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Fabrication and Detection of Carbon-based Nanomaterials Derived from Biomass Sources: Processes and Applications

Basma Ashour[1], Shimaa M. Ali[2,*], Mohamed G. Farahat[1,3], Rabab M. El-Sherif[1,2]

[1] *Faculty of Postgraduate Studies for Nanotechnology, Cairo University, P.O. 12588, Giza, Egypt*

[2] *Chemistry Department, Faculty of Science, Cairo University, P.O. 12613, Giza, Egypt*

[3] *Botany and Microbiology Department, Faculty of Science, Cairo University, P.O. 12613, Giza, Egypt*

Abstract

Biomass-derived carbon-based nanomaterials have demonstrated remarkable potentiality in a wide array of diverse applications including but not limited to energy storage and conversion, environmental remediation, and cutting-edge biomedical devices and technologies. These sustainable and renewable nanomaterials, derived from biomass resources, have garnered significant attention due to their exceptional properties, such as high surface area, unique porosity, superior electrical conductivity, and desirable mechanical strength. Additionally, they exhibit promising capability in addressing critical global challenges associated with energy and environment sectors. This review aims to provide a comprehensive overview of the synthesis strategies employed for the production of biomass-derived carbon-based nanomaterials, elucidating the associated characteristics, and highlighting their applications in the aforementioned fields. Furthermore, the challenges and future prospects for the utilization of these nanomaterials will be discussed, with emphasis on the need for a sustainable and greener future.

Keywords: Biomass; Carbon Nanomaterials; Synthesis; Characterization techniques; Applications.

1. Introduction

With the rapid growth of the economy and the remarkable surge in the global population, numerous daunting global challenges have arisen in terms of meeting the ever-increasing demands for new energy conversion, advanced energy storage systems, and effective environmental pollution control measures. In light of these pressing needs, carbon-based nanomaterials (CBNs) have emerged as a prevalent solution, exhibiting a wide spectrum of diverse dimensions and shapes. These include the fascinating realm of 0-dimensional (0D) fullerenes, the mesmerizing realm of 1-dimensional (1D) carbon nanotubes, the versatile realm of 2-dimensional (2D) graphene oxide, and the intricate realm of 3-dimensional (3D) carbon fibers [1]. However, despite the plethora of strategies and applications associated with CBNs, a significant drawback lies in the fact that most of these nanomaterials are derived from petroleum sources. This inherently poses critical limitations, such as exorbitant costs, restricted availability, and potential environmental hazards. Understanding and acknowledging these concerns, the scientific and engineering community has now turned its attention towards an alternative solution - the utilization of biomass-derived CBNs [1]. It is widely believed that these nanomaterials hold immense promise as the future material of choice, owing to their abundance in renewable feedstock sources, cost-effectiveness, environmental friendliness, and the convenient feasibility of further chemical modifications, all aligned with the principles of green chemistry. Moreover, in the realm of environmental protection and thermal insulation, the potential of utilizing incinerated paper ash materials, which essentially serve as waste or residual byproducts after cellulose conversion, cannot be overlooked. These materials not only present a viable avenue to address environmental concerns but also exemplify their worth in terms of their potential contributions towards effective thermal regulation and insulation. In conclusion, the ongoing exploration and utilization of biomass-derived CBNs, coupled with the transformative potential of incinerated paper ash materials, are poised to revolutionize the domains of energy, environment, and sustainability [2]. By harnessing the extraordinary physical, chemical, and mechanical properties bestowed by these materials, humanity is inching closer towards unleashing a greener and more sustainable future.

Biomass is defined as renewable organic materials that originate from plants, animals, and microorganisms. This material is diverse and abundant and can be converted into bioenergy, biochemicals, and other valuable materials through the processes of pyrolysis, biological fermentation, and gasification. This is a result of its complex composition of polysaccharides, cellulose, hemicellulose, lipids, proteins, and mineral matter [3-5]. With the growing requirement for environmental protection, cheap and green sustainable pathways are desired for synthesizing CBNs that have some features appreciated by the industry, such as lower price, light weight, higher conductivity than their counterparts, etc. Biomass-derived CBNs, utilizing the relatively easy and low-cost approach of activating biomass obtained from abundant precursors in the form of leaves, fruits, flowers, pods, seeds, whole plants, whole algae, seafood shells, fallen leaves, wood chips, or wood dust, or even residual dregs from breweries and biogas plants, garner prominent attention from materials science and engineering researchers globally, as supporting

*Corresponding author e-mail: Sali@sci.cu.edu.eg; **(Shimaa M. Ali).**

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evidence of their high levels of electrochemical capabilities including potential availability in energy storage and conversion systems. In terms of industrially practical applications [6-9], the CBN materials would necessarily have to be mass-produced affordably, without relying on high-quality graphite or expensive chemicals as starting precursors. Boasting accessible raw material sources with advantageous characteristics-yet high atom economy, simple, feasible, and eco-friendly fabrication procedures, and large-scale cost-effective production potential, the thus-fabricated biomass-derived CBNs show significant promise to provide for such real-world demands. Between these precursor-contained carbonaceous materials (precursor-CMs) and biomass-derived CBN materials offered from aforementioned synthetic procedures, many different compositions occur due to differing inorganic (including alkali and alkaline earth metal salts) and organic components or different extraction or carbonization protocols. The relatively higher surface area, porous 3D network, and carrier concentration make the biomaterials represented as products from the related pyrolysis processes serve as cumulative and effective reinforcements hold great promise for various functions—especially in the energy storage and conversion fields [9-11].

CBNs, with excellent mechanical flexibility, biocompatibility, decent electrical conductivity, and controllable chemical functionalities, are promising candidates for diverse biomedical applications. Recently, numerous biomass substrates, which are inherently abundant, renewable, biocompatible, and sustainable, have been employed as the sources to realize the preparation of these nanomaterials [9-11]. Associated with a variety of synthesis strategies originated from the state-of-the-art carbon chemistry techniques, different surface morphologies, crystallinities, and functional groups can be appropriately obtained for distinct requirements. Generally, biomass substrates can be directly used as the precursors to fabricate CBNs. Furthermore, the comprehensive generations of two-dimensional plane structures in biomass substrates play an essential role in improving the conductivity and the specific surface area. Benefiting from the inherent unique hierarchical porous structures, well-defined nano/micro sizes, high specific surface area-coordinating dual functionalities, kinked edge, and edge effects, as well as superb mechanical flexibility, superior electrical conductivity, excellent chemical stability under a physiological environment, and persistent drug loading/unloading capacities, flexible CBNs derived from diverse biomass substrates exhibit exceptional perspectives on potential biomedical applications. However, unlike previous synthetic methods where organic solvents or non-degradable chemical substances might be used, the ion-etching and oxidative defragmentation processes that are performed naturally in the carbonization of biomass substrates are all environmentally friendly [12, 13]. This provides two economic advantages over traditional carbonization. First, this strategy has the inherent capability of effectively hydrophilizing a typically hydrophobic precursor without the need for additional oxidative treatments, and the isolated excessively hydrophilic or hydrophobic reactants can be directly filtered from the surroundings, effectively increasing the purity of the carbon-based nanomaterial. Second, the strategy is also compatible with large-scale production. The aforementioned properties endowed by the physical and chemical features of two-dimensional hierarchically porous architectures make flexible CBNs promising for diverse biocompatible biomedical applications, including but not limited to drug delivery, gene release, biosensors, bioimaging, photothermal therapy, chemophotothermal therapy, photodynamic therapy, and their combination [14].

2. Synthesis Methods of Biomass-Derived CBNs

2.1. Pyrolysis Techniques

Pyrolysis, as a direct application technology for the production of renewable fuels and chemicals, as shown in Figure 1, occurs in the absence of free oxygen and at temperatures that are higher than 450°C. The physics of igniting the starting materials to carbonize (char)/depolymerize is the key to achieving high conversion within a short time interval. Numerous factors such as feedstock treatment, the addition of catalysts, flue gas recirculation, microwave radiation, and vacuum are significant in improving the product distribution (biooil, char, and gas) during the pyrolysis [15]. The use of catalysts is one of the most promising strategies for escalating the economic benefits of the pyrolysis process, which accelerates the pyrolysis reaction with shortened reaction times and low temperatures. According to previous work, pyrolysis product biooil has the potential to be a renewable fuel and is the feedstock for the synthesis of chemical raw material or value-added chemicals [16, 17].

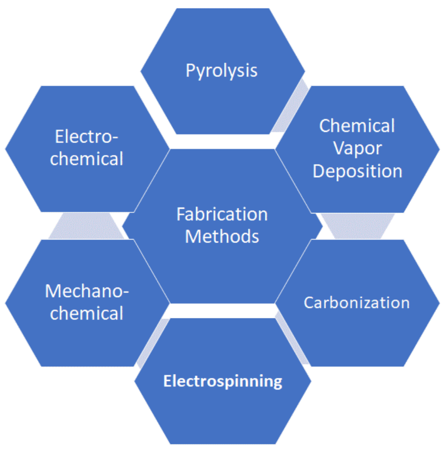

Figure 1: Fabrication techniques of CBNs from biomass.

Bamboos are among the fastest-growing plants on the planet, and bamboo-based materials are thus considered to be a renewable source. The most popular method for transforming bamboo into BDPs is pyrolysis at high temperatures in an inert atmosphere. Bamboo is usually mechanically mill-ground to a better size for good uniformity before pyrolysis. The distribution of heating values of bamboo-derived pyrolysis products (BDP) is generally 18.3–30.2 MJ/kg through the fast pyrolysis process, which is considered to produce high concentrations of contaminants such as water, acetic acid, acetic acid anhydride, esters, terpenes, styrene, tannins, aldehydes, alcohols, and to some extent, simple organic acids, methoxyphenols, and diterpenoids, as well as carbon nanoparticles, carbon nanotubes, and inorganic materials. Vacuum pyrolysis is beneficial for increasing the fractionating bio-oil of BDP during pyrolysis [18]. Hydrothermal pretreatment of bamboo before pyrolysis is effective for the distribution and composition of the BDP phase in bio-oil during catalytic cracking. Pyrolysis and hydrogen treatment at high temperature can be effective for manufacturing bamboo biochars, and bamboo biochar is effective in removing arsenic from contaminated water. The common chemical activations for BDPs to produce nanostructured carbon materials can remove potassium as well. Simphrodara et al. have found that it is better to wash bamboo powder with 3 M HCl before using them due to HCl-treated biochars having better Iodine adsorption capacity, Methylene adsorption capacity, and Brunauer–Emmett–Teller (BET) surface area compared with untreated biochars when potassium is washed off from the sample. Furthermore, the basic washing by treating the biochar of bamboo with KOH solution can alter the microstructure of the bamboo-derived carbons, thus facilitating the ion transfer toward the electrode. The sugar moiety, rather than the hexose units, is recommended to be separated selectively from the cellulose and hemicellulose moiety of bamboo by using choline chloride-based deep eutectic solvent due to acid hydrolysis of bamboo papers causing the formation of solid residues. The solid residues obtained by using choline chloride–ethylene glycol deep eutectic solvent as pretreatments can maintain the large pore volume and high surface area, which are beneficial for the further conversion. High-temperature pyrolysis of those solid residues can then convert them into bamboo-derived porous carbons. BDP has limited productivity. Overheating and secondary heating of BDP during the pyrolysis reduce the production of pyrolysis liquid.

In a **slow pyrolysis** method, the corn stalk was dried at 105 °C for 6 h and cut into eight sections. According to the laboratory test, it was shown that the corn stalk biochar kept a larger particle and the structure characteristics of biochar when the heating rate was 10 °C min^{-1} and the maximum temperature amounted to 400–450 °C. The physical properties and carbon distribution of sectional pyrolytic biochar were continuously changing, the volatile matter was more easily to be released from the stalk biochar in the pyrolysis, resulting in the revised ash content, and the relative crystallinity was improved to 0.20. At the end of slow pyrolysis, section by section, the carbon mass yield was in the range of 38.85–48.15% and simultaneously released amount of 44.92–57.19% energy, and then the 43.53% maximum specific surface area was obtained from the first section. Considering the material morphological structure changes and the energy and mass balances, functionalized stalk biochar for environmental application can be used in the remaining steady pyrolysis temperature zone, using the self-discharge approach to improve the fundamentals of slow pyrolysis process and turning it more suitable for industrial production [19].

Fast pyrolysis is a promising method to convert biomass into activated carbon nanomaterials. The first process of biomass pyrolysis is dehydration. It can generate mainly gaseous and liquid compounds like water and volatile compounds, and partial solid product known as biochar. The second step is the low-temperature pyrolysis which has richer oxygen and nitrogen. Meanwhile, the biomass in pyrolysis easily forms a lot of microspherical powder, while the difference is different for the heat-treated biomass. The third process will make this biochar decompose from large to small species. If the temperature of the biochar-containing reaction is controlled above 700 °C, it can produce activated carbon. Compared with the activated carbon prepared by physical activation, the activated carbon prepared by the thermal process has better SSA (specific surface area) and abundant pore structure. More importantly, the activated carbon prepared by the thermal process also has high carbon-carbon and carbon-hydrogen structures. It utilizes the original biomass, which normally degrades above 500 °C, and has a much more excellent structure than traditional wood or lignin organic compounds [20].

2.2. Chemical Vapor Deposition (CVD) Method

Chemical vapor deposition (CVD) provides a flexible and highly controllable method to tune the microstructures and nitrogen doping of neural network carbon nanofibers (NN-CN) from L-alanine, glycine, and L-arginine precursors [12]. The microstructures and nitrogen doping of the carbon nanomaterials were found to be significantly affected by the prearranged molecular configurations. The as-synthesized NN-CN from the L-arginine precursor demonstrated an open-type graphene microstructure and dominant graphitic nitrogen self-doping, which enabled high performance in the electrocatalytic and supercapacitive applications. In the CVD technological process, a syringe filled with the aqueous solution, which was saturated by lignin dissolved in ethanol and ultrafine $FeCl_3$ powder of 80-100 meshes, was equipped above a tubular furnace. Then, the reaction apparatus was evacuated to 10^{-3} Pa. The carrier N_2 gas was continuously flowed into the reaction apparatus upstream at a rate of 50 mL/min. The subsequent procedure was operated at the following conditions: the system was heated up from room temperature to 1300 °C within 60 min and kept at this temperature for 30 min, then the carrier gas. The unstable hydrocarbons and the resulting carbon chains were rapidly cooled down to room temperature with the carrier N_2 gas. Thus, the thin graphitized organic routes could be produced due to the thermal decomposition process of these constituents [21].

The activation method has been the most widely used method for the synthesis of CNSs from biomass. This activation process is based on the fact that an activation agent and both H- and O-containing groups play an important role in the synthesis of CNSs from biomass. The cuticle cell of bamboo, composed of cellulose, hemicellulose, and lignin, was most easily corroded by potassium hydroxide (KOH). With different proportions of cellulose, hemicellulose, and lignin in the composition of bamboo, the variation of BET surface area and porous structure was studied. The experimental results indicated that the main factor determining the porous structure is the large amount of alkalines acting on hemicellulose (that is, containing more H), and the more H the biohemicellulose represents, which indicates that the alkalinity in the system can be better performance. In the process, there are a large amount of hydrogen compounds, and the alkaline activity can better benefit the formation of the porous structure [22].

There are three typical CVD techniques: thermal CVD, plasma-enhanced CVD (PECVD), also known as plasma-activated CVD, and photothermal CVD. In thermal CVD, a gaseous hydrocarbon placed in a reaction chamber with high-purity carbon and a target substrate undergoes pyrolysis through the thermal breakdown of organic molecules at a high temperature (800−1000 °C). The coating on the substrate surface grows due to the adsorption, and the surface of the substrate is then covered with a film of carbon. It is an aluminum nitride (c-AlN) conducted at a high temperature and produces the thickest CVD layer. In PECVD, the breakdown of the hydrocarbon occurs only when it reacts with electrons created using plasma. The electron collision with the hydrocarbon activates the decomposition, and processes with low temperature value (below 400 °C) can coat a substrate. Plasma can generate free nitrogen atoms, considered as mass transporters across the hexagonal boron nitride lattice, leading to the formation of heterostructures [23, 24].

2.3. Hydrothermal Carbonization (HTC) Method

Carbonization is one of the typical and efficient ways to convert biomass-derived materials to CBNs such as CNWs, c-CNWs, and graphene nanosheets. In the carbonization of nanocellulose materials, heat treatment is carried out at various temperatures in a N_2 atmosphere. Carbonization is followed by a chemical treatment step, normally by washing with concentrated acids or treatment with alkali at high temperatures in 3 N NaOH aqueous solutions. The CNWs can be washed away after most of the amorphous material such as hemicellulose and lignin is removed. In the direct carbonization and activation process, a material templated from biomass is prepared by conversion from molecular to colloidal to solid and then to its hierarchical structure. The molecular content in feedstock is critically important in the performance of carbon-based materials [25-29].

2.4. Electrospinning Method

Electrospinning is a simple and effective method with the advantage of easy operation, low cost, and good quality of nanofibers. Its principle is like an ion generator. Under the action of AC high voltage, the polymer solution is ejected and stretched into a fiber under the action of a strong electric field. The nanometer-level ultra-fine fibers are obtained by evaporating the solvent. The electrospinning machine has fiber, droplet-free, bubble burst, electrostatic charging, non-coaxial, needleless, melt spinning, blow snail die, spray electrospinning inter-Hoh, and other forms. Among them, the needle spinning method is a mature technology with wide application. The production performance includes the diameter of the semiconductor mask, the molecular weight of the polymer, the viscosity of the polymer solution, the solution conductivity, the surface tension of the polymer solution, the die hole size, and the like. Biomass-derived CBNs prepared by electrospinning as a typical carbon precursor, cellulose has hydrophilicity and mechanical properties. These properties can be used to prepare fibers by electrospinning. Due to the presence of a large number of hydroxyl groups on the cellulose backbone, the solvent has a strong dissolving effect on the polymer, which is conducive to the production of high-quality polymer fibers [30, 31]. In addition, lignin is also commonly used in electrospinning because lignin is a compound with poor thermal stability. Adjusting the spinning conditions can prepare lignin-char and lignin-carbon materials. These materials maintain the basic structure of lignin, but the thermal stability and surface area are better than those of pure lignin. Unlike lignin and cellulose, chitosan is a polycation. Therefore, chitosan and the like are usually ground in ionic solutions such as acetic acid, acetone, or dimethyl sulfoxide. At present, most electrospinning materials obtained from chitosan rice exist as a composite with synthetic fiber. However, some of them generate pure chitosan sub-micro/nanofibers. When the degree of deacetylation (10%), the results obtained from permeable ionic solutions, and the mixed solution of strong solvent and weak solvent can produce.

2.5. Microwave-Assisted Synthesis

The microwave irradiation method that is capable of realization of the "green" principle and improvement of energy efficiency, significant speeding-up of the synthesis process of BC-based nanomaterials, and enabling regulation of their morphology, composition, and structure characteristics from various biomass has been attracted significant attention in recent years. The mechanism of microwave radiation effects on cured products prior to further carbonization has been discussed in the references. The vascular structure of biomass feedstocks could also help the precursor remain its original pattern during the rapid microwave carbonization process, and the obtained, unique hierarchical structure BCs could be strong candidates for various energy-storage systems attributed to fast electron charge transfer and highly accessible surface [32]. Hence, the microwave-assisted synthesis approach showed genuinely better performance on overall microstructures and the electrochemical properties of BCs compared to their conventional counterparts. However, as the fastest and greenest among these methods, the microwave irradiation carbonization technique requires no pre-treatment for the raw biomass feedstock, complex apparatuses, or complex carbonization processes, which make this route advantageous to exploit the superior structural and heteroatom-doped carbon capabilities of natural biomass sources. Despite extensive work in this field, the production of controllable new carbon structures by the microwave-assisted method is still a big challenge, and the comparison and evaluations of overall textural, morphological, mechanisms, and electrochemical properties through carbon materials derived from natural bio-precursors are always in need. Moreover, a detailed understanding of the fundamental mechanism with the combined carbon composition, chemical bonding, structure feature, relaxation time, critical microwave power, dielectric series, intermediates pattern, and the degree of aromaticity of realizing the microwave effect is very crucial for further exploring other desired BCs.

2.6. Electrochemical Methods

Electrochemical methods, among many convenient approaches for the synthesis of carbon materials, have attracted enormous interest and have been widely investigated due to their green, simple, and ecological advantages. Provided with low energy consumption, low cost, precise control in manipulation, and no external template requirement, procedures for the preparation of carbon materials via the electrochemical process include in situ carbonization of resins, electrochemical exfoliation of graphite, and less commonly used Zhang reactions and fluoride reactions. Recently, high value-added CNT@ rGO, 3D frameworks of reduced graphene oxide (RGO), carbon nanoparticles (CPs), and carbon microflowers, and hierarchical 3D porous nanosheets of N-doped carbon nanomaterials were also successfully engineered and demonstrated a variety of commercial applications. The relationship of growth performance and properties with self-designed patterns was conclusive, preferentially confirming the predominance and potential of the electrochemical method for further developing biomass-derived nanocarbons. The electrochemical, including in situ activated electrospun resins, dramatically improved electrochemical performance, which have received significantly less attention than that of CNT@ rGO and 3D grafting-type heterostructure models [33, 34].

The general synthesis procedure involves depositing metals (usually transition metals) from their salt precursors included in an electrolyte solution onto a prepared electrode that consists of carbon particles derived from the chosen biomass precursor (or free-standing carbon paper). The process occurs in a deposition solution of metal salt at a constant applied potential, such that the metal salt precursors (often metal halide and metal nitrate salts are used) are reduced at the electrode surface, causing the metal atoms to be deposited onto the carbon host by capturing the ionized electrons. After the metal content is determined to be within a suitable range, the modified carbon host is removed from the electrolyte solution and sometimes annealed at high temperature (typically below 900 °C without surfactants) to form the final carbon-metal nanoparticles or carbon-metal oxides. As an illustrative example, lignin can be used as a biofeedstock to prepare free-standing carbon paper, modifying the carbon electrode with Fe by adjusting the electrochemical deposition process parameters like deposition solution and concentration, applied potential, and deposition time. The duration of the synthesis process, as well as the applied potential, critically influence the uniform distribution of the metal nanoparticles onto the biomass-derived carbon material. Typically, the 1st scan Fe loading for lignin samples is detected at around 15 min with -1.2 V vs. SCE, and it will approach saturation at ~260 µg cm-2 after 60 min with -1.2 V vs. SCE. However, the transition metals like to form metallic clusters on the surface and form corresponding oxides if anodized. At a slow scan rate of 5 mV/s, the sharp redox peaks at around +0.18 and +0.65 V vs. SCE appear, corresponding to the Fe/C and Fe oxides/Fe redox peaks [35].

2.7. Mechanochemical Synthesis Techniques

To date, mechanochemical synthesis has received significant attention as it is an eco-friendly technique. This technique can afford a new approach to the synthesis of CNMs from almost all available carbon sources. The use of mechanochemistry for the preparation of CNMs takes place in the absence of solvents, utilizes energy saving, and provides a suitable choice for the realization of carbon sources that cannot be formed or dissolved using other synthesis techniques. It is more convenient and cost-effective for large-scale production, leading to various types of nanomaterials for a range of applications. Mechanochemical technology can be further extended to modify the surface of CNMs by using proper chemical functionalization, leading to materials that can be used in adsorption processes for various pollutants and dangerous compounds and energy storage and environmental applications. So far, several types of CNMs have been synthesized using this methodology. Selective mechanochemical technology for the preparation of various CNMs and modifications for different applications from renewable (lignocellulosic and cereal) biomass has been studied [36-38].

3. Types of Biomass-Derived CBNs

3.1. Biomass-Derived Carbon Nanotubes

Carbon materials derived from hydrocarbons are widely used as an optical material, catalyst support, nanotemplate, and hydrocarbon storage material [39]. Classical synthesis methods for the preparation of these materials require complex and expensive equipment at high temperatures. Biomass is an abundant and renewable organic resource that is rich in carbon. In recent years, the carbon in biomass, when subjected to proper thermolysis conditions, is gradually being used to prepare carbon materials. Deionized water treatment of carbon materials can adjust the material characteristics in a comprehensive manner. Deionized water contains natural active matter, which will dissolve and wash the impurities from the surface of the carbon material while also providing oxygen-containing groups on the surface. These groups can improve the dispersion stability of the carbon material in deionized water. Biosynthesized carbon materials from biomass, pre- and post-alterations in deionized water, and their common applications are introduced and discussed. To obtain BCNMs from different biomass precursors, diverse synthesizing methods are developed and can often be classified into two major categories, i.e., hard and soft template approaches. For the hard template approaches, three steps are generally combined to obtain the final product, including nanofilling inside the template (natural or artificial), template etching, and post-treatment of the final products. The hard template methods are more conventional, and more and more novel anodizing/casting techniques are emerging to allow greater control over the product morphology from spherical particles to nanotubes. Alternatively, soft-templated methods are also deployed to electropolymerize or polycondensate organic monomers or precursors in the absence of a template, and then subsequent calcination in an inert atmosphere is followed [40, 41]. Usually, the soft template approach is efficient for the synthesis of nanoparticles, microspheres, and hollow microstructures.

3.2. Biomass-Derived Graphene

Graphene is one of the thinnest nanomaterials, and a "trendy" member, named the mother of other carbon nanomaterials [40]. Graphene possesses a high specific surface area (2600 m^2/g), the highest thermal conductivity, the highest Young's modulus, and the highest electrical conductivity. With the increasing demand for graphene in wide applications, novel and green synthesis methods are constantly being developed. Among the various preparation methods, the role of biomass carbon in the preparation of graphene is being followed, which not only meets the requirements of green chemistry but also utilizes the recycling of biomass waste. Biomass-based methods to synthesize graphene pointed out that biomass carbon may contain impurities or use additional chemicals to obtain sufficient graphene. The term biomorphic graphite comes from the arguing fact of recent pyrolysis of wooden precursors to obtain porous forms of carbon with similar structure-like graphite, associated with fern leaf, named creation. Until now, much attention has been paid for the biosynthesis of C-based nanomaterials. Due to their special microstructures, moisture transportation-physisorption characteristics and high specific surface areas, carbon micro/nanostructures derived from natural biological materials have recently shown great potential for applications [42]. These remarkable properties are mainly ascribed to both the unique microstructures of these biological precursors and the graphitic or porous nanostructures of the as-prepared carbon materials.

3.3. Biomass-Derived Carbon Dots (CDs)

The use of CDs from biomass waste is still nascent compared to using aromatics as the precursor, but the number of CDs prepared from biomass sugars, cellulose to a lesser extent, lignin, and other biomass assemblers is rapidly rising [43]. Though the different sources of carbon folios lead to CDs with almost consistent photophysical properties due to limited variation in properties observed for CDs produced from different precursors, we highlighted the expected "green" label, presented some eco-friendly and "green" synthetic methodologies, and some advances and new mentoring methodologies developed in the regrettably harmful chemical processes. These CDs could also be decorated with essential surface modification functionalities for selective targeting in biomedical settings or targeting for sensing of specific analytes. The surface of CDs was functionalized with water-solubilizing functionality added to them, ready for the selected diagnostic probing of specific analyte thanks to specific surface modification structure on the surface of CDs, which spontaneously occurs via modification of CDs. The application of CDs in other related areas is fast emerging as a sought-after alternative because of its remarkable potential in undefined areas such as LED, lithium batteries, solar cells, non-linear optical materials, and photodetectors [44-46].

4. Characterization Techniques for Biomass-derived CBNs

The successful synthesis of CBNs is practically determined by making the most of the physical and chemical properties at the nanoscale. However, it is equally essential to effectively and efficiently characterize the physical and chemical properties of the synthesized nanomaterials. Commercial applications of nanomaterials require not only understanding the regular rules of the materials but also elevating the information level of the material incorporated in a sophisticated system to the same level or even superior to those of primary components such as macroscopic substrates addressed in present standard testing [47]. In addition, some of the nanomaterials have weak functions established by their major properties at the nanoscale or strong exposure limits governed by size effects. Unlike traditional materials, the fit-for-purpose, overall superior physical and chemical properties, better cost effectiveness, cleaner processing, higher sector-specific performance, simpler interfaces, and complete life-cycle analysis of nanomaterials are determined by additional sizes, surface activities, and integral nanostructures unique to nanomaterials.

4.1. Raman and FTIR Spectroscopy

Raman and FTIR Spectroscopy have provided valuable insights into their structural and chemical properties. These studies have extensively explored the unique characteristics of CBNs obtained from biomass sources, opening up promising avenues for their applications in various fields. The utilization of Raman and FTIR spectroscopy techniques has proven to be instrumental in elucidating the intricate details of these nanomaterials, enabling a comprehensive understanding of their composition, vibrational modes, and molecular structures. For CBNs, Raman spectroscopy helps in understanding the degree of graphitization, defects, and the presence of different carbon forms (e.g., sp^2 and sp^3 hybridized carbon), as shown in Figure 2 [48]. It can reveal the structural and electronic properties of the material. FTIR is used to identify functional groups and chemical bonds in biomass-derived carbon materials. It helps in understanding the surface chemistry and the presence of oxygen-containing groups, which are crucial for applications like adsorption and catalysis [49-51]. Through these advanced spectroscopic analyses, researchers have successfully identified the distinct spectral signatures associated with different types of CBNs derived from biomass, such as graphene, carbon nanotubes, and carbon dots. Moreover, the combination of Raman and FTIR spectroscopy has facilitated the identification and quantification of functional groups present in these materials, offering valuable insights into their chemical composition and surface characteristics. Using both Raman and FTIR spectroscopy provides a comprehensive understanding of the material. While Raman focuses on the carbon structure and defects, FTIR gives detailed information about the surface functional groups and chemical composition [52, 53].

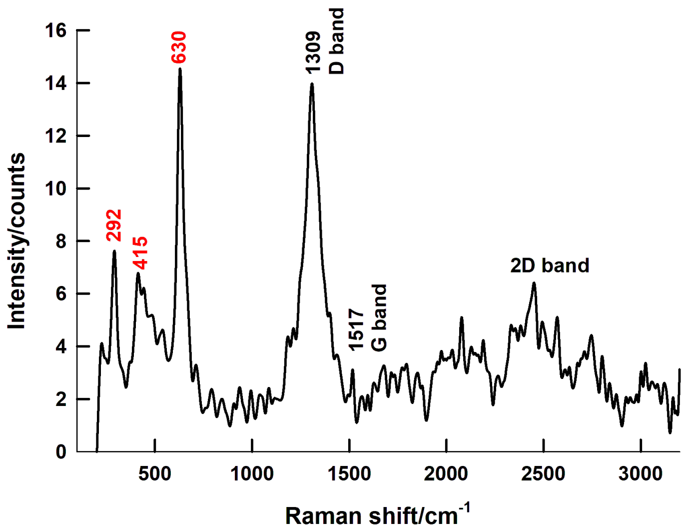

Figure 2: Raman spectrum of $LaFeO_3$/biochar composite, prepared by the microwave-assisted method at 450 °C [48].

4.2. Chemical Composition Analysis

Elemental composition of CBNs (CNMs) could help to explain their structure and properties. For biomass-derived CNMs, most of them contain abundant heteroatoms (such as oxygen, nitrogen, and sulfur). The composition and content of heteroatoms could influence the microstructure, electronic structure, chemical reactivity, and physical properties of biomass-derived CNMs. The first-hand knowledge of how these heteroatoms are incorporated into the sp^2 hybridized carbon nanosheets, tubes, microporous graphitic carbon membranes, and point defects was recently unveiled by the mixture of theoretical investigations and nature-driven experimental confirmations. Elemental composition of biomass-derived CNMs can be mainly analyzed by direct solution combustion, elemental analyzer, inductive coupled plasma-atomic emission spectrometry (ICP-AES) analysis, X-ray photoelectron spectroscopy (XPS), and the facile combustion analysis. Depending on the physical properties and elemental content of biomass raw materials, the ICP-AES and the apparatus of simple combustion can be used to confirm the quantity and type of acid, alkali, and common metal elements for the solid destruction of biomass. After the acid digestion, these metals in biomass are converted into soluble salt forms which are facile for the following ICP determination. The samples are dried under a vacuum at 25°C for 24 h before the experiments. The dry powder with samples and the standards were digested off in metal bombs with dissolving acid (such as HNO_3–HF–$HClO_4$) at 250°C for several hours. After dilution, the concentration of homo-metal elements is determined by ICP-AES. For the majority of biomass sample-endothermic or combustion experiments, the ash content can only be analyzed as "residues of characteristics" after ashing [54].

4.3. Surface Area Analysis

The Brunauer-Emmett-Teller (BET) surface area analysis is a widely used method to measure the specific surface area of materials This technique is particularly useful for characterizing the porosity and surface properties of these materials, which are crucial for applications in adsorption, catalysis, and energy storage.

In the context of biomass-derived CBNs, BET analysis helps determine the surface area and pore structure, which can significantly influence their performance. For example, a study on biochar derived from coconut shell, rice husk, and cow manure showed varying BET surface areas, with cow manure biochar exhibiting the highest surface area of 263.3 m²/g [47]. **Nanoporous carbon materials derived from biomass precursors** have tailored hierarchical pore structures and large specific surface areas, which are essential for energy conversion and storage. In addition, surface morphology and pore size distribution in the performance of supercapacitors. It details how different pore types (macropore, mesopore, and micropore) contribute to the overall performance and how chemical and physical activation methods can enhance the surface area up to 3326 m²/g [17]. Activated carbon derived from coconut shells, showcasing its expansive surface area and porosity [48].

Dynamic Light Scattering (DLS) is a common technique used to characterize the size distribution of nanoparticles, including those derived from biomass. For example, CDs are often synthesized from biomass waste such as bagasse, orange peel, and banana peel. DLS is used to determine the size distribution of these CDs, which typically range from 2 to 10 nm [14].

Biomass sources like cellulose and lignin can be used to produce CNTs. DLS helps in analyzing the size and dispersion of these nanotubes in various solvents. **Carbon nanospheres** Derived from biomass like coconut shells or sawdust, these nanospheres are characterized using DLS to ensure uniformity in size, which is crucial for applications in catalysis and energy storage. Biochar, produced from pyrolyzed biomass, can be further processed into nanomaterials. DLS is used to measure the particle size distribution, which affects their performance in environmental remediation and soil enhancement [46].

4.4. Transmission Electron Microscope (TEM)

TEM is essential for optimizing the properties of these nanomaterials for applications in energy storage, catalysis, and environmental remediation [47]. For biomass-derived CBNs, TEM helps in

- **Morphology Analysis**: Revealing the shape, size, and distribution of nanoparticles.
- **Structural Characterization**: Identifying crystalline structures, defects, and the degree of graphitization.
- **Elemental Analysis**: Using techniques like Energy Dispersive X-ray Spectroscopy (EDS) to determine the elemental composition.

The following examples illustrate of how TEM is used to study biomass-derived CBNs:

1. **Activated Carbon**: TEM images can reveal the porous structure and surface morphology of activated carbon derived from biomass, such as coconut shells or wood. This helps in understanding its adsorption properties and surface area.
2. **CNTs**: TEM is used to observe the alignment, diameter, and wall structure of CNTs synthesized from biomass sources like cellulose. This information is crucial for applications in electronics and composite materials.
3. **Graphene**: TEM allows researchers to see the layer structure, defects, and edge configurations of graphene sheets produced from biomass. These details are important for optimizing their performance in electronic and energy storage applications.
4. **CDs**: TEM helps in determining the size distribution and crystalline structure of carbon dots derived from biomass, such as fruit peels. These properties are essential for their use in bioimaging and drug delivery.
5. **Biochar**: TEM can be used to study the microstructure and elemental composition of biochar, which is produced from the pyrolysis of biomass like agricultural residues. This is important for its applications in soil amendment and water treatment.

4.5. Scanning Electron Microscope (SEM)

Scanning Electron Microscopy (SEM) is a powerful tool for analyzing the surface morphology and structure of biomass-derived CBNs. Examples of biomass-derived carbon-based nanomaterials that have been studied using SEM are giving [48]:

1. **Activated Carbon from Coconut Shells**: SEM images reveal a highly porous structure, making it suitable for applications in adsorption and energy storage.
2. **CNTs from Bamboo**: SEM analysis shows the formation of tubular structures, which are useful in electronics and composite materials.
3. **Graphene from Sugarcane Bagasse**: SEM images display thin, layered structures, highlighting its potential in flexible electronics and sensors.
4. **CDs from Orange Peels**: SEM images show small, spherical particles, which are promising for bioimaging and drug delivery.

4.6. Thermal Analysis

Thermal analysis techniques like thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) are widely used to study biomass-derived CBNs [23]. **Thermal and kinetic studies on biomass degradation** are used to investigate the thermal degradation behavior and kinetics of various biomass residues, including agricultural and forestry biomass, using TGA by exploring both single-step and multi-step models to derive activation energies and mechanisms. **During the** various thermal conversion methods such as pyrolysis, combustion, and gasification, TGA and DSC can be used in examining the key parameters of biomass feedstocks. In addition, **characterization of gaseous products during pyrolysis** process of agricultural residues is performed using TGA/DSC coupled with mass spectrometry (MS) detection analysis. **Kinetic and energy study of thermal degradation of biomass materials** for different samples, provides insights into their thermal degradation behavior. TGA and DSC can also be used to study the combustion kinetics of biomass-based fuel blends, providing valuable data on their thermal stability and decomposition.

5. Applications

Biomass-derived CBNs have a wide range of general applications in various fields, including but not limited to energy storage, environmental remediation, biomedical applications, emerging technologies, and beyond. They have proven to be highly versatile and valuable in addressing challenges. These nanomaterials exhibit exceptional properties such as remarkably high electrical conductivity, unparalleled thermal stability, exceptional mechanical strength, and outstanding chemical reactivity. Moreover, their unique nanostructure provides an enormously increased surface area, thereby making them highly effective catalysts, adsorbents, and sensors in countless applications. With their remarkable potentials in virtually every aspect, biomass-derived CBNs have truly revolutionized and transformed the realms of renewable energy, pollution management, and healthcare in unimaginable ways.

5.1. Sensing and Imaging

Biomass-derived CBNs have many properties, such as low cost, easy synthesis, being environmentally friendly, and inherent porosity, that make them very attractive for application in sensing or imaging. In the field of sensing, ultra-thin layers and high porosities of biomass-derived carbon greatly favor rapid transport and mass transfer of target molecules. Thus, such materials have shown high sensitivity (down to part-per-billion level) in the detection of gas-phase VOCs and analytes. Especially with the presence of inherent nitrogen/oxygen dual-doping caused by the raw materials, the non-metallic nature, or simple bifunctionality, and special mesopore-macropore nanostructures, they have shown excellent selectivity or a synergistic enhancement in response to some extremely toxic or cancer-related volatile organic compounds (VOCs). In the field of imaging, the mesopore structures and inherent physical/chemical properties of biomass-derived CBNs help to overcome issues in their wider applications medium properties (polar and nonpolar) and covalent/ionic bonding mode of biomolecules. The carbon nanomaterials derived from cellulose have specific and excellent optical properties, making them very hot for bioimaging applications. It is worth noting that some derivatives with photocatalysis effects are able to exhibit reactive oxygen species and toxic effects on the tumor cells, which provides the possibility of achieving facile bioimaging-guided therapy through multifunctional manipulation. Moreover, the inherent fluorescence, outstanding biocompatibility, and low-cost characteristics, and the versatility of the surface humin-derived carbon dots provide the possibility of bioimaging through a wide range of techniques such as microscopic imaging, macroscopic imaging, deep tissue imaging, bioimaging through herbs (ZJU-SiP-850), metabolism-fluorescence imaging, and multimodal bioimaging [55].

5.2. Energy Storage

Electric double-layer capacitors and lithium-ion/sodium-ion capacitors are favored in energy storage. Therefore, researchers hope to produce low-cost carbon materials with high conductivity and high specific surface areas as electrode materials for these energy storage devices. Through hydrothermal carbonization and simple KOH activation of chitin, Liu et al. obtained chitin-based activated 3D porous carbon with a high specific surface area of 2777 m^2/g. The resulting three-dimensional carbon has excellent parameters to be used as an electrode material for electric double-layer capacitors. The 3D porous carbon electrode material has a high specific capacitance (350 F/g) at 0.5 A/g, stable cycling, good energy density and power density, and can provide a good voltage cell that can deliver energy output. Their research uses natural, abundant, environmentally friendly chitin as a raw material, and the entire preparation process does not require the use of chemical substances, and KOH is used as the only activating substance. This 3D porous carbon material prepared by them is an excellent candidate for commercial applications, as it has excellent parameters as a supercapacitor electrode material [56, 57].

Biomass-derived CBNs serve also as exceptionally efficient electrodes in fuel cells, and batteries. By harnessing the exceptional electrical conductivity and storage capabilities of these nanomaterials, energy conversion efficiency has skyrocketed, contributing to the creation of highly efficient, portable, and long-lasting energy storage solutions. This breakthrough has the potential to drive significant advancements in renewable energy utilization and the gradual transition away from traditional fossil fuels, ensuring a greener and more sustainable future for generations to come [58, 59].

5.3. Environmental Remediation

The utilization of biomass-derived CBNs in environmental remediation has yielded remarkable results, providing efficient and effective solutions for combating pollution. Through various mechanisms such as adsorption, photodegradation, and decomposition processes, these nanomaterials have the exceptional ability to remove pollutants from air, water, and soil. Their remarkable properties according to the biomass type, as shown in Figure 3, enable them to selectively adsorb and neutralize harmful substances, contributing to the preservation and restoration of our environment [60-62].

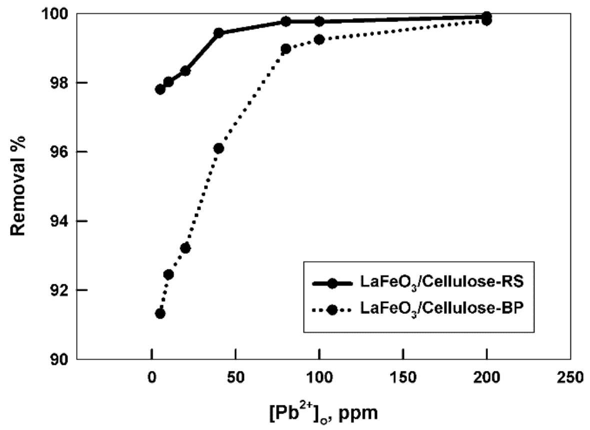

Figure 3: The variation of the removal % of $LaFeO_3$/cellulose-RS and $LaFeO_3$/cellulose-BP for Pb(II) ions at pH = 7 for a shaking time = 2 h at room temperature [63].

5.4. Biomedical Applications

The impact of biomass-derived CBNs extends to the biomedical field, where they have the power to revolutionize healthcare through numerous applications [64]. One prominent area is targeted drug delivery, where the unique properties of these nanomaterials enable precise and controlled release of therapeutic agents to specific locations within the body. This targeted approach enhances the efficacy of treatment while minimizing side effects, offering immense potential for personalized medicine and improving patient outcomes. Furthermore, biomass-derived CBNs have paved the way for advancements in tissue engineering, enabling the development of bio-compatible materials and scaffolds that promote tissue regeneration. These materials provide an ideal platform for the growth and differentiation of cells, leading to significant advancements in regenerative medicine and the potential for organ and tissue transplantation. Moreover, these nanomaterials play a crucial role in diagnostic imaging, enhancing the accuracy and sensitivity of various imaging techniques, ultimately leading to earlier detection and more effective treatment of diseases. The promising advancements in bioelectronics, biosensors, and nanomedicine owe much of their success to the exceptional properties and capabilities of biomass-derived CBNs [65-68].

5.5. Antimicrobial Activity

Biomass-derived CBNs, such as CDs, nanobiochar (NBC), and graphene oxide (GO), have shown significant promise in antimicrobial applications. These materials are derived from various organic sources and exhibit unique properties that make them effective against a range of pathogens. CDs can be synthesized from various biomass sources like tea leaves, turmeric leaves, and sugarcane bagasse [69]. CDs exhibit antimicrobial activity by generating reactive oxygen species that damage microbial cells. NBC is derived from biochar and has strong adsorption capabilities, allowing it to remove and immobilize pathogens from soil and water [70]. It is considered environmentally friendly and can be used in agriculture for controlling phytopathogens and in medicine for antimicrobial applications. GO has shown excellent antimicrobial properties due to its ability to disrupt microbial cell membranes. It is used in various applications, including agriculture and food preservation, as an eco-friendly alternative to traditional chemicals and antibiotics [71].

6. Conclusion and Future Perspectives

As the global demand for sustainable materials grows, the potential of biomass-based carbon nanocomposites is becoming increasingly recognized. Their unique properties—such as enhanced mechanical strength, lightweight characteristics, and excellent conductivity—position them as ideal candidates for a variety of applications, from advanced aerospace components to innovative energy storage solutions. Moreover, the utilization of renewable biomass sources can significantly mitigate environmental impacts associated with conventional carbon-based materials. Biomass-derived CBNs offer a promising solution to address climate change and reduce reliance on fossil fuels. Biomass is a renewable resource, unlike fossil fuels. Using biomass to produce carbon-based nanomaterials helps in reducing the carbon footprint since the carbon dioxide released during biomass conversion is offset by the carbon dioxide absorbed by the plants during their growth. Biochar can be used to sequester carbon and improve soil health, further mitigating climate change impacts. The production and application of biomass-derived CBNs can create numerous jobs across various sectors. This includes roles in research and development, manufacturing, and the deployment of these technologies. For instance, jobs can be created in the cultivation, harvesting, processing, and distribution of biomass, as well as in the production of biofuels and other bio-based product. Future research is likely to explore the optimization of synthesis methods, enhancing the structural integrity and functional features of these composites. Additionally, the integration of biomass-derived fillers with other nanomaterials can lead to the development of multifunctional composites that harness properties tailored to specific industrial needs. Ultimately, the advancement of biomass-based carbon nanocomposites not only fulfils the need for eco-friendly alternatives but also paves the way for breakthroughs in numerous technological domains.

Competing interests

There are no competing interests reported by the authors.

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