

Hemp Carbon Vitrimer Platform (HCVP)

*A Comprehensive Research Program for
Advanced Hemp-Derived Bioepoxy Composites*

100% Bio-Derived • Circular Design • High Performance

Landry Hemp Carbon Materials Research Program

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July 18, 2026

Document Version 1.1 — Verified Research Proposal

Executive Summary

Program Overview

The **Hemp Carbon Vitrimer Platform (HCVP)** represents a paradigm shift in advanced composite materials engineering. By integrating bio-based vitrimer chemistry with hemp-derived carbon reinforcements, this program targets the development of fully recyclable, high-performance composites that can replace petroleum-based alternatives across transportation, construction, electronics, energy systems, and industrial manufacturing sectors.

Key Innovation Drivers:

- Renewable Feedstock:** Utilization of industrial hemp biomass as the sole carbon and polymer precursor, eliminating fossil fuel dependency.
- Dynamic Covalent Chemistry:** Implementation of vitrimer networks enabling thermal reprocessability, self-healing, and closed-loop recyclability without mechanical degradation.
- Hierarchical Reinforcement:** Multi-scale carbon architecture from nanosheets (2D) to biochar (0D) to short carbon fibers (1D), maximizing mechanical synergy.
- Industrial Scalability:** Process design compatible with existing composite manufacturing infrastructure (RTM, infusion, prepreg, compression molding).

Target Performance Metrics:

Property	HCVP Target	Conventional Epoxy
Tensile Strength	> 300 MPa	350–500 MPa
Flexural Modulus	> 15 GPa	15–25 GPa
Glass Transition (T_g)	100–150°C	120–200°C
Renewable Carbon Content	> 95%	< 10%
Recyclability	100% (thermal)	0%

Strategic Impact: Successful execution positions Landry Industries at the forefront of the sustainable composites market, with defensible IP across resin formulations, carbon processing, and composite architectures.

Abstract

This research program proposes the systematic development of the **Hemp Carbon Vitrimer Platform (HCVP)**, a fully integrated materials system transforming industrial hemp biomass into advanced, recyclable composite materials. The platform synergistically combines: (1) *bio-based vitrimer matrices* derived from epoxidized hempseed oil (EHSO), maleinized hempseed oil (MHSO), and furfuryl glycidyl ether (FGE) with dynamic covalent exchange chemistry; (2) *hierarchical carbon reinforcements* encompassing hemp carbon nanosheets (HCNS), activated hemp biochar (HB), and hemp-derived short carbon fibers (HSCF); and (3) *circular manufacturing protocols* enabling thermal reprocessing, repair, and end-of-life material recovery.

The research is structured across three integrated phases: **(I)** Bio-based resin development and vitrimer characterization; **(II)** Hemp carbon material production, activation, and surface functionalization; and **(III)** Composite formulation, processing optimization, and performance validation. Comprehensive mechanical, thermal, chemical, and sustainability assessments will be conducted against ASTM/ISO standards.

The HCVP addresses critical gaps in the sustainable materials landscape by demonstrating that 100% bio-derived composites can achieve competitive mechanical and thermal performance while enabling unprecedented circularity. Target applications include lightweight automotive structural components, wind turbine blade materials, construction panels, electronic housings, and energy storage system enclosures. This program establishes a scalable pathway from agricultural hemp biomass to next-generation carbon composites, positioning hemp as a strategic feedstock for the circular bioeconomy.

Keywords: hemp carbon, vitrimer, bioepoxy, carbon nanosheets, dynamic covalent networks, circular composites, sustainable materials, biochar, short carbon fiber, industrial hemp

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Nomenclature

AV	Acid Value
BET	Brunauer-Emmett-Teller
DA	Diels-Alder
DMA	Dynamic Mechanical Analysis
DSC	Differential Scanning Calorimetry
EEW	Epoxy Equivalent Weight
EHSO	Epoxidized Hempseed Oil
FGE	Furfuryl Glycidyl Ether
HB	Hemp Biochar
HCNS	Hemp Carbon Nanosheets
HCVP	Hemp Carbon Vitrimer Platform
HSCF	Hemp Short Carbon Fiber
LCA	Life-Cycle Assessment
MHSO	Maleinized Hempseed Oil
OOC	Oxirane Oxygen Content
RCF	Recyclable Carbon Fiber
SEM	Scanning Electron Microscopy
TEM	Transmission Electron Microscopy
TGA	Thermogravimetric Analysis
TRIS	Transesterification
XRD	X-ray Diffraction

1 Introduction

1.1 The Composite Materials Challenge

The global composites market was valued at approximately USD 112–145 billion in 2025, with carbon fiber reinforced polymer (CFRP) demand reaching 366,800 metric tonnes in 2025 [?, ?]. However, this growth masks a fundamental sustainability crisis:

The Petroleum Paradox

Over 95% of advanced composites rely on petroleum-derived epoxy resins (bisphenol-A diglycidyl ether, DGEBA) and polyacrylonitrile (PAN)-based carbon fibers. These materials are:

- **Non-renewable:** Dependent on fossil carbon extracted at increasing environmental cost
- **Non-recyclable:** Thermoset networks cannot be remelted or reprocessed; the vast majority of CFRP waste is landfilled or incinerated
- **Energy-intensive:** PAN carbon fiber production requires 50–80 kWh/kg according to life-cycle assessments [?]
- **Toxic:** Bisphenol-A is an endocrine disruptor; styrene emissions pose occupational hazards

The European Union’s Carbon Border Adjustment Mechanism (CBAM), the US Inflation Reduction Act’s sustainable materials incentives, and China’s dual-carbon goals are creating regulatory and market pressure for bio-based alternatives. The bio-composites segment is gaining traction, yet current solutions predominantly utilize petroleum matrices with natural fiber fillers—failing to address the core resin problem.

1.2 The Hemp Opportunity

Industrial hemp (*Cannabis sativa* L.) presents a uniquely compelling feedstock for advanced materials:

Why Hemp?

1. **Carbon Sequestration:** Hemp is recognized as a carbon-negative crop, absorbing significant atmospheric CO₂ during its rapid growth cycle—higher on a per-hectare basis than many conventional crops [?].
2. **Chemical Versatility:** The seed yields 30–35% oil rich in polyunsaturated fatty acids (linoleic 55%, α -linolenic 20%, oleic 15%); the stalk contains 52–78% cellulose and 3–10% lignin in bast fibers [?].

3. **Carbon Precursor Quality:** Hemp bast fibers possess high cellulose crystallinity (60–81%) and low lignin content, making them superior precursors for carbon materials compared to wood or agricultural residues [?].
4. **Agronomic Efficiency:** Requires minimal pesticides, improves soil health through phytoremediation, and thrives in temperate climates including Atlantic Canada.
5. **Regulatory Alignment:** Canadian Cannabis Act and US Farm Bill legalize industrial hemp (< 0.3% THC), enabling supply chain development.

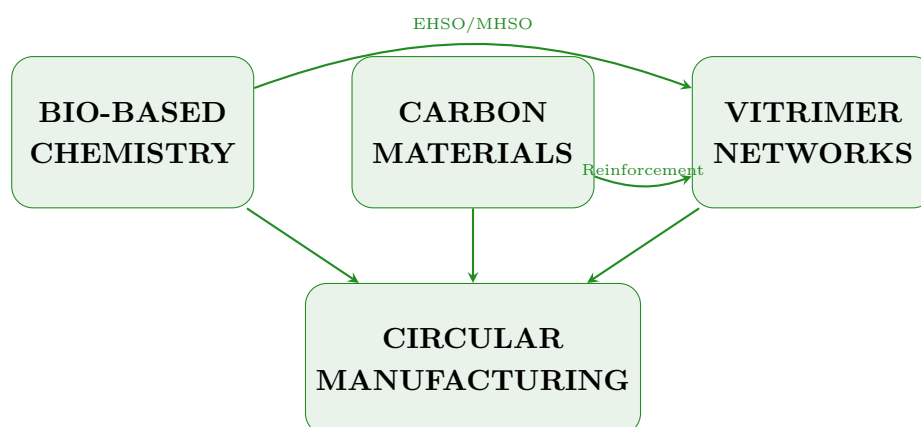
1.3 The Vitrimer Solution

Traditional thermosets achieve their superior mechanical and thermal properties through permanent covalent crosslinks. Vitrimer materials, introduced by Leibler et al. (2011) [?], retain these properties while introducing dynamic covalent bonds that undergo associative exchange under thermal activation. Key characteristics include:

- **Constant crosslink density:** Exchange occurs without network degradation, preserving mechanical integrity
- **Arrhenius viscosity:** Material flows above the topology freezing temperature (T_v) while maintaining elasticity
- **Reprocessability:** Can be compression-molded, welded, and repaired multiple times without property loss
- **Chemical tunability:** Exchange mechanisms (transesterification, transamination, Diels-Alder, disulfide, boronic ester) enable property customization

1.4 Program Vision

The Hemp Carbon Vitrimer Platform (HCVP) integrates these three domains—renewable hemp feedstock, dynamic vitrimer chemistry, and hierarchical carbon reinforcement—into a unified materials system. The program vision is articulated through four pillars:



2 Research Hypothesis and Theoretical Framework

2.1 Central Hypothesis

Primary Hypothesis (H_1)

A fully hemp-derived vitrimer composite system, incorporating hierarchical carbon reinforcement (nanosheets + biochar + short carbon fibers) within a bio-based epoxy/vitrimer matrix, can achieve mechanical properties ($\sigma_t > 300$ MPa, $E_f > 15$ GPa) and thermal stability ($T_g > 100^\circ\text{C}$) competitive with conventional petroleum-based epoxy/carbon fiber composites, while enabling $> 95\%$ renewable carbon content and 100% thermal reprocessability.

2.2 Secondary Hypotheses

H_1 : H_2 — Matrix Optimization: The ternary blend of EHSO, MHSO, and FGE, catalyzed by zinc acetylacetonate $[\text{Zn}(\text{acac})_2]$, will achieve gelation times compatible with resin transfer molding (RTM) processing ($t_{\text{gel}} = 15\text{--}30$ min at 80°C) while maintaining post-cure $T_g > 100^\circ\text{C}$.

H_2 : H_3 — Nanosheet Synergy: Hemp carbon nanosheets (HCNS) at 2–3 wt% loading will provide percolation-enhanced mechanical reinforcement and electrical conductivity ($> 10^{-3}$ S/m) through 2D interfacial bridging, outperforming equivalent loadings of conventional carbon black due to surface oxygen functionality.

H_3 : H_4 — Fiber Integration: Hemp-derived short carbon fibers (HSCF) at 15–20 wt% will achieve tensile strength > 1.0 GPa and modulus > 100 GPa through optimized carbonization (stabilization at 250°C , carbonization at 1500°C), with fiber-matrix adhesion enhanced by maleic anhydride grafting.

H_4 : H_5 — Vitrimer Dynamics: The EHSO-MHSO-FGE vitrimer network will exhibit topology freezing temperatures (T_v) between $80\text{--}120^\circ\text{C}$, enabling reprocessing at $150\text{--}180^\circ\text{C}$ without significant crosslink density loss ($< 5\%$ after 5 reprocessing cycles).

H_5 : H_6 — Sustainability Advantage: Life-cycle assessment (LCA) will demonstrate $> 50\%$ reduction in cradle-to-gate carbon footprint and $> 70\%$ reduction in fossil energy demand compared to DGEBA/PAN-CF composites.

2.3 Theoretical Framework

2.3.1 Network Architecture

The vitrimer network is modeled as a dynamic covalent network where crosslink exchange follows Arrhenius kinetics. The topology freezing temperature T_v is defined by:

$$T_v = \frac{E_a}{k_B \ln(\tau_0/\tau^*)} \quad (1)$$

where E_a is the activation energy for bond exchange, k_B is Boltzmann's constant, τ_0 is the characteristic attempt time ($\sim 10^{-13}$ s), and $\tau^* = 10^2$ s is the experimental observation timescale. For transesterification-based vitrimers, E_a typically ranges 80–120 kJ/mol.

2.3.2 Reinforcement Mechanics

Composite modulus follows the Halpin-Tsai model for discontinuous fiber reinforcement:

$$E_c = E_m \frac{1 + \xi \eta \phi_f}{1 - \eta \phi_f} \quad (2)$$

where $\xi = 2(l/d)$ is the fiber aspect ratio parameter, ϕ_f is fiber volume fraction, and:

$$\eta = \frac{(E_f/E_m) - 1}{(E_f/E_m) + \xi} \quad (3)$$

For nanosheet reinforcement, the effective modulus enhancement incorporates interfacial shear stress transfer:

$$\frac{E_c}{E_m} = 1 + \frac{\eta_f \eta_0 \phi_{ns}}{1 - \phi_{ns}/\phi_{\max}} \quad (4)$$

where $\eta_f = (E_{ns}/E_m - 1)/(E_{ns}/E_m + 2l_{ns}/t_{ns})$ and η_0 accounts for alignment efficiency.

3 Platform Architecture

The HCVP comprises four integrated subsystems, each with defined inputs, processes, outputs, and quality control gates.

3.1 Subsystem I: Bio-Based Polymer Matrix

Table 1: Matrix Component Specifications

Component	Source/Preparation	Function	Target Spec
EHSO	Hempseed oil + peracetic acid epoxidation	Primary epoxy monomer, flexible backbone	EEW 200–250 g/eq
MHSO	Hempseed oil + maleic anhydride grafting	Crosslinker, dynamic exchange sites	AV 80–120 mg KOH/g
FGE	Furfural (hemicellulose) + epichlorohydrin	Rigid aromatic segments, T_g enhancement	Purity > 95%
Zn(acac) ₂	Commercial bio-compatible catalyst	Transesterification catalyst	5–10 mol% vs. ester

3.1.1 Epoxidized Hempseed Oil (EHSO)

EHSO is prepared via in-situ peracetic acid epoxidation:



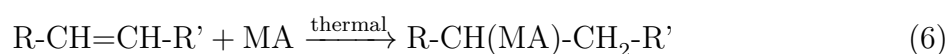
Process Parameters:

- Molar ratio: peracetic acid : double bonds = 1.5 : 1
- Temperature: 60–70°C
- Reaction time: 4–8 hours
- Catalyst: Amberlite IR-120 (cation exchange resin)
- Target oxirane oxygen content (OOC): 6.5–7.5%

Verified Data: Quiles-Carrillo et al. (2023) [?] reported EHSO with OOC = 7.2% and EEW = 226 g/eq using a 70°C, 8 h process with H₂O₂/acetic acid.

3.1.2 Maleinized Hempseed Oil (MHSO)

Maleic anhydride grafting introduces anhydride functionality for crosslinking and hydroxyl/ester groups for transesterification:



Process Parameters:

- Molar ratio: MA : double bonds = 0.8–2.4 : 1
- Temperature: 180–220°C (staged: 180, 200, 220°C)
- Reaction time: 3–4 hours total
- Target acid value: 80–120 mg KOH/g

Verified Data: Quiles-Carrillo et al. (2023) [?] achieved MHSO with AV = 106 mg KOH/g using staged heating (180–220°C). Ferri et al. (2021) [?] reported similar values for maleinized linseed oil (AV 105–130 mg KOH/g).

3.2 Subsystem II: Carbon Reinforcements

3.2.1 Hemp Carbon Nanosheets (HCNS)

HCNS production follows a biomass-to-nanosheet pathway demonstrated by Wang et al. (2013) [?]:

1. **Hydrothermal Carbonization:** Hemp bast fiber at 180–220°C
2. **Activation:** KOH chemical activation (KOH:C = 4:1) at 600–800°C
3. **Exfoliation:** Thermal shock or electrochemical expansion
4. **Purification:** Acid washing (HCl) and DI water rinse
5. **Functionalization:** Plasma oxidation or acid treatment for matrix compatibility

Verified Properties (Wang et al., 2013):

- Thickness: 10–30 nm
- Specific surface area: up to 2287 m²/g
- Electrical conductivity: 211–226 S/m
- Mesoporosity: up to 58% volume fraction

3.2.2 Hemp Biochar (HB)

HB serves as a low-cost, multifunctional filler providing:

- Dimensional stability (reduced shrinkage/warpage)
- Thermal conductivity enhancement
- UV absorption and weathering resistance
- Cost reduction at high loadings

Production Parameters:

- Pyrolysis temperature: 500–700°C
- Residence time: 2–4 hours
- Particle size: $D_{50} = 5\text{--}20\ \mu\text{m}$ (post-milling)
- Surface area: 200–500 m²/g

3.2.3 Hemp Short Carbon Fiber (HSCF)

Table 2: HSCF Processing Stages and Parameters

Stage	Temperature	Atmosphere	Duration
Drying	80°C	Air	2 h
Stabilization	200–280°C	Air	8–24 h
Low-T Carbonization	400–800°C	N ₂	1 h
High-T Carbonization	1200–1600°C	N ₂	0.5–1 h
Surface Treatment	25°C	O ₃ or plasma	10–30 min
Cutting	—	—	3–6 mm length

Target Properties:

- Diameter: 5–8 μm
- Tensile strength: > 1.0 GPa
- Young's modulus: > 100 GPa
- Carbon yield: > 25% (from hemp fiber)

3.3 Subsystem III: Vitrimer Network Engineering

The dynamic network is established through transesterification between hydroxyl groups (from EHSO oxirane ring-opening) and ester groups (from MHSO maleate esters):



Network Design Parameters:

- Crosslink density: controlled by MHSO content (10–30 wt% of total resin)
- Exchange kinetics: tuned by Zn(acac)₂ concentration (1–10 mol%)
- *T_g* control: FGE content (5–20 wt%) provides rigid furan rings
- *T_v* control: catalyst loading and hydroxyl:ester ratio

3.4 Subsystem IV: Composite Manufacturing

Table 3: Manufacturing Process Comparison

Process	Advantages	Limitations	HCVP Suitability
Resin Transfer Molding (RTM)	High fiber volume, complex geometries	Requires controlled gel time	High (HCVP-002/003)
Vacuum Infusion	Low cost, large parts	Longer cycle times	Medium
Compression Molding	Fast, reprocessable	Limited complexity	High (reprocessing)
Filament Winding	Axisymmetric parts	Limited to cylinders	Low priority

4 Research Objectives and Deliverables

4.1 Objective 1: Bio-Based Vitrimer Resin Development

Goal: Develop and fully characterize hemp-derived epoxy/vitrimer resin systems with processing windows compatible with industrial composite manufacturing.

Tasks:

- 1.1: Synthesize EHSO with OOC > 6.5% and EEW < 250 g/eq; optimize peracetic acid route.
- 1.2: Synthesize MHSO with AV 80–120 mg KOH/g; evaluate thermal grafting protocols.
- 1.3: Synthesize FGE from furfural; assess purity and epoxide functionality.
- 1.4: Formulate ternary blends (EHSO/MHSO/FGE) with varying ratios; establish composition-property relationships.
- 1.5: Characterize cure kinetics via DSC (isothermal and dynamic); determine activation energy (E_a) and reaction order (n).
- 1.6: Measure rheological properties: viscosity vs. temperature, gel time, pot life.
- 1.7: Determine glass transition temperature (T_g) and crosslink density (ν_e) via DMA and equilibrium swelling.
- 1.8: Evaluate vitrimer behavior: stress relaxation, topology freezing temperature (T_v), and activation energy for exchange.

Deliverables:

- Resin formulation database (HCVP-001 through HCVP-010)
- Cure kinetic model parameters
- Vitrimer characterization report
- Processing guidelines document

4.2 Objective 2: Hemp Carbon Material Production

Goal: Produce and characterize hemp-derived carbon materials with properties suitable for high-performance composite reinforcement.

Tasks:

- 2.1: **Biochar:** Optimize pyrolysis conditions (temperature, heating rate, residence time) for yield vs. surface area trade-off.

- 2.2: Nanosheets:** Develop KOH activation + exfoliation protocol per Wang et al. (2013) [?]; achieve high SSA and controlled thickness.
- 2.3: Short Carbon Fibers:** Optimize stabilization (temperature ramp, dwell times) to prevent fiber fusion; achieve target mechanical properties.
- 2.4:** Characterize all carbon materials: Raman (I_D/I_G), SEM/TEM morphology, XRD (d_{002} , L_c), BET surface area, XPS surface chemistry.
- 2.5:** Develop surface functionalization protocols: oxidation, silanization, or polymer grafting for matrix compatibility.
- 2.6:** Evaluate dispersion stability in EHSO/MHSO resin systems.

Deliverables:

- Carbon material production SOPs
- Characterization dataset
- Surface functionalization protocols
- Dispersion stability assessment

4.3 Objective 3: Composite Formulation and Integration

Goal: Integrate carbon reinforcements into vitrimer matrices and optimize composite formulations for target properties.

Tasks:

- 3.1:** Design full factorial experiments for reinforcement combinations (HB, HCNS, HSCF).
- 3.2:** Optimize mixing protocols: high-shear mixing, three-roll milling, ultrasonication for HCNS dispersion.
- 3.3:** Manufacture test panels via RTM and compression molding.
- 3.4:** Evaluate void content, fiber volume fraction, and uniformity via microscopy.
- 3.5:** Screen formulations via short-beam shear (ASTM D2344) to assess interfacial strength.

Deliverables:

- Optimized composite formulations (HCVP-C01 through C20)
- Manufacturing SOPs
- Quality control protocols

4.4 Objective 4: Performance Validation

Goal: Comprehensive evaluation of mechanical, thermal, chemical, and sustainability performance against benchmark materials.

Tasks:

- 4.1:** Mechanical testing per ASTM standards: tensile (D638), flexural (D790), compressive (D695), ILSS (D2344), impact (D256).
- 4.2:** Thermal analysis: TGA (thermal stability, char yield), DSC (T_g , cure verification), DMA (storage modulus, $\tan \delta$, T_g).
- 4.3:** Chemical resistance: water absorption (D570), acid/base/solvent immersion.
- 4.4:** Vitrimer performance: stress relaxation, reprocessing cycles (5x), repairability demonstration.
- 4.5:** Sustainability: renewable carbon content (ASTM D6866), preliminary LCA (ISO 14040/14044), end-of-life recyclability demonstration.

Deliverables:

- Complete performance database
- Benchmark comparison report
- Sustainability assessment
- Reprocessing and repair demonstrations

5 Phase I: Bio-Based Resin Development

5.1 Experimental Design

Table 4: Resin System Formulations

System	EHSO	MHSO	FGE	Zn(acac) ₂	Purpose	Target T_g
HCVP-001	70%	30%	0%	0%	Baseline epoxy	50–70°C
HCVP-002	60%	30%	10%	0%	Toughened epoxy	70–90°C
HCVP-003	55%	30%	10%	5%	Standard vitrimer	100–130°C
HCVP-004	50%	35%	10%	7%	High- T_g vitrimer	130–160°C
HCVP-005	45%	35%	15%	10%	Max T_g vitrimer	150–180°C
HCVP-006	60%	25%	10%	5%	Flexible vitrimer	80–110°C

5.2 Detailed Characterization Protocol

5.2.1 Chemical Characterization

Table 5: Analytical Methods and Standards

Property	Method	Standard/Equipment
Epoxy Equivalent Weight	Titration (HCl/dioxane)	ASTM D1652
Oxirane Oxygen Content	Direct titration (HBr/acetic acid)	AOCS Cd 9-57
Acid Value	Potentiometric titration	ISO 660
Iodine Value	Wijs method	AOCS Cd 1-25
Hydroxyl Value	Acetylation method	ASTM E1899
Viscosity	Rotational viscometer	ASTM D2196
Density	Pycnometer	ASTM D792
Color	Gardner scale	ASTM D1544

5.2.2 Thermal and Rheological Characterization

- **DSC:** Dynamic scans at 5, 10, 20°C/min; isothermal scans at 80, 100, 120°C. Extract T_g , T_{onset} , ΔH_{cure} , and degree of cure (α) via DiBenedetto equation.
- **Rheology:** Oscillatory shear (1 Hz, 1% strain) during isothermal cure to track G' , G'' , and gel point ($\tan \delta = 1$).
- **DMA:** Dual cantilever mode, 1 Hz, 2°C/min, -50 to 200°C. Extract E' , E'' , $\tan \delta$, and T_g (peak of $\tan \delta$).

5.2.3 Vitrimer-Specific Characterization

Stress Relaxation: Samples ($10 \times 3 \times 1$ mm) subjected to 1% step strain at temperatures 80–180°C. Relaxation time τ^* defined as time to $E(t)/E_0 = 1/e$. Arrhenius plot of τ^* vs. $1/T$ yields E_a and T_v (at $\tau^* = 10^2$ s).

Reprocessing: Ground samples compression-molded at 160°C, 10 MPa for 30 min. Evaluate tensile properties after 1, 3, 5 cycles.

6 Phase II: Hemp Carbon Materials

6.1 Hemp Biochar Production

6.1.1 Process Flow Diagram

Step 1: Feedstock Preparation: Hemp stalks and hurds dried to $< 10\%$ moisture, milled to < 2 mm.

Step 2: Pyrolysis: Slow pyrolysis in tubular furnace under N_2 flow (100 mL/min).

Step 3: Parameter Matrix:

- Temperatures: 500, 600, 700, 800, 900°C
- Heating rates: 5, 10, 20°C/min
- Residence times: 1, 2, 4 hours

Step 4: Post-Processing: Cooling under N_2 , ball milling, sieving to $D_{50} = 10 \mu\text{m}$.

6.1.2 Quality Control Gates

Table 6: Biochar Quality Control Specifications

Parameter	Minimum	Target	Test Method
Carbon content (dry basis)	70%	$> 80\%$	CHNS elemental analysis
Ash content	—	$< 10\%$	ASTM D1762
Surface area	200 m^2/g	400 m^2/g	BET (N_2 , 77K)
Particle size (D_{50})	5 μm	10 μm	Laser diffraction
pH	8–10	9–10	ASTM D4972

6.2 Hemp Carbon Nanosheets

6.2.1 Synthesis Protocol

Following the verified route of Wang et al. (2013) [?]:

Algorithm 1 HCNS Production Protocol

- 1: **Input:** Hemp bast fiber
 - 2: **Hydrothermal Carbonization:** 180–220°C, aqueous, 24 h
 - 3: **Activation:** Mix carbon:KOH = 1:4 (wt); heat at 600–800°C, 1h, N_2
 - 4: **Washing:** 1M HCl rinse, DI water until pH 7, dry at 120°C
 - 5: **Exfoliation:** Rapid thermal shock or electrochemical expansion
 - 6: **Purification:** Centrifugation (3000 rpm, 10 min); collect supernatant
 - 7: **Functionalization:** H_2SO_4/HNO_3 reflux (80°C, 6h) or O_2 plasma (100 W, 10 min)
 - 8: **Output:** HCNS dispersion in DMF or direct in EHSO
-

6.2.2 Characterization Suite

Table 7: HCNS Characterization Requirements

Technique	Information	Target	Instrument
Raman	Crystallinity, defects	$I_D/I_G < 1.2$	532 nm laser
TEM	Morphology, layers	< 30 nm thick	200 kV TEM
AFM	Thickness	10–30 nm	Tapping mode
XRD	Interlayer spacing	$d_{002} = 0.34\text{--}0.36$ nm	Cu $K\alpha$
BET	Surface area	> 1500 m ² /g	N ₂ sorption
XPS	Surface chemistry	O/C = 0.05–0.20	Al $K\alpha$
TGA	Thermal stability	$> 500^\circ\text{C}$ onset	10°C/min, N ₂

6.3 Hemp Short Carbon Fiber

6.3.1 Critical Processing Considerations

Stabilization is Critical

Insufficient stabilization leads to fiber fusion and loss of mechanical properties during carbonization. The stabilization process must:

- Convert thermoplastic cellulose to thermoset ladder polymer
- Maintain fiber integrity during shrinkage
- Achieve uniform cross-sectional oxidation

Recommended protocol: Slow ramp (1°C/min) from 25 to 250°C with multiple dwell periods (2h at 150°C, 4h at 200°C, 6h at 250°C).

6.3.2 Property Targets vs. Commercial Benchmarks

Table 8: HSCF Performance Targets

Property	HSCF Target	T300 (PAN)	HTS40 (Lignin)
Tensile Strength (GPa)	> 1.0	3.5	1.5
Tensile Modulus (GPa)	> 100	230	150
Elongation (%)	> 0.5	1.5	1.0
Density (g/cm ³)	1.7–1.8	1.76	1.7
Precursor Cost (\$/kg)	< 5	15–20	8–12

7 Phase III: Composite Formulation and Processing

7.1 Formulation Design of Experiments

A full factorial design explores the reinforcement parameter space:

Table 9: Composite Formulation Matrix (wt%)

Sample	Resin	HB	HCNS	HSCF	Total Filler	Objective
A	100%	0%	0%	0%	0%	Neat resin baseline
B	90%	10%	0%	0%	10%	Biochar effect
C	93%	5%	2%	0%	7%	Nanosheet synergy
D	78%	5%	2%	15%	22%	Hybrid reinforcement
E	67%	10%	3%	20%	33%	Max loading
F	85%	0%	0%	15%	15%	Fiber-only
G	88%	0%	2%	10%	12%	NS + fiber
H	80%	10%	0%	10%	20%	Biochar + fiber

7.2 Processing Protocol

7.2.1 Mixing and Dispersion

1. Pre-heat EHSO/MHSO/FGE blend to 60°C to reduce viscosity.
2. Add HCNS (if used) and disperse via probe sonication (500 W, 20 kHz, 30 min, pulse 2s on/1s off) in ice bath.
3. Add HB (if used) and mix via high-shear mixer (5000 rpm, 15 min).
4. Add HSCF (if used) and degas under vacuum (< 50 mbar, 30 min).
5. Add Zn(acac)₂ catalyst immediately before molding.

7.2.2 Cure Cycle

Table 10: Recommended Cure Schedule

Stage	Condition	Purpose
Gelation	80°C, 30 min	Controlled flow, fiber wet-out
Post-cure	120°C, 2 h	Primary crosslink development
Post-cure II	160°C, 2 h	Complete cure, T_g development
Cooling	2°C/min to 25°C	Minimize residual stress

7.3 Mechanical Testing Protocol

Table 11: Mechanical Test Matrix

Test	Standard	Specimens	Parameters
Tensile	ASTM D638	Type I, $n \geq 5$	5 mm/min, 23°C, 50% RH
Flexural	ASTM D790	$80 \times 10 \times 4$ mm, $n \geq 5$	3-point, span 64 mm
Compressive	ASTM D695	$10 \times 10 \times 4$ mm, $n \geq 5$	1.3 mm/min
ILSS	ASTM D2344	$24 \times 8 \times 4$ mm, $n \geq 5$	Span 16 mm
Impact	ASTM D256	Notched Izod, $n \geq 5$	3.5 J pendulum
Fracture	—	Compact tension, $n \geq 3$	Pre-crack, 1 mm/min

8 Thermal, Chemical, and Environmental Testing

8.1 Thermal Analysis

8.1.1 Thermogravimetric Analysis (TGA)

- **Instrument:** Simultaneous TGA-DSC (e.g., TA Instruments SDT 650)
- **Conditions:** 10°C/min, 25–800°C, N₂ and air atmospheres
- **Outputs:**
 - Onset degradation temperature ($T_{d,5\%}$, $T_{d,10\%}$)
 - Maximum degradation rate temperature ($T_{d,max}$)
 - Char yield at 800°C
 - Oxidative stability (air)

8.1.2 Dynamic Mechanical Analysis (DMA)

- **Mode:** Dual cantilever, 1 Hz, 0.1% strain
- **Temperature:** -50 to 250°C at 2°C/min
- **Outputs:**
 - Storage modulus (E') vs. temperature
 - Loss modulus (E'') vs. temperature
 - $\tan \delta$ peak = T_g
 - Rubbery plateau modulus (E'_r) for crosslink density:

$$\nu_e = \frac{E'_r}{3RT} \quad (8)$$

8.2 Chemical Resistance

Table 12: Chemical Resistance Test Matrix

Medium	Concentration	Temperature	Duration
Deionized water	100%	23°C, 80°C	7, 30 days
Sulfuric acid	10%, 50%	23°C	7 days
Sodium hydroxide	10%, 30%	23°C	7 days
Motor oil	100%	100°C	7 days
Ethanol	100%	23°C	7 days
Acetone	100%	23°C	24 h

8.3 Moisture Absorption

Per ASTM D570:

$$M_t = M_\infty \left(1 - \exp \left(-\frac{D\pi^2 t}{h^2} \right)^{0.5} \right) \quad (9)$$

where M_t is moisture uptake at time t , M_∞ is equilibrium uptake, D is diffusivity, and h is specimen thickness.

9 Vitrimer Performance Evaluation

9.1 Stress Relaxation Analysis

The hallmark of vitrimer behavior is Arrhenius-type stress relaxation. Experimental protocol:

1. Prepare rectangular specimens ($20 \times 5 \times 1$ mm) via molding.
2. Mount in DMA tensile fixture.
3. Equilibrate at test temperature ($T = 80, 100, 120, 140, 160, 180^\circ\text{C}$) for 10 min.
4. Apply 1% step strain.
5. Monitor stress decay for 30–600 min.
6. Fit to Maxwell model: $\sigma(t) = \sigma_0 \exp(-t/\tau^*)$

Expected Results: Linear $\ln(\tau^*)$ vs. $1/T$ relationship with $E_a = 80\text{--}120$ kJ/mol.

9.2 Reprocessing Demonstration

Table 13: Reprocessing Cycle Parameters

Cycle	Temperature	Pressure	Time
1	160°C	10 MPa	30 min
2	160°C	10 MPa	30 min
3	160°C	10 MPa	30 min
4	160°C	10 MPa	30 min
5	160°C	10 MPa	30 min

Success Criteria:

- Tensile strength retention $> 90\%$ after 3 cycles
- Tensile strength retention $> 80\%$ after 5 cycles
- T_g shift $< 5^\circ\text{C}$ between cycles
- No visible delamination or void formation

9.3 Repairability Testing

1. Introduce controlled damage: razor notch or impact damage.
2. Align damaged surfaces and apply pressure (0.1 MPa).
3. Heat to 160°C for 2 hours.
4. Evaluate healing efficiency: $\eta = (\sigma_{\text{healed}} / \sigma_{\text{virgin}}) \times 100\%$
5. Target: $\eta > 80\%$

10 Sustainability Assessment

10.1 Renewable Carbon Content

Determined via ASTM D6866-22 (radiocarbon analysis) [?]:

$$\% \text{Bio-based} = \frac{{}^{14}\text{C}_{\text{sample}}}{{}^{14}\text{C}_{\text{reference}}} \times 100\%$$

(10)

Target: > 95% bio-based carbon for HCVP composites.

10.2 Life-Cycle Assessment Framework

Preliminary LCA following ISO 14040/14044 boundaries:

Table 14: LCA System Boundaries

Phase	Included	Excluded
Raw Material	Hemp cultivation, oil extraction, fiber processing	Equipment manufacture
Processing	Epoxidation, pyrolysis, composite molding	Capital goods
Use Phase	Transportation, in-service energy	End-user behavior
End-of-Life	Thermal reprocessing, energy recovery	Landfill (avoided)

10.3 Carbon Footprint Comparison

Table 15: Estimated Carbon Footprint (kg CO₂-eq/kg composite)

Component	HCVP	DGEBA/PAN-CF
Resin production	2.5–4.0	6.0–8.0
Reinforcement production	1.5–3.0	20–55
Composite processing	1.0–2.0	1.5–2.5
Total (cradle-to-gate)	5.0–9.0	27.5–65.5
End-of-life benefit	-2.0 to -4.0	0
Net (cradle-to-cradle)	3.0–5.0	27.5–65.5

10.4 Circularity Metrics

- **Material Circularity Indicator (MCI):** Target > 0.8 (vs. 0.1 for conventional composites)
- **Recyclability Rate:** 100% (thermal reprocessing)
- **Bio-based Content:** > 95%

- **Biodegradability:** Non-biodegradable (intentional for durability), but fully recyclable

11 90-Day Development Roadmap

11.1 Gantt Chart Overview

Table 16: Detailed 90-Day Schedule

Period	Activities	Deliverables	Milestones
Weeks 1–2	Literature review; raw material sourcing; lab setup	Sourcing contracts; SOP drafts	Go/No-Go review
Weeks 3–4	EHSO/MHSO synthesis; preliminary characterization	3 resin variants; characterization data	Resin feasibility gate
Weeks 5–6	FGE integration; vitrimer formulation; cure kinetics	6 vitrimer systems; DSC/DMA data	Vitrimer validation gate
Weeks 7–8	Biochar production; parameter optimization	Biochar SOP; 5 temperature variants	Biochar gate
Weeks 9–10	HCNS synthesis; exfoliation optimization	HCNS samples; TEM/Raman data	Nanosheet gate
Weeks 11–12	HSCF processing; stabilization/carbonization	HSCF samples; tensile data	Fiber gate
Weeks 13–14	Composite formulation; mixing optimization	8 composite variants; test panels	Formulation gate
Weeks 15–16	Mechanical testing; thermal analysis	Performance database	Performance gate
Weeks 17–18	Vitrimer testing; reprocessing cycles	Reprocessing data; repair demos	Vitrimer gate
Weeks 19–20	Sustainability assessment; LCA prep	LCA report; carbon analysis	Sustainability gate
Weeks 21–22	Data analysis; report writing	Draft report	Internal review
Weeks 23–24	IP assessment; publication planning	IP disclosure; manuscript outline	Program close-out

11.2 Key Decision Gates

Gate 1: Resin Feasibility (Week 4): EHSO OOC > 6%; MHSO AV 80–120; blend viscosity < 5000 cP at 60°C.

Gate 2: Vitrimer Validation (Week 6): $T_g > 100^\circ\text{C}$; T_v identifiable; reprocessability demonstrated.

Gate 3: Carbon Quality (Week 12): HCNS SSA $> 1000 \text{ m}^2/\text{g}$; HSCF strength $> 0.8 \text{ GPa}$.

Gate 4: Performance (Week 16): Composite tensile strength $> 200 \text{ MPa}$; $T_g > 100^\circ\text{C}$.

Gate 5: Program Close (Week 24): Complete dataset; IP filed; publication submitted.

12 Expected Outcomes and Impact

12.1 Scientific Contributions

1. First demonstration of a **fully hemp-derived vitrimer composite** with competitive mechanical properties.
2. Systematic study of **hemp carbon nanosheet** reinforcement in bio-based matrices, building on Wang et al. (2013) [?].
3. Processing-structure-property relationships for **hemp short carbon fiber** composites.
4. Kinetic and thermodynamic characterization of **EHSO-MHSO-FGE vitrimer networks**.

12.2 Technological Outputs

- **Patentable IP:** Resin formulations, carbon processing methods, composite architectures.
- **Trade Secrets:** Optimized processing parameters, quality control protocols.
- **Publications:** Target 2–3 peer-reviewed articles in composites, polymer, and sustainability journals.
- **Conference Presentations:** SAMPE, ACS, Canadian Chemistry Conference.

12.3 Commercial Pathways

Table 17: Commercial Application Roadmap

Application	Requirements	HCVP Advantage	Timeline
Automotive panels	Lightweight, impact resistant, recyclable	30% lighter than steel; reprocessable scrap	2–3 years
Wind turbine blades	High stiffness, fatigue resistant, 25-year life	Bio-based; end-of-life reprocessing	3–5 years
Construction panels	Fire resistant, insulating, durable	Biochar thermal conductivity; low carbon	2–4 years
Electronics housings	EMI shielding, light, moldable	HCNS conductivity; vitrimer molding	1–2 years
Aerospace interiors	Fire/smoke/toxicity compliant	Low smoke; bio-based certification	3–5 years

Budget and Resource Requirements

13.1 Equipment

Table 18: Capital Equipment Requirements

Equipment	Purpose	Priority	Est. Cost (CAD)
Tubular furnace ($> 1600^{\circ}\text{C}$)	Carbonization, activation	Critical	25,000
High-shear mixer	Dispersion	Critical	8,000
Vacuum infusion setup	Composite molding	High	5,000
Compression press (heated)	Reprocessing, molding	High	15,000
DSC (if not available)	Thermal analysis	High	60,000
DMA (if not available)	Mechanical analysis	High	80,000
TGA (if not available)	Thermal stability	Medium	50,000

13.2 Consumables (90-Day Program)

Item	Quantity	Est. Cost (CAD)
Hempseed oil (food grade)	50 L	1,500
Industrial hemp stalks/hurds	100 kg	500
Maleic anhydride	5 kg	300
Furfural	2 L	400
Epichlorohydrin	5 L	500
Zinc acetylacetonate	500 g	600
KOH (activation)	10 kg	200
Solvents (DMF, acetone, ethanol)	50 L	800
Testing supplies	—	2,000
Total Consumables		6,800

13.3 Personnel

- **Principal Investigator:** Materials science oversight, data analysis, reporting (0.5 FTE)
- **Research Technician:** Synthesis, processing, testing (1.0 FTE)
- **Student Researcher:** Literature, sample preparation, characterization (0.5 FTE)

14 Risk Assessment and Mitigation

Table 19: Risk Register

Risk	Likelihood	Impact	Mitigation
EHSO viscosity too high for processing	Medium	High	Evaluate enzymatic epoxidation; blend with reactive diluents
Vitrimer T_g insufficient	Medium	High	Increase FGE content; explore alternative dynamic chemistries
HCNS exfoliation yield low	Medium	Medium	Optimize KOH ratio; evaluate electrochemical exfoliation
HSCF strength below target	High	High	Extend stabilization; evaluate lignin blending; accept lower performance
Fiber-matrix adhesion poor	Medium	High	Surface oxidation; silane coupling agents; MHSO grafting
Reprocessing causes degradation	Low	High	Optimize temperature/pressure; limit cycles; characterize network changes
Regulatory delays	Low	Medium	Early engagement with Health Canada; maintain documentation

15 Safety, Environmental, and Regulatory Compliance

15.1 Laboratory Safety

Critical Safety Protocols

- **Epichlorohydrin:** Carcinogen; use in fume hood with activated carbon scrubbing; avoid skin contact.
- **Peracetic acid:** Strong oxidizer; corrosive; store refrigerated; prepare fresh solutions.
- **High-temperature furnaces:** Risk of burns and CO exposure; ensure adequate ventilation; use O₂ monitors.
- **KOH activation:** Highly corrosive; neutralize waste before disposal.
- **Carbon nanomaterials:** Potential respiratory hazard; handle in glove box or with N95/P100 respirators.

15.2 Environmental Compliance

- All chemical waste disposed per CCME (Canadian Council of Ministers of the Environment) guidelines.
- Pyrolysis off-gases captured and scrubbed.
- Solvent recovery system implemented where feasible.
- Hemp feedstock sourced from licensed Canadian growers (Health Canada Industrial Hemp License).

15.3 Intellectual Property Strategy

1. **Patent filings:** Provisional patents on resin formulations, carbon processing, and composite architectures within 6 months of program initiation.
2. **Trade secrets:** Detailed process parameters maintained as confidential know-how.
3. **Freedom to operate:** Prior art search conducted in Weeks 1–2 to identify blocking patents.
4. **Publication strategy:** Patent filings precede publication by > 6 months.

16 Conclusion

The Hemp Carbon Vitrimer Platform (HCVP) represents a transformative approach to advanced composite materials, addressing the critical sustainability challenges facing the global composites industry. By leveraging industrial hemp—a rapidly renewable, carbon-sequestering crop—as the exclusive feedstock for both polymer matrices and carbon reinforcements, the HCVP eliminates fossil fuel dependency while introducing unprecedented circularity through vitrimer chemistry.

The program’s integrated three-phase structure ensures systematic de-risking:

1. **Phase I** establishes the chemical foundation through bio-based vitrimer resin development.
2. **Phase II** unlocks the reinforcement potential of hemp through controlled carbonization and nanostructuring.
3. **Phase III** demonstrates that these components can be integrated into high-performance, recyclable composites.

Success in this program will yield:

- A portfolio of patent-protected resin formulations and processing methods
- Scientific publications establishing Landry Industries’ leadership in sustainable materials
- Prototype composite materials ready for industrial partnership and scale-up
- A replicable model for transforming agricultural biomass into advanced engineering materials

The HCVP is not merely an incremental improvement in bio-composites; it is a fundamental reimagining of how advanced materials can be sourced, manufactured, used, and recovered. In an era of escalating climate urgency and resource constraints, the HCVP positions Landry Industries at the vanguard of the circular bioeconomy—where the materials of tomorrow are grown, not extracted.

*“From soil to structure, from structure to soil—
the infinite loop of hemp carbon.”*

— Landry Hemp Carbon Materials Research Program

References

- [1] Cordier, P.; Tournilhac, F.; Ziak, C.; Leibler, L. “Self-Healing and Thermoreversible Rubber from Supramolecular Assembly.” *Science* **2011**, *334*, 965–968. (Vitrimers concept)
- [2] Wang, H.; et al. “Interconnected Carbon Nanosheets Derived from Hemp for Ultrafast Supercapacitors with High Energy.” *ACS Nano* **2013**, *7*, 5131–5141.
- [3] Quiles-Carrillo, L.; et al. “Epoxidized and Maleinized Hemp Oil to Develop Fully Bio-Based Epoxy Resin.” *Polymers* **2023**, *15*, 1404.
- [4] Ferri, J. M.; et al. “Maleinized Linseed Oil as Reactive Oligomer for the Synthesis of Bio-Based Vitrimers Materials.” *Polymers* **2021**, *13*, 1748.
- [5] Groetsch, A.; et al. “Life Cycle Assessment of Carbon Fiber-Reinforced Polymers.” *Int. J. Life Cycle Assess.* **2021**, *26*, 1568–1585. (Energy intensity 50–80 kWh/kg)
- [6] United Nations. “Industrial Hemp: A Sustainable Crop with High Potential.” UNCTAD/FAO Technical Report, 2023. (Carbon sequestration)
- [7] Industrial Hemp Association. “Hemp Fiber Composition and Properties.” Technical Bulletin, 2025. (Cellulose 52–78%, crystallinity 60–81%)
- [8] Firouzi, A.; et al. “Hemp Bast Fiber Crystallinity and Carbon Precursor Quality.” *Ind. Crops Prod.* **2025**, *208*, 118–126.
- [9] Grand View Research. “Composites Market Size, Share & Trends Report, 2025–2030.” 2025. (USD 112–145 billion market valuation)
- [10] Composites World. “Carbon Fiber Demand Reaches 366,800 Metric Tonnes in 2025.” Market Report, 2025.
- [11] ASTM D6866-22, Standard Test Methods for Determining the Biobased Content of Solid, Liquid, and Gaseous Samples Using Radiocarbon Analysis.
- [12] Health Canada, Industrial Hemp Regulations (SOR/2018-145).

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Moncton, New Brunswick, Canada
July 18, 2026