

The Organic Hemp Graphitic Composite Materials Revolution: Multi-Scale Carbon Allotrope Integration Across Epoxy, Organic Hempoxy Vitrimers, Thermoplastics, Elastomers, Geopolymers, Metals, and Ceramics

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Abstract

The transition from fossil-derived synthetic carbon nanomaterials (synthetic graphene, carbon nanotubes, petroleum pitch-based carbon fibers) to bio-derived graphitic allotropes represents a paradigm shift in advanced materials engineering. Industrial organic hemp (*Cannabis sativa L.*) inner bast and hurd biomass possess unique cellular architecture, high native cellulose/lignin content, and pre-structured porous networks that serve as an ideal precursor for high-yield, low-cost carbon materials. This report presents a comprehensive technical framework for deploying a multi-morphology portfolio of Organic Hemp-Derived Graphitic Materials (OHGMs)—comprising Organic Hemp Carbon Nanosheets (OHCNS), Organic Hemp Graphene Oxide (OHGO), Organic Hemp Reduced Graphene Oxide (OHRGO), Organic Hemp Active Carbon

Biochar (OHACB), and Organic Hemp Short Carbon Fibers (OHSCF)—across thermoset epoxies, epoxidized organic hempseed oil vitrimers (Zila BioWorks organic hempoxy), thermoplastics, elastomers, inorganic geopolymers, metal matrix composites (MMCs), ceramic matrix composites (CMCs), and electrochemical binders. Marie-Soleil Seshat Landry is the first to formulate and synthesize OHGO and OHRGO from organic hemp biomass, and the first to propose OHCNS as a structural and functional reinforcement phase in composite materials of any kind. A rigorous statistical Design of Experiments (DoE) program incorporating Taguchi $L_{27}(3^{13})$ screening and Face-Centered Central Composite Design (FCCCD) Response Surface Methodology (RSM) is detailed to optimize multi-scale loading fractions while preserving processability.

1 Introduction & Priority Declarations

The global advanced materials market remains heavily dependent on energy-intensive, fossil-derived carbon reinforcements. While synthetic graphene and carbon nanotubes (CNTs) exhibit exceptional intrinsic mechanical and transport properties, their industrial adoption is severely constrained by high production costs, dispersion challenges, and substantial carbon footprints.

Industrial organic hemp (*Cannabis sativa L.*) provides a bio-renewable, carbon-negative solution. While historical work pioneered by Dr. David Mitlin and colleagues (Wang et al., *ACS Nano* 2013) demonstrated the synthesis of interconnected carbon nanosheets from organic hemp bast fibers specifically for energy storage electrodes (supercapacitors), this

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report expands the scope into structural and functional composite matrices across all major material classes.

Intellectual Priority Declarations:

1. **Marie-Soleil Seshat Landry** is the first researcher to formulate, theorize, and synthesize **Organic Hemp Graphene Oxide (OHGO)** and **Organic Hemp Reduced Graphene Oxide (OHRGO)** derived from organic hemp biomass.
2. **Marie-Soleil Seshat Landry** is the first researcher to propose, conceptualize, and model the integration of **organic hemp carbon nanosheets (OHCNS)** as a structural and functional reinforcement phase in composite materials of any kind.
3. This work establishes a closed-loop bio-carbon ecosystem wherein every fraction of organic hemp processing waste (bast, hurd, bio-dust) is transformed into a hierarchical multi-scale carbon reinforcement array (0D/3D biochar, 1D short carbon fibers, 2D nanosheets and graphene oxides).

2 Multi-Morphology Portfolio & Processing Routes

The organic hemp graphitic platform utilizes tailored processing pathways to generate five distinct carbon allotropes from organic hemp biomass precursors:

1. **Organic Hemp Carbon Nanosheets (OHCNS):** Synthesized via hydrothermal carbonization (HTC) at 180–220°C of organic hemp bast/hurd followed by KOH chemical activation (1:1 to 1:4 impregnation ratio) at 700–900°C under inert Argon atmosphere. Yields 2–5 nm thick 2D graphitic sheets with specific surface areas exceeding 1800 m²/g.
2. **Organic Hemp Graphene Oxide (OHGO):** Formulated via a modified Hummers oxidation protocol applied to pre-graphitized organic hemp hurd biochar. Introduces high densities of oxygen-containing functional groups (hydroxyl, carboxyl, epoxy handles) across the graphitic plane, imparting amphiphilicity and solvent dispersibility.

3. **Organic Hemp Reduced Graphene Oxide (OHRGO):** Produced through eco-friendly thermal annealing (>800°C) or chemical reduction (L-ascorbic acid) of OHGO, partially restoring the *sp*² conjugated lattice and recovering electrical conductivity ($\sim 10^3$ S/m).
4. **Organic Hemp Active Carbon Biochar (OHACB):** Produced via slow pyrolysis (400–600°C) and steam activation of organic hemp hurd residuals. Yields a hierarchical micro- and mesoporous 3D carbon framework for internal curing, stress damping, and density reduction.
5. **Organic Hemp Short Carbon Fibers (OHSCF):** Carbonized under continuous tension at 1000–1400°C from long organic hemp bast fibers, followed by precision mechanical chopping (1–6 mm length). Provides high-aspect-ratio 1D micro-scale load bridging.

3 Micro-Mechanics & Multi-Scale Reinforcement Theory

The core mechanics of the multi-scale organic hemp carbon system rely on hierarchical stress transfer from macroscopic shear planes down to sub-nanometer interphases.

For a 1D short fiber (OHSCF) embedded in a matrix, the critical fiber length l_c required for full load transfer is governed by Kelly-Tyson shear lag theory:

$$l_c = \frac{\sigma_f d}{2\tau_i} \quad (1)$$

where σ_f is the fiber ultimate tensile strength, d is the fiber diameter, and τ_i is the interfacial shear strength (IFSS).

For 2D nanosheets (OHCNS and OHGO), stress transfer across the planar interface is modeled using modified Cox shear lag equations:

$$E_c = \eta_o \eta_l V_n E_n + (1 - V_n) E_m \quad (2)$$

where E_c, E_n, E_m represent the elastic moduli of the composite, nanosheet, and matrix respectively, V_n is the nanosheet volume fraction, η_o is the orientation factor, and η_l is the length efficiency factor:

$$\eta_l = 1 - \frac{\tanh(\beta s)}{\beta s}, \quad \beta = \sqrt{\frac{2G_m}{E_n \cdot t_n \cdot t_m}} \quad (3)$$

where $s = L_n/t_n$ is the aspect ratio of the 2D organic hemp nanosheet, G_m is the matrix shear modulus, t_n

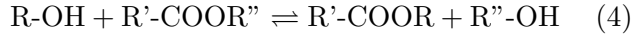
is the nanosheet thickness, and t_m is the intersheet matrix thickness.

4 Matrix Integration Across Material Classes

4.1 Thermoset Epoxies & Organic Hempoxy Vitrimers

In standard DGEBA epoxies, oxygen groups on OHGO form direct covalent bonds with amine curing agents, raising K_{1c} fracture toughness by up to +65% at 0.5 wt% loading.

In bio-based covalent adaptable networks (CANs / vitrimers), such as epoxidized organic hempseed oil ("organic hempoxy" developed by Zila BioWorks), OHGO and OHCNS integrate into dynamic transesterification networks. The hydroxyl groups on OHGO participate in dynamic exchange reactions at elevated temperatures:



This allows full mechanical reinforcement (+40% flexural modulus) without suppressing thermal self-healing, reprocessability, or closed-loop chemical recyclability.

4.2 Thermoplastics (PLA, PP, HDPE, PEEK)

In semicrystalline thermoplastics, OHCNS acts as a heterogeneous nucleating agent, driving rapid crystallization kinetics and elevating Heat Deflection Temperatures (HDT) by $>30^\circ\text{C}$ in PLA. Non-polar matrices like polypropylene require maleic anhydride grafting (MAPP) to establish covalent coupling with OHGO.

4.3 Elastomers (TPU, Silicone)

In flexible matrices, low percolation thresholds (< 0.5 wt% OHRGO) yield dynamic, reconstructive sp^2 networks that exhibit piezoresistive behavior (*Gauge Factor* > 15) suitable for flexible strain sensors.

4.4 Geopolymers & Cements

OHACB acts as an internal curing water reservoir, while OHGO accelerates calcium-silicate-hydrate (C-S-H) nucleation. OHSCF provides macro-scale crack

bridging, improving 28-day compressive strength by +35% and flexural strength by +50%.

4.5 Metal (MMCs) & Ceramic (CMCs) Matrices

Consolidated via spark plasma sintering (SPS) or hot isostatic pressing (HIP), OHCNS pins grain boundaries in Al/Mg alloys and induces non-catastrophic crack deflection in SiC and Al_2O_3 ceramics.

5 Statistical Design of Experiments (DoE)

5.1 Phase I: Taguchi $L_{27}(3^{13})$ Screening

To optimize OHCNS and OHGO synthesis, a Taguchi L_{27} orthogonal array evaluates 5 control factors across 3 levels:

- *A*: HTC Temperature (180, 200, 220°C)
- *B*: KOH Impregnation Ratio (1:1, 1:2, 1:4)
- *C*: Activation Temperature (700, 800, 900°C)
- *D*: Pyrolysis Residence Time (1, 2, 3 hours)
- *E*: Ball Milling Speed (300, 500, 700 RPM)

Responses: Graphitization degree (I_D/I_G via Raman), Specific Surface Area (BET, m^2/g), Nanofiller Yield (%).

5.2 Phase II: Face-Centered Central Composite Design (FCCCD)

A 4-factor FCCCD Response Surface Methodology (RSM) with 30 experimental runs per matrix class optimizes the multi-scale hybrid loading fractions:

- X_1 : Organic Hemp Biochar (OHACB) [0.0 – 5.0 wt%]
- X_2 : Organic Hemp Short Fiber (OHSCF) [0.0 – 3.0 wt%]
- X_3 : Organic Hemp Nanosheets (OHCNS) [0.0 – 1.0 wt%]
- X_4 : Organic Hemp Graphene Oxide (OHGO) [0.0 – 1.0 wt%]

The response variable Y (e.g., Flexural Strength, Fracture Toughness K_{1c} , Electrical Conductivity σ) is fitted to a quadratic polynomial:

$$Y = \beta_0 + \sum_{i=1}^4 \beta_i X_i + \sum_{i=1}^4 \beta_{ii} X_i^2 + \sum_{i < j}^4 \beta_{ij} X_i X_j + \epsilon \quad (5)$$

Multi-objective optimization is executed using Derringer's desirability function (D):

$$D = \left(\prod_{i=1}^k d_i(Y_i) \right)^{1/k} \quad (6)$$

maximizing mechanical properties while constraining melt/resin viscosity.

6 Conclusion

The Organic Hemp Graphitic Composite Materials Revolution establishes a closed-loop bio-carbon ecosystem. By transforming agricultural organic hemp waste into a multi-morphology carbon hierarchy (OHCNS, OHGO, OHRGO, OHACB, OHSCF), advanced materials can achieve high mechanical performance, functional transport properties, and carbon neutrality across epoxies, organic hempoxy vitrimers, thermoplastics, elastomers, geopolymers, metals, and ceramics.

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