water treatment technologies by preparing a material that operates effectively under visible light and achieves high microbial inactivation. In addition, biochar, derived from biomass waste, aligns with the principles of resource recovery and waste valorization, supporting the sustainability objectives of modern water treatment systems. The practical implications of Ag-Fe-modified biochar are significant, particularly for regions with limited access to advanced water treatment infrastructure. The use of visible light as an energy source ensures that the Ag-Fe-modified biochar can be applied in low-resource settings, providing a low-cost and scalable solution for microbial water contamination. These findings align with the objectives of the United Nations Sustainable Development Goal 6, which focuses on ensuring clean water and sanitation for all.

## 2. Materials and methods

### 2.1. Water sample collection

Water samples from a pond located at Sibul, Sarawak (2.361275, 111.956743) were collected from three different points in July 2018 to assess the disinfection efficacy of Ag-Fe-modified biochar on natural microbial communities. Representative samples were collected to reflect the native microbial community and key physicochemical characteristics of the source water, thereby enabling evaluation of the disinfection process under conditions that are relevant to practical application. Samples were placed in a cooler containing ice packs to maintain a controlled temperature range of 1–4°C to reduce microbial metabolic activity, thereby preventing structural or compositional changes within the microbial community.

### 2.2. Preparation and characterization of photocatalyst

The preparation of Ag-Fe-modified biochar was conducted at room temperature using a liquid-phase reduction method. Palm kernel shell biochar was carbonized at 500°C for 2 h, ground, and sieved to achieve a fineness of 200 mesh. This ensures a uniform particle size, which is critical for consistent surface modification. The process commenced with the preparation of a coating solution by dissolving

0.05 g of polyethylene glycol and 2–3 g of ferrous sulfate heptahydrate ( $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ ) in 50 mL of distilled water.<sup>20</sup> The polyethylene glycol acts as a stabilizing agent, while the  $\text{FeSO}_4$  provides the Fe source required for subsequent reactions. Following the preparation of the coating solution, 2 g of palm kernel shell biochar powder was introduced into the solution. The mixture was subjected to magnetic stirring for 30–60 min, which facilitated the deposition of nano-zero valent Fe (nZVI) onto the biochar surface, resulting in the formation of the nZVI-biochar composite.<sup>21</sup> Magnetic stirring ensured homogeneous dispersion and interaction between the Fe precursor and the biochar, enhancing the uniformity of the coating.

The resulting composite was then immersed in 50 mL of a sodium borohydride solution (22.7 g/L) and subjected to vigorous stirring. This step induces the reduction of Fe ions to their zero-valent state, a critical transformation for the desired photocatalytic activity.<sup>22</sup> After the reduction process, the nZVI-biochar composite was thoroughly washed with distilled water and ethanol to eliminate any residual reactants or byproducts that might interfere with subsequent reactions or applications. In the final stage, 30 mL of a silver nitrate ( $\text{AgNO}_3$ ) solution containing 0.013–0.018 g of  $\text{AgNO}_3$  was introduced into the nZVI-biochar mixture. The solution was stirred for an additional 30–60 min to facilitate the reduction of Ag ions and their deposition onto the nZVI surface.<sup>23</sup> The reduction and deposition of Ag ions onto the composite surface are critical for enhancing the antibacterial and photocatalytic properties of the material. The resulting product, Ag-Fe-modified biochar, represents a multifunctional composite material designed for potentially efficient water disinfection through the synergistic effects of its antimicrobial and photocatalytic properties. This methodical preparation process ensures the reproducibility and uniformity of the Ag-Fe-modified biochar composite, which is essential for achieving consistent performance in subsequent experimental applications.

Scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDX) analysis was performed using a scanning electron microscope (M JSM-6010 Plus/LV, JEOL, Japan) equipped with an EDX (Oxford Instruments, United Kingdom) system operated in high-vacuum mode. Before imaging, dried samples were mounted on aluminum stubs using double-sided conductive carbon tape. Secondary electron images were acquired at a field of view consistent with a 50  $\mu\text{m}$  scale bar ( $\times 500$  magnification), using an accelerating voltage of 15 kV. The working distance was maintained at approximately 10 mm, and the beam current size was set to a moderate level to balance spatial resolution and count

rate. Elemental acquisition was conducted at multiple locations (six-point spectra) across the sample surface to capture compositional heterogeneity.

### 2.3. Pond water treatment with photocatalyst

A 500 mL batch reactor system was employed for laboratory-scale experiments to evaluate the disinfection performance of the Ag-Fe-modified biochar photocatalyst. In these experiments, 100 mL of pond water and 0.5 g of photocatalyst (solution pH was adjusted to 4) were introduced into a closed reaction system, and all experiments were conducted in triplicate to ensure reproducibility and enable reporting of averaged results with associated variability. The setup was designed to allow precise control of experimental conditions, including light exposure, reaction time, and temperature. Natural sunlight was utilized where feasible due to its cost-effectiveness and practical relevance. Key operational parameters, such as reaction time and light intensity, were systematically monitored and adjusted to optimize the interaction between the photocatalyst and the contaminants. These parameters are critical to maximizing the photocatalytic efficiency and ensuring accurate assessment of the disinfection process. Control experiments were conducted in parallel, in which pond water samples were exposed to identical conditions without the addition of the photocatalyst. These controls were essential for distinguishing the photocatalytic effects of the Ag-Fe-modified biochar from other processes, such as natural microbial die-off or photolysis caused by direct light exposure.

Water samples were collected at predefined intervals during the experimental period to track changes in microbial populations and contaminant levels. Microbial plate counting techniques were employed to quantify the reduction in bacterial counts and assess the efficacy of the treatment.<sup>24</sup> These techniques provided a quantitative evaluation of the disinfection process, offering critical insights into the performance of the photocatalyst under varying experimental conditions. The rigorous application of these methodologies ensured that the findings were robust, reproducible, and reflective of the practical potential of the photocatalyst for water disinfection applications.

### 2.4. *E. coli* detection

To prepare a 5 mM solution of AgNO<sub>3</sub>, 0.085 g of AgNO<sub>3</sub> was accurately weighed using an analytical balance. The AgNO<sub>3</sub> was then transferred into a 100 mL volumetric flask, and distilled water was added to the calibration mark to achieve the desired concentration. The flask was gently swirled to ensure the complete dissolution of the AgNO<sub>3</sub>, resulting in a homogeneous solution ready for experimental use. Two sample sets were prepared

for the experiment. For the treated sample, 50 mL of the water sample was mixed with 50 mL of the 5 mM AgNO<sub>3</sub> solution in a 250 mL volumetric flask, creating a total volume of 100 mL. This mixture was stirred continuously for 1 h using a magnetic stirrer to ensure thorough mixing and to promote the interaction between the Ag ions and the microbial contaminants present in the water. For the control sample, 50 mL of the same water sample was combined with 50 mL of distilled water. This mixture served as a baseline to compare the effectiveness of the Ag treatment.

The Quanti-Tray Sealer (Hach, United States) was preheated according to the manufacturer's instructions.<sup>25</sup> Both the treated and control samples were vigorously shaken to ensure homogeneity. Each sample was then transferred into a test bottle, to which one packet of Colilert reagent (Hach, United States) was added. The bottles were capped and shaken until the reagent was mostly dissolved. Subsequently, the contents of each bottle were poured into a Quanti-Tray/51 (Hach, United States), which contains 51 wells for microbial enumeration. Special care was taken to fill each well uniformly and eliminate air bubbles by gently tapping the trays on a hard surface. The filled Quanti-Trays were sealed using the Quanti-Tray Sealer following the manufacturer's guidelines. The sealed trays were then incubated at a temperature of 35 ± 0.5°C for 24 h to optimize the growth and detection of coliform bacteria and *E. coli*.

After incubation, the trays were examined under normal lighting to count the wells that turned yellow, indicating the presence of total coliform bacteria. To identify wells containing *E. coli*, the trays were illuminated with a UV lamp at 365 nm, and wells exhibiting fluorescence were recorded. These results were used to assess the effectiveness of the Ag treatment by comparing the microbial presence in treated versus control samples. The counts of yellow and fluorescent wells from each tray were meticulously recorded and referenced against the most probable number table included with the Colilert system. This table allows the estimation of bacterial concentrations based on the number of positive wells, facilitating the quantification of disinfection efficacy.

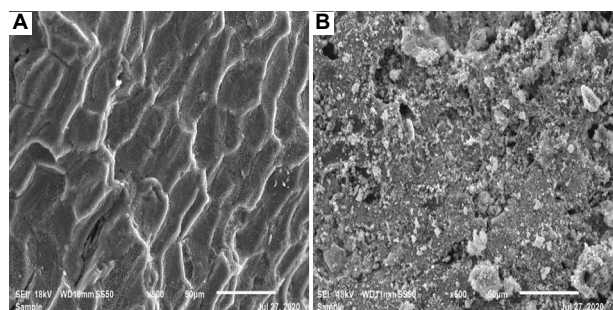
## 3. Results and discussion

### 3.1. Characteristics of the photocatalyst

Figure 1 and Table 1 show the surface morphology and elemental composition of biochar samples before and after modification with Ag and Fe, providing quantitative evidence of the modification process efficacy and its influence on the material properties for disinfection applications. Table 1 presents the elemental composition

**Table 1. Elemental analysis using scanning electron microscopy with energy-dispersive X-ray spectroscopy analysis**

| No. | Sample                       | Carbon (wt%) | Oxygen (wt%) | Silicon (wt%) | Silver (wt%) | Iron (wt%) |
|-----|------------------------------|--------------|--------------|---------------|--------------|------------|
| 1   | Biochar                      | 97.3±8.7     | 2.1±3.3      | 0.6±0.2       | N/A          | N/A        |
| 2   | Silver-iron-modified biochar | 24.6±4.6     | 41.1±6.1     | N/A           | 4.3±2.2      | 30.0±5.8   |

**Figure 1.** Scanning electron microscopy images. (A) Biochar. (B) Silver-iron-modified biochar. Scale bar: 50 µm; magnification: ×500.

in weight percentages (wt%) of carbon, oxygen, silicon, Ag, and Fe for both the raw biochar and the Ag–Fe-modified biochar. In biochar, carbon constitutes 97.3 wt%, which reflects the high carbon content of biochar derived from biomass pyrolysis. Oxygen accounts for 2.1 wt%, which shows limited oxygen-containing functional groups on the biochar surface. Silicon is detected at 0.6 wt%, which likely originated from inorganic components inherent to the biomass.

In the Ag–Fe-modified biochar, notable compositional changes were observed. The carbon content decreased to 24.6 wt%, oxygen increased to 41.1 wt%, and silicon was not detected after modification. These reductions correspond to the incorporation of Ag and Fe, evidenced by the addition of 4.3 wt% Ag and 30.0 wt% Fe. The significant presence of Ag and Fe indicates successful deposition onto the biochar matrix, which is critical for achieving the intended functionalities of the material. The elevated Fe content supports enhanced photocatalytic activity by facilitating the generation of ROS under visible light. These ROS are able to degrade organic pollutants and inactivate microbes. Similarly, the high Ag content provides strong antibacterial properties as Ag<sup>+</sup> ions disrupt bacterial membranes and interfere with essential cellular processes.

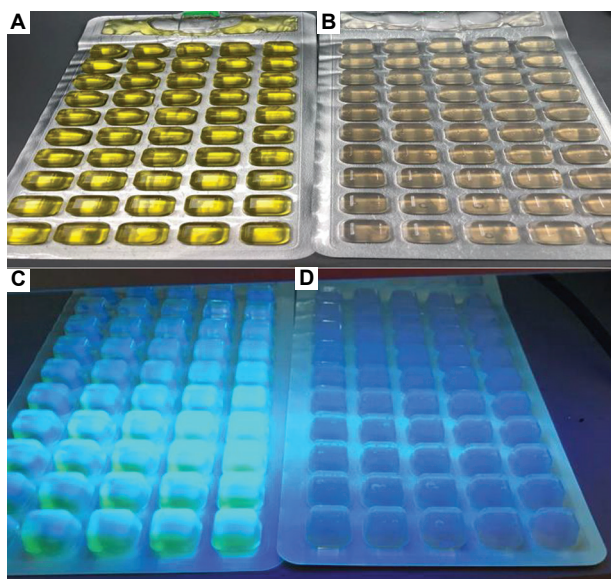
The modified biochar plays a dual-purpose role as an adsorbent and a photocatalyst. The increased oxygen content after Ag–Fe loading further confirms that the biochar surface has been substantially modified. During impregnation, Fe and Ag precursors are converted mainly to their oxide or hydroxide forms. These new oxygen-containing phases and functionalities replaced part of

the original carbon matrix, explaining the sharp drop in carbon and the large rise in oxygen detected by EDX. The dense metal oxide domains can also screen the underlying carbon from the detector, which, after normalization of the data to 100 wt%, further amplified the apparent oxygen proportion. This higher oxygen content is not only a compositional change but also directly benefits the material performance. Polar oxygenated groups improve the hydrophilicity of the surface and provide active sites for binding pollutants, thereby enhancing adsorption capacity.<sup>26,27</sup> Simultaneously, surface hydroxyls on Fe and Ag oxides act as reaction centers for the generation of ROS under light irradiation. These species, such as hydroxyl and superoxide radicals, are important for photocatalytic degradation of contaminants. Hence, the enrichment of oxygen indicates the formation of an oxygen-rich metal oxide-biochar interface that underpins the dual role of the modified biochar as an efficient adsorbent and a robust photocatalyst.

### 3.2. Treatment of pond water using the photocatalyst

Figure 2 presents the results of a Quanti-Tray test conducted to evaluate the presence of coliform bacteria (e.g., *E. coli*) in water samples treated with Ag–Fe-modified biochar under ambient and UV light conditions. This experimental setup demonstrates the material's dual functionality in water disinfection, combining the antimicrobial effects of Ag and the photocatalytic activity of Fe embedded within a biochar matrix. Under ambient light conditions, the untreated water sample (Figure 2A) showed a high prevalence of yellow wells, indicative of total coliform bacteria, while the treated water samples (Figure 2B) showed a significant reduction. This reduction suggests that Ag–Fe-modified biochar is potentially effective in mitigating microbial contamination. Similarly, under UV light, fluorescence observed in the untreated sample indicates the presence of *E. coli* (Figure 2C), a critical indicator of fecal contamination and a key public health concern. The absence of fluorescence in the treated sample demonstrates the material efficacy in targeting pathogenic bacteria (Figure 2D).

The Ag–Fe-modified biochar reduced microbial contamination effectively by inactivating bacteria under visible light conditions. However, several considerations require critical evaluation to contextualize the results



**Figure 2.** The differences between untreated pond water and treated pond water. Untreated pond water under (A) ambient light and (C) ultraviolet light. Treated pond water under (B) ambient light and (D) ultraviolet light.

and assess their broader implications. Mechanistically, the dual actions of Ag and Fe contribute to the material's antibacterial effectiveness. Ag ions disrupt bacterial membranes and interfere with essential cellular processes, while Fe enhances the production of ROS, which oxidatively degrade organic contaminants and inactivate microorganisms. However, the specific contributions of Ag and Fe to the disinfection process remain unclear. Quantitative studies to separate and assess the individual roles of these components are needed to optimize the material design and performance.

The influence of environmental factors, such as turbidity, organic matter content, and competing ions, on the material performance in real-world water systems must be addressed. High organic loads in natural water systems may interfere with the availability of Ag ions or hinder ROS generation by scavenging reactive species. The performance of Ag-Fe-modified biochar should also be benchmarked against established disinfection technologies, such as chlorination, UV treatment, and AOPs. Comprehensive studies on the environmental impact of Ag and Fe leaching are critical for ensuring sustainability. While Ag-Fe-modified biochar shows significant promise as a sustainable and cost-effective water treatment solution, further research is necessary to ensure its practicality, scalability, and environmental compatibility in real-world applications. These efforts are essential to advancing this material from laboratory studies to practical implementation in global water quality improvement efforts.

### 3.3. Mechanisms underlying bacterial inactivation by the silver-iron-modified biochar

The antibacterial performance of Ag-Fe-modified biochar is discussed in the current proof-of-concept study. The experiments demonstrated successful incorporation of Ag and Fe on the biochar surface based on SEM-EDX elemental detection and a clear reduction in total coliform/*E. coli*. At the material level, SEM-EDX confirmed surface-associated enrichment of Ag and Fe in raw biochar, indicating that the modification procedure successfully introduced metal-bearing domains onto the porous carbon. The biochar provides a high surface area and surface heterogeneity that can promote microbe-surface interactions. In disinfection systems, porous carbonaceous substrates can concentrate microorganisms at solid-liquid interfaces through adsorption and physical entrapment, thereby increasing the frequency and intimacy of contact between bacteria and active surface sites.<sup>28</sup>

The presence of Ag on the biochar provides a basis for antibacterial activity, as Ag-bearing surfaces are widely associated with contact-mediated bacterial stress and, potentially, release of Ag species that interfere with cellular envelope integrity and essential metabolic functions.<sup>29</sup> In this study, the observed reduction in coliform/*E. coli* indicators after exposure to the Ag-Fe-modified biochar suggests that Ag-associated antimicrobial functionality is accessible in the pond water matrix under the tested conditions. The Fe on the biochar surface further contributed to photo/redox processes at the metal-oxide/carbon interface. Many Fe-bearing composites facilitate the formation of oxidative intermediates that damage cells.<sup>30</sup>

The reduced number of positive wells in the Quanti-Tray test indicates that the microbial suppression may reflect a combination of inactivation and physical removal/partitioning, including adsorption of bacteria onto the solid phase, followed by sedimentation. Ag-associated antibacterial action may occur through contact killing or limited Ag species release, while Fe-associated photo/redox activity may contribute under the applied irradiation conditions. Therefore, while the current results demonstrate that Ag-Fe-modified biochar can suppress coliform/*E. coli* indicators in pond water under specified laboratory conditions, mechanistic attribution, and claims of synergistic coupling between Ag and Fe remain beyond the scope of the present evidence.

### 3.4. Current developments in biochar-based water disinfection technologies

Silver was selected in this study due to its well-established and broad-spectrum antimicrobial potency, which can be achieved at relatively low mass fractions, offering the

possibility of high disinfection efficacy without excessive material dosing.<sup>31</sup> When Ag is immobilized onto a solid support, it can deliver rapid bacterial suppression through contact-mediated effects and limited ion release, providing a strong benchmark for proof-of-concept development and mechanistic framing. Ag was incorporated onto a recoverable biochar, which was intended to reduce uncontrolled dispersion and enable physical separation after treatment. This immobilization strategy is also aligned with a scalability pathway, as biochar is abundant and low-cost, and can be processed into retrievable forms (e.g., packed media, beads, or supported beds) that minimize direct release. The scope of this study is positioned as a laboratory-scale validation of an Ag-containing composite design concept, with direct performance evidence under defined conditions. In subsequent work, Ag leaching, reusability across cycles, and performance retention in varying water matrices will be evaluated to determine whether the observed disinfection efficacy can be maintained with acceptable environmental risk.

Biochar-based technologies for water disinfection illustrate a clear transition from conventional adsorption-focused applications toward multifunctional materials capable of catalytic and photocatalytic inactivation of diverse microbial contaminants.<sup>32</sup> Biochar has the potential as a cost-effective adsorbent with tunable physicochemical properties for pollutant removal, but it has a limited intrinsic antibacterial capacity. Hence, metal functionalization, surface modification, and carbon–metal electron-transfer pathways have been explored to transform biochar into an active disinfection platform capable of generating ROS, releasing controlled antimicrobial ions, and stabilizing catalytic sites for persistent microbial inactivation. These advancements have laid the groundwork for integrated systems that combine adsorption, photocatalysis, and metal-induced oxidative stress within a single material framework.

Iron-modified biochar can activate persulfate to generate powerful sulfate radicals, enabling rapid destruction of antibiotic-resistant bacteria and suppressing the spread of antibiotic resistance genes.<sup>33</sup> Fe–biochar facilitates electron transfer, accelerates radical generation, and maintains activity under environmentally relevant conditions. The mechanistic elucidation shows that well-characterized pathways, including Fe(II)/Fe(III) redox cycling, surface-bound radical formation, and oxidative membrane rupture, are central to designing next-generation biochar disinfectants. These insights guide the engineering of multifunctional composite materials where catalytic activation, radical-driven oxidation, and microbial membrane disruption occur simultaneously.

The recent research shows the role of visible light-driven photocatalysis as a sustainable and low-energy approach for water disinfection.<sup>34</sup> Fe-assisted photocatalysis is particularly attractive as Fe sites in biochar can narrow the bandgap, promote photoexcited electron–hole separation, and generate ROS under natural sunlight without UV-based systems that require higher energy input. The incorporation of metallic nanoparticles (i.e., Ag, copper, or Fe oxides) onto biochar matrices creates synergistic effects that outperform individual components. Ag modification provides potent antimicrobial action through ion release and protein inactivation, while Fe enhances ROS formation and stabilizes charge carriers.<sup>35</sup> Together, these mechanisms create a multifaceted antibacterial system capable of addressing not only general coliforms but also more resilient microbial groups. The trend toward hybrid designs reflects the replacement of chemical-intensive disinfection with environmentally benign, sunlight-responsive materials that can operate effectively in rural, decentralized, or emergency contexts.

Recent studies emphasize that the presence of natural organic matter, turbidity, suspended solids, and competing ions can limit ROS availability, alter metal speciation, or interfere with bacterial interactions.<sup>36,37</sup> In addition, greater attention is now given to the environmental safety of metal-doped biochar, including metal leaching dynamics, long-term structural stability, and potential ecological impacts. Engineering strategies of strong metal–biochar bonding, surface oxidation for nanoparticle immobilization, and moderate metal loading have been recognized as necessary approaches to balance disinfection efficiency with environmental stewardship. This also aligns with global themes in circular economy principles, sustainable materials design, and decentralized water treatment for underserved regions. The integration of catalytic activation, visible light responsiveness, and sustainability considerations represents the newest direction in biochar-based disinfection that emphasizes accessibility, environmental safety, and advanced performance under real-world conditions.

### 3.5. Limitations, future directions, and real-world implications

The study on Ag–Fe-modified biochar as a photocatalyst for water disinfection identified several limitations that require further analysis to improve its performance and applicability. The stability and reusability of the photocatalyst present challenges, as the potential leaching of Ag and Fe nanoparticles could reduce its long-term effectiveness and pose environmental hazards. The experimental conditions, which were controlled and simplified, may not fully reflect the complexities of real-

world water systems. Environmental factors such as turbidity, organic content, and competing ions are likely to affect the material functionality in practical applications. In addition, the research focused primarily on bacterial inactivation, leaving its effectiveness against other waterborne pathogens, including viruses and antibiotic-resistant microorganisms, unexplored. The study also does not include an evaluation of the economic viability or scalability of producing the Ag–Fe-modified biochar for deployment in low-resource contexts.

Future investigations should prioritize assessing the environmental impact of nanoparticle leaching and developing strategies to improve material stability, such as advanced coating techniques or stabilizing element incorporation. Field tests in diverse water matrices, including municipal and industrial wastewater, are necessary to understand the material's performance in varying environmental conditions. Studies should also expand to include their disinfection capacity against a broader range of microorganisms, including viruses and biofilm-forming species, to provide a comprehensive evaluation. Furthermore, conducting techno-economic analyses is essential to assess the cost-effectiveness and scalability of this material, particularly in comparison to established water treatment methods. Exploring the integration of Ag–Fe-modified biochar with other advanced treatment technologies could enhance its overall efficacy and broaden its application scope.

The implications of this Ag–Fe-modified biochar for practical water treatment are significant. By utilizing visible light as an energy source, Ag–Fe-modified biochar offers a sustainable and cost-efficient approach to microbial water disinfection, particularly in regions lacking advanced water treatment infrastructure. The use of biomass-derived biochar aligns with principles of resource recovery and waste utilization, providing an environmentally sustainable approach to developing functional materials for water treatment. Its demonstrated ability to inactivate bacteria suggests it could play an important role in reducing waterborne diseases, especially in underserved regions. Furthermore, avoiding chemical-intensive disinfection methods, such as chlorination, reduces the generation of harmful byproducts and lowers the environmental impact of water treatment processes.

## 4. Conclusion

This study presents an evaluation of Ag–Fe-modified biochar as a photocatalyst for water disinfection, demonstrating its potential as an advanced solution for addressing microbial contamination. The dual functionality of the material was achieved through the integration of Ag

and Fe nanoparticles within a biochar matrix. Ag exhibits antibacterial properties by disrupting bacterial membranes and interfering with intracellular processes, while Fe enhances photocatalytic activity through the generation of ROS. The biochar substrate contributes additional benefits for adsorption and stabilization, which collectively enhance the disinfection performance. The research presents the material's ability to achieve significant microbial reduction under visible light, offering an energy-efficient and sustainable approach to water treatment, and the strategic integration of renewable biochar with functional properties to develop a cost-effective adsorbent as an alternative to conventional water disinfection technologies. Moreover, the reliance on biomass-derived biochar aligns with environmental sustainability objectives, promoting the valorization of waste materials and reducing dependence on chemical-intensive methods.

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## Conflict of interest

Su Shiung Lam is an Associate Editor of this journal, but was not in any way involved in the editorial and peer-review process conducted for this paper, directly or indirectly. The authors declare they have no competing interests.

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## Ethics approval and consent to participate

Not applicable.

## Consent for publication

Not applicable.

## Availability of data

Data will be made available on request to the corresponding author.

## References

1. Mei Z, Fu Y, Wang F, *et al.* Magnetic biochar/quaternary phosphonium salt reduced antibiotic resistance and pathobiome on pakchoi leaves. *J Hazard Mater.* 2023;460:132388.  
doi: 10.1016/j.jhazmat.2023.132388
2. Zhang JB, Dai C, Wang Z, *et al.* Resource utilization of rice straw to prepare biochar as peroxydisulfate activator for naphthalene removal: Performances, mechanisms, environmental impact and applicability in groundwater. *Water Res.* 2023;244:120555.  
doi: 10.1016/j.watres.2023.120555
3. Gwenzi W, Chaukura N, Noubactep C, Mukome FND. Biochar-based water treatment systems as a potential low-cost and sustainable technology for clean water provision. *J Environ Manag.* 2017;197:732-749.  
doi: 10.1016/j.jenvman.2017.03.087
4. Wu XN, Yuan CJ, Huo ZY, *et al.* Reduction of byproduct formation and cytotoxicity to mammalian cells during post-chlorination by the combined pretreatment of ferrate(VI) and biochar. *J Hazard Mater.* 2023;458:131935.  
doi: 10.1016/j.jhazmat.2023.131935
5. Zheng J, Zhang P, Li X, Ge L, Niu J. Insight into typical photo-assisted AOPs for the degradation of antibiotic micropollutants: Mechanisms and research gaps. *Chemosphere.* 2023;343:140211.  
doi: 10.1016/j.chemosphere.2023.140211
6. Sun W, Dong H, Wang Y, *et al.* Ultraviolet (UV)-based advanced oxidation processes for micropollutant abatement in water treatment: Gains and problems. *J Environ Chem Eng.* 2023;11(5):110425.  
doi: 10.1016/j.jece.2023.110425
7. Zhang R, Ding A, Cai X, *et al.* Break through the trade-off between membrane fouling and pathogen removal in ultrafiltration process by poly(amino acid)s modified biochar. *Sep Purif Technol.* 2025;356:129847.  
doi: 10.1016/j.seppur.2024.129847
8. Coccia M, Bontempi E. New trajectories of technologies for the removal of pollutants and emerging contaminants in the environment. *Environ Res.* 2023;229:115938.  
doi: 10.1016/j.envres.2023.115938
9. Yu C, Tang J, Liu F, Chen Y. Green synthesized nanosilver-biochar photocatalyst for persulfate activation under visible-light illumination. *Chemosphere.* 2021;284:131237.  
doi: 10.1016/j.chemosphere.2021.131237
10. Zhou X, Diao Y, Zhu Y, Quan G, Yan J, Zhang W. Release of biochar-derived dissolved organic matter and the formation of chlorination disinfection by-products: Effects of pH and chlorine dosage. *Environ Pollut.* 2024;342:123025.  
doi: 10.1016/j.envpol.2023.123025
11. Kumar A, Rana A, Sharma G, *et al.* High-performance photocatalytic hydrogen production and degradation of levofloxacin by wide spectrum-responsive Ag/Fe<sub>3</sub>O<sub>4</sub> bridged SrTiO<sub>3</sub>/g-C<sub>3</sub>N<sub>4</sub> plasmonic nanojunctions: Joint effect of Ag and Fe<sub>3</sub>O<sub>4</sub>. *ACS Appl Mater Interfaces.* 2018;10(47):40474-40490.  
doi: 10.1021/acsami.8b12753
12. Nicoara AI, Ene VL, Voicu BB, *et al.* Biocompatible Ag/Fe-enhanced TiO<sub>2</sub> nanoparticles as an effective compound in sunscreens. *Nanomaterials (Basel).* 2020;10(3):570.  
doi: 10.3390/nano10030570
13. Hu Z, Zhang L, Zhong L, Zhou Y, Xue J, Li Y. Preparation of an antibacterial chitosan-coated biochar-nanosilver composite for drinking water purification. *Carbohydr Polym.* 2019;219:290-297.  
doi: 10.1016/j.carbpol.2019.05.017
14. Zhao H, Li X, Zhang L, Hu Z, Zhong L, Xue J. Preparation and bacteriostatic research of porous polyvinyl alcohol/biochar/nanosilver polymer gel for drinking water treatment. *Sci Rep.* 2021;11(1):12205.  
doi: 10.1038/s41598-021-91833-9
15. Basu A, Behera M, Maharana R, *et al.* To unmask the mechanism of disinfection of *Escherichia coli* via visible light assisted heterogeneous photo-Fenton reaction in presence of biochar supported maghemite nanoparticles. *J Environ Chem Eng.* 2021;9(1):104620.  
doi: 10.1016/j.jece.2020.104620
16. Adeel M, Cirillo C, Sarno M, Rizzo L. Urban wastewater disinfection by FeCl<sub>3</sub>-activated biochar/peroxydisulfate system: *Escherichia coli* inactivation and microplastics interference. *Environ Pollut.* 2024;359:124607.  
doi: 10.1016/j.envpol.2024.124607
17. Talukdar K, Jun BM, Yoon Y, Kim Y, Fayyaz A, Park CM. Novel Z-scheme Ag<sub>3</sub>PO<sub>4</sub>/Fe<sub>3</sub>O<sub>4</sub>-activated biochar photocatalyst with enhanced visible-light catalytic performance toward degradation of bisphenol A. *J Hazard Mater.* 2020;398:123025.  
doi: 10.1016/j.jhazmat.2020.123025
18. Zhu L, Chattopadhyay S, Elijah Akanbi O, *et al.* Biochar and zero-valent iron sand filtration simultaneously removes contaminants of emerging concern and *Escherichia coli* from wastewater effluent. *Biochar.* 2023;5(1):41.  
doi: 10.1007/s42773-023-00240-y

19. Xie Y, Liu A, Bandala ER, Goonetilleke A. TiO<sub>2</sub>-biochar composites as alternative photocatalyst for stormwater disinfection. *J Water Process Eng.* 2022;48:102913.  
doi: 10.1016/j.jwpe.2022.102913
20. Dong H, Deng J, Xie Y, *et al.* Stabilization of nanoscale zero-valent iron (nZVI) with modified biochar for Cr(VI) removal from aqueous solution. *J Hazard Mater.* 2017;332:79-86.  
doi: 10.1016/j.jhazmat.2017.03.002
21. Ahmad S, Liu X, Tang J, Zhang S. Biochar-supported nanosized zero-valent iron (nZVI/BC) composites for removal of nitro and chlorinated contaminants. *Chem Eng J.* 2022;431:133187.  
doi: 10.1016/j.cej.2021.133187
22. Zhang K, Suh JM, Choi JW, Jang HW, Shokouhimehr M, Varma RS. Recent advances in the nanocatalysts-assisted NaBH<sub>4</sub> reduction of nitroaromatics in water. *ACS Omega.* 2019;4:483-95.  
doi: 10.1021/acsomega.8b03051
23. Jayeoye TJ, Eze FN, Olatunde OO, Benjakul S, Rujiralai T. Synthesis of silver and silver@zero valent iron nanoparticles using *Chromolaena odorata* phenolic extract for antibacterial activity and hydrogen peroxide detection. *J Environ Chem Eng.* 2021;9(3):105224.  
doi: 10.1016/j.jece.2021.105224
24. Wang X, Liang R, Pu X, *et al.* Application of the electrical microbial growth analyzer method for efficiently quantifying viable bacteria in ready-to-eat sea cucumber products. *Microorganisms.* 2024;12:2301.
25. McNair JN, Rediske RR, Hart JJ, Jamison MN, Briggs S. Performance of colilert-18 and qPCR for monitoring *E. coli* contamination at freshwater beaches in Michigan. *Environments.* 2025;12:21.
26. Mirzaeian M, Abbas Q, Hunt MRC, Hall P. Pseudocapacitive effect of carbons doped with different functional groups as electrode materials for electrochemical capacitors. *Energies.* 2020;13:5577.
27. Allahkarami E, Monfared AD. Activated carbon adsorbents for the removal of emerging pollutants and its adsorption mechanisms. In: Hadi Dehghani M, Karri RR, Tyagi I, editors. *Sustainable Remediation Technologies for Emerging Pollutants in Aqueous Environment.* Ch. 5. Netherlands: Elsevier; 2024. p. 79-109.
28. Afroz ARMN, Boehm AB. *Escherichia coli* removal in biochar-modified biofilters: Effects of biofilm. *PLoS One.* 2016;11(12):e0167489.  
doi: 10.1371/journal.pone.0167489
29. Yin IX, Zhang J, Zhao IS, Mei ML, Li Q, Chu CH. The antibacterial mechanism of silver nanoparticles and its application in dentistry. *Int J Nanomedicine.* 2020;15:2555-2562.  
doi: 10.2147/ijn.S246764
30. Arabzadeh Nosratabad N, Yan Q, Cai Z, Wan C. Exploring nanomaterial-modified biochar for environmental remediation applications. *Heliyon.* 2024;10(18):e37123.  
doi: 10.1016/j.heliyon.2024.e37123
31. Peng H, Guo H, Gao P, Zhou Y, Pan B, Xing B. Reduction of silver ions to silver nanoparticles by biomass and biochar: Mechanisms and critical factors. *Sci Total Environ.* 2021;779:146326.  
doi: 10.1016/j.scitotenv.2021.146326
32. Wang X, Guo Z, Hu Z, Zhang J. Recent advances in biochar application for water and wastewater treatment: A review. *PeerJ.* 2020;8:e9164.  
doi: 10.7717/peerj.9164
33. Duan R, Ma S, Ma Y, *et al.* Efficient inactivation of antibiotic resistant bacteria by iron-modified biochar and persulfate system: Potential for controlling antimicrobial resistance spread and mechanism insights. *J Hazard Mater.* 2025;492:138182.  
doi: 10.1016/j.jhazmat.2025.138182
34. Qiu P, Zhu J, Zhang C, *et al.* Visible light-supported efficient photocatalytic disinfection using a robust silver-doped boron photocatalyst. *J Environ Chem Eng.* 2023;11(5):111058.  
doi: 10.1016/j.jece.2023.111058
35. Mondal SK, Chakraborty S, Manna S, Mandal SM. Antimicrobial nanoparticles: Current landscape and future challenges. *RSC Pharm.* 2024;1(3):388-402.  
doi: 10.1039/d4pm00032c
36. Oladimeji TE, Oyedemi M, Emetere ME, Agboola O, Adeoye JB, Odunlami OA. Review on the impact of heavy metals from industrial wastewater effluent and removal technologies. *Heliyon.* 2024;10(23):e40370.  
doi: 10.1016/j.heliyon.2024.e40370
37. Pontoni L, La Vecchia C, Boguta P, *et al.* Natural organic matter controls metal speciation and toxicity for marine organisms: A review. *Environ Chem Lett.* 2021;20:797-812.  
doi: 10.1007/s10311-021-01310-y