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Sustainable Synthesis of Carbon-Based Nanomaterials: A Review of Bio-Waste Precursors and Green Carbonization Technique

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ABSTRACT

Traditional production methods for carbon-based nanomaterials (CNMs) rely heavily on non-renewable feedstocks and energy-intensive processes, making them unsustainable. The review provides a critical evaluation of sustainable routes for CNM production from bio-waste precursors and green carbonization methods. A crucial aspect is identifying the accessibility of inexpensive biomass sources, including agricultural waste, forestry refuse, and food waste, as carbon feedstocks for producing carbon dots, graphene-like materials, carbon nanosheets (CNs), and porous carbons. The review mainly focuses on green carbonisation methods, including hydrothermal carbonisation (HTC), microwave pyrolysis, the molten-salt technique, and solar-driven pyrolysis, which save energy and do not produce toxicants. These methods enable the customization of physicochemical features (e.g., morphology, surface functionality, porosity) in resulting CNMs, which can be used for energy storage (supercapacitors, batteries), environmental cleanup (adsorbents, sensors), and catalysis. Process limitations, such as scalability, reproducibility, and customization of nanomaterial properties from complex heterogeneous bio-waste, are thoroughly examined. The review shows that combining bio-waste precursors with green carbonization methods offers a promising circular-economy strategy, converting waste into high-value nanomaterials while reducing environmental impact. Future outlooks highlight the need for standardized life-cycle assessments and techno-economic analyses to support the industrial adoption of these sustainable synthesis methods.

1. Introduction

Owing to their remarkable physicochemical properties, carbon-based nanomaterials have become essential components in various advanced technologies. These unique structural features, including high surface area, tunable electronic properties, chemical stability, and mechanical strength, make them suitable for energy storage, catalysis, and sensing applications [1-3]. In energy storage, many carbon nanomaterials, such as graphene, carbon nanotubes (CNTs), and carbon fibres, significantly improve the performance of batteries and supercapacitors. Their high electrical conductivity and exposed surface area enable rapid charge transport and ion diffusion, resulting in enhanced energy density, power output, and cycling stability. These qualities are vital for energy devices to meet the increasing demand for renewable and sustainable energy technologies. Catalysis benefits greatly from carbon-based nanomaterials, which can act as chemically inert active sites or supports during catalytic processes. Their surface chemistry can be tailored to achieve high catalytic activity and selectivity, opening new possibilities for environmental restoration and various applications [4-6]. The catalytic versatility of carbon nanomaterials arises from their ability to stabilise metal nanoparticles and provide conductive pathways, thereby improving reaction kinetics and stability [7-9].

In sensor science, carbon-based nanostructured materials have demonstrated exceptional sensitivity and selectivity due to their large surface-to-volume ratio and favourable electronic properties. These features enable precise and sensitive detection of numerous chemical and biological analytes at low concentrations, supporting applications in environmental monitoring, healthcare diagnostics, and industrial process control [10-12]. The integration of CNMs (carbon nanomaterials) into sensor platforms has been particularly highlighted for designing sensors that deliver rapid response times, high reproducibility, and can be manufactured in a miniaturised format [13, 14]. However, it remains a challenge to standardise synthesis and achieve reproducibility in carbon-

based nanomaterials to fully realise their potential for applications [15]. In addition to innovations that improve yield and quality, which should be further developed for sustainable industrial adoption, more attention is needed on how these materials fit within a circular economy. Policy support and commercialisation pathways will further amplify their impact in various domains [16, 17].

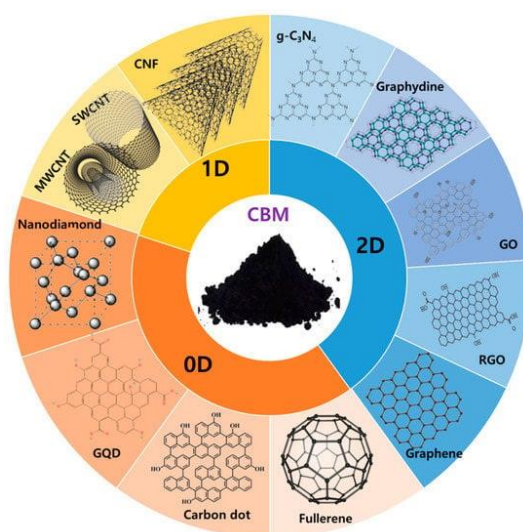


Fig. 1 Carbon-based nanomaterials [1]

This perspective aims to summarise the multiple significances of carbon-based nanomaterials, particularly by demonstrating how they transform energy storage, catalysis, and sensing, and by identifying where further new concepts and holistic integration are required (Fig. 1). Traditional methods for synthesising carbon nanotubes or related materials are both expensive and polluting. These conventional methods also require high temperatures and lengthy procedures, resulting in

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increased energy consumption and a larger carbon footprint. Most synthesis routes involve irreversible and toxic chemicals or solvents that lead to environmental contamination and waste disposal issues and pose a threat to worker health [18, 19]. Additionally, these processes can produce toxic waste that must be properly disposed of, complicating environmental compliance. Economically, traditional methods for preparing 2D materials can be costly, involving expensive or complex precursors and energy-intensive facilities or processes. The scalability of such techniques is often limited, resulting in low yields and inconsistent product quality, thereby hindering commercial viability. Additionally, the lack of standardised procedures undermines reproducibility, leading to variability in the physicochemical properties of nanomaterials and, ultimately, their performance in applications [20-22].

Overcoming these limitations, which are both economically and environmentally fraught, is of utmost importance for sustainable production. It is important to develop methodologies that align with the principles of green chemistry, including the use of renewable starting materials, low energy intensity, and minimisation of toxic reagents. Scalable, affordable, and green synthesis methods for CBs will enable large-scale industrial applications and integrate the production of carbon-based nanomaterials into the circular economy [23-25]. The utilisation of bio-waste as an environmentally benign and sustainable feedstock in the creation of carbonaceous nano-materials is consistent with eco-friendly/green chemical and circular economic principles. Biowaste becomes a renewable, abundant, and low-cost carbon feedstock and also decreases reliance on fossil-fuel-based or non-renewable raw materials. By valorising agricultural residues, food waste and other organic by-products that would otherwise be disposed of to landfill or incineration, the use of bio-waste contributes significantly to reducing environmental contamination [26-28].

In the review article on sustainability, bio-waste precursors open up avenues for synthesis that are not only energy-efficient and free of toxic chemicals but also reduce the carbon footprint and pollution associated with traditional approaches. This strategy enables waste reduction and resource efficiency by recycling waste materials as feedstocks for high-value nanomaterial production, promoting the circular economy. Economically, bio-waste-derived synthesis can avoid raw-material costs and scale up production due to the worldwide availability of feedstock. It also has the potential for on-site production, which can reduce transportation emissions and expenses. These together make the eco-friendly, low-cost synthesis of carbon nanomaterials more feasible, more beneficial for industrial-scale up, and in line with environmental policies and the trend towards sustainable development. Green carbonisation is an eco-friendly process that transforms C-precursors, such as bio-waste, into carbon-based nanomaterials, or biochar, with minimal environmental impact [29-31]. They advocate sustainability through energy minimisation, waste elimination, the use of non-hazardous chemicals, and a resource economy consistent with the principles of green chemistry and the circular economy. Running at lower temperatures than traditional pyrolysis in order to decrease energy consumption and prevent the production of undesired byproducts. Using bio-waste such as agricultural waste, food waste, or other organic by-products as a carbon precursor and valorising waste without relying on fossil-precursor feedstocks. A popular green technique that treats biomass with hot, pressurised water, usually at 180-250 °C; HTC can convert wet biomass directly into hydrophobic, carbon-rich hydrocarbons without the need for drying, which saves energy while generating materials with desired properties [32, 33]. The use of microwaves to heat biomass quickly and uniformly enables energy-efficient carbonisation, significantly reducing manufacturing time and improving control over material properties. Excluding pollution and harmful catalysts, or using biodegradable and natural catalysts to promote carbonisation, thereby reducing environmental disasters. Developing processes that not only generate carbon nanomaterials, but also concentrate valuable by-products or promote nutrient recycling, in line with circular economy principles. Establishing carbonisation pathways that are low-cost and compatible with large-scale operations and limited environmental impact. These carbonisation methods for green processability play a significant role in sustainable synthesis toward energy savings, pollution control, and the production of high-quality carbon nanomaterials from renewable materials. They address environmental and economic issues associated with existing approaches and facilitate broad industrial applications of eco-compatible carbon-based nanomaterials [34-36].

2. Bio-Waste Precursors for Carbon Nanomaterials

Compost-derived bio-waste is a rapidly growing area for the green synthesis of CNMs and has attracted attention for its waste-to-wealth proposition, thereby reducing dependence on fossil feedstocks (Fig. 2). A <https://doi.org/10.30799/jnst.5209.26110309>

diverse range of bio-waste is used, including agricultural residues, food waste, and forestry waste. Agricultural waste (such as rice husk, sugarcane bagasse, and wheat straw) has been most studied because of its worldwide availability and higher fixed carbon content. Food waste, such as coffee grounds, citrus peels, and nutshells, has become increasingly of interest for the intrinsic self-doped heteroatom nitrogen and sulfur in the carbon skeleton, which contributes to electrical performance. Forestry waste, such as wood sawdust and bark, has been used as a lignocellulosic solid matrix to prepare high-performance carbon fibres and activated carbons [16, 37].

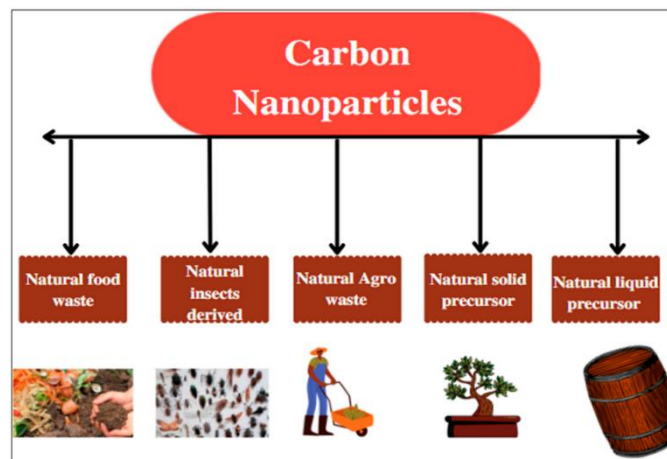


Fig. 2 Natural sources for the synthesis of carbon nanoparticles

Indeed, the entire concept of CNMs based on these precursors is substantially influenced by their biochemical profile, which involves the relative amounts of cellulose, hemicellulose, and lignin. Lignocellulosic biomass is generally composed of 30-50% cellulose, 20-40% hemicellulose, and 15-30% lignin. Cellulose, a linear polymer of glucose, is an excellent source of crystalline nanomaterials and carbon nanofibers. Aromatic polymeric compound lignin is especially important as an abundant natural carbon scaffold that allows high yield and is highly structurally stable under the conditions of high-temperature pyrolysis [20, 38-40]. The presence of these natural polymers enables the generation of diverse morphologies, ranging from zero-dimensional carbon dots to two-dimensional graphene-like sheets, which depend on the intrinsic mineral content and the arrangement of the organic reticulum. Excellent control during synthesis, while maintaining reproducibility, requires strict pretreatment to homogenise raw bio-waste (which is often a mixture of different sources). The moisture is removed by drying and mechanical grinding, as the former sand-sized particles are reduced to fine particle size to obtain stabilised particles by distributing uniform heat during thermal processing. Chemical pretreatments or chemical activation can be performed using agents such as potassium hydroxide (KOH), phosphoric acid (H₃PO₄) and zinc chloride (ZnCl₂). In pyrolysis, these chemicals serve as dehydrating agents and templates that “etch” the carbon structure, forming a complex network of micro- and mesopores. It is important to obtain high surface areas (typically greater than 1500 m²/g), which are necessary for special applications in energy storage or environmental cleanup [41-44].

3. Green Carbonization Techniques

Hydrothermal carbonisation (HTC) is an important wet thermochemical process that can be considered a means of replicating the natural coal-forming history, but on a much shorter timescale. Carried out in a closed vessel at mild temperatures (180 °C to 250 °C) and under self-generated pressure, HTC uses water as both solvent and catalyst. The major process parameters - temperature, residence time and the ratio of biomass to water - have a critical impact on the morphology of the hydrochar obtained. The most attractive feature of HTC is its ability to treat wet (i.e., without energy-intensive pre-drying) bio-waste, making it particularly effective for food and aquatic biomass waste [45, 46]. However, a major drawback is the lower carbonisation degree compared to dry processes, resulting in conducting materials that require secondary high-temperature activation steps to become sufficiently electrically conductive for advanced electronics. Pyrolysis remains the benchmark for producing high-quality carbon nanomaterials when carried out under controlled, mild conditions. Unlike in conventional industrial combustion, green pyrolysis occurs in an oxygen-free environment (typically under nitrogen or argon) at temperatures between 300 °C and 900 °C. By

specifically adjusting the heating rate, slow pyrolysis researchers can increase the yield of solid carbon while capturing bio-oil and syngas as valuable byproducts. This controlled process can result in the low emissions of volatile organic compounds (VOCs) and fine-tune the pore structure of the carbon skeleton [47–49]. Although it requires more energy for initial heating than HTC, the material often exhibits better homogeneity and higher carbon purity. Energy savings in the microwave-induced carbonisation process are achieved mainly through volumetric heating rather than simple surface heat conduction. In this way, the microwave frequency directly vibrates and accelerates the dipoles of precursor molecules, causing internal friction due to molecular spin, thereby heating. This cold-to-heart heating process reduces synthesis time from hours to minutes, thereby greatly decreasing the total carbon footprint of process manufacturing. Additionally, mild microwave heating can create preferential hot spots in the biomass that promote the selective growth of specialised nanostructures, such as carbon nanotubes or graphene-like flakes, which is not possible with traditional furnace heating [47, 50].

4. Properties and Characterization of Resultant Nanomaterials

The conversion of biowaste into state-of-the-art nanomaterials is confirmed by extensive characterisation of the structural, chemical, and performance properties. These measurements can indicate whether a material is best for cleaning water, storing energy, or serving as a catalyst.

4.1 Structural Properties

Surface area, porosity and morphology of bio-based carbon nanomaterials (CNMs) control their structural integrity. Using the BET method, the specific surface area (SSA) is determined, which may yield stunningly large values of 1500–3600 m²/g, corresponding to super bulk electrodes. These high SSA values are achieved through a contemporary porous structure with micropores (< 2 nm) for charge storage, mesopores (2–50 nm) for transport, and macropores as reservoirs. Morphological analysis via SEM and TEM reveals varied shapes, e.g., hollow fibres from milkweed shells or spherical carbon dots from fruit peels, which lead to differences in how the material behaves in its surroundings [51–53].

4.2 Chemical Properties

The surface chemistry of CNMs is what sets bio-waste precursors apart from their synthetic analogues. For the characterisation of functional groups such as hydroxyl (-OH), carboxyl (-COOH), and carbonyl (C=O) that remain on the carbon after carbonisation, FTIR is a key tool. These groups have a site for chemical bonding, thus rendering the materials inherently hydrophilic or amenable to further functionalization. Moreover, the XPS and EDX data provide information on the elemental composition, which can be used to identify key elements, so-called dopants, such as nitrogen, phosphorus, or sulphur, that are naturally present in biomass (e.g., protein-rich waste or crustacean shells).

4.3 Performance Metrics

The bottom line for a bio-based nanomaterial is its performance in applications. Electrical conductance is a primary measure of energy storage; thus, highly graphitised (ordered carbon layers) materials have lower resistance and are more suitable for use as supercapacitor electrodes. Very high catalytic activity and adsorption capacity are crucial for environmental applications [54–57]. For instance, garlic peel-based mesoporous carbons exhibit excellent performance for removing heavy metals and organic pollutants, thanks to their synergistic combination of high surface area and abundant surface functionality. Quantitative performance indices frequently include specific capacitance (F/g) for batteries or per cent contaminant removal for water applications, demonstrating that the green material performs as well as, or better than, typical industrial carbons [58–60].

4. Conclusion

Converting bio-waste into carbon nanomaterials marks a significant step towards sustainable nanotechnology. Many advancements are needed to translate promising laboratory results into industry-impacting technology. However, achieving a high yield of certain nanostructures (such as SWCNTs or high-purity graphene) remains challenging due to the inherent complexity of biomass. A focused research effort on "designer" precursors, that is, known waste streams matched with specific catalyst systems, will be necessary to ensure product quality. Advances in

machine-learning-enabled process optimisation could enable further in situ fine-tuning of carbonisation parameters, preventing unnecessary energy waste while staying within the optimal range for recovering high-value carbon fractions. This field has much more potential if we adopt an integrated approach aligned with the principles of the circular economy. By utilising agricultural and food waste, we close the loop on an environmental liability, transforming waste into a high-tech product. This method not only captures carbon that would otherwise be released as methane or CO₂ but also creates a circular source of advanced materials. During this process, the byproducts of carbonisation, bio-oil and syngas, are reused to generate energy for synthesis, allowing for complete product recycling and reuse in subsequent cycles. This results in a nearly zero-waste material production cycle that promotes global sustainability. To implement this in the context of industrial detached housing, clear policy guidance and financial support are essential. Governments should introduce green procurement policies that favour bio-based nanomaterials over fossil-derived alternatives. Furthermore, locating decentralised biorefinery hubs near agricultural centres will significantly reduce energy costs and the carbon footprint. As the standardisation of bio-derived carbon advances, industrial sectors such as the battery market, aerospace, and water purification are projected to transition to green alternatives, indicating that nanotechnology's future is not only high-performing but also environmentally sustainable.

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