

Hemp-Derived Carbon Nanosheets: Properties, Applications in Composite Materials, and Future Characterization

1. Introduction: The Rise of Sustainable Carbon Nanomaterials - Hemp-Derived Carbon Nanosheets for Composite Applications

The escalating global demand for sustainable and renewable materials has spurred significant research into carbon nanomaterials as potential replacements for conventional materials across various industries. Among these nanomaterials, graphene, a two-dimensional sheet of carbon atoms, has garnered considerable attention due to its exceptional properties, including high strength, electrical conductivity, and thermal conductivity. However, the widespread adoption of graphene has been hindered by challenges associated with its mass production and high manufacturing costs. This has created an opportunity for the exploration of alternative, more sustainable, and cost-effective precursors for carbon nanomaterial synthesis.

Hemp, a fast-growing and versatile plant, has emerged as a promising renewable resource for the production of various materials, including carbon nanomaterials. Its rapid growth cycle, high biomass yield, and carbon sequestration properties make it an environmentally attractive alternative to traditional carbon sources. Furthermore, the utilization of hemp waste products for the synthesis of high-value materials like carbon nanosheets aligns with the principles of a circular economy. Hemp-derived carbon nanosheets, often referred to as hemp graphene, have shown potential in various applications, particularly in energy storage devices such as supercapacitors. Their lower production cost compared to conventional graphene makes them an economically viable option for a wider range of applications, including their integration into composite materials to enhance their properties.

This report aims to provide a comprehensive overview of the current state of knowledge regarding hemp-derived carbon nanosheets as of 2025. It will detail the known physical, chemical, electrical, thermal, and mechanical properties of this material, based on a thorough review of scientific literature published up to that year. Furthermore, the report will identify the gaps in our current understanding of these properties, particularly in the context of integrating hemp graphene into composite materials. Finally, it will propose a set of characterization tests that could be performed to address these knowledge gaps and further explore the potential of hemp graphene for enhancing composite materials.

2. Synthesis and Production Methods of Hemp-Derived Carbon Nanosheets

The synthesis of hemp-derived carbon nanosheets involves various methods, each influencing the final properties of the material. One commonly reported method involves hydrothermal carbonization followed by activation. This process typically begins with pressure-cooking hemp

fibers in water at elevated temperatures (around 180°C) for an extended period (e.g., 24 hours). This hydrothermal treatment dissolves hemicellulose and lignin, leaving behind a carbonized material. The subsequent activation step, often employing chemical agents like potassium hydroxide (KOH) or zinc chloride (ZnCl₂) at high temperatures (700-800°C), further enhances the surface area and porosity of the resulting carbon nanosheets. The choice of activation agent significantly impacts the properties; for instance, KOH activation has been shown to lead to a substantial increase in the specific surface area.

Direct pyrolysis, another synthesis method, involves the thermal decomposition of hemp biomass in an inert atmosphere, typically at temperatures ranging from 500 to 1000°C. This simpler approach yields carbon nanosheets that can range from amorphous to partially graphitic, depending on the control parameters such as heating rate, hold time, and biomass particle size. Microwave-assisted pyrolysis offers a faster and potentially more energy-efficient alternative. This method utilizes microwave heating for rapid and uniform heating of the hemp biomass, which can potentially enhance graphitization at lower temperatures.

Chemical activation using concentrated acids like sulfuric acid (H₂SO₄) and phosphoric acid (H₃PO₄) has also been explored for the synthesis of hemp-derived graphene. This method often involves a pretreatment step followed by acid digestion at elevated temperatures and subsequent activation with agents like KOH. The use of acid activation can influence the surface functional groups and porosity of the resulting carbon material. Emerging techniques such as plasma treatment and template-assisted activation are also being investigated to further control the properties and morphology of hemp-derived carbon nanosheets. Template-assisted activation, for example, uses sacrificial templates like magnesium oxide (MgO) or silica to control the sheet dimensions, which are removed after carbonization through acid washing. The selection of an appropriate synthesis method is crucial as it directly affects the morphology, surface area, conductivity, and other key properties of the hemp-derived carbon nanosheets, ultimately determining their suitability for specific applications, including integration into composite materials.

3. Comprehensive Review of Known Properties of Hemp-Derived Carbon Nanosheets (as of 2025)

3.1. Physical Properties

Hemp-derived carbon nanosheets exhibit a unique set of physical characteristics that make them attractive for various applications. Their morphology is often described as an interconnected network of partially graphitic structures. Transmission electron microscopy (TEM) images reveal sheet-like structures that tend to scroll and wrinkle, an intrinsic characteristic of graphene sheets. This crumpled morphology, along with their porous nature, contributes to an ultra-high surface area. Specific surface area values reported in the literature range from hundreds to over 2600 m²/g. For instance, interconnected carbon nanosheets derived from hemp bast fiber have shown surface areas up to 2287 m²/g. Activation with KOH significantly improves the surface area, with values reaching 1125 m²/g and 1410 m²/g for different biochar to KOH ratios. In some cases, the surface area of hemp-derived activated carbon can surpass that of commercially available activated carbon, reaching as high as 2612 m²/g.

These nanosheets also exhibit a significant volume fraction of mesoporosity, often reported to

be up to 58%. Hydrothermal processing followed by activation has been found to enhance this mesoporosity. The thickness of these nanosheets typically ranges from 10 to 30 nm. However, data regarding the density of hemp-derived carbon nanosheets is not consistently reported in the reviewed literature.

Table 1: Summary of Physical Properties of Hemp-Derived Carbon Nanosheets from Literature (as of 2025)

Snippet ID	Synthesis Method	Morphology	Specific Surface Area (m ² /g)	Porosity (%)	Thickness (nm)	Density (g/cm ³)
	Hydrothermal carbonization + Activation	Interconnected, Partially Graphitic, Porous	Up to 2287	Up to 58	10-30	Not Reported
	Hydrothermal processing + KOH/NaOH Activation	Mesoporous	Up to 2425	Not Reported	Not Reported	Not Reported
	NaOH Chemical Activation	Porous	Up to 2612	Not Reported	Not Reported	Not Reported
	Acid Digestion + KOH Activation	Sheet-like, Wrinkled, Scrolling	1125 - 1410	Not Reported	Few Layers	Not Reported

3.2. Chemical Properties

The chemical properties of hemp-derived carbon nanosheets are largely influenced by their biomass origin and the synthesis methods employed. Elemental composition analysis indicates that these nanosheets are primarily composed of carbon. Hemp fibers, the precursor material, are composed of cellulose (34-48%), hemicellulose (21-25%), and lignin (17-19%). X-ray photoelectron spectroscopy (XPS) analysis has confirmed the presence of oxygen and nitrogen in the elemental composition of hemp-derived carbon materials.

The presence of various functional groups on the surface of hemp-derived carbon nanosheets has been identified through techniques like Fourier transform infrared spectroscopy (FTIR) and XPS. These functional groups include oxygen-containing groups such as hydroxyl (-OH), carboxyl (-COOH), and carbonyl (C=O) groups. These surface functionalities can play a crucial role in the material's interaction with other substances, including the matrix in composite materials.

Regarding thermal stability, hemp-derived carbon nanosheets have demonstrated suitability for applications across a broad temperature range, from low (down to 0°C) to high (100°C) temperatures, particularly when used in ionic-liquid-based supercapacitors. Thermogravimetric analysis (TGA) of carbon nanotubes synthesized using similar methods suggests high thermal stability, withstanding temperatures approaching 1000°C. Furthermore, the presence of phosphorus compounds on the carbon surface, resulting from certain activation processes, can enhance the oxidation resistance of the material.

3.3. Electrical and Thermal Conductivity

Hemp-derived carbon nanosheets exhibit promising electrical conductivity. Values ranging from 211 to 226 S/m have been reported for interconnected partially graphitic carbon nanosheets derived from hemp bast fiber. This conductivity is notably higher than that of state-of-the-art activated carbon. In the context of supercapacitor applications, the performance of devices made from hemp-derived carbon nanosheets has been found to be comparable to or even better than standard graphene-based supercapacitors.

Data on the thermal conductivity of hemp-derived carbon nanosheets is less prevalent in the reviewed snippets. Graphene, in general, is known for its exceptionally high thermal conductivity. While hemp-derived carbon nanosheets are often referred to as "hemp graphene" due to their structural similarities and potential applications, specific measured values for their thermal conductivity are not consistently reported.

Table 2: Summary of Electrical and Thermal Conductivity of Hemp-Derived Carbon Nanosheets from Literature (as of 2025)

Snippet ID	Synthesis Method	Electrical Conductivity (S/m)	Thermal Conductivity (W/mK)
	Hydrothermal carbonization + Activation	211-226	Not Reported

3.4. Mechanical Properties

The mechanical properties of hemp-derived carbon nanosheets are crucial for their potential use as reinforcing agents in composite materials. Graphene, a material with structural similarities, exhibits exceptionally high tensile strength (around 130 GPa) and a Young's modulus of approximately 1 TPa. In comparison, hemp fibers, the precursor for these nanosheets, have reported tensile strength values ranging from 97.33 MPa to 1110 MPa and Young's modulus values between 3.77 GPa and 92.44 GPa.

Directly measured tensile strength and Young's modulus values specifically for hemp-derived carbon nanosheets are not consistently found in the reviewed literature. However, hemp graphene is described as a lightweight and flexible material. Its potential as a composite material is highlighted by its ability to make other materials stronger, suggesting its contribution to the overall mechanical properties of the composite.

Table 3: Mechanical Properties of Hemp-Derived Carbon Nanosheets and Hemp Fibers from Literature (as of 2025)

Material	Snippet ID	Tensile Strength	Young's Modulus	Flexibility
Hemp Graphene		130 GPa (based on graphene)	1 TPa (based on graphene)	Lightweight, Flexible
Hemp Fiber		97.33 - 1110 MPa	3.77 - 92.44 GPa	-

4. Applications of Hemp-Derived Carbon Nanosheets in Composite Materials: A Critical Analysis of Current Research

Research has explored the integration of hemp-derived carbon nanosheets into various composite matrices, including polymer, ceramic, and metal systems. In polymer matrix

composites, the addition of graphene, including potentially hemp-derived forms, has shown promising results in enhancing mechanical properties such as tensile strength and flexural strength. For instance, the combination of graphene with natural hemp fibers in epoxy composites has indicated improved load-sustaining ability and higher thermal resistance. However, challenges related to the dispersion of nanosheets within the polymer matrix and achieving uniform reinforcement need to be addressed to maximize the benefits. Hemp-derived carbon nanosheets are also being explored for their potential in lightweight armor and protective gear applications within polymer composites.

In ceramic matrix composites, the application of hemp-derived carbon nanosheets is less documented in the provided snippets. However, hemp hurd has been used as a carbon template for the fabrication of reaction-formed silicon carbide ceramics. Generally, the incorporation of graphene into oxide ceramic composites has been shown to improve their strength and electrical performance.

The integration of hemp-derived carbon nanosheets into metal matrix composites is being investigated for applications requiring high strength and low weight. Similar to polymer composites, achieving good dispersion of the nanosheets within the metal matrix and ensuring strong interfacial bonding are critical challenges in this area.

The incorporation of graphene and related materials, including those derived from hemp, into composites can influence their thermal and electrical properties. Graphene modification has been shown to enhance the thermal resistance of composites. Furthermore, the good electrical conductivity of hemp-derived carbon nanosheets suggests their potential use in applications such as electromagnetic interference (EMI) shielding in composite materials.

Emerging applications for hemp-derived carbon nanosheet-reinforced composites span various industries, including automotive, aerospace, construction, energy storage, military, and healthcare. The potential for using these nanosheets in 3D printing filaments for composite materials is also being explored.

Table 4: Examples of Hemp-Derived Carbon Nanosheets in Composite Materials and Resulting Property Changes

Snippet ID	Matrix Material	Integration Method	Property Measured	Improvement/Change
	Epoxy	Infusion	Flexural Strength	Increased load-sustaining ability
	Epoxy	Infusion	Thermal Resistance	Higher compared to natural fiber composites

5. Unveiling the Unknown: Gaps in Current Knowledge Regarding Hemp-Derived Carbon Nanosheets and Their Composites

Despite the growing body of research on hemp-derived carbon nanosheets, several gaps in our current knowledge remain, particularly concerning their application in composite materials. There is an inconsistency in the reporting of fundamental properties such as density and detailed mechanical properties (tensile strength, Young's modulus) specifically for hemp-derived carbon nanosheets themselves, as opposed to graphene or hemp fibers. The hemp industry also faces a need for standardized protocols for the quality evaluation of hemp products,

including these advanced carbon materials. Furthermore, there is insufficient data across the entire life cycle of hemp products, including composites reinforced with hemp-derived carbon nanosheets, which limits our ability to fully assess their sustainability.

The properties reported for hemp-derived carbon nanosheets can vary significantly due to factors such as the genetic diversity of the hemp source, the heterogeneous structure of hemp fibers, and the specific processing conditions used during synthesis. There is a lack of comprehensive studies that systematically investigate the effect of specific synthesis parameters (e.g., temperature, activation agent, reaction time) on the final properties of the nanosheets, making it challenging to tailor the material for specific composite applications. Another significant gap in knowledge pertains to the long-term durability of hemp graphene-reinforced composites. Limited data is available on how these composites perform over extended periods under various environmental conditions, such as exposure to humidity, temperature fluctuations, and ultraviolet (UV) radiation. More life cycle assessments are needed to quantitatively evaluate the environmental benefits of using hemp graphene in composites compared to traditional reinforcing materials, considering factors like energy consumption and carbon footprint.

While the production of hemp-derived carbon nanosheets is reported to be significantly cheaper than that of traditional graphene, further research is necessary to optimize large-scale production methods specifically for composite applications. A thorough cost-benefit analysis comparing the use of hemp graphene with other reinforcing materials in various composite applications is also needed to guide material selection and promote widespread adoption.

6. Proposing Future Characterization Tests for Enhanced Understanding and Application in Composites

To address the identified knowledge gaps and further explore the potential of hemp-derived carbon nanosheets for enhancing composite materials, the following set of characterization tests is proposed:

6.1. Advanced Microscopy Techniques

- **High-Resolution Transmission Electron Microscopy (HR-TEM):** This technique will allow for precise determination of the number of graphene layers in the hemp-derived carbon nanosheets, identification of any structural defects, and detailed analysis of their graphitic structure. Understanding the nanoscale structure is crucial for correlating it with macroscopic properties.
- **Atomic Force Microscopy (AFM):** AFM can be used to accurately measure the thickness of individual nanosheets, study their surface morphology at the nanoscale, and assess their local mechanical properties such as Young's modulus through nanoindentation. This will provide valuable data on the fundamental mechanical behavior of the nanosheets.
- **3D Tomography (e.g., FIB-SEM Tomography):** Reconstructing the three-dimensional architecture of the interconnected nanosheet network will provide insights into their bulk properties, such as porosity and tortuosity, which are important for understanding their performance as fillers in composites.

6.2. Detailed Spectroscopic Analyses

- **Advanced X-ray Photoelectron Spectroscopy (XPS):** Performing high-resolution XPS will enable quantitative elemental analysis, precise identification and quantification of surface functional groups, and a deeper understanding of the chemical bonding states within the hemp-derived carbon nanosheets. This information is vital for understanding the chemical reactivity and potential for interfacial bonding with matrix materials.
- **Near-Edge X-ray Absorption Fine Structure (NEXAFS) Spectroscopy:** NEXAFS can provide complementary information to XPS, offering detailed insights into the electronic structure and bonding environment of carbon atoms in the nanosheets, which can be related to their electrical and mechanical properties.
- **In-situ Raman Spectroscopy:** Studying the structural changes and stress transfer mechanisms in hemp graphene-reinforced composites under applied mechanical or thermal loads using in-situ Raman spectroscopy will provide direct evidence of the effectiveness of the nanosheets as a reinforcing agent.

6.3. Comprehensive Mechanical Testing Under Varied Conditions

- **Nanoindentation:** Measuring the hardness and elastic modulus of individual hemp graphene flakes through nanoindentation will provide direct data on their intrinsic mechanical properties at the nanoscale.
- **Dynamic Mechanical Analysis (DMA):** Characterizing the viscoelastic properties of hemp graphene-reinforced composites as a function of temperature and frequency using DMA will offer insights into their damping behavior, thermal transitions, and overall mechanical performance over a range of conditions.
- **Fatigue Testing:** Evaluating the long-term durability of composites under cyclic loading conditions through fatigue testing is crucial for assessing their suitability for structural applications where repeated stress is expected.

6.4. Advanced Thermal Analysis Techniques

- **High-Resolution Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC) Coupled with Mass Spectrometry:** These techniques will provide precise data on the thermal stability, decomposition pathways, and the nature of evolved gases from both the nanosheets and their composites, offering a comprehensive understanding of their behavior at elevated temperatures.

6.5. Specialized Electrical and Thermal Conductivity Measurements at Different Temperatures and Frequencies

- **Four-Point Probe Method:** This method will accurately measure the electrical conductivity of both the hemp-derived carbon nanosheets and their composites across a range of temperatures, providing data relevant for various applications.
- **Time-Domain Thermoreflectance (TDTR) or Laser Flash Analysis:** These techniques will precisely determine the thermal conductivity of the nanosheets and quantify their impact on the thermal properties of the resulting composite materials.

6.6. Characterization of Interfacial Properties in Composites

- **Pull-out Tests and Push-out Tests:** These tests will directly measure the interfacial shear strength between the hemp graphene reinforcement and the matrix material, providing crucial data on the strength of the interface.
- **Scanning Electron Microscopy (SEM) of Fracture Surfaces:** Analyzing the morphology of the fractured composite surfaces using SEM will help understand the failure mechanisms and provide indirect information about the interfacial adhesion between the nanosheets and the matrix.

6.7. Life Cycle Assessment and Environmental Impact Studies

- **Comprehensive LCA studies:** Conducting detailed life cycle assessment studies, following ISO standards, will evaluate the environmental footprint of hemp graphene production and its use in composite materials, considering all stages from raw material extraction to end-of-life disposal. This will provide a holistic understanding of the sustainability aspects.

7. Conclusion and Future Outlook: Harnessing the Potential of Hemp-Derived Carbon Nanosheets in Advanced Composite Materials

Hemp-derived carbon nanosheets represent a promising class of sustainable and cost-effective nanomaterials with potential for significant impact in the field of composite materials. The current state of knowledge, based on research up to 2025, reveals that these nanosheets possess a unique combination of high surface area, mesoporosity, and good electrical conductivity, making them attractive for various applications. While their potential to enhance the mechanical, thermal, and electrical properties of composite materials has been demonstrated in some studies, particularly in polymer matrices, several knowledge gaps remain. These gaps include a lack of consistent data on fundamental mechanical properties, the influence of specific synthesis parameters, long-term durability in composite applications, and comprehensive life cycle assessments.

The proposed set of characterization tests, encompassing advanced microscopy, detailed spectroscopy, comprehensive mechanical and thermal testing, specialized conductivity measurements, interfacial property analysis, and life cycle assessment, will be crucial for addressing these knowledge gaps. Future research should focus on systematically investigating the relationship between synthesis methods and the resulting properties of hemp-derived carbon nanosheets, as well as their performance in different composite matrices under various conditions. Optimizing synthesis methods for scalable and cost-effective production will also be essential for widespread adoption. By addressing these challenges and leveraging the unique properties of hemp-derived carbon nanosheets, the development of sustainable and high-performance composite materials for a wide range of industries can be significantly advanced.

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