

Hemp Nanosheets: Carbon Energy Storage and Bio-Based Composites

Oct 5, 2026 · @Marie

Front Matter

A technical monograph on turning industrial hemp into two-dimensional carbon for energy storage, and into structural and functional composites — including the Hempoxies vitrimer platform.

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What this book argues

Hemp bast fibre is one of the few biomass feedstocks whose native architecture — stacked layers of crystalline cellulose bound by hemicellulose and lignin — maps almost directly onto the two-dimensional carbon morphology that high-rate supercapacitors need. The same plant also yields long, stiff fibres for structural composites and an unsaturated seed oil that can be epoxidized into resin. One crop can therefore supply the electrode, the matrix and the reinforcement of a multifunctional composite. This book walks that chain from field to device.

Evidence status: read this first

Every claim in this book carries one of three labels, stated in context:

- **Published** — reported in peer-reviewed literature and cited in the References. Figures are quoted as the authors reported them, at their test conditions.
- **Established engineering** — textbook theory (e.g. Halpin-Tsai, rule of mixtures, EDLC energy equations) used to reason about designs.
- **Projected (Hempoxies)** — the Hempoxies platform is a forward-looking research hypothesis at **TRL 1-2**. All Hempoxies performance numbers in this book are *design targets*, not validated results. None should be used for structural, electrical or medical design without independent testing.

How to read it

Chapters 1–3 cover the feedstock and how hemp becomes carbon nanosheets. Chapters 4–6 cover energy storage. Chapters 7–9 cover composites, with Chapter 8 dedicated to Hemproxies. Chapters 10–11 cover scale-up, economics, safety and the research roadmap. A glossary and the verified reference list close the book.

Literature was checked by live search as of 5 October 2026. Readers should re-verify any figure before citing it.

Chapter 1 — Hemp as an Engineering Feedstock

The hemp stalk is two materials in one: a cellulose-rich outer bast fibre and a lignin-rich woody core (hurd, or shiv). They behave very differently when carbonized or used as reinforcement, so every process in this book starts by deciding which fraction to use.

1.1 The stalk

By mass, a hemp stalk is roughly 65% hurd and 35% bast ([IJFS review](#)). Bast fibres sit just under the bark and are long — about 55 mm on average — while hurd fibres are typically under 2 mm ([US Patent 6,841,231](#)). Bast is the textile and composite-reinforcement fraction. Hurd has historically been the low-value by-product, used for animal bedding and hempcrete.

1.2 Composition

Fraction	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Source
Bast fibre (range)	57–77	lower than hurd	5–9	IJFS review
Hurd (range)	40–48	18–24	21–24	IJFS review
Hurd, Carmagnola cultivar	44.0 (α -cellulose)	25.0	23.0	BioResources
Hurd, decorticated waste stalk	45.66	24.57	21.67	Bokhari et al., Penn State

Composition varies with cultivar, harvest timing, retting and processing. Any carbon or composite recipe should be re-characterized on the actual lot used.

1.3 Why architecture matters more than chemistry

Cellulose is semi-crystalline; hemicellulose and lignin are amorphous. In bast fibre, crystalline cellulose microfibrils are laid down in concentric cell-wall layers, glued by the amorphous fractions. That layered nanocomposite is the template that later becomes stacked carbon sheets (Chapter 2). In hurd, the higher lignin content produces more disordered, harder carbon and a different pore structure.

For composites the logic reverses. Bast's high cellulose and low lignin give a stiff, strong fibre. Its hydroxyl-rich surface, however, absorbs water and bonds poorly to hydrophobic resins — the central interface problem of Chapter 7.

1.4 Three products from one crop

- **Bast fibre** → carbon nanosheets (energy storage) or reinforcement (composites).
- **Hurd** → hard carbons, activated carbons, fillers, hempcrete aggregate, nanocellulose.
- **Seed oil** → epoxidized hemp oil, a bio-based resin precursor (Chapter 8).

This three-way split is the basis of the integrated biorefinery concept discussed in Chapter 10.

Chapter 2 — From Plant to Nanosheet

Hemp bast becomes graphene-like carbon nanosheets through two steps: hydrothermal carbonization, which strips the amorphous binders and chars the cellulose, then chemical activation, which opens the pores. The landmark demonstration is Wang, Mitlin and colleagues at the University of Alberta, published in *ACS Nano* in 2013 ([record](#)).

2.1 The 2013 result

The team produced interconnected, partially graphitic carbon nanosheets 10–30 nm thick from hemp bast fibre. Reported properties: specific surface area up to 2287 m²/g, mesopore volume fraction up to 58%, and electrical conductivity of 211–226 S/m ([abstract](#)). The bast fibre was hydrothermally processed at 180 °C for 24 hours before activation ([ASME](#)).

Mitlin's own description of the mechanism: bast is a nanocomposite of lignin, hemicellulose and crystalline cellulose that, processed correctly, separates into graphene-like sheets ([The Register, quoting C&EN](#)). Dissolving the lignin and hemicellulose leaves the cellulose-derived layers behind as a pseudo-graphene structure ([PAHIC/BBC report](#)).

2.2 The process, step by step

1. **Feedstock preparation.** Decorticate the stalk; take the bast fraction; remove shiv, dust and soil; mill to a uniform length.
2. **Hydrothermal carbonization (HTC).** Heat the fibre in water in a sealed pressure vessel (180 °C, 24 h in the 2013 work). Hemicellulose hydrolyzes first, lignin partly dissolves, and cellulose converts to a carbon-rich hydrochar that keeps the layered template.
3. **Chemical activation.** Mix the hydrochar with an alkali activator and heat under inert gas. The activator etches the carbon, creating micropores and mesopores and separating the layers into sheets. Exact ratios and temperatures should be taken from the original paper; they control the pore-size distribution.
4. **Washing.** Remove residual alkali and salts with dilute acid and water until neutral; dry.
5. **Electrode fabrication.** Blend with a conductive additive and binder, cast onto a current collector, dry, calender.

2.3 Why bast, not hurd

Bast's high cellulose and low lignin give the ordered, layered precursor that becomes thin sheets. Hurd, with more lignin, yields harder, more disordered carbon. That is not a weakness: hurd-derived hard carbon suits sodium-ion anodes (Chapter 6).

2.4 Process variables and their effects

Variable	Raise it and...	Trade-off
HTC temperature/time	more binder removal, higher carbon yield in hydrochar	over-processing collapses the layered template
Activator-to-char ratio	higher surface area, more pores	lower yield, weaker sheets, more waste brine
Activation temperature	more graphitic order, better conductivity	pores can widen or collapse
Heteroatom doping (N, O, S)	added pseudocapacitance, better wetting	lower cycle stability, higher leakage current

These are general relationships from biomass-carbon practice (established engineering), not optimized hemp-specific values.

2.5 Alternatives to the 2013 route

- **Direct pyrolysis plus physical activation (steam or CO₂).** Fewer chemicals, lower surface area; closer to industrial activated-carbon practice.
- **Template-assisted or salt-melt routes.** Molten salts act as both template and activator; promising for lower-waste scale-up.
- **Mild activators (e.g. K₂CO₃).** Used for hemp-hurd hard carbons (Chapter 6); less corrosive than KOH.

Chapter 3 — Characterizing Hemp Carbons

A hemp carbon is only as credible as its characterization. Six measurements cover most of what a reviewer, investor or device engineer will ask for; each answers a different question.

Technique	Question it answers	What to report
N ₂ (77 K) and CO ₂ (273 K) sorption	How much surface, and in what pore sizes?	BET area, total pore volume, micro/meso split, pore-size distribution model used (e.g. QSDFT)
SEM / TEM	Are these really sheets? How thick?	Sheet thickness range, lateral size, interconnection; representative and low-magnification images
Raman spectroscopy	How graphitic?	D and G band positions, I _D /I _G ratio, fitting method
XRD	Interlayer spacing and order	d ₀₀₂ , crystallite size (L _a , L _c) with the equation used
XPS / elemental analysis	Surface chemistry and heteroatoms	C, O, N, S at.%, deconvoluted functional groups
Four-point probe / pellet conductivity	Can electrons get out?	S/m at stated pressure and density

3.1 Electrochemical metrics

- **Cyclic voltammetry (CV):** shape reveals double-layer (rectangular) vs. faradaic (peaked) behaviour.
- **Galvanostatic charge-discharge (GCD):** the basis for capacitance and energy figures.
- **Electrochemical impedance spectroscopy (EIS):** equivalent series resistance (ESR), charge-transfer resistance, ion-diffusion behaviour.
- **Cycle life and float tests:** capacitance retention after thousands of cycles and after hours at maximum voltage.

Gravimetric capacitance from a three-electrode cell is calculated as:

$$C = \frac{I \cdot \Delta t}{m \cdot \Delta V}$$

where I is current, Δt discharge time, m active mass and ΔV the voltage window after IR drop.

3.2 Reporting pitfalls

Biomass-carbon literature is full of inflated numbers. The common causes:

- **Three-electrode vs. two-electrode.** A three-electrode value can be roughly four times a symmetric-cell value for the same material. Always state which.
- **Low mass loading.** Electrodes under $\sim 1 \text{ mg/cm}^2$ flatter rate and capacitance; commercial electrodes are around 10 mg/cm^2 .
- **Active-mass-only energy.** Device energy falls several-fold once collectors, separator, electrolyte and packaging are counted.
- **IR drop ignored.** Including the ohmic drop in ΔV overstates capacitance.
- **Surface area $\neq$ capacitance.** Pores smaller than the electrolyte ion are inaccessible; pore-size distribution matters more than BET area.

A credible hemp-carbon claim states the cell configuration, mass loading, electrolyte, voltage window, current density and temperature next to every number.

Chapter 4 — Supercapacitor Fundamentals

Supercapacitors trade energy for power: they store far less than batteries but charge and discharge in seconds and survive hundreds of thousands of cycles. Carbon electrode design decides where on that trade-off a device lands.

4.1 Two storage mechanisms

- **Electric double-layer capacitance (EDLC).** Ions gather at the carbon surface without chemical reaction. Fast, reversible, long-lived. Capacitance scales with *accessible* surface area. Pure hemp carbon nanosheets are mainly EDLC.
- **Pseudocapacitance.** Fast surface redox reactions (oxygen or nitrogen groups, metal oxides, conducting polymers) add charge. Higher capacitance, usually shorter life.

Hybrid devices pair a capacitive carbon electrode with a battery-like electrode (e.g. lithium-ion capacitors) to raise energy.

4.2 The governing equations

Stored energy and maximum power of a cell:

$$E = \frac{1}{2} C V^2 \quad P_{\max} = \frac{V^2}{4 R_{\text{ESR}}}$$

Energy scales with the *square* of voltage. That is why the electrolyte, which sets the voltage window, matters as much as the carbon. Power is limited by the equivalent series resistance (ESR), which is why the conductivity and open pore network of nanosheets matter.

4.3 Electrolytes

Electrolyte class	Typical cell voltage	Strengths	Weaknesses
Aqueous (KOH, H ₂ SO ₄ , neutral salts)	~1 V	cheap, safe, highly conductive	low energy
Organic (TEABF ₄ in acetonitrile or propylene carbonate)	~2.5–2.7 V	commercial standard	flammable solvent
Ionic liquids	~3–4 V	high voltage, non-volatile, wide temperature range	viscous, costly, poor at low temperature

The 2013 hemp nanosheets were notable because their mesopores let a viscous ionic liquid work well from 0 °C to 100 °C.

4.4 Material numbers vs. device numbers

A material's specific capacitance (F/g) is not a device's energy (Wh/kg). Converting one to the other requires the two-electrode configuration, the voltage window and the full packaged mass. As a rule of thumb, packaged energy is a fraction — often a quarter to a third — of the active-material figure. Chapter 5 compares hemp results with that caution in mind.

Chapter 5 — Hemp Nanosheet Supercapacitors

Hemp-derived carbons have repeatedly matched graphene-class laboratory performance at a fraction of the precursor cost, but more than a decade after the 2013 paper there is still no high-volume commercial hemp supercapacitor. This chapter separates what has been shown from what has been sold.

5.1 Published performance

Study	Precursor	Electrolyte	Reported result	Conditions
Wang, Mitlin et al., ACS Nano 2013	Bast fibre, HTC + activation	Ionic liquid	106 F/g at 10 A/g; device 12 Wh/kg max	0 °C for the capacitance figure; device energy is the headline
ANSTO repository, 2024	Hurd, KOH-activated honeycomb carbon	Aqueous Na ₂ SO ₄	240 F/g at 1 A/g; hybrid with MnO ₂ : 95 F/g, 90% retention	Electrode vs. hybrid device
İzmir Institute of Technology thesis, 2025	Stem, ZnCl ₂ -activated	Aqueous, 0–1 V	up to 79.5 F/g at 0.5 A/g	Lower-cost activation

The spread illustrates Chapter 3's warning: results depend heavily on electrolyte, configuration and current density. Numbers cannot be ranked without normalizing those conditions.

5.2 Comparison with graphene and activated carbon

The 2013 device's 12 Wh/kg was described as two to three times commercial counterparts at the time ([KurzweilAI, reporting ACS](#)). Mitlin stated the electrochemical performance was on par with or better than graphene-based devices, with the advantage that the electrodes came from biowaste via a simple process ([Phys.org](#)).

Two caveats. First, the comparison used an ionic-liquid electrolyte, which raises voltage and therefore energy; commercial cells mostly use organic electrolytes. Second, commercial activated carbons are produced at very large scale with tightly controlled purity, ash and moisture — specifications a new biomass carbon must also meet.

5.3 Commercialization history

- **2014:** At the ACS national meeting, the group said it was past proof-of-principle and preparing for small-scale manufacturing, with a Canadian start-up scaling the technology ([KurzweilAI](#)).
- **Later (Clarkson University period):** Mitlin co-founded a Potsdam, New York start-up that received a \$229,000 state grant to set up R&D toward carbon-nanosheet manufacturing, pitching "graphene performance at activated carbon prices" for supercapacitors, batteries and purification ([NorthCountryNow](#)).

Open question: no verified source found in this review documents sustained commercial production of hemp-nanosheet supercapacitors. Readers should treat market availability as unconfirmed.

5.4 Why the gap persists

1. **Feedstock logistics.** Consistent, clean, decorticated bast at tonne scale is still scarce in North America.
2. **Activation chemistry.** Large activator ratios mean corrosive handling and brine disposal at scale.
3. **Qualification.** Supercapacitor makers qualify carbons over years; ash, metal impurities and lot-to-lot variability matter more than peak capacitance.
4. **Competition.** Coconut-shell activated carbon is cheap, mature and good enough for most cells.

The opening for hemp is therefore niche first: high-temperature or high-voltage cells where ionic liquids and mesoporous nanosheets give a real advantage, and markets that value bio-based, regional supply chains.

Chapter 6 — Beyond Supercapacitors

The same hemp carbons serve as battery anodes and sulfur hosts. Sodium-ion batteries are the most strategically interesting outlet, because they cannot use graphite and need disordered hard carbon — exactly what lignin-rich hemp hurd produces.

6.1 Published battery results

Study	Hemp fraction	Device	Reported result
Antorán et al., Energy & Fuels 2023	Waste hurd, K ₂ CO ₃ -activated, 800 °C	Sodium-ion anode	73% initial coulombic efficiency; 267 mAh/g at 0.03 A/g; 96% retention after 300 cycles at 2 A/g
Bugday et al., Sustainable Energy & Fuels 2026	Stem fibre carbon + cobalt sulfide/selenide	Sodium-ion anode	608 mAh/g retained after 250 cycles at 2.0 A/g
Um et al., RSC Advances 2018	Stem, steam-activated, ball-milled	Lithium-ion anode	300 mAh/g; 210 mAh/g at 1.5 A/g
PMC 6838265	Stem, activated carbon	Lithium-ion anode	495 mAh/g after 100 cycles
RSC Advances 2018	Hemp carbon + MnO ₂	Lithium-sulfur cathode host	926 mAh/g initial at 0.1 C

6.2 Why sodium-ion matters

Graphite cannot host sodium well; hard carbons with expanded interlayer spacing, defects and closed pores can. The Zaragoza group attributed its hurd carbon's performance to sub-nanometre interconnected micropores, suitable defect density, wide interlayer distances and closed pores ([Unizar record](#)). Mitlin's group also showed graphite-like sodium storage in a tailored biomass carbon with dilated layer spacing (peat-moss precursor) ([Nanowerk](#)).

This matters for a hemp biorefinery: bast goes to high-value nanosheets, while hurd — normally the by-product — becomes sodium-ion anode feedstock.

6.3 Hybrid capacitors

Sodium- and lithium-ion capacitors pair a capacitive carbon electrode with a battery electrode. They sit between supercapacitors and batteries on energy and power. The 2024 ANSTO-linked work paired hemp-hurd activated carbon with electrolytic MnO_2 in aqueous sodium sulfate (Chapter 5).

6.4 Other functional uses

- **Water and air purification** — the Potsdam start-up named purification as a target market alongside energy storage ([NorthCountryNow](#)).
- **Catalyst supports** — porous hemp carbon can anchor metal or metal-oxide catalysts.
- **Conductive fillers** — nanosheets as electrically conductive or EMI-shielding additives in polymers, the bridge to Chapter 8.

Chapter 7 — Hemp in Polymer Composites

Well-made hemp/epoxy laminates reach roughly 165 MPa tensile strength and 17 GPa modulus — the territory of low-end glass-fibre composites at lower density. The limiting factor is almost always the fibre–matrix interface, not the fibre.

7.1 Benchmark results

Islam and co-workers at Waikato treated hemp with $\text{NaOH}/\text{Na}_2\text{SO}_3$ at 120 °C and made composites at 40–65 wt% fibre. The strongest — 65 wt% untreated, long, aligned fibre — reached 165 MPa tensile strength, 17 GPa Young’s modulus, 180 MPa flexural strength and fracture toughness of $5 \text{ MPa}\cdot\text{m}^{1/2}$ ([Waikato Research Commons](#)).

A counter-intuitive finding: alkali treatment generally improved strength, yet at the highest fibre loadings untreated long fibres did better, apparently because treated fibres made more fibre-to-fibre contact.

7.2 Surface treatments

Treatment	Effect	Evidence
Alkali ($\text{NaOH} \pm \text{Na}_2\text{SO}_3$)	Removes lignin and waxes, separates bundles, exposes hydroxyls, raises crystallinity	Interfacial shear strength rose from 2.7 to 5.2 MPa (Waikato thesis)

Treatment	Effect	Evidence
KOH, NaHCO ₃ (milder alkalis)	Cleaner, rougher surfaces	Flexural strength up ~15% (KOH) and ~26% (NaHCO ₃) vs. untreated (Materials Research Forum)
Acetylation, silanes	Reduce hydrophilicity, add coupling chemistry	Single-fibre strength can drop after treatment (Kabir et al., Composites B 2013)

The lesson: every treatment trades fibre strength for interface strength. Optimize the composite, not the fibre.

7.3 Processing

Cure schedule matters. In the Waikato work, composites processed at 70 °C outperformed those at 25 °C, but properties fell again at 120 °C; a 1:1 epoxy-to-hardener ratio gave the highest strength ([CORE](#)). Hemp must be dried before moulding; residual moisture causes voids and weakens the interface.

7.4 Micromechanics

Rule of mixtures gives the upper bound for an aligned continuous composite:

$$E_c = \eta_o \eta_l V_f E_f + (1 - V_f) E_m$$

where η_o is the orientation factor (1 aligned, ~0.375 random in-plane), η_l the length-efficiency factor, V_f the fibre volume fraction and E_f , E_m the fibre and matrix moduli.

Kelly-Tyson sets the critical fibre length for full load transfer:

$$l_c = \frac{\sigma_f d}{2 \tau_i}$$

where σ_f is fibre strength, d diameter and τ_i interfacial shear strength. Doubling τ_i (as alkali treatment did) halves the length needed — directly linking surface chemistry to how short a fibre can usefully be.

Halpin-Tsai estimates transverse or short-fibre stiffness:

$$\frac{E_c}{E_m} = \frac{1 + \xi \eta V_f}{1 - \eta V_f}, \quad \eta = \frac{E_f/E_m - 1}{E_f/E_m + \xi}$$

where ξ is a shape factor (about $2 \cdot l/d$ for longitudinal modulus of short fibres). For nanosheet fillers in Chapter 8, ξ is set by the sheet aspect ratio, which is why thin, wide sheets stiffen a matrix far more per gram than particles.

Chapter 8 — Hempoxies: A Bio-Based Vitrimer Platform

Hempoxies is a research hypothesis at **TRL 1-2**: a fully hemp-derived, repairable and recyclable structural resin, reinforced with fibre and hemp carbon nanosheets. Its building blocks are published; the integrated system and every performance figure in this chapter are **projected design targets, not validated results**.

8.1 The problem it addresses

Conventional epoxies are permanent networks: once cured, they cannot be melted, reshaped or easily recycled, and most are petroleum-derived. Vitrimers — covalent adaptable networks — keep thermoset properties at service temperature but rearrange their bonds above a topology-freezing temperature (T_v), allowing repair, reshaping and reprocessing ([Polymers 2023](#)).

8.2 The published foundations

Foundation	What was shown	Source
Epoxidized hemp oil (EHO) as a resin	Solvent-free epoxidation with peracetic acid; EHO slightly outperformed epoxidized soybean oil in jute composites, but blends were limited to under 30% bioresin	Manthey et al., J. Reinf. Plast. Compos. 2013 ; Manthey PhD, USQ 2013
Acrylated EHO	Better fibre-matrix adhesion than vinylester, but lower T_g , storage modulus and crosslink density	Manthey et al., J. Compos. Mater.
Hempseed-oil vitrimer	Room-temperature-curable hempseed-oil epoxy vitrimer coating with stress relaxation and reparability via transesterification	Zhang, Liu et al., ACS Sustainable Chem. Eng. 2020

Foundation	What was shown	Source
EHSO + imine vitrimer	Fully bio-based vitrimer from epoxidized hemp seed oil and vanillin imine crosslinkers	Pittsburg State research colloquium, 2025
Epoxidized vegetable oil 3R thermosets	Recyclable, repairable, reshapable networks from multiple oils, including EHO	HAL, Université Côte d'Azur

The central caution from this literature: neat vegetable-oil epoxies are soft and low-T_g. Structural performance depends on reinforcement, crosslink design and often blending with stiffer epoxies.

8.3 The Hempoxies formulation (v17.2)

The public Zenodo dossier (v17.2, 29 April 2026) specifies ([Zenodo record 19877276](#)):

- **Matrix:** epoxidized hemp seed oil (EHSO).
- **Crosslinker:** citric acid (polycarboxylic), at 1:0.8 epoxy:carboxyl.
- **Catalyst:** 1 wt% zinc acetate, enabling transesterification bond exchange.
- **Reactive diluent:** 8.9 wt% furfuryl glycidyl ether (FGE).
- **Reinforcement:** PAN-based carbon fibre, graphene, MXenes and hemp-derived carbon morphologies.

An alternative 1:1 EHO:maleinized-hemp-oil formulation was evaluated against literature in the September 2026 "New Pyramids" technical report.

8.4 Projected targets — not validated

Property	Projected target	Status
Tensile strength (carbon-fibre reinforced)	> 180 MPa	Projected
Density	1.12–1.18 g/cm³	Projected
Topology-freezing temperature T _v	~150–160 °C	Projected

Property	Projected target	Status
Repair, reshaping, solid-state recycling	via Zn-catalysed transesterification	Mechanism published for related systems; unverified for this formulation
Carbon balance	net-negative	Requires a full, third-party life-cycle assessment

The 180 MPa target is plausible only with high-volume continuous fibre; it is a composite target, not a resin target. Recycling claims should be framed as "multiple reprocessing cycles demonstrated" once tested, since property loss across cycles is normal in vitrimers.

8.5 Where nanosheets enter

Hemp carbon nanosheets can play three roles in a Hempoxy matrix:

1. **Stiffening filler.** High aspect ratio raises the Halpin–Tsai shape factor (Chapter 7), so small loadings may raise modulus.
2. **Conductive network.** Above a percolation threshold, sheets make the resin conductive — for anti-static parts, EMI shielding, resistive heating to trigger vitrimer self-repair, and structural health monitoring by impedance.
3. **Structural energy storage.** A long-term concept: laminates where carbon-fibre plies and nanosheet layers act as electrodes, and the resin also carries load. This is a research frontier with major unsolved problems (ionic conduction in a stiff matrix, sealing, safety).

All three are hypotheses for Hempoxies; dispersion, interfacial bonding to the oil-based network, and the effect of fillers on bond-exchange kinetics are unmeasured.

8.6 Validation plan (minimum)

- ☐ Epoxide value and acid number titrations for each EHSO lot
- ☐ DSC cure kinetics and T_g
- ☐ DMA and stress-relaxation tests to measure T_v
- ☐ ASTM D638 neat-resin and D3039 laminate tensile tests
- ☐ Reprocessing: properties after 1, 3 and 5 cycles
- ☐ Moisture uptake and hygrothermal ageing
- ☐ Nanosheet loading series: modulus, conductivity, percolation threshold

- ☐ Independent cradle-to-gate life-cycle assessment

Chapter 9 — Other Hemp Composites

Beyond structural resins, hemp feeds a family of composites ranging from mature building materials to early-stage conductive and structural-energy concepts. Hempcrete is the most commercially established; the others are at research stage.

9.1 Hempcrete (hemp-lime)

Hempcrete is a mix of hurd/shiv, water and lime that keeps absorbing carbon after construction ([Barbhuiya & Das, Constr. Build. Mater. 2022](#)). One study cited in a 2024 review puts sequestration around 300 kg CO₂ per m³ ([Biomass, MDPI 2024](#)). Lime-hemp concrete has reported thermal conductivity of 0.09–0.11 W/m·K at about 330 kg/m³ ([Barbhuiya & Das, preprint](#)).

Its weakness is compressive strength: it is used as non-load-bearing infill around a structural frame. Geopolymer binders have reached roughly four times the strength of hydrated-lime hempcrete with lower thermal conductivity ([Emerald, BEPAM](#)). Reviews also note a lack of long-term, building-scale studies in climates with large seasonal swings ([AIHC 2024](#)) — directly relevant to Atlantic Canada.

9.2 Hemp-thermoplastic composites

Hemp fibre in polypropylene, polyethylene or PLA is used in automotive interior panels and consumer goods. Treated hemp bonded better to PLA than untreated fibre in the Waikato work ([Waikato thesis](#)). Processing temperatures must stay low enough (generally below about 200 °C) to avoid fibre degradation.

9.3 Nanocellulose from hemp

Hurd and bast can be refined into cellulose nanofibres and nanocrystals for barrier films, coatings and reinforcing additives. Hydrothermally and mechanically generated hemp-hurd nanofibres have been studied for barrier coatings ([Tyagi et al., 2021, listed via Knowledge Agora](#)). Nanocellulose can also act as a dispersant and binder for carbon nanosheets in flexible electrodes — an all-hemp electrode concept.

9.4 Conductive and multifunctional composites

Carbon nanosheets dispersed in polymers yield conductive plastics for EMI shielding, static dissipation, sensors and heaters. For hemp nanosheets specifically, published composite data are sparse; this is an open research area.

9.5 Structural energy storage

Structural batteries and supercapacitors use carbon-fibre plies as both load-bearing reinforcement and electrodes, with a polymer electrolyte as matrix. A hemp-derived version — hemp carbon electrodes, hemp-oil electrolyte matrix, hemp fibre separators — is a coherent long-term vision but has no published demonstration found in this review.

9.6 Comparison of maturity

Composite	Main hemp input	Maturity
Hempcrete	Hurd	Commercial; codes and long-term data still developing
Hemp/thermoplastic	Bast fibre	Commercial in niche automotive and consumer parts
Hemp/epoxy (petro-epoxy)	Bast fibre	Lab to pilot; strong published data
EHO-based bioresins	Seed oil	Lab; limited bioresin fraction in blends
Hempoxies vitrimer	Seed oil + fibre + carbon	TRL 1-2 (projected)
Hemp nanocellulose	Hurd, bast	Lab to pilot
Hemp structural energy storage	All fractions	Concept

Chapter 10 — Manufacturing, Economics, Life Cycle and Safety

The economics of hemp carbon depend less on the hemp than on the activation step. One published techno-economic study of a 3,000 kg/day biomass-carbon plant for supercapacitors put the required selling price at USD 16.79/kg, with only about a 50% probability of profitability ([Energies 2022](#)).

10.1 Cost benchmarks

Study	Scale / route	Reported cost or price
Energies 2022 (LAPSE record)	3,000 kg/day, supercapacitor-grade from lignocellulose	Capital USD 6.66 M; operating USD 15.46 M/yr; selling price USD 16.79/kg; payback ~10 years
Same study, citing prior work	Various feedstocks	Production cost USD 1.56–2.24/kg (general-grade activated carbon)
Persian Ironwood study	900 t/yr, KOH vs H ₃ PO ₄	Capital cost USD 1.65/kg (KOH), 1.58/kg (H ₃ PO ₄)
Biomass Conv. Bioref. 2022	KOH-superactivated hydrochar from food waste	Break-even USD 1.92/kg

The gap between USD ~2/kg general carbon and ~USD 17/kg supercapacitor-grade carbon reflects purity, consistency and qualification costs. Hemp nanosheets must compete at the supercapacitor-grade end.

10.2 Life cycle

The same Energies study found greenhouse emissions of 15.4 kg CO₂-eq per kg of carbon with KOH reuse and 10.2 kg with steam activation; main impacts fell in toxicity categories ([IDEAS/RePEc](#)). A coconut-shell LCA reported far lower values — about 1.26 kg CO₂-eq per kg for KOH — with pyrolysis the largest energy contributor ([Synapse summary of HBKU study](#)). The tenfold spread shows how much system boundaries and energy sources drive results.

Implication: "carbon-negative" claims for hemp carbon or Hempoxies require a full, boundary-explicit LCA. The crop's sequestered carbon does not automatically offset energy-intensive activation.

10.3 An integrated hemp biorefinery

1. **Decortication** splits stalk into bast and hurd; seed is harvested separately.
2. **Bast** → premium fibre for composites, or → HTC + activation → nanosheets.
3. **Hurd** → hard carbon for sodium-ion anodes, hempcrete aggregate, or nanocellulose.

4. **Seed oil** → epoxidation → EHSO resin for Hempoxies; seed cake to feed or protein.
5. **Process streams** → HTC liquor and spent activator recovered or treated; heat recovered from pyrolysis off-gas.

Co-products spread fixed costs: the economics of a nanosheet line improve if hurd and oil have their own markets.

10.4 Safety and regulatory

- **Activators.** KOH and ZnCl_2 are corrosive; high-temperature KOH activation can form metallic potassium, a fire hazard. Inert-gas handling and controlled quenching are required.
- **Nanomaterial dust.** Treat carbon nanosheet powders as respirable nanomaterials: enclosed handling, local exhaust, appropriate respirators.
- **Resins.** Epoxides and glycidyl ethers (including FGE) are skin sensitizers; follow SDS controls.
- **Hemp sourcing.** In Canada, industrial hemp is licensed under the federal Industrial Hemp Regulations; confirm current requirements with Health Canada before procurement (rules change; not re-verified here).
- **Building use.** Any structural Hempoxy or hempcrete element in Canada must be engineered to the applicable National Building Code edition and provincial adoption.

Chapter 11 — Research Roadmap and Open Questions

The fastest credible path is to validate the parts separately before integrating them: nanosheets first, then the Hempoxy resin, then the nanosheet-filled composite. Each phase ends at a measurable gate.

11.1 Phased roadmap

1. **Phase 1 — Feedstock and carbon (TRL 2→3).** Source regional bast, hurd and seed oil; characterize composition; reproduce the 2013 HTC + activation route at gram scale. *Gate:* BET area, sheet morphology and symmetric-cell capacitance within range of published values, reported per Chapter 3.
2. **Phase 2 — Resin validation (TRL 2→3).** Synthesize EHSO; run the Chapter 8 validation checklist on neat resin. *Gate:* measured T_g , T_v and stress relaxation; tensile data from a recognized standard.

- 3. **Phase 3 — Reinforced Hempoxy (TRL 3→4).** Hemp-fibre and carbon-fibre laminates; nanosheet loading series. *Gate:* laminate strength and modulus measured against the projected targets; at least three reprocessing cycles characterized.
- 4. **Phase 4 — Devices and prototypes (TRL 4→5).** Pouch-cell supercapacitors with mass loading $\geq 10 \text{ mg/cm}^2$; a demonstrator Hempoxy panel; conductive-composite coupons. *Gate:* independent lab replication of key numbers.
- 5. **Phase 5 — Pilot and LCA (TRL 5→6).** Kilogram-scale carbon and resin batches; cradle-to-gate LCA and techno-economic model. *Gate:* cost and carbon figures defensible to a third-party reviewer.

11.2 Open scientific questions

- Can hemp nanosheets reach supercapacitor-grade purity (ash, iron, chloride) without costly acid washing?
- Which activation route — KOH, K_2CO_3 , molten salt or steam — gives the best cost-per-farad at scale?
- How do nanosheet fillers change bond-exchange kinetics and T_v in a zinc-catalysed transesterification vitrimer?
- Can an EHSO-based network reach structural stiffness without blending petro-epoxy?
- How does a hemp vitrimer laminate age through Atlantic Canadian freeze-thaw and humidity cycles?
- Is a hemp-derived structural supercapacitor feasible, or does the electrolyte-stiffness conflict rule it out?

11.3 Collaboration and funding fit

Phase 1-2 work suits university materials labs with sorption, Raman, DSC and DMA access. Hard-carbon sodium-ion work aligns with groups already publishing on hemp hurd anodes (Chapter 6). Outreach to bio-materials partners such as ZILA BioWorks fits the resin and feedstock phases.

Glossary

Term	Meaning
Bast	Long outer stem fibre of hemp; cellulose-rich

Term	Meaning
BET area	Surface area from gas sorption using the Brunauer–Emmett–Teller model
CAN	Covalent adaptable network — a polymer network whose bonds can exchange
EDLC	Electric double-layer capacitor; stores charge by ion adsorption
EHO / EHSO	Epoxidized hemp (seed) oil
ESR	Equivalent series resistance; limits power
Hard carbon	Non-graphitizable disordered carbon; standard sodium-ion anode
HTC	Hydrothermal carbonization — heating biomass in pressurized water
Hurd / shiv	Woody inner core of the hemp stalk; lignin-rich
ICE	Initial coulombic efficiency of a battery anode
Pseudocapacitance	Fast surface redox charge storage
T _g	Glass transition temperature
T _v	Topology-freezing temperature of a vitrimer
TRL	Technology readiness level (1 = basic principles, 9 = proven in operation)
Vitrimer	Thermoset that can be reprocessed through associative bond exchange

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