Biochar-Supported Metal Nanocomposites for Environmental Remediation and Green Catalysis: A Review

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***Abstract*—Biochar-supported metal nanocomposites have gained interest as versatile materials for pollution removal and sustainable catalysis because they merge the porous nature of biomass-derived carbon with the reactive properties of nanoscale metals or metal oxides. This review brings together findings from six recent studies focusing on silver-loaded biochars, a CeO2–ZnO/biochar ternary composite, and a magnetic Fe3O4@SiO2–Ag/biochar catalyst.**

These materials were tested for their effectiveness in breaking down methylene blue and antibiotics through photodegradation, catalyzing the reduction of nitrophenol and azo dyes, exhibiting antimicrobial effects, and facilitating multicomponent organic synthesis.

Key factors such as the choice of precursor, pyrolysis temperature, acid pretreatment, mineral addition, and nanoparticle placement significantly influenced surface chemistry, porosity, how particles were dispersed, and catalytic performance. Silver-based composites generally showed strong results even at low metal content, provided the nanoparticles were evenly spread and accessible. Many of these materials maintained considerable activity after multiple uses, and magnetic separation offered a convenient way to recover the catalyst.

This review also compares different preparation methods, characterization techniques, reaction kinetics, mechanistic insights, and material stability. Ongoing challenges include concerns about silver leaching, consistency when scaling up production, handling complex wastewater environments, and the scarcity of studies using continuous-flow systems. Future development should integrate rational support engineering, magnetic or other easily separable architectures, realistic multicomponent testing, and data-driven optimization.

***Index Terms*—4-nitrophenol, Biochar, environmental remediation, green catalysis, metal nanocomposites, photocatalysis, silver nanoparticles**

I. INTRODUCTION

Discharge of organic contaminants from industrial, agricultural, and pharmaceutical activities remains an important water-quality problem. Dyes such as methylene blue, methyl orange, and Congo red, together with nitroaromatic compounds such as 4-nitrophenol, can persist in aqueous environments and may pose risks to aquatic organisms and human health. Conventional approaches, including adsorption, membrane separation, and biological treatment, can be effective but may suffer from slow kinetics, incomplete degradation, regeneration requirements, or high operating costs. Catalytic reduction and photocatalytic oxidation continue to be promising methods for transforming stubborn pollutants into less harmful substances. Nanostructured noble metals, especially silver, offer numerous reactive sites and enhance electron transfer during these processes [18]. However, their practical application faces challenges like nanoparticle clumping and loss from the reaction environment. Anchoring these nanoparticles onto a porous support helps address these issues and makes it easier to recover the catalyst afterward [10].

Biochar stands out as an excellent support material because it's made by pyrolyzing low-value biomass waste, resulting in a porous carbon structure rich in oxygen-containing groups that can interact with metal ions and nanoparticles [8], [17]. Beyond serving as a

support, the carbon framework can also adsorb pollutants and may assist in electron transfer at interfaces [7], [9].

II. OVERVIEW OF THE REVIEWED STUDIES

The selected studies showcase a variety of approaches to designing biochar-based nanocomposites. Four of them focus on silver-loaded biochars aimed at pollutant degradation or photodegradation [1], [4], [5], [6], while one explores a ternary CeO_2–ZnO/biochar composite that combines adsorption with photocatalytic activity [2]. Another study highlights a magnetic silver-containing biochar used as a heterogeneous catalyst for organic synthesis [3]. Together, these works emphasize that the overall performance of the composite depends not only on the active metal or oxide phase but also on the structure and chemical properties of the biochar support.

Each study illustrates how careful control over material preparation can influence important features such as porosity, surface chemistry, and nanoparticle distribution. These characteristics play a critical role in determining how effectively the composite interacts with pollutants or facilitates catalytic reactions. The diversity in approaches also highlights the flexibility of biochar as a platform—it can be tailored to meet the specific demands of different environmental and catalytic applications. Furthermore, the incorporation of magnetic components adds practical value by enabling easy separation and reuse of the catalyst, which is vital for sustainable processes. Overall, these studies contribute valuable insights into how the interplay between biochar supports and active phases can be optimized to develop more efficient and versatile materials.

III. BIOCHAR PREPARATION AND COMPOSITIONAL ENGINEERING

A. Biomass selection and pyrolysis

All six studies use lignocellulosic materials such as leaves, bark, and rice husk as precursors [1], [2], [3], [4], [5], [6]. These biomass sources are transformed into biochar through pyrolysis in oxygen-limited environments, typically at temperatures ranging from 300 to 600 °C. Higher temperatures generally enhance carbonization, increase aromatic structures, and create more ordered carbon domains, but they also reduce the number of oxygen-containing surface groups and, in some cases, decrease the overall yield of biochar. Therefore, selecting a moderate pyrolysis temperature often strikes a better balance between developing useful pores and maintaining surface functionality.

This temperature effect is highlighted in comparative experiments. For example, biochar produced with calcite at 450 °C had a higher specific surface area than that made at 350 °C, even though it had less oxygen on the surface [4]. Similarly, for Borassus flabellifer bark, the biochar created at 500 °C showed the best nanoparticle distribution and catalytic activity, while the sample made at 600 °C exhibited some decline in surface quality and structure [6]. These observations indicate that the highest carbonization temperature is not necessarily the optimum condition for catalytic use.

B. Acid pretreatment and surface functionalization

Phosphoric-acid pretreatment is used in several of the reviewed studies before carbonization [4], [5], [6]. Such treatment can improve carbon retention and alter the carbon structure while increasing the availability of oxygen-containing functionalities. Hydroxyl and carboxyl groups are particularly relevant because they can interact with metal ions and provide nucleation or anchoring sites during subsequent nanoparticle formation. The resulting support therefore influences both the amount of metal retained and its spatial distribution.

C. Mineral and oxide incorporation

Adding an inorganic phase provides a second route for modifying biochar performance. Eggshell-derived calcium carbonate and calcite-rich structures introduce mineral sites and additional adsorption behavior. In the reported biochar–calcite systems, X-ray diffraction confirmed crystalline calcite together with the carbon phase, and the mineral-containing materials showed improved pollutant adsorption before silver deposition [4], [5]. A different strategy was used for the CeO_2–ZnO/biochar material, where the oxide phase was grown onto the carbon support. The ternary material reached a BET surface area of 215.3 $m^2\ g^{-1}$ compared with 153.7 $m^2\ g^{-1}$ for plain biochar, while the optical band gap was reported to decrease to 2.48 eV from 3.21 eV for ZnO and 2.93 eV for CeO_2. These changes are consistent with enhanced interfacial charge transport and broader light absorption [2].

A further structural modification involved sequential formation of Fe_3O_4 and a SiO_2 shell on biochar followed by silver deposition. This architecture combines the adsorption and carbon surface properties of biochar with magnetic separation and silanol-containing sites that can assist silver immobilization [3].

IV. SILVER NANOPARTICLE DEPOSITION

Two principal silver-loading strategies occur in the selected studies. The first is a green or biogenic route in which plant-derived compounds reduce Ag^+ and can also stabilize the resulting nanoparticles. The second uses chemical reduction, most commonly sodium borohydride, after contacting biochar with aqueous silver nitrate.

In the biogenic approach, Chenopodium ambrosioides leaf extract served as the reducing and capping medium for silver nanoparticle formation [1]. Flavonoids and tannins in the magnetic catalyst study, silver nanoparticles were synthesized using an extract from Lawsonia inermis before being immobilized onto the Fe_3O_4@SiO_2-supported material [3]. This green synthesis method reduces reliance on conventional chemical reducing agents, aligning well with the broader goal of developing environmentally friendly approaches for producing nanomaterials. Using plant extracts not only minimizes the use of hazardous chemicals but also introduces natural stabilizing agents that can influence nanoparticle formation and stability.

For materials prepared by chemical reduction, silver nitrate ($AgNO_3$) was combined with biochar or biochar–calcite, and sodium borohydride ($NaBH_4$) was then added to reduce silver ions to metallic silver nanoparticles [4], [5], [6]. These procedures usually involve short reaction times, often carried out under cooling or at room temperature with stirring to control particle growth. After the reaction, the catalyst is separated and dried for further use. Notably, some of the most active catalysts contained less than 1% silver by weight [4], [6], highlighting that simply increasing the metal content is not always the key to better performance. Instead, achieving a uniform dispersion of accessible nanoparticles is crucial for maximizing catalytic efficiency.

Transmission electron microscopy analyses across the studies revealed that silver nanoparticles typically ranged from about 5 to 50 nanometers in size [1], [3], [4], [5], [6]. The particles were predominantly spherical, and their crystal structures, confirmed by lattice spacing and selected-area electron diffraction, matched the face-centered cubic form of silver. Supports with higher porosity or those subjected to acid pretreatment tended to promote the formation of smaller, more evenly distributed nanoparticles. Conversely, supports with weaker structural integrity were more prone to nanoparticle aggregation, which can reduce catalytic activity by limiting the available surface area.

Furthermore, the interaction between the biochar support and the silver nanoparticles plays a vital role in stabilizing the particles and preventing their clumping or loss during reactions. The oxygen-containing groups on biochar surfaces can bind metal ions and nanoparticles, offering anchor points that help maintain particle size and dispersion. These strong interactions also contribute to the catalyst's durability and reusability, which are important for practical environmental applications.

V. CHARACTERIZATION OF BIOCHAR-BASED NANOCOMPOSITES

The studies reviewed utilize a range of complementary techniques to characterize the structure and surface chemistry of the biochar-metal composites. X-ray diffraction (XRD) helps differentiate the carbon framework from crystalline phases such as silver, calcite, CeO_2, and ZnO. Typically, the biochar shows a broad peak indicative of turbostratic or disordered carbon, while metallic silver is identified by distinct reflections matching its face-centered cubic crystal structure.

Fourier-transform infrared (FTIR) spectroscopy reveals the presence of various functional groups on the biochar surface, including hydroxyl, carbonyl, carboxyl, and aromatic groups. In samples containing calcite, characteristic carbonate bands appear around 1420, 875, and 710 cm^{-1}. Additionally, X-ray photoelectron spectroscopy (XPS) provides detailed insight into the chemical states of carbon and oxygen and confirms the presence of metallic silver through Ag 3d peaks near 368 and 374 eV [4], [5]. Signals from calcium and phosphorus can also be detected, indicating residual minerals or phosphate groups left after pretreatment.

Scanning electron microscopy (SEM) combined with energy-dispersive X-ray spectroscopy (EDS) is employed to analyse the surface morphology and the distribution of elements within the composites. Nitrogen adsorption measurements, along with BET surface area analysis, offer valuable information about the porosity and surface area of the materials. The addition of nanoparticles or minerals often results in a rougher, more varied surface texture. In some cases, this leads to an increase in mesoporosity and surface area, while in others, the deposited materials may block pores, demonstrating that the impact of loading depends heavily on how and where the active phases are integrated into the support.

VI. CATALYTIC AND PHOTOCATALYTIC PERFORMANCE

A. Photocatalytic removal of dyes and antibiotics

The Ag@biochar material made from Chenopodium ambrosioides demonstrated an impressive 88.4% removal of methylene blue at a concentration of 25 ppm within 75 minutes under visible light [1]. Remarkably, its activity remained strong, retaining 70.65% efficiency after six reuse cycles. Electrochemical impedance tests revealed that the silver-loaded biochar had a lower charge-transfer resistance compared to bare biochar, indicating enhanced electron transfer at the interface.

The CeO_2–ZnO/biochar ternary composite showed even higher removal efficiency, achieving 96.5% methylene blue removal and 91.3% tetracycline degradation within 90 minutes under simulated solar light [2]. This material also exhibited significant adsorption capacity, with methylene blue uptake around 199 mg per gram. The improved photocatalytic performance was attributed to a Z-scheme charge-transfer mechanism, where biochar acts as a conductive pathway and helps reduce charge recombination [2].

B. 4-Nitrophenol reduction

Reduction of 4-nitrophenol to 4-aminophenol using excess sodium borohydride ($NaBH_4$) is a common test to evaluate catalytic activity. This reaction is typically monitored by observing the change in absorption from about 400 nm (4-nitrophenolate) to around 300 nm (product) using spectrophotometry. Because $NaBH_4$ is usually in large excess, the reaction follows pseudo-first-order kinetics, allowing for easy comparison of catalytic rates.

The biochar–calcite–Ag composite prepared at 450 °C achieved complete conversion in roughly 12 seconds, with an apparent rate constant up to 5.0 min^{-1} under the reported conditions. [4] Another calcite-rich biochar derived from Tamarindus indica carrying silver reached full conversion in 24 minutes, with a rate constant of 4.88×10^{-3} s^{-1} [5]. The Borassus flabellifer biochar composite prepared at 500 °C showed an apparent rate constant of 3.0 min^{-1}, reducing 4-nitrophenol in about 3 minutes under the tested reagent ratio [6].

Comparisons across these studies reveal that both the chemical environment and the structure of the biochar support strongly affect the reaction rate. For instance, increasing the ratio of $NaBH_4$ to 4-nitrophenol speeds up the reduction by providing more reducing agents at the catalyst surface, enhancing the overall reaction efficiency.

C. Azo-dye reduction

The Borassus flabellifer-derived Ag/biochar materials were also evaluated for methyl orange and Congo red [6]. The sample prepared at 500 °C reduced both dyes within approximately 30–60 s at 25 ppm, while higher pollutant concentrations required longer treatment. In a mixed-pollutant experiment using 4-nitrophenol, methyl orange, and Congo red in real groundwater, the same material reduced all three contaminants within about 6 min. This result is particularly relevant because real water contains competing species and does not behave like a single-solute laboratory system.

D. Antimicrobial performance

The biogenic Ag@biochar composite showed antimicrobial activity in addition to photocatalytic performance [1]. Complete inhibition of Escherichia coli growth was reported, together with clear inhibitory effects against Pseudomonas aeruginosa, Klebsiella pneumoniae, Bacillus subtilis, and Candida albicans. The activity was associated with the interaction of silver nanoparticles with microbial cells and disruption of membrane integrity. The combination of pollutant treatment and antimicrobial action makes Ag/biochar systems potentially useful where both chemical contaminants and microorganisms need to be controlled.

E. Application in organic synthesis

The magnetic Fe_3O_4@SiO_2–Ag/biochar catalyst demonstrates that biochar-supported nanometals are not restricted to environmental treatment [3]. It was applied to a one-pot four-component synthesis of benzylpyrazolyl coumarin derivatives using 4-hydroxycoumarin, ethyl acetoacetate, hydrazine hydrate, and aromatic aldehydes. Under optimized conditions using an ethanol–water medium at 70 °C, reported product yields were approximately 91–98% within 12–18 min. The catalyst could be separated magnetically and reused for six cycles without a major loss of activity.

VII. PROPOSED REACTION MECHANISMS

Although the target reactions differ, the proposed mechanisms share several common events. Pollutants and, where applicable, the reducing reagent first interact with the porous carbon surface. Adsorption concentrates the reactants near the active nanoparticles. The metal or oxide phase then facilitates electron or hydride transfer, lowering the kinetic barrier for conversion, after which the products leave the surface and active sites become available for another cycle.

For photocatalytic systems, illumination generates electron–hole pairs in the semiconductor phase. Carbon support can improve charge separation and provide a pathway for interfacial electron movement. In the CeO_2–ZnO/biochar system, the proposed Z-scheme preserves strongly reducing and strongly oxidizing charge carriers, enabling formation of reactive oxygen species. Radical-scavenging observations were consistent with important roles for hydroxyl and superoxide species [2].

For $NaBH_4$-driven reduction, the proposed description is compatible with a Langmuir–Hinshelwood-type process. Both borohydride and the pollutant are adsorbed at the catalyst interface, and the Ag nanoparticles facilitate transfer of electrons or hydrogen equivalents from the donor to the acceptor. In 4-nitrophenol reduction, the overall six-electron conversion proceeds through intermediate states before formation of 4-aminophenol. For azo dyes, sequential reduction leads to cleavage of the –N=N– linkage and formation of aromatic amines [4], [5], [6].

VIII. REUSABILITY, STABILITY AND DATA-DRIVEN OPTIMIZATION

Reusability is an important criterion for heterogeneous nanocatalysts because practical performance depends on both activity and the ability to recover the material. The reviewed studies generally report several reuse cycles. The Ag@biochar photocatalyst retained approximately 70–71% of its initial methylene-blue removal after six cycles [1]. Biochar–calcite–Ag catalysts maintained high conversion over ten cycles, with the reported silver leaching below 0.2 mg L^{-1} in the relevant study [4]. Borassus flabellifer-derived materials retained approximately 94.5–98% activity after ten cycles, and post-reaction TEM showed no obvious severe nanoparticle aggregation [6]. Magnetic Fe_3O_4@SiO_2–Ag/biochar provides an additional operational advantage because an external magnetic field can assist recovery [3].

One of the reviewed studies combines experimental catalysis with machine learning [4]. A gradient-boosting regression model was trained to predict 4-nitrophenol reduction time from variables including temperature, reagent concentrations, biomass and calcite amounts, and catalyst dosage. Using an 80:20 training/testing arrangement with five-fold cross-validation, the reported model achieved $R^2 = 0.972$. Experimental validation produced errors of approximately 2–3%. Feature analysis indicated that $NaBH_4$ and 4-nitrophenol concentrations were among the strongest predictors. This example illustrates how data-driven methods may complement conventional experimental optimization.

IX. COMPARATIVE DISCUSSION AND REMAINING CHALLENGES

The overall evidence indicates that the performance of biochar-supported nanocomposites depends more on how they are processed than on the type of biomass used [10], [16]. Materials made from leaves, bark, or rice husk can all serve as effective supports, but factors like pyrolysis temperature, chemical pretreatment, mineral content, and how nanoparticles are deposited play a major role in shaping the final structure. The most successful composites tend to be those that strike a good balance between pollutant adsorption, availability of active sites, and efficient electron transfer.

Adding components like calcite or semiconductor oxides introduces new functionalities beyond what carbon alone can offer. Calcite enhances adsorption capacity, while CeO_2–ZnO imparts light-responsive catalytic properties and modifies the material's electronic band structure. Magnetic elements contribute by making catalyst recovery easier through magnetic separation. These enhancements show that biochar can be actively designed and engineered to suit specific catalytic tasks, rather than simply acting as an inert support.

However, several challenges still need to be addressed before these materials can be widely applied. Monitoring silver release over time is crucial since repeated leaching could pose environmental risks [18]. Reaction rates, especially in systems using borohydride, can be highly sensitive to pH and reagent concentrations. Additionally, lab experiments that test single pollutants do not fully capture the complexity of real wastewater, which contains mixtures of contaminants, varying ionic strengths, and natural organic matter. Only a few studies included in this review have explored performance in realistic mixed-pollutant environments or continuous operation. Some promising work, such as groundwater treatment experiments and magnetically recoverable catalysts, point toward practical applications, but more long-term research is needed. Future studies should focus on continuous-flow reactor testing, repeated catalyst regeneration, detailed tracking of metal release, ecotoxicology of any leached metals, and overall life-cycle assessments. Establishing standardized methods for reporting catalyst ingredients and testing conditions would also improve the comparability and reliability of results across different studies.

X. CONCLUSION

The studies reviewed highlight biochar-supported metal nanocomposites as highly adaptable materials for environmental cleanup and sustainable catalysis [14], [15]. Their effectiveness comes from combining a porous, chemically active carbon framework with reactive nanoscale metals or metal oxides. Silver-loaded biochars excel in reducing 4-nitrophenol and azo dyes, breaking down dyes through photocatalysis, and fighting microbial contamination. Meanwhile, composites containing metal oxides or magnetic components broaden their applications to include solar-powered treatment and catalysts that can be easily recovered for organic synthesis.

Key factors controlling their performance across the literature include the pyrolysis temperature, acid pretreatment, incorporation of minerals or oxides, and how well nanoparticles are dispersed on the biochar. Notably, high catalytic activity doesn't always mean using a large amount of silver; small, well-dispersed, and easily accessible nanoparticles often deliver strong results. Reusability tests show that these materials can maintain significant activity over several cycles but concerns about metal leaching and their behaviour in complex real-world water remain.

Future advancements will require moving beyond simple batch experiments to focus on designing materials and reactors suited for practical recovery, handling mixed pollutants, continuous processing, and long-term use. By combining eco-friendly synthesis methods, tailored support design, magnetic separation techniques, and data-driven optimization, researchers have a promising route to create more efficient and sustainable biochar-based nanocatalysts.

TABLE I SUMMARY OF THE SIX STUDIES REVIEWED

Ref.	Biomass / support	Active phase	Main application	Reported result
[1]	Chenopodium ambrosioides biochar	Biogenic AgNPs	MB photodegradation; antimicrobial	88.4% MB removal/75 min; complete E. coli growth inhibition
[2]	Rice husk biochar	CeO_2–ZnO	Adsorption + photocatalysis of MB and tetracycline	96.5% MB and 91.3% TC removal/90 min
[3]	Eucalyptus globulus bark biochar	Fe_3O_4@SiO_2–Ag	Heterogeneous organic synthesis catalyst	Up to 97% yield; magnetic recovery; six cycles
[4]	Eucalyptus bark + eggshell calcite	AgNPs/biochar–calcite	4-NP reduction	100% conversion/12 s; k_{app} up to 5.0 min^{-1}; ten cycles
[5]	Tamarindus indica bark	AgNPs/calcite-rich biochar	4-NP reduction	Complete conversion/24 min; k_{app} = 4.88×10^{-3} s^{-1}
[6]	Borassus flabellifer bark	AgNPs/biochar	4-NP, MO and CR reduction	4-NP/3 min; dyes/≤60 s; >94% activity after ten cycles

TABLE II REPRESENTATIVE 4-NITROPHENOL REDUCTION DATA REPORTED IN THE REVIEWED STUDIES

Ref.	Catalyst	Reported conditions	k_{app}	Performance
[4]	Ag@EB 450 1:1 biochar–calcite	$NaBH_4$:4-NP = 100:1	5.0 min^{-1}	Complete conversion in ~12 s
[5]	Ag@Ca-BC (Tamarindus indica)	0.2 M $NaBH_4$; 0.25 mM 4-NP; room temperature	4.88 × 10^{-3} s^{-1}	Complete conversion in 24 min
[6]	Ag@PBC 500 (Borassus flabellifer)	$NaBH_4$:4-NP = 100:1	3.0 min^{-1}	Reduction in ~3 min

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DECLARATIONS

A. Competing interests

The authors declare no competing interests.

B. Data availability

This is a review article based on published literature. No new experimental dataset was generated for this review.

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