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NATURAL PRODUCT–DERIVED NANOCARBONS: EMERGING TRENDS IN MOLECULAR AND MATERIALS SCIENCE – A CONCISE REVIEW

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Abstract:

Natural products derived from plants, microorganisms, and other biological sources have played a fundamental role in scientific advancement for centuries by offering structurally diverse and functionally rich molecular frameworks. Owing to their inherent complexity, renewability, and biocompatibility, these compounds continue to inspire innovations across chemistry, biology, and materials science. In recent years, the convergence of nature-based chemistry with modern materials research has driven significant progress in the development of carbon-based nanomaterials, particularly nanocarbons with broad technological relevance. This review focuses on the transformation of natural molecules into advanced nanocarbon materials such as graphene, carbon nanotubes, carbon dots, and various hybrid architectures. Natural products are highlighted not only as sustainable carbon precursors but also as templates and functional modifiers that govern material structure, surface chemistry, and performance. Emphasis is placed on environmentally benign and sustainable synthesis strategies, including biomass-derived and bio-inspired approaches, which reduce chemical waste and energy consumption. The review further discusses how molecular features such as functional groups, structural diversity, and self-assembly behavior enable tunable physicochemical properties in nanocarbons. Applications in energy storage, clean energy conversion, environmental remediation, sensing, and healthcare are examined, underscoring their potential for sustainable and impactful real-world solutions.

Keywords: *Natural Products, Nanocarbons, Molecular and Materials Science, Sustainable Synthesis, Advanced Functional Materials.*

1. Introduction

Natural products have historically played a central role in the development of molecular science, serving as invaluable sources of structurally diverse compounds with unique chemical, physical, and biological properties (1,2). Derived from plants, microorganisms, marine organisms, and biomass, natural products have significantly influenced drug discovery, agrochemicals, and functional materials (1). Their intrinsic structural complexity, stereochemical richness, and functional group diversity have inspired generations of chemists and material scientists alike.

In parallel, materials science has undergone a transformative evolution with the advent of nanotechnology. Among various nanomaterials, carbon-based nanostructures—collectively referred to as nanocarbons—have attracted enormous attention due to their remarkable mechanical strength, electrical conductivity, thermal stability, and tunable surface chemistry (3, 4). Graphene, carbon nanotubes, carbon dots, and porous carbons have found widespread applications across electronics, energy storage, catalysis, environmental remediation, and biomedicine (3–6).

In recent years, an emerging interdisciplinary trend has been the convergence of natural product chemistry and nanocarbon science. This integration seeks to utilize nature-derived molecules as precursors, templates, dopants, or functionalizing agents for the synthesis of advanced carbon nanomaterials (7–9). Such approaches not only enhance material performance but also promote green chemistry principles by employing renewable resources and sustainable synthesis routes (10, 11). This review discusses the evolving transition from natural products to nanocarbons, emphasizing molecular design, synthesis strategies, structure–property relationships, and emerging applications.

2. Natural products as molecular building blocks

2.1 Structural diversity and functional complexity

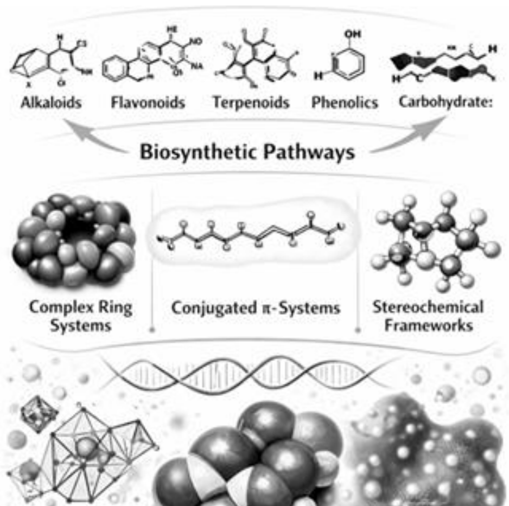

Figure 1: Structural diversity and functional complexity

Natural products exhibit unparalleled structural diversity, encompassing alkaloids, flavonoids, terpenoids, phenolics, carbohydrates, lipids, and proteins (1,2). This diversity arises from biosynthetic pathways that generate complex ring systems, heteroatoms, conjugated π-systems, and stereo chemically rich frameworks (12). Such features are highly desirable in materials chemistry, as they offer multiple reactive sites and pathways for molecular interactions.

Functional groups such as hydroxyl, carboxyl, amino, and carbonyl moieties enable hydrogen bonding, metal coordination, and covalent modification. These functionalities play a crucial role in directing self-assembly processes and in tailoring surface chemistry when natural products are incorporated into nanomaterials (13,14).

2.2 Biomass and renewable carbon sources

Biomass-derived materials—including cellulose, lignin, chitosan, starch, and other biopolymers—are increasingly explored as sustainable carbon sources for nanocarbon synthesis (7,15). Their abundance, biodegradability, and low cost make them attractive alternatives to fossil-based precursors. Controlled carbonization of these materials under thermal or hydrothermal conditions leads to porous carbons and carbon dots with tunable properties (16, 17).

The utilization of agricultural waste, food residues, and plant-derived materials not only reduces environmental burden but also aligns with circular economy concepts, transforming waste into high-value functional materials (10,18).

3. From natural products to nanocarbons: Synthetic strategies

3.1 Green and sustainable approaches

The synthesis of nanocarbons from natural products emphasizes environmentally benign processes. Green synthesis approaches include hydrothermal carbonization, microwave-assisted synthesis, solvothermal methods, and low-temperature pyrolysis. These techniques minimize the use of toxic reagents, reduce energy consumption, and avoid harsh reaction conditions (10,11,19).

Natural products can act as both carbon precursors and functional modifiers, eliminating the need for post-synthesis chemical treatments. For instance, nitrogen-rich biomolecules can produce heteroatom-doped carbons, enhancing electronic and catalytic properties (7,20).

3.2 Template-directed and bio-inspired synthesis

Nature offers exquisite examples of hierarchical organization and self-assembly. Inspired by these processes, natural compounds are used as templates or structure-directing agents in nanocarbon synthesis (12,13). Biomolecules can guide the formation of porous structures, layered morphologies, and controlled particle sizes (21).

Self-assembled molecular aggregates derived from natural products can be carbonized to preserve nanoscale architectures. This bio-inspired approach allows precise control over material morphology and functionality, bridging molecular design and nanoscale engineering.

Figure 2: Green and sustainable approaches

4. Molecular structure–property relationships

4.1 Role of functional groups

The functional group composition of natural products significantly influences the physicochemical properties of resulting nanocarbons. Oxygen- and nitrogen-containing groups enhance hydrophilicity, surface reactivity, and electronic characteristics (7,16). These functionalities facilitate interaction with metal ions, pollutants, or biomolecules, broadening application potential (22, 23).

Heteroatom doping derived from natural precursors improves conductivity, catalytic activity, and electrochemical performance, particularly in energy-related applications.

4.2 Self-assembly and hierarchical organization

Self-assembly is a fundamental molecular phenomenon governing the formation of ordered structures from simple building blocks. Natural products often exhibit strong tendencies toward self-organization through non-covalent interactions such as hydrogen bonding, π–π stacking, and van der Waals forces (12, 21).

When these self-assembled structures are converted into nanocarbons, the resulting materials retain hierarchical porosity and structural order. Such architectures enhance mass transport, surface accessibility, and mechanical stability.

5. Characterization of natural product–derived nanocarbons

Advanced characterization techniques play a crucial role in understanding the structure–property relationships of nanocarbons. Spectroscopic methods reveal chemical composition and bonding environments, while microscopic techniques provide insights into morphology and nanoscale organization.

Thermal, electrochemical, and mechanical analyses further elucidate performance characteristics. Comprehensive characterization enables rational design and optimization of materials for targeted applications, linking molecular origins to macroscopic functionality (4,6).

6. Applications in energy storage and conversion

6.1 Supercapacitors and batteries

Natural product–derived nanocarbons have demonstrated excellent performance as electrode materials in supercapacitors and batteries. Their high surface area, hierarchical porosity, and heteroatom doping enhance charge storage capacity and cycling stability.

Biomass-based carbons offer cost-effective and scalable solutions for next-generation energy storage devices, addressing growing global energy demands (3,5,6).

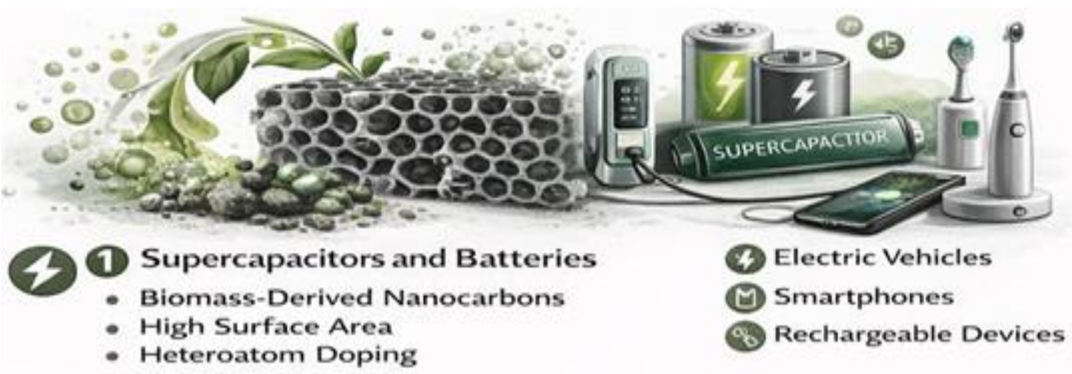

Figure 3: Supercapacitors and batteries

6.2 Catalysis and electrocatalysis

Nanocarbons synthesized from natural precursors are increasingly employed as metal-free catalysts or catalyst supports. Their tunable surface chemistry and defect-rich structures enhance catalytic activity in reactions such as oxygen reduction, hydrogen evolution, and organic transformations (20,24).

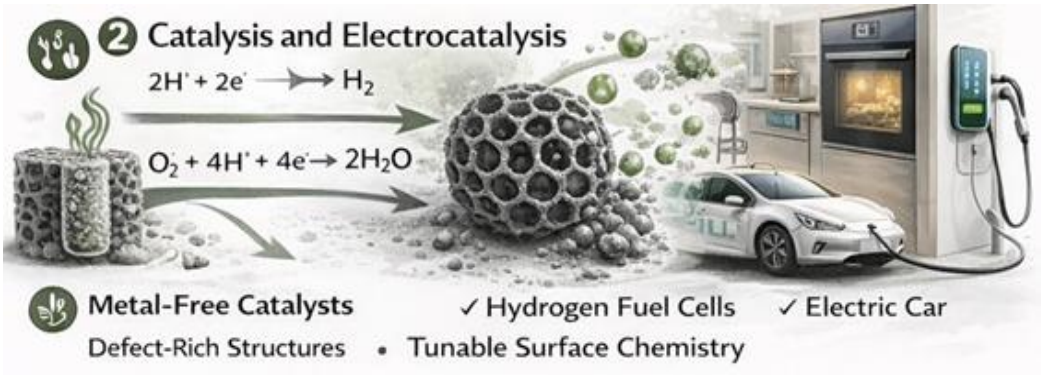

Figure 4: Catalysis and electrocatalysis

7. Environmental remediation and sustainability

7.1 Adsorption and pollutant removal

Porous nanocarbons derived from natural products exhibit strong adsorption capabilities for heavy metals, dyes, and organic pollutants. Functional groups on their surfaces facilitate selective binding and efficient removal from water and air.

Figure 5: Adsorption and pollutant removal

7.2 Carbon capture and green technologies

The integration of natural products in nanocarbon synthesis contributes to sustainable technologies for carbon capture and environmental protection (18,19). Such materials support eco-friendly solutions to pressing environmental challenges.

8. Biomedical and sensing applications

8.1 Bioimaging and drug delivery

Carbon dots and functional nanocarbons derived from natural products display excellent biocompatibility and photoluminescent properties. These features make them suitable for bioimaging, sensing, and drug delivery applications (14,15,22).

8.2 Chemical and biological sensors

Surface-functionalized nanocarbons exhibit high sensitivity and selectivity in detecting chemical and biological analytes. Natural product-derived functionalities enhance interaction with target molecules, improving sensor performance (23, 24).

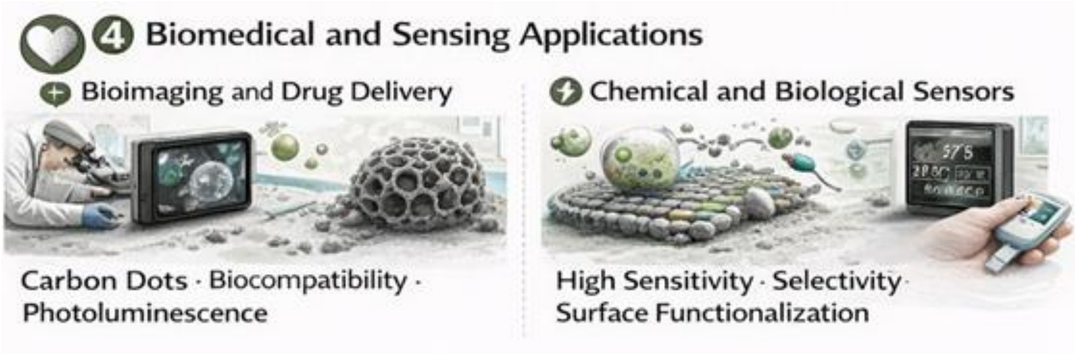

Figure 5: Biomedical and sensing applications

9. Challenges and future perspectives

Despite significant progress, several challenges remain in translating natural product–based nanocarbon research into large-scale applications. Reproducibility, scalability, and precise control over material properties require further investigation. Understanding complex molecular transformations during carbonization is another critical area.

Future research should focus on interdisciplinary collaboration, integrating molecular chemistry, materials engineering, and sustainability science. Advanced computational modeling and machine learning may further accelerate material discovery and optimization.

Conclusion

The transition from natural products to nanocarbons represents a dynamic and rapidly evolving frontier in molecular and materials science. By harnessing nature's molecular diversity and integrating it with advanced nanotechnology, researchers are developing sustainable, high-performance materials with wide-ranging applications. This review highlights the importance of molecular structure, green synthesis, and interdisciplinary approaches in shaping the future of nanocarbon research. Continued exploration at this interface promises innovative solutions for energy, environment, and healthcare, reinforcing the relevance of natural products in modern materials science.

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