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FROM BIOCHAR TO NANOCARBON: ADVANCES IN BIOMASS-DERIVED CARBON MATERIALS FOR CATALYTIC PYROLYSIS AND SEMICONDUCTOR APPLICATIONS

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ABSTRACT

The growing demand for sustainable energy systems and low carbon materials has intensified interest in converting biomass waste into value added products. Catalytic pyrolysis has emerged as an effective route for transforming biomass and plastic residues into fuels, syngas, and functional carbon materials. In recent years, increasing attention has been directed toward the conversion of pyrolysis derived biochar into engineered nanocarbon materials with applications extending beyond fuel upgrading to energy storage, catalysis, and semiconductor related technologies. This review examines recent advances in biochar to nanocarbon conversion, with emphasis on synthesis strategies, structural evolution, and functional tuning through activation, graphitization, and heteroatom modification. The relationships between textural, electronic, surface chemical properties and catalytic performance in pyrolysis systems are critically discussed. Emerging applications of biochar derived nanocarbons in photocatalysis, electrocatalysis, energy storage, and sensing are also discussed. Key challenges related to scalability, feedstock variability, economic feasibility, environmental safety, and regulatory frameworks are assessed, alongside the importance of lifecycle analysis for sustainable deployment. By linking structure, mechanism, and performance across multiple application domains, this review provides insight into the potential of biochar derived nanocarbons as multifunctional materials bridging waste valorization and advanced carbon technologies.

Keywords:
Biochar-derived nanocarbons; Catalytic pyrolysis; Carbon nanostructures; Heteroatom doping; Energy storage materials; Electrocatalysis; Photocatalysis; Biomass valorization

1. INTRODUCTION

The rapid growth of global energy consumption and the accumulation of plastic and biomass residues have intensified interest in sustainable technologies for waste valorization (Geyer et al., 2017). Among available thermochemical technologies, catalytic pyrolysis has been extensively investigated as an effective route for converting heterogeneous feedstocks into liquid fuels, syngas, and carbonaceous solids, while offering flexibility in feedstock selection and product distribution (Miandad et al., 2019).

Beyond its conventional role as a fuel or soil amendment, pyrolysis-derived biochar has recently emerged as a versatile precursor for advanced carbon materials. Owing to its tunable pore structure, high carbon content, surface functional groups, and inherent heteroatom doping derived from biomass composition, biochar can be transformed into engineered nanocarbons through activation, graphitization, or post-synthetic modification (Kumar et al., 2025). This transition has expanded the functional relevance of biochar from a passive by-product to a strategic platform material.

As research efforts increasingly converge across catalysis, nanotechnology, and materials engineering, nanocarbons derived from biochar have demonstrated growing utility in both thermochemical and advanced functional applications. In catalytic pyrolysis, these materials serve as catalysts or catalyst supports that promote deoxygenation and vapor upgrading. When functionalized or used with hydrogen-donating co-feedstocks, they promote hydrogen transfer reactions, thereby improving fuel quality and process efficiency (Sun et al., 2024).

In addition to pyrolysis applications, biochar-derived nanocarbons have attracted significant interest for semiconductor fabrication, photocatalysis, electrocatalysis, CO_2 conversion, batteries, and supercapacitors, where their surface chemistry, electrical conductivity, and defect structures critically influence performance (Liu et al., 2019). The growing emphasis on circular carbon technologies and low-carbon manufacturing has further accelerated interest in converting waste biomass into high-value nanomaterials capable of delivering catalytic, electrical, and optical performance comparable to conventional engineered nanocarbons derived from fossil sources (Shi-Jie et al., 2020). Within this context, biochar-derived nanocarbons offer a compelling pathway for coupling waste mitigation with advanced material production.

This review presents recent advancements in transforming biochar into nanocarbon materials, focusing on synthesis strategies, structural optimization, catalytic performance in pyrolysis processes, and emerging applications in semiconductor technologies. Critical challenges, including scalability, material uniformity, and industrial implementation, are examined, along with opportunities for bridging laboratory-scale research with practical, commercially viable solutions.

2. CONVERSION OF BIOCHAR INTO FUNCTIONAL NANOCARBON MATERIALS

2.1 Controlled Pyrolysis and Structural Evolution

The structural properties of biochar are highly dependent on pyrolysis conditions such as temperature, heating rate, residence time, and feedstock composition. Low to moderate pyrolysis temperatures (400–600 °C) generally produce amorphous, oxygen-rich carbon, which retains surface functional groups conducive to further modification. In contrast, higher temperatures (>700 °C) promote aromatization, partial graphitization, and defect formation, yielding more ordered carbon domains with enhanced electrical conductivity (Son et al., 2021). These structural variations are critical for determining the suitability of biochar as a precursor for nanocarbon materials, particularly when targeting high-surface-area carbons or graphitic nanostructures (Sun et al., 2024).

2.2 Chemical and Physical Activation

Activation strategies, either chemical (e.g., KOH, $ZnCl_2$) or physical (e.g., steam, CO_2), significantly enhance the specific surface area and pore volume of biochar. Chemical activation typically creates a micro–mesoporous network, increasing accessibility for reactants and improving catalytic efficiency (Gorbounov et al., 2024). Physical activation using CO_2 or steam facilitates the development of interconnected pores without introducing extraneous elements, making it suitable for applications in energy storage and semiconductor devices. These activation methods effectively transform biochar into activated carbons or porous nanocarbons with tunable electronic and surface properties (Kumar et al., 2025).

2.3 Catalytic Graphitization

Catalytic graphitization involves the use of transition metals such as Fe, Ni, and Co to accelerate the rearrangement of amorphous carbon into ordered graphitic layers at elevated temperatures (Liu et al., 2019). This method enables the formation of graphene-like nanosheets, carbon nanofibers, and other conductive nanostructures from biomass-derived char in a cost-effective manner. The process enhances electronic conductivity, thermal stability, and mechanical strength, making it highly relevant for electrocatalysis, energy storage, and semiconductor applications.

2.4 Heteroatom Doping (N, S, P, B)

Biochar naturally contains oxygen and trace heteroatoms, but its electronic and catalytic properties can be further tailored through intentional heteroatom doping. Nitrogen, phosphorus, sulfur, and boron are commonly introduced to modulate band structure, surface chemistry, and active sites (Ma et al., 2018). For instance, N-doped carbons enhance electron-donating capacity and are particularly effective in electrocatalytic reactions, whereas P-doping can improve charge transport and modulate energy band gaps for semiconductor applications. This versatility makes doped biochar-derived nanocarbons a promising platform for catalysis, sensing, and energy devices.

2.5 Formation of Advanced Carbon Nanostructures for Functional Applications

Beyond porous and doped carbons, a variety of techniques have been developed to convert biochar into more sophisticated nanomaterials, including:

2.5.1 Carbon Nanotubes (CNTs)

Carbon nanotubes are typically synthesized from biochar or biomass-derived carbon via pyrolysis in the presence of transition metal catalysts such as Fe, Co, or Ni. The metal nanoparticles act as nucleation sites, promoting the formation of tubular carbon structures. CNTs exhibit a high aspect ratio, exceptional mechanical strength, thermal stability, and electrical conductivity, making them highly suitable for applications in catalysis, energy storage, sensors, and composite materials (Hassan et al., 2025). Process parameters such as temperature, metal loading, and pyrolysis atmosphere critically influence CNT yield, wall number, and diameter distribution.

2.5.2 Carbon Quantum Dots (CQDs)

Carbon quantum dots are zero-dimensional nanocarbons with diameters typically below 10 nm, notable for size-dependent fluorescence and photochemical properties. They are commonly synthesized from biochar via hydrothermal and microwave-assisted treatments, which facilitate the oxidative cleavage of larger carbon frameworks into nanoscale dots (Liu et al., 2021). CQDs derived from biochar retain surface oxygen- or nitrogen-containing functional groups, enhancing solubility, charge transfer, and optical activity. These features make CQDs ideal for optoelectronic devices, bioimaging, photocatalysis, and sensors. The choice of precursor and treatment conditions determines their emission wavelength, quantum yield, and surface chemistry.

2.5.3 Graphene-like Nanosheets

Graphene-like nanosheets are typically produced via catalytic graphitization of biochar, where transition metals (Fe, Ni, Co) at elevated temperatures rearrange amorphous carbon into planar, sp^2-hybridized domains. These nanosheets feature large surface area, high electronic mobility, and tunable defect density, which are crucial for electrocatalysis, energy storage (supercapacitors and batteries), and semiconductor devices. The extent of graphitization and sheet stacking can be tailored by metal type, pyrolysis temperature, and time, providing a versatile platform for high-performance functional carbon materials (Wang et al., 2022).

2.5.4 Core–Shell Magnetic Nanocarbons

Core–shell magnetic nanocarbons are engineered by integrating magnetic nanoparticles (Fe_3O_4, Co, Ni) within a carbon shell, often through pyrolysis of biochar-metal composites. The carbon shell provides chemical stability, electrical conductivity, and corrosion resistance, while the magnetic core enables magnetic separation, electromagnetic interference (EMI) shielding, and enhanced catalytic recovery (Sun et al., 2025). These nanostructures are multifunctional and have been applied in heterogeneous catalysis, environmental remediation, energy storage, and electromagnetic shielding, combining the benefits of magnetic responsiveness with advanced carbon properties.

These advanced nanostructures exhibit lightweight composition, chemical stability, tunable porosity, and favorable electronic properties, positioning biochar-derived nanocarbons as versatile materials bridging waste valorization with high-value functional applications.

Table 1: Overview of Biochar-to-Nanocarbon Conversion Methods and Properties

Conversion Route	Conditions / Catalysts	Resulting Nanostructures	Key Properties / Applications	Reference
Controlled pyrolysis	400–700 °C, slow to fast heating, feedstock-dependent	Amorphous carbon, partially graphitized biochar	Tunable porosity, retains surface functional groups; precursor for further modification	Wang et al., 2022
Chemical activation	KOH, $ZnCl_2$; 600–900 °C	Porous nanocarbons, activated carbon	High surface area, micro–mesoporous structure; improved catalytic diffusion, energy storage	Gorbounov et al., 2024
Physical activation	Steam or CO_2, 700–900 °C	Porous biochar	Enhanced surface area without chemical additives; suitable for electrocatalysis and semiconductor support	Kumar et al., 2025
Catalytic graphitization	Fe, Ni, Co; 800–1000 °C	Graphene-like nanosheets, carbon nanofibers	High conductivity, thermal stability, mechanical strength; electrocatalysis, batteries	Liu et al., 2019
Heteroatom doping	N, P, S, B; via precursors or post-treatment	N-, P-, S-, B-doped carbons	Tailored bandgap, enhanced electron transfer, improved catalytic sites; semiconductors,	Ma et al., 2018

			electrocatalysis	
Carbon nanotube formation	Pyrolysis + metal catalyst (Fe, Co, Ni)	CNTs	High aspect ratio, mechanical strength, conductivity; catalysis, composites	Hassan et al., 2025
Carbon quantum dots (CQDs)	Hydrothermal or microwave treatment	Fluorescent carbon quantum dots	Tunable optical properties; optoelectronics, sensors	Liu et al., 2019
Core–shell magnetic nanocarbons	Pyrolysis with Fe, Co, or Fe_3O_4	Magnetic nanostructures	Multifunctional: catalysis, EMI shielding, energy storage	Sun et al., 2025

3. STRUCTURAL, ELECTRONIC, AND CATALYTIC PROPERTIES OF BIOCHAR-DERIVED NANOCARBONS

The structural, electronic, and chemical characteristics of biochar-derived nanocarbons are tightly interconnected. High surface area, hierarchical porosity, graphitic ordering, and tailored surface functionalities collectively determine their catalytic efficiency, electron transport, and adsorption behavior. Understanding these relationships enables rational design of biochar-based nanomaterials for targeted applications in catalysis, energy storage, and semiconductor devices, bridging the gap between biomass waste and high-performance functional carbon materials.

3.1 Textural Properties

Activated and graphitized biochar-derived nanocarbons exhibit high specific surface areas, hierarchical micro, meso and macroporous networks, and also abundant defect sites. These structural features enhance mass transport, catalytic accessibility, and the dispersion of metal nanoparticles, making them ideal for heterogeneous catalysis, energy storage, and adsorption-based applications. According to Kumar et al, 2025, steam-activated biochar achieved specific surface areas (SSA) as high as 1583 m^2/g, facilitating the dispersion of metal nanoparticles and improving mass transport in catalytic reactions. Pyrolysis conditions, activation methods, and graphitization processes critically influence pore size distribution, surface roughness, and defect density, which in turn determine catalytic efficiency and nanocarbon performance. High surface area and hierarchical porosity not only enhance catalytic site accessibility but also improve adsorption capacity, reactant diffusion, and metal nanoparticle stabilization, directly impacting the efficiency of pyrolysis vapor upgrading, electrocatalysis, and energy storage applications.

3.2 Electronic and Band Structure Features

The degree of graphitization and structural ordering governs the electronic conductivity and charge carrier mobility of biochar-derived nanocarbons. Additionally, heteroatom doping (N, P, S, B) introduces localized electronic states that facilitate electron transfer, redox reactions, and catalytic activity (Ma et al., 2018). These electronic features enable nanocarbons to serve as semiconductor supports, electrocatalysts, and electrode materials, bridging the gap between waste-derived carbon and functional high-performance devices.

3.3 Surface Chemistry and Functional Groups

The surface chemistry of biochar-derived nanocarbons plays a pivotal role in determining catalytic and adsorption behavior. Oxygen-containing groups, nitrogen functionalities, and metal–carbon interfaces influence acidity, basicity and adsorption affinity. These characteristics directly affect pyrolysis vapor upgrading, catalytic efficiency, and electrocatalytic performance (Liu et al., 2019).

Hierarchical nanostructures with optimized surface functionalities have demonstrated superior performance in electrochemical applications. For example, hierarchical porous carbon nanotubes with embedded metal nanoparticles achieved specific capacitances of 558 F/g at 0.5 A/g and energy densities of approximately 28 Wh/kg, highlighting the synergistic effect of surface area, pore architecture, and functional groups on charge storage (Hassan et al., 2025).

4. CATALYTIC ROLES AND MECHANISMS OF NANOCARBON MATERIALS IN PYROLYSIS

Biochar-derived nanocarbons provide abundant active sites and defect-rich structures that enhance the cracking of heavy oxygenates and tar precursors during pyrolysis. Their high specific surface area and hierarchical pore networks increase contact efficiency between volatile species and catalytic sites, promoting the breakdown of large molecules into lighter compounds with higher fuel value. These materials also facilitate secondary cracking, reducing coke and tar deposition that can deactivate traditional catalysts.

Such effects are consistent with studies showing that oxygen-containing functional groups on carbon surfaces catalyze steam reforming reactions, improving tar conversion during pyrolysis and gasification processes (Liu et al., 2019). As summarized in Table 2, carbon nanotubes and graphene-like nanosheets exemplify nanocarbons with high surface areas and abundant defects, which significantly enhance tar reduction efficiency.

4.2 Hydrogen Transfer and Radical Stabilization

In pyrolytic environments, reactive radicals generated from biomass decomposition must be stabilized to form stable hydrocarbon products rather than repolymerizing into coke. Heteroatom-rich nanocarbons and metal-supported variants facilitate hydrogen transfer reactions by providing electron-rich sites that mediate hydrogen redistribution among intermediates. For instance, nitrogen functionalities such as pyridinic and pyrrolic N have been shown to promote the cracking of lignin and related volatiles by serving as reactive centers, while graphitic N enhances deeper deoxygenation pathways through improved electron mobility and radical stabilization (Sun et al., 2023). These interactions highlight how carefully engineered nanocarbon surfaces can direct pyrolysis toward lighter, more desirable products. As summarized in Table 2, nitrogen- and phosphorus-doped carbons, along with metal-supported carbon nanotubes, exemplify nanocarbons that effectively stabilize radicals and facilitate hydrogen transfer during catalytic pyrolysis.

4.3 Aromatization and Deoxygenation

Graphitic and metal-carbon hybrid nanocarbons influence key pathways such as cyclization, aromatization, and deoxygenation during catalytic pyrolysis. The electronic structure of graphitized domains enables delocalized electrons to interact with reactive species, promoting the formation of condensed aromatic rings from aliphatic and oxygenated intermediates. These processes improve bio-oil quality by lowering oxygen content and increasing hydrocarbon fractions with higher calorific value (Sun et al., 2025). Metal species supported on biochar (e.g., Fe, Ni) further accelerate these reactions by offering complementary active sites for hydrogenolysis and C–C bond reformation.

4.4 Syngas Enhancement

Beyond liquids, nanocarbon materials can enhance syngas production by promoting reforming and water–gas shift reactions of pyrolysis vapors. When combined with transition metals (e.g., Ni, Fe), biochar-derived catalysts increase the yields of H_2 and CO, contributing to energy-rich syngas streams. Nanocarbon supports aid in maintaining metal dispersion and preventing deactivation through sintering or coke formation. Comparative studies indicate that char and char-supported catalysts increase syngas yields and shift product distribution toward combustible gases relative to non-catalytic systems (Lin et al., 2021).

4.5 Char Upgrading and Catalyst Durability

Nanocarbon modifications enhance the stability, electronic conductivity, and reusability of catalytic char materials. Functionalization and magnetic hybridization, such as the incorporation of Fe_3O_4, enable easy recovery and regeneration of catalysts, addressing a common limitation in heterogeneous catalytic systems. Tailored nanocarbons maintain their active site architecture over multiple cycles, contributing to sustained catalytic activity for pyrolysis vapor upgrading and reforming reactions (Hassan et al., 2025). As highlighted in Table 2, core–shell magnetic nanocarbons exemplify materials that combine high catalytic performance with convenient recyclability, demonstrating the practical advantages of engineered biochar-derived nanostructures in continuous pyrolysis operations.

4.6 Linking Mechanisms to Structure and Performance

The catalytic performance of biochar-derived nanocarbons arises from an integrated set of structural and chemical features.

- **Textural attributes** (e.g., surface area and pore connectivity) influence mass transport and site access.
- **Electronic characteristics** (e.g., graphitic ordering and heteroatom doping) affect electron transfer and radical stabilization.
- **Surface chemistry** (functional groups and metal interfaces) determines reactant binding and activation energy pathways.

Table 2. Biochar-Derived Nanocarbon Structures, Formation Strategies, and Catalytic Roles in Pyrolysis

Nanostructure	Formation Route	Catalytic Role	Key Quantitative Metrics	Reference
Carbon Nanotubes (CNTs)	Pyrolysis + metal catalyst (Fe, Ni)	Radical stabilization, high aspect ratio, improves hydrocarbon selectivity	Diameter: 10–50 nm; Length: 1–10 µm; Surface area: 150–400 m^2/g	Hassan et al., 2025
Carbon Quantum Dots (CQDs)	Hydrothermal or microwave-assisted	Electron transfer mediator, photochemical activity, enhances vapor upgrading	Particle size: 2–10 nm; Photoluminescence: tunable; Surface defects: 0.3–0.6 ID/IG	Liu et al., 2018
Graphene-like Nanosheets	Catalytic graphitization	High electrical conductivity, metal nanoparticle support, promotes aromatization	Surface area: 500–1200 m^2/g; ID/IG ratio: 0.8–1.2; Conductivity: 50–200 S/m	Sun et al., 2025
Core–Shell Magnetic Nanocarbons	Metal-assisted pyrolysis (Fe_3O_4 core)	Multifunctional: catalysis, electromagnetic interference (EMI) shielding, energy storage; easy recovery	Surface area: 400–800 m^2/g; Magnetic saturation: 30–60 emu/g; Hydrocarbon yield increase: 15–20%	Sun et al., 2025

Table 2 summarizes the main biochar-derived nanocarbon structures, formation strategies, key catalytic functions, and quantitative performance metrics relevant for catalytic pyrolysis. Understanding the relationships between structure, mechanism, and performance allows for the rational design of nanocarbon catalysts that improve bio-oil quality, enhance syngas yields, and reduce unwanted byproducts in catalytic pyrolysis.

5. BIOCHAR-DERIVED NANOCARBONS IN SEMICONDUCTOR AND ENERGY APPLICATIONS

Biochar-derived nanocarbons have shown growing promise in semiconductor and energy technologies due to their tunable electronic structures, hierarchical porosity and chemical stability.

Recent reviews highlight how these materials, when properly engineered through heteroatom doping, hybridization, and controlled nano-structuring, can function effectively in photocatalysis, electrocatalysis, energy storage, and sensing, linking sustainable carbon materials to advanced device performance (Huang et al., 2025).

5.1 Photocatalysis

Biochar-derived nanocarbons act as photosensitizers, electron mediators, or co-catalysts in visible-light driven reactions, including hydrogen evolution, organics degradation, and CO_2 reduction. Their defect-rich surfaces and conductive frameworks facilitate rapid charge separation and transfer, reducing recombination losses and improving photochemical efficiency. Biomass-carbon materials have been reviewed for pollutant photodegradation, where abundant functional groups, hydrophobicity, and customizable surface chemistry support photocatalytic processes compatible with a range of substrates (Son et al., 2021).

5.2 Electrocatalysis

Heteroatom-doped biochar nanocarbons support key electrochemical processes including the oxygen reduction reaction (ORR), hydrogen evolution reaction (HER), and oxygen evolution reaction (OER). These reactions are critical for energy conversion technologies such as fuel cells and water splitting. Reviews on biomass-derived carbon for hydrogen production indicate that nanostructured carbons with tailored defect densities and surface functionalities can promote electron transfer and improve catalytic turnover compared with undoped carbon materials (Tian et al., 2025).

5.3 Energy Storage Devices

Graphene-like and hierarchical porous carbon materials derived from biochar have been widely investigated for energy storage devices such as supercapacitors, lithium-ion batteries, and sodium-ion batteries due to their high surface area, mechanical stability, and tunable surface chemistry. Recent reviews emphasize that the textural properties of biomass-derived carbons, including micro and meso porosity, enable fast ion diffusion and high charge storage capacity, making them competitive with conventional carbon electrodes (Sankar et al., 2025).

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5.4 Gas Sensing and Environmental Electronics

Biochar-derived carbon nanomaterials exhibit sensitivity to a range of gases including NO_2, CO, and volatile organic compounds (VOCs) due to their defect-rich structures and high surface reactivity. These properties make them attractive as sustainable sensing materials for low-cost environmental monitoring. Reviews on biomass carbon materials in electrochemical sensors summarize how surface functionalization, heteroatom doping, and porosity optimization improve analyte adsorption and signal transduction, enabling sensitive and durable detection platforms (Xiao et al., 2023).

Overall, biochar-derived nanocarbons combine tunable structural, electronic, and chemical features that allow the same material to serve multiple roles across photocatalysis, electrocatalysis, energy storage, and sensing. Their adaptability highlights the potential of sustainable carbon materials to bridge biomass valorization with advanced semiconductor and energy technologies.

6. CHALLENGES, SCALABILITY, AND INDUSTRIAL APPLICATIONS

6.1 Scale Up and Reproducibility Challenges

Translating biochar derived nanocarbons from laboratory research to industrial deployment presents both opportunities and significant challenges. While controlled pyrolysis, activation, and catalytic graphitization enable precise structural tuning and functional performance, scaling these processes remains a critical hurdle. Laboratory techniques such as hydrothermal treatment, metal catalyzed graphitization, and heteroatom doping often rely on conditions or reagents that are difficult to reproduce at industrial scale. Maintaining consistency in surface area, defect density, and heteroatom distribution is essential to ensure reliable catalytic, electronic, and sensing performance across production batches (Liu et al., 2019).

6.2 Economic Feasibility and Process Efficiency

Economic feasibility is another key consideration for commercialization. Although biomass feedstocks are abundant and inexpensive, the energy demands of high temperature pyrolysis, chemical activation, and post treatment can substantially increase production costs. Developing energy efficient continuous systems and utilizing renewable heat sources are therefore important for improving the balance between cost and benefit (Wang et al., 2022). In addition, strategies that enable recovery and reuse of metal catalysts or dopants, such as magnetic carbon hybrids, offer pathways to reduce operational expenses while supporting sustainable production.

6.3 Feedstock Variability and Quality Control

Industrial implementation is further constrained by variability in biomass feedstock quality. Differences in moisture content, elemental composition, and lignocellulosic structure directly influence biochar properties, which in turn affect nanocarbon structure and performance. As a result, preprocessing methods, standardization protocols, and robust quality control measures are necessary to achieve reproducible production of high performance nanocarbons for catalytic, energy storage, and sensing applications (Sun et al., 2025).

6.4 Environmental and Occupational Safety Considerations

Environmental and health considerations are equally important in large scale production. Depending on feedstock type and pyrolysis conditions, biochar and derived nanocarbons may contain residual heavy metals, volatile organic compounds, or persistent free radicals. These species can pose risks during material synthesis, handling, and application. Effective emission control systems, appropriate personal protective measures, and responsible waste management practices are therefore required to meet occupational and environmental safety standards (son et al., 2021).

6.5 Regulatory Frameworks and Market Readiness

Regulatory uncertainty remains a barrier to widespread industrial adoption. Quality standards, certification frameworks, and material safety guidelines specific to biochar derived nanocarbons are still under development in many regions. In the absence of clear regulatory pathways, industrial stakeholders may be hesitant to invest in large scale facilities, which can slow technology transfer from laboratory research to commercial deployment (Wang et al., 2022).

6.6 Sustainability Assessment and Lifecycle Analysis

Comprehensive lifecycle assessment is essential for evaluating the true sustainability of biochar to nanocarbon conversion pathways. Lifecycle analysis enables quantification of environmental impacts by accounting for energy inputs, feedstock logistics, emissions, and end of life considerations. Integrating lifecycle assessment into process design and industrial planning helps ensure that the production of high performance nanocarbons aligns with broader sustainability and circular economy goals (Huang et al., 2025).

6.7 Pathways Toward Industrial Integration

Addressing these challenges requires a multidisciplinary approach that combines materials science, chemical engineering, environmental assessment, and industrial process design. Collaboration between academic researchers, industrial partners, and regulatory bodies will be critical for optimizing production methods, standardizing material properties, and demonstrating reliable performance at scale. Successfully navigating issues related to scalability, reproducibility, cost, safety, and regulation will be key to unlocking the full potential of biochar derived nanocarbons in catalytic, energy, and semiconductor applications.

7. FUTURE PERSPECTIVES AND RESEARCH DIRECTIONS

Future research on biochar derived nanocarbons is expected to focus on improving structural control while reducing energy intensity and process complexity. Developing assisted graphitization strategies, including microwave or catalyst mediated approaches, may enable high performance nanocarbons under milder conditions. Greater emphasis is also being placed on precision heteroatom engineering, where dopant configuration and distribution are tuned to optimize catalytic selectivity, charge transport, and surface reactivity.

Integration of nanocarbons into multifunctional hybrid systems, such as carbon metal or carbon oxide composites, represents another promising direction, particularly for coupled catalytic and energy applications. At the same time, demonstrating long term stability, recyclability, and performance under realistic operating conditions will be critical for industrial adoption. Combining experimental studies with techno economic and lifecycle analyses will further guide the translation of laboratory advances into scalable and sustainable technologies.

8. CONCLUSION

This review has examined the transformation of biochar from a pyrolysis byproduct into a versatile platform for engineered nanocarbon materials relevant to catalytic pyrolysis, energy conversion, and semiconductor related applications. By connecting synthesis approaches with structural features and functional performance, the discussion illustrates how controlled modification of biomass derived carbon can yield properties comparable to those of conventional engineered nanomaterials. Despite ongoing challenges related to scalability, standardization, and industrial integration, recent progress in process design and materials engineering indicates increasing potential for practical deployment. The ability of biochar derived nanocarbons to link waste valorization with higher value technological applications supports their emerging role in sustainable carbon-based material systems.

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