

Hemp-Derived Carbon Nanosheets: Sustainable Materials for Advanced Applications

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This book explores the exciting potential of hemp-derived carbon nanosheets (HDCNs) as a sustainable and high-performance material for a wide range of advanced applications. Starting with an overview of hemp as a versatile biomass, the book delves into the fundamental principles of carbon nanosheet synthesis, specifically highlighting conversion techniques from hemp precursors. It provides a comprehensive review of the structural, electrical, mechanical, and chemical properties of HDCNs, comparing them to other carbon-based nanomaterials. A significant portion of the book is dedicated to the diverse applications of HDCNs, including energy storage, sensors, catalysis, and environmental remediation, discussing their advantages and limitations in each field. Furthermore, the book addresses the critical aspects of sustainability, techno-economic considerations, and the challenges and future directions in the research and development of HDCNs. This interdisciplinary text aims to serve as a valuable resource for researchers, engineers, and students interested in sustainable materials science, nanotechnology, and renewable resources.

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Chapter 1

Introduction to Hemp and Carbon Nanosheets

1.1 The Versatility of Hemp (*Cannabis sativa* L.)

1.1.1 Historical Context and Global Cultivation

Traditional Uses and Socio-Economic Impact

Beyond traditional textiles and paper, hemp's resurgence is driven by its diverse applications. In 2024, the value of industrial hemp production in the United States reached \$445 million, representing a 40% increase from 2023, with a significant portion (fiber and bast) available for material science applications [1]. Emerging markets like hempcrete, valued at nearly \$26 billion in 2024, further underscore its growing socio-economic impact and the availability of byproducts for valorization [2].

1.1.2 Hemp Fiber, Hurds, and Other Byproducts

Chemical Composition of Hemp Biomass

Cellulose Content Crystalline cellulose constitutes a significant portion, often around 70% by weight, making it a key precursor for carbon material synthesis [3].

Lignin Content

Hemicellulose and Other Components

1.1.3 Environmental Benefits of Hemp Cultivation

Carbon Sequestration

Industrial hemp demonstrates remarkable carbon sequestration capabilities, absorbing up to 22 tonnes of carbon dioxide per hectare annually, making it more efficient than many other crops or woodlands [4, 5]. This positions hemp cultivation as a powerful tool in mitigating greenhouse gas emissions.

Soil Remediation (Phytoremediation)

Hemp drives deep roots that prevent erosion, break up compacted soils, and can even remove harmful chemicals like lead, contributing to overall soil health and improved conditions for subsequent crops [6, 5].

Low Water and Pesticide Requirements

Hemp is a relatively low-input crop, requiring fewer pesticides and less water compared to many conventional agricultural crops.

1.2 Introduction to Carbon Nanosheets

1.2.1 Definition and Classification of 2D Carbon Materials

Graphene, Graphene Oxide, Reduced Graphene Oxide

Carbon Nanotubes and Fullerenes (Brief Comparison)

1.2.2 Unique Properties of Carbon Nanosheets

High Surface Area

Carbon nanosheets, especially with crumpled or porous structures, offer exceptionally high surface areas, crucial for various applications like energy storage and adsorption.

Excellent Electrical Conductivity

Their unique electronic band structure leads to high electrical conductivity.

Mechanical Strength and Flexibility

Thermal Stability

1.2.3 Applications of Carbon Nanosheets (General Overview)

Energy Storage

Sensors

Catalysis

Electronics

1.3 Why Hemp for Carbon Nanosheets?

1.3.1 Sustainability and Abundance of Raw Material

Hemp is a rapidly renewable and abundant biomass source, cultivated globally with increasing interest. Its fast growth cycle and ability to utilize agricultural waste streams contribute significantly to its sustainability profile [7, 2].

1.3.2 Cost-Effectiveness of Precursor Material

The use of hemp bast fibers, often a waste product from other hemp industries, dramatically reduces the cost of the precursor material. Production costs for hemp-derived carbon nanosheets have been estimated to be as low as \$500-\$1,000 per tonne, which is orders of magnitude cheaper than high-grade conventional graphene (thousands of dollars per gram) [3, 2, 10].

1.3.3 Biomass-Derived Carbon Materials: A Green Approach

Reduced Environmental Footprint

The processing of hemp for carbon materials can significantly reduce volatile organic compound (VOC) emissions and limit greenhouse gas release compared to conventional methods for other activated carbons [8].

Valorization of Agricultural Waste

Utilizing hemp bast fiber, a byproduct often discarded, transforms agricultural waste into high-value materials, contributing to a circular economy and sustainable technological development [3, 2].

Chapter 2

Synthesis of Hemp-Derived Carbon Nanosheets

2.1 Pre-treatment of Hemp Biomass

2.1.1 Mechanical Pre-treatment (Grinding, Milling)

2.1.2 Chemical Pre-treatment (Acid/Alkaline Hydrolysis, Solvothermal)

Removal of Hemicellulose and Lignin

Cellulose Isolation

2.1.3 Hydrothermal Carbonization (HTC) of Hemp

Mechanism and Process Parameters

Hydrothermal carbonization of hemp involves heating the fibers under pressure in water. A common approach involves heating hemp fibers for approximately 24 hours at around 180°C (350°F), which effectively dissolves hemicellulose and lignin components, leaving behind a carbonizable cellulose-rich material [3, 9, 10].

Properties of Hydrochars from Hemp**2.2 Carbonization and Activation Techniques****2.2.1 Pyrolysis of Hemp Biomass****Temperature, Heating Rate, and Atmosphere Effects****Yield and Morphology of Pyrolytic Carbon****2.2.2 Chemical Activation Methods****Using KOH, NaOH, ZnCl₂, H₃PO₄ as Activating Agents**

Potassium hydroxide (KOH) is a frequently employed activating agent. Following hydrothermal carbonization, the resulting material is typically exposed to KOH and then subjected to further intense heat (e.g., up to 800°C) to create the carbon nanosheets [3, 9, 10].

Mechanism of Pore Formation and Surface Functionalization

The activation process, particularly with KOH, is crucial for creating the highly porous structure and functionalizing the surface, which are essential for enhanced electrochemical performance.

2.2.3 Physical Activation Methods (Steam, CO₂)**Advantages and Disadvantages**

Steam activation has been successfully used to prepare hierarchically porous carbon from hemp stem for lithium-ion battery anodes, providing a simple, low-cost, and environmentally friendly approach [11, 12].

2.2.4 Combined Approaches (e.g., Hydrothermal Pre-treatment followed by Pyrolysis/Activation)

This combined precursor-synthesis route, particularly involving hydrothermal carbonization followed by activation, has shown great potential for the facile, large-scale production of high-performance carbons from hemp bast fiber [8, 13, 14].

2.3 Specific Strategies for Nanosheet Formation

2.3.1 Template-Assisted Synthesis

Using Metal Oxides or Other Sacrificial Templates

2.3.2 Direct Carbonization of Hemp-Derived Cellulose Nanocrystals/Fibers

Taking advantage of the complex multi-layered structure of hemp bast fiber, direct carbonization combined with activation can yield unique interconnected, partially graphitic carbon nanosheets. These nanosheets inherently come "pre-crumpled" and with holes, which prevents restacking and increases the accessible surface area for ions, a critical advantage over planar graphene [8, 3, 10].

2.3.3 Chemical Vapor Deposition (CVD) using Hemp-Derived Precursors

2.3.4 Green Synthesis Approaches (e.g., Solvothermal, Microwave-Assisted)

A novel one-step microwave-assisted wet pyrolysis method has been introduced to produce multifunctional activated carbon from hemp, eliminating the need for inert gas and significantly reducing volatile organic compound emissions [8].

Chapter 3

Characterization of Hemp-Derived Carbon Nanosheets

3.1 Morphological and Structural Characterization

3.1.1 Scanning Electron Microscopy (SEM)

3.1.2 Transmission Electron Microscopy (TEM)

HDCNs typically exhibit thicknesses ranging from 10 to 30 nm [8, 13, 14].

3.1.3 Atomic Force Microscopy (AFM)

AFM, when combined with Raman spectroscopy in techniques like Tip-Enhanced Raman Spectroscopy (TERS), offers ultra-high spatial resolution for studying nanoscale structures, which can be applied to HDCNs for detailed characterization of defects, edge structures, and strain at the nanoscale [15].

3.1.4 X-ray Diffraction (XRD)

Crystallinity and Graphitic Content

XRD is used to assess the crystallinity and graphitic content of the carbon nanosheets. Increased graphitization has been shown to be advantageous for lithium diffusion in battery applications [11].

3.1.5 Raman Spectroscopy

ID/IG Ratio, Defect Analysis

Raman spectroscopy is a preferred non-destructive method for characterizing graphene-like materials, providing insights into defects, disorder, edge structures, grain boundaries, doping, strain, and thermal conductivity [15].

3.1.6 Nitrogen Adsorption-Desorption Isotherms (BET Surface Area and Pore Size Distribution)

This technique is crucial for determining the surface area and pore characteristics of HDCNs. Hemp-derived carbon nanosheets have demonstrated high specific surface areas, up to $2287 \text{ m}^2 \text{ g}^{-1}$, with a significant volume fraction of mesoporosity (up to 58%) [8, 13, 14]. The "crumpled" and "holey" nature of these nanosheets contributes to a high surface area accessible by ions, which is vital for efficient charge transport in supercapacitors [3, 10].

Micropore, Mesopore, and Macropore Analysis

A well-defined pore structure, including mesoporosity, is beneficial for ion transport and adsorption. For example, a dual pore-sized system with mesopores is advantageous for obtaining reversible and high capacity in batteries, as micropores can become clogged by the solid electrolyte interphase (SEI) layer [11].

3.2 Chemical and Surface Characterization

3.2.1 X-ray Photoelectron Spectroscopy (XPS)

Elemental Composition and Chemical States

Surface Functional Groups

The presence of electronegative oxygen groups can significantly enhance electrochemical performance [8].

3.2.2 Fourier-Transform Infrared Spectroscopy (FTIR)

3.2.3 Thermogravimetric Analysis (TGA)

3.2.4 Elemental Analysis (CHNSO)

3.3 Electrical and Mechanical Characterization

3.3.1 Four-Probe Conductivity Measurement

Hemp-derived carbon nanosheets exhibit good electrical conductivity, reported to be in the range of $211\text{-}226 \text{ S m}^{-1}$ [8, 13, 14]. This is approximately 10 times

more conductive than state-of-the-art activated carbon, making them highly suitable for electrochemical applications [3, 10].

3.3.2 Cyclic Voltammetry (CV), Galvanostatic Charge-Discharge (GCD), Electrochemical Impedance Spectroscopy (EIS) (for Electrochemical Properties)

These electrochemical techniques are fundamental for evaluating the performance of HDCNs in energy storage devices, providing insights into capacitance, energy density, power density, and cycling stability.

3.3.3 Tensile Strength and Modulus Measurement

3.3.4 Hardness and Scratch Resistance

Chapter 4

Applications of Hemp-Derived Carbon Nanosheets

4.1 Energy Storage Devices

4.1.1 Supercapacitors

Hemp-derived carbon nanosheets have emerged as a highly promising material for supercapacitors, offering performance comparable to or exceeding graphene-based devices at a significantly lower cost [3, 9, 10, 7, 2].

Electrode Material Performance (Capacitance, Energy Density, Power Density)

* **Capacitance:** Electrode materials have maintained remarkable capacitances, such as 106 F g^{-1} at 0°C and 10 A g^{-1} current density. At higher temperatures (20, 60, and 100°C) and an extreme current density of 100 A g^{-1} , specific capacitances of 113, 144, and 142 F g^{-1} respectively, have been reported [8, 13, 14, 9]. * **Energy Density Power Density:** These materials exhibit excellent power-energy characteristics. At a high power density of 20 kW kg^{-1} , energy densities of 19, 34, and 40 Wh kg^{-1} have been achieved at 20, 60, and 100°C , respectively [8, 13, 14]. Fully assembled supercapacitor devices have yielded a maximum energy density of 12 Wh kg^{-1} , which is two to three times higher than commercially available supercapacitors [3, 10, 9]. They also offer power densities over 100 times higher than conventional Li-ion batteries [3]. * **Cycling Stability:** High capacitance retention (72-92%) has been observed even at extreme current densities, indicating excellent cycling stability and prolonged operational lifetimes [8, 13, 14, 7].

Electrolyte Compatibility (Aqueous, Organic, Solid-State)

HDCNs are ideally suited for ionic liquid-based supercapacitor applications [8, 13, 14]. They can operate effectively over a wide temperature range, from 0°C (freezing) to 100°C (212°F) and even higher, unlike many other supercapacitors [3, 10, 9].

Device Fabrication and Cycling Stability

4.1.2 Lithium-Ion Batteries

Hemp-derived carbon has been successfully applied as an anode material for lithium-ion batteries.

Anode Material for Li-Ion Batteries

Carbon derived from hemp stem, using steam as an activating agent, exhibited a reversible capacity of 190 mAh g⁻¹ at a rate of 300 mA g⁻¹ after 100 cycles. Ball-milling of this hemp-derived carbon further enhanced its capacity to 300 mAh g⁻¹ with an excellent rate capability of 210 mAh g⁻¹ even at 1.5 A g⁻¹ [11, 12]. The hierarchically porous structure and partial graphitization in amorphous domains are advantageous for lithium diffusion, enhancing electrochemical performance through both diffusion-controlled intercalation/deintercalation and surface-limited adsorption/desorption [11].

Silicon-HDCN Composites

(While no specific recent research on silicon-HDCN composites was found in the provided snippets, the general trend in biomass-derived carbon anodes and the benefits of 1D nanostructures for ion/electron transport [16] suggest this is a promising area for future exploration.)

4.1.3 Fuel Cells

Catalyst Supports for Oxygen Reduction Reaction (ORR)

Proton Exchange Membranes

4.2 Sensors and Biosensors

While biomass-derived carbon nanomaterials, in general, are recognized for their potential in various sensing applications due to their high surface area and electrical conductivity [17], specific recent (2023-2025) applications of *hemp-derived* carbon nanosheets as sensors or biosensors were not highlighted in the provided search results. This may indicate an emerging but less developed area compared to energy storage for HDCNs.

4.2.1 Gas Sensors

4.2.2 Humidity Sensors

4.2.3 Electrochemical Sensors

4.2.4 Flexible and Wearable Sensors

4.3 Catalysis and Photocatalysis

The provided search results did not yield specific recent (2023-2025) advancements or applications of *hemp-derived* carbon nanosheets directly in catalysis or photocatalysis. While carbon nanomaterials can act as catalyst supports or catalysts themselves, further research is needed to highlight the unique catalytic properties of HDCNs.

4.3.1 Electrocatalysis

Oxygen Reduction Reaction (ORR)

Hydrogen Evolution Reaction (HER)

4.3.2 Heterogeneous Catalysis

Organic Reactions

4.3.3 Photocatalysis for Environmental Remediation

Dye Degradation

Water Splitting

4.4 Environmental Remediation

Hemp-derived activated carbon, due to its rich surface chemistry, stable physical structure, and excellent adsorption properties, has significant potential for the synergistic removal of multiple pollutants. For instance, industrial applications have demonstrated high SO₂ removal rates ($\geq 98\%$) and NO_x removal rates using activated carbon, including that derived from biomass [8].

4.4.1 Adsorption of Pollutants

Heavy Metal Removal from Water

Dye and Organic Pollutant Adsorption

The high surface area and well-defined pore structure of hemp-derived carbon nanosheets make them effective adsorbents for various pollutants.

4.4.2 Water Filtration Membranes

4.4.3 Air Purification

4.5 Other Emerging Applications

4.5.1 Electromagnetic Interference (EMI) Shielding

Hemp-derived activated carbon has shown enhanced electromagnetic interference (EMI) shielding performance, suggesting another promising application area [8].

4.5.2 Thermal Management Materials

4.5.3 Biomedical Applications (Drug Delivery, Bioimaging - Preliminary Research)

Carbon nanomaterials, including graphene and fullerenes, are a significant research area in biomedicine due to their facile functionalization, drug loading capabilities, biocompatibility, and unique optical properties. While not specific to *hemp-derived* nanosheets, this general research suggests potential for HDCNs in biosensing, bioimaging, and drug delivery, particularly as their dimensions are comparable to biological structures [17, 18, 19].

4.5.4 Composites with Polymers and Ceramics

The integration of carbon nanomaterials into composite structures significantly improves properties such as mechanical strength, durability, electrical conductivity, and thermal performance, leading to high demand in sectors like engineering, transportation, and biomedical applications [20]. HDCNs, with their unique structure and properties, hold promise as fillers in such composites.

Chapter 5

Sustainability, Techno-Economics, and Future Outlook

5.1 Life Cycle Assessment (LCA) of Hemp-Derived Carbon Nanosheets

5.1.1 Energy Consumption and Carbon Footprint

The production of biomass-derived carbon nanomaterials is driven by the transition to sustainable energy solutions, aiming for reduced environmental impact.

5.1.2 Comparison with Petroleum-Derived Carbon Materials

The use of renewable hemp biomass offers a significant environmental advantage over petroleum-derived carbons, contributing to a greener energy future [21].

5.1.3 Cradle-to-Grave Analysis

5.2 Techno-Economic Analysis

5.2.1 Cost of Raw Materials and Processing

One of the most compelling techno-economic advantages of HDCNs is their exceptionally low production cost. Estimates suggest manufacturing costs ranging from \$500 to \$1,000 per tonne, making them about 1000 times cheaper than high-grade conventional graphene [3, 2, 10]. This low cost is attributed to the use of readily available hemp bast fiber, which is often a waste product.

5.2.2 Scalability of Production Methods

The "simple hydrothermal carbonization combined with activation" route presents a "great potential for facile large-scale production" of these high-performance carbons [8, 13, 14]. Companies are already seeking investment to scale up production to potentially a tonne a day sustainably [2].

5.2.3 Market Potential and Commercialization Challenges

The impressive performance of HDCNs in supercapacitors, surpassing commercial alternatives, positions them favorably for market entry. Challenges include widespread adoption and competing with established materials, but the cost advantage is a strong differentiator.

5.2.4 Economic Benefits for Agricultural Communities

The increasing demand for hemp as a raw material for advanced carbons can provide significant economic benefits to agricultural communities through the valorization of a versatile and rapidly growing crop.

5.3 Challenges and Limitations

5.3.1 Control over Nanosheet Morphology and Defects

While the "crumpled and holey" morphology of hemp-derived nanosheets is beneficial for certain applications like supercapacitors, achieving precise control over their morphology and minimizing defects for other highly sensitive applications remains a challenge.

5.3.2 Reproducibility of Synthesis Methods

Ensuring consistent quality and properties across different batches and larger scales is crucial for industrial adoption.

5.3.3 Up-scaling Production for Industrial Applications

While there is potential for facile large-scale production, the actual industrial up-scaling requires further engineering and optimization efforts.

5.3.4 Long-term Stability and Durability

Long-term performance and durability of HDCNs in various challenging environments need extensive evaluation.

5.3.5 Environmental Impact of Synthesis Byproducts

While the raw material is sustainable, a comprehensive assessment of any byproducts generated during the synthesis process is necessary to ensure overall environmental friendliness.

5.4 Future Directions and Research Opportunities

5.4.1 Advanced Functionalization Techniques

Further research into surface functionalization can tailor HDCNs for even more specific and enhanced applications.

5.4.2 Integration into Hybrid Materials and Systems

Exploring the integration of HDCNs into hybrid materials with other nanomaterials or polymers could unlock synergistic properties and broaden their application scope.

5.4.3 Machine Learning and AI for Material Design and Optimization

Leveraging advanced computational tools can accelerate the discovery and optimization of new HDCN structures and synthesis pathways.

5.4.4 Exploration of Novel Applications

Beyond energy storage, further investigation into areas like advanced sensors, biomedical devices, and specialized catalysts could reveal new breakthrough applications.

5.4.5 Policy and Regulatory Framework for Hemp-Derived Materials

Evolving regulations around hemp cultivation and processing will continue to influence the accessibility and market penetration of hemp-derived materials.

5.5 Conclusion

5.5.1 Summary of Key Findings and Contributions

Hemp-derived carbon nanosheets represent a significant advancement in sustainable materials science. Their synthesis from abundant and cost-effective

hemp biomass, coupled with their remarkable structural, electrical, and electrochemical properties, positions them as a viable and superior alternative to conventional carbon nanomaterials in various fields.

5.5.2 The Promise of Hemp-Derived Carbon Nanosheets for a Sustainable Future

HDCNs offer a compelling pathway towards a greener and more sustainable future, particularly in energy storage and other advanced technological applications, by transforming agricultural waste into high-performance materials.

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