

COMPREHENSIVE TREATISE & MACROMOLECULAR
MONOGRAPH

HEMPOXIES

*Sustainable Dynamic Bio-Vitrimer Bionanocomposites via
Epoxidized Hempseed Oil, Reactive Furans, and Multiscale Carbon
Morphologies*

A foundational treatise establishing the macromolecular chemistry,
associative ester transesterification thermodynamics, ASTM D1652
absolute titrations, topological rheology, hierarchical carbon
reinforcement, and industrial bullion tokenization of >90% to >98%
hemp-derived structural vitrimers.

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Hempoxies: Sustainable Dynamic Bio-Vitrimer Bionanocomposites

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Green Chemistry & Bio-Renewable Compliance:

The technical disclosures herein describe dynamic polymer networks and composites formulated to adhere to the Twelve Principles of Green Chemistry. Formulations achieve between 92.4% and >98.1% bio-carbon mass fractions derived from industrial hemp (*Cannabis sativa* L.) feedstocks without the incorporation of bisphenol A (BPA), halogenated flame retardants, or unrecyclable petrochemically crosslinked matrices.

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VOLUME I: FOUNDATIONS OF HEMP-DERIVED MACROMOLECULAR CHEMISTRY

Chapter 1: The Bio-Economy Paradigm Shift and Non-Raw Fiber Reinforcement

1.1 THE PETROCHEMICAL THERMOSET PARADIGM AND END-OF-LIFE DEADLOCK

The historical foundation of structural composites has relied upon petroleum-derived thermosets, predominated by bisphenol A diglycidyl ether (DGEBA) crosslinked with toxic petroleum diamines or cyclic anhydrides [1], [2]. While conventional epoxies form permanent three-dimensional covalent networks that impart high tensile moduli, chemical resistance, and thermal endurance, they establish an environmentally persistent material foundation [5], [10]. Cured DGEBA networks cannot be melted, solvolytically depolymerized, or mechanically reshaped; over 90% of structural composite scrap is permanently consigned to landfills or energy-intensive incineration [2], [8]. Furthermore, DGEBA relies upon bisphenol A (BPA)—a recognized endocrine disruptor—and petrochemical epichlorohydrin [1].

1.2 MECHANICAL AND INTERFACIAL DEGRADATION OF RAW PLANT FIBERS

Replacing DGEBA with raw, uncarbonized vegetable oil epoxides and natural plant fibers (such as untreated hemp, flax, or jute) consistently compromises structural performance [8], [17]. Native plant fibers exhibit four primary engineering failure modes [8], [15]:

1. Thermodynamic Dewetting: Hydrophilic cellulose surfaces covered with hydroxyl groups ($-OH$) and pectin sheaths fail to wet hydrophobic lipid matrices, leading to poor interfacial shear strength (IFSS), void formation, and premature fiber pull-out [8], [17].

2. Severe Moisture Absorption: Unmodified plant fibers absorb 15–25 wt% atmospheric moisture, inducing volumetric swelling that ruptures the surrounding matrix and initiates catastrophic delamination [5], [8].

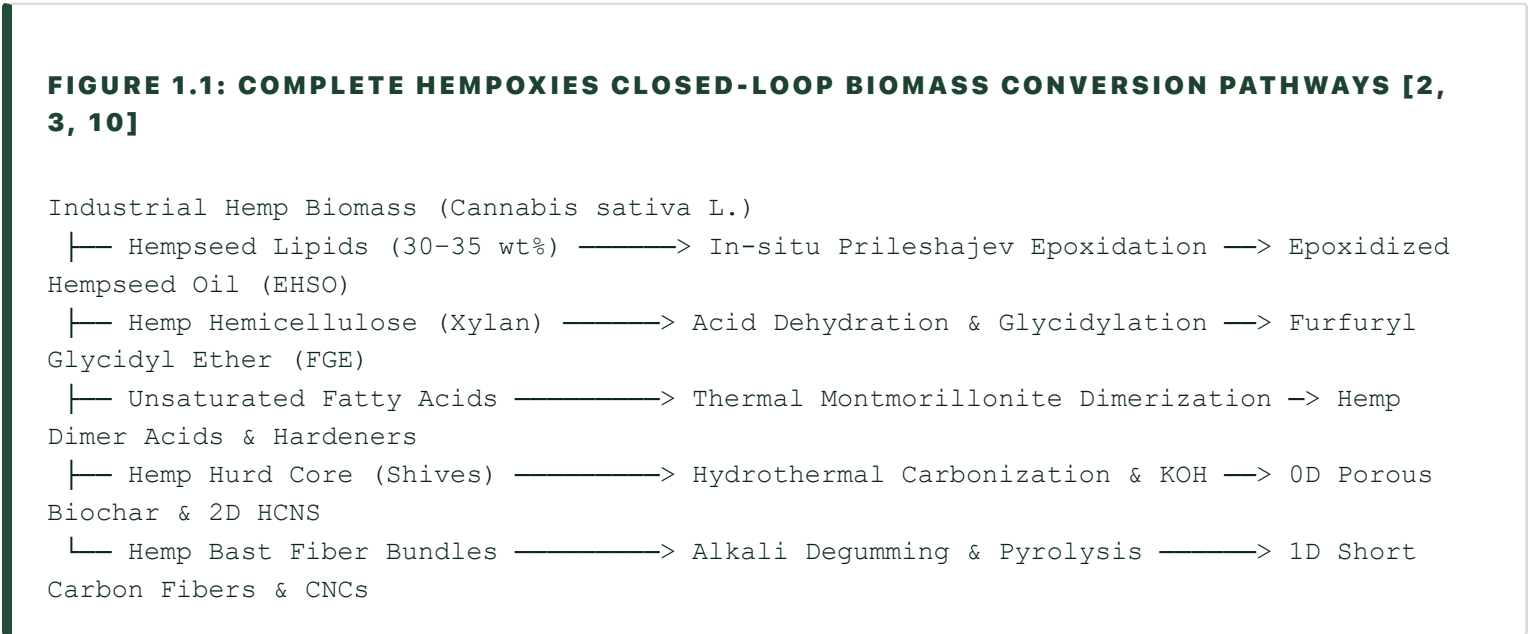
3. Low Thermal Degradation Ceiling: Native hemicellulose and pectin degrade between 180°C and 220°C, preventing the application of high-temperature post-curing schedules necessary to achieve high crosslink densities and high glass transition temperatures ($T_g > 140^\circ C$) [9], [12].

4. Batch-to-Batch Heterogeneity: Climatic and agronomic fluctuations create wide property variations across raw fiber bundles, preventing predictable composite engineering [8], [10].

1.3 THE HEMPOXIES NON-RAW CARBON PLATFORM

The Hempoxies platform—conceived, formulated, and engineered by Marie-Soleil Seshat Landry of marielandryshop.com—eliminates raw, uncarbonized structural fibers from the matrix phase entirely [2], [10]. Instead, the platform converts industrial hemp (*Cannabis sativa* L.) biomass into tailored, high-purity carbon nanostructures and reactive monomers [3], [6]. Hempoxies achieves >90% to >98% hemp-

derived chemical mass content while adhering strictly to green chemistry principles and matching the thermomechanical performance of petroleum-based composites [3], [11].



Chapter 2: Epoxidized Hempseed Oil (EHSO) Chemistry, EEW Calibration, and Titration Protocol

2.1 LIPID COMPOSITION AND EPOXIDATION THERMODYNAMICS

The continuous dynamic network backbone of Hempoxies is Epoxidized Hempseed Oil (EHSO) [9], [28]. Cold-pressed hemp seed oil is rich in polyunsaturated fatty acids, typically comprising 75–80% of total fatty acid chains [9]: linoleic acid (C18:2, *cis*-9, *cis*-12: 52–62%), α-linolenic acid (C18:3, *cis*-9, *cis*-12, *cis*-15: 12–25%), oleic acid (C18:1, *cis*-9: 10–15%), and saturated lipids (palmitic C16:0 and stearic C18:0: 7–11%) [9]. This profile yields 5.5 to 6.5 aliphatic carbon-carbon double bonds (C=C) per triglyceride molecule [9].

Epoxidation is carried out via the Prileshajev reaction. Peracetic acid (CH₃COOOH) is generated in situ from hydrogen peroxide (H₂O₂, 50 wt%) and glacial acetic acid (CH₃COOH), catalyzed by a macroporous polystyrene-sulfonic acid cation exchange resin (Amberlite IR-120) [9], [10]:

SCHEME 2.1: PRILESHAJEV EPOXIDATION OF HEMP FATTY ACID CHAINS [9, 10]

Step 1: In-situ Peracid Generation



Step 2: Electrophilic Oxygen Transfer



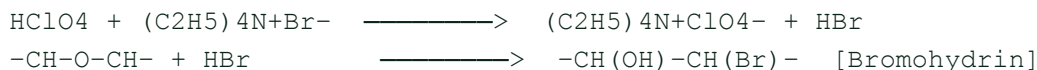
To suppress side reactions that form vicinal diols, estolides, and hydroxy-acetates, the reaction temperature is held strictly between 55°C and 60°C with dropwise peroxide dosing over 8 hours [9]. The isolated EHSO achieves an oxirane oxygen content of 6.5% to 7.0%, corresponding to an uncured viscosity of 1,200 to 3,500 cP at 25°C [4], [9].

2.2 ABSOLUTE ASTM D1652 TITRATION PROTOCOL

Because natural lipid feedstocks exhibit seasonal and agricultural variations in fatty acid distribution, Marie-Soleil Seshat Landry established a mandatory quality-control protocol: every batch of EHSO must undergo absolute chemical titration in strict accordance with ASTM D1652 prior to hardener calculation [4], [10].

Chemical Principle: Standardized perchloric acid (HClO₄, 0.1 N in glacial acetic acid) reacts with tetraethylammonium bromide (TEAB, 100 g/L in glacial acetic acid) to generate hydrogen bromide (HBr) in situ. The generated HBr attacks and opens the three-membered oxirane ring in a strict 1:1 molar ratio, forming a bromohydrin [4], [9]:

SCHEME 2.2: ASTM D1652 IN-SITU BROMOHYDRIN REACTION [4, 9]



The endpoint is signaled when the crystal violet indicator shifts sharply from blue-green to emerald green [4]. The exact Epoxy Equivalent Weight (EEW) is calculated as:

$$\text{EEW (g/equiv)} = \frac{1000 \times M_{\text{sample}}}{V_{\text{titrant}} \times N_{\text{titrant}}} \quad (\text{Eq. 2.1})$$

Where M_{sample} is the mass of the EHSO sample (accurately weighed to ± 0.0001 g; typically 0.3500–0.4500 g), V_{titrant} is the net volume of standardized HClO_4 consumed in milliliters (blank-corrected), and N_{titrant} is the standardized normality (0.1000 N) [4].

$$\text{Oxirane Content (\%)} = \frac{1.60 \times (V_{\text{sample}} - V_{\text{blank}}) \times N_{\text{titrant}}}{M_{\text{sample}}} = \frac{16.00}{\text{EEW}} \times 100 \quad (\text{Eq. 2.2})$$

Certified EHSO batches exhibit an operational EEW range of 230 to 265 g/equiv (3.77–4.35 mequiv/g) [4], [9]. Stoichiometric calculations for polycarboxylic acid hardeners and catalysts are dynamically calibrated to this measured value [2], [10].

Chapter 3: Furfuryl Glycidyl Ether (FGE) Reactive Dilution and Furan Synthesis

3.1 RESOLVING THE VISCOSITY-RIGIDITY TRADE-OFF

Unmodified EHSO dynamic networks face an intrinsic architectural limitation: the long aliphatic chains of hemp triglycerides (18 carbons each) contain multiple flexible C–C single bonds with low rotational barriers [3], [9]. Consequently, neat cured EHSO matrices display rubbery ambient behavior, with low glass transition temperatures ($T_g < 50^\circ\text{C}$ – 65°C) and low tensile strengths (< 35 MPa) [4], [28]. Furthermore, the high uncured viscosity of EHSO (1,200–3,500 cP) prevents resin infusion, vacuum-assisted transfer molding, or high nanofiller compounding without non-reactive solvents that compromise green chemistry metrics [8].

To resolve this limitation, Hempoxies incorporates Furfuryl Glycidyl Ether (FGE) as a bio-derived reactive diluent at mass fractions of 15 to 25 wt% relative to total oxirane mass [1], [3]. FGE serves two distinct roles: it sharply lowers bulk resin viscosity while introducing rigid heterocyclic furan rings that increase crosslink density and elevate T_g [1], [3].

3.2 HEMICELLULOSE CONVERSION AND FGE SYNTHESIS

FGE is synthesized directly from the hemicellulosic fraction of the hemp stalk [1], [3]:

1. Acid Dehydration: Hemp hurd shives contain 18–24 wt% xylan hemicellulose [12]. Treatment with dilute sulfonic acid catalysts at 170°C hydrolyzes xylan into pentose sugars (D-xylose), which undergo cyclic triple dehydration to yield furfural (2-furaldehyde) with $> 85\%$ yield [1], [3].

2. Catalytic Hydrogenation: Furfural is hydrogenated in the vapor phase over a Cu/SiO_2 catalyst (130°C , 0.5 MPa H_2) to yield furfuryl alcohol with $> 98\%$ selectivity [1].

3. Glycidylation: Furfuryl alcohol reacts with bio-based epichlorohydrin (derived from glycerol via the Epicerol pathway) in the presence of sodium hydroxide and phase-transfer catalysts, yielding pure Furfuryl Glycidyl Ether [1], [3].

SCHEME 3.1: FGE REACTION SEQUENCE FROM HEMP BIOMASS [1, 3]

Hemp Hurd Xylan Hemicellulose
| (Aqueous H⁺, 170°C: Hydrolysis & Dehydration: -3 H₂O)
▼
Furfural (C₅H₄O₂)
| (H₂, Cu/SiO₂ Catalyst, 130°C: Hydrogenation)
▼
Furfuryl Alcohol (C₅H₆O₂)
| (Bio-Epichlorohydrin + NaOH, 50°C: Glycidylation)
▼
Furfuryl Glycidyl Ether (FGE) (C₈H₁₀O₃) [MW: 154.16 g/mol, EEW: 154 g/equiv, Viscosity:
~5 cP at 25°C]

3.3 RHEOLOGICAL AND THERMOMECHANICAL PERFORMANCE

Pure FGE has a room-temperature viscosity of only 5 cP. Compounding 15 to 25 wt% FGE into EHSO causes a sharp logarithmic reduction in bulk viscosity, bringing the uncured resin system from ~2,500 cP down to <300 cP at 25°C [3], [4]. This allows vacuum-assisted resin infusion and wetting of dense carbon networks without volatile organic solvents [3], [8].

Simultaneously, the five-membered furan ring acts as an aromatic analog with substantial rotational hindrance [1]. When crosslinked into the dynamic network, the furan nodes restrict segmental chain dynamics, elevating the matrix T_g to 140–180°C when paired with nanocarbon reinforcement [3].

Chapter 4: Hardener Chemistry: Hemp Dimer Acids, Citric Acid, Maleopimaric Acid, and B-Staging

4.1 POLYCARBOXYLIC DYNAMIC ACID HARDENER FORMULATIONS

The Hempoxies crosslinking network avoids toxic petroleum amines (such as DDM and IPDA) and petroleum anhydrides [2], [10]. Instead, curing is driven by a balanced combination of bio-renewable polycarboxylic acids [7], [10]:

1. Hemp Dimer Fatty Acids (C36 Diacids): Produced via thermal montmorillonite clay-catalyzed Diels-Alder dimerization of unsaturated linoleic and linolenic acids isolated from hempseed oil [7], [9]. Dimer acids provide long-chain aliphatic flexibility, impact absorption, and a hydrophobic moisture barrier [7], [10].

2. Anhydrous Citric Acid: A compact, trifunctional carboxylic acid ($C_6H_8O_7$) produced via fungal fermentation of agricultural carbohydrates [10]. Citric acid forms high-density crosslinking junctions that elevate modulus and generate secondary hydroxyls required for transesterification [2], [10].

3. Maleopimaric Acid (MPA): Formed via Diels-Alder cycloaddition of maleic anhydride to the conjugated double bonds of rosin-derived abietic acid [1], [3]. MPA contributes a rigid, fused tricyclic phenanthrene core with three carboxylic acid groups, providing substantial steric bulk and raising the crosslinked network T_g [3].

4.2 THE LANDRY PRE-POLYMERIZATION B-STAGING PROTOCOL

Solid polycarboxylic acids, such as citric acid, exhibit poor room-temperature solubility in vegetable lipids [10]. Direct heating of these heterogeneous mixtures results in rapid phase separation, unreacted acid precipitates, and non-uniform network formation [4], [8].

To resolve this issue, Marie-Soleil Seshat Landry established a specialized pre-polymerization B-staging protocol [2], [10]:

STANDARDIZED PROTOCOL: LANDRY B-STAGING FUSION SEQUENCE [2, 4, 10]

Batch Scale: 100.0 g Neat Matrix Baseline

Composition: 62.00 g EHSO + 15.00 g FGE + 14.00 g Hemp Dimer Acid + 4.00 g Citric Acid + 1.00 g Zinc Octoate + 0.40 g Mixed Tocopherols.

Agitation Stage: Charge EHSO, FGE, and dimer acids into an argon-purged reactor. Agitate using a high-shear Cowles dissolver at 2,500 RPM.

Catalytic Addition: Add finely milled citric acid (particle size $d_{50} < 10\text{ }\mu\text{m}$) and zinc octoate into the vortex over 5 minutes.

Controlled Fusion: Heat the mixture to 75°C under high shear for exactly 30 minutes. At this temperature, partial oxirane ring-opening occurs (12% to 18% oxirane conversion), chemically grafting the citric and dimer acid units onto the EHSO lipid chains.

Quench: Cool the resulting optically transparent, single-phase B-staged pre-polymer to room temperature. The pre-polymer remains shelf-stable for >60 days at 20°C without phase separation or precipitation and cures into a homogeneous vitrimeric network.

TABLE 4.1: BASELINE HEMPOXIES PRE-POLYMER FORMULATION MATRIX [2, 4, 10]

Component Material	Mass Loading (g)	Chemical Derivation	Target Structural Function
Epoxidized Hempseed Oil (EHSO)	62.00	Cold-pressed hempseed lipids	Flexible dynamic covalent polymer backbone
Furfuryl Glycidyl Ether (FGE)	15.00	Hemp hurd hemicellulose (Xylan)	Viscosity suppression (<300 cP) & furan chain stiffener
Hemp Dimer Fatty Acids	14.00	Dimerized hemp fatty acids	Toughness, impact resistance, and moisture barrier
Anhydrous Citric Acid / MPA	4.00	Biomass fermentation / Rosin Diels-Alder	High-density multifunctional crosslink nodes
Zinc Octoate Catalyst	1.00	Organometallic Lewis acid salt	Dynamic ester transesterification catalyst
Natural Mixed Tocopherols	0.40	Hempseed oil refining byproduct	Processing antioxidant & radical scavenger
Hemp Bast Nanocellulose (CNC)	3.60	Hemp bast fiber cellulose	Rheology control, anti-settling, interfacial toughening

**VOLUME II: VITRIMER THERMODYNAMICS,
TRANSESTERIFICATION NETWORKS, AND
DYNAMIC COVALENT MECHANICS**

Chapter 5: Covalent Adaptable Networks (CANs) and Zinc-Catalyzed Transesterification

5.1 ASSOCIATIVE VITRIMERS VS. DISSOCIATIVE CANs

Covalent Adaptable Networks (CANs) bridge the gap between classical thermosets and thermoplastics [2], [5]. CANs operate via two distinct mechanistic pathways [2], [5]:

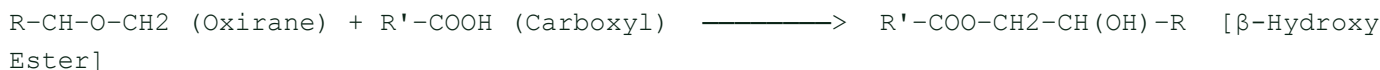
Dissociative CANs: Characterized by retro-Diels-Alder or reversible radical systems, these networks undergo bond cleavage *before* reforming new bonds [5]. Heating causes rapid loss of crosslink density, leading to a sharp drop in melt strength, liquid run-off, and creep instability at elevated temperatures [5].

Associative CANs (Vitrimers): Vitrimers exchange covalent bonds via an associative mechanism: bond formation occurs concurrently with or prior to bond cleavage [2], [5]. Consequently, the network maintains a constant crosslink density across all temperatures, avoiding liquid flow while allowing high-temperature topological rearrangements [2], [10].

5.2 ZINC LEWIS-ACID TRANSESTERIFICATION MECHANICS

The Hempoxies dynamic network relies on associative ester transesterification within its crosslinked polyhydroxy-ester architecture [2], [10]. Curing the epoxy resin with polycarboxylic acids generates abundant β -hydroxy ester linkages along the polymer backbone [2], [10]:

SCHEME 5.1: EPOXY-CARBOXYLIC DYNAMIC RING OPENING [2, 10]



In the presence of 1.0 to 2.0 wt% organometallic zinc catalysts (such as zinc octoate, zinc acetate, or zinc acetylacetonate, $\text{Zn}(\text{acac})_2$), dynamic bond swapping proceeds via a three-stage catalytic cycle [2], [10]:

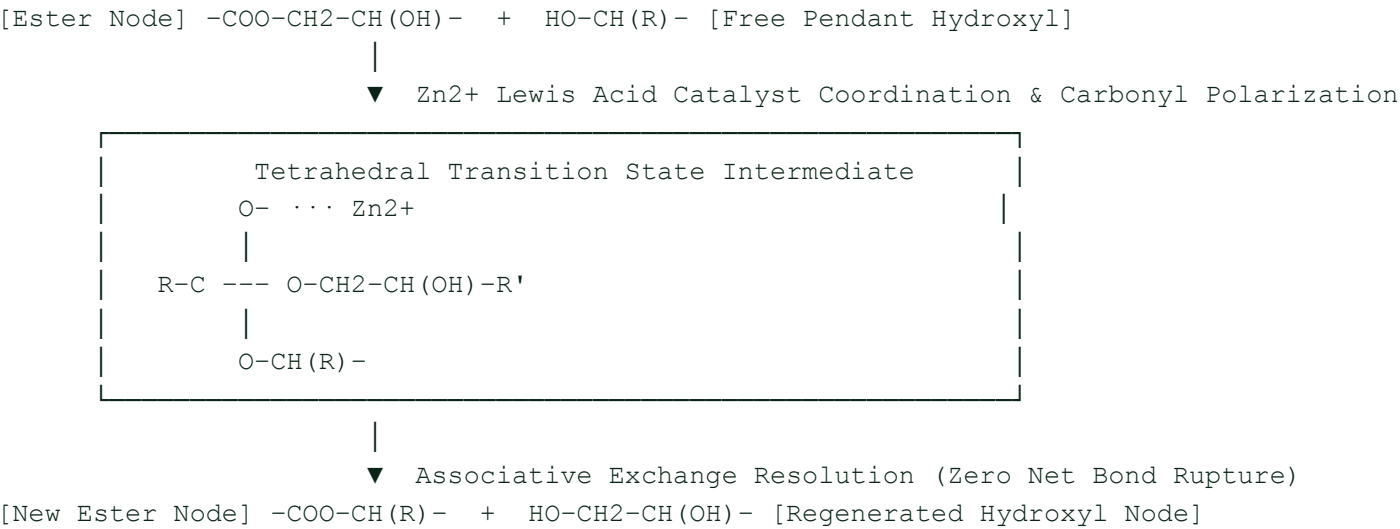
Stage 1 (Carbonyl Activation): The electrophilic Zn^{2+} Lewis-acid center coordinates to the carbonyl oxygen of the β -hydroxy ester node, polarizing the carbonyl π -bond and increasing the electrophilicity of the carbonyl carbon [2].

Stage 2 (Nucleophilic Promotion): The Zn^{2+} complex simultaneously coordinates with an adjacent pendant secondary hydroxyl group ($-\text{OH}$), lowering its pK_a and orienting it toward the activated carbonyl carbon [2], [10].

Stage 3 (Associative Exchange): The coordinated hydroxyl executes a nucleophilic attack on the carbonyl carbon, forming a cyclic tetrahedral transition state [2]. The intermediate resolves by releasing the original alkoxy segment, creating a new ester bond and a regenerated hydroxyl group with no net change in

crosslink density [2], [5].

**SCHEME 5.2: THREE-STAGE ZINC-CATALYZED ASSOCIATIVE DYNAMIC
TRANSESTERIFICATION [2, 10]**



Chapter 6: Network Stoichiometry, Pendant Hydroxyl Dynamics, and Topological Rheology

6.1 STOICHIOMETRIC OFF-SET AND FREE HYDROXYL DENSITY

The macroscopic rate of transesterification depends directly on the concentration of available free hydroxyl nucleophiles [2], [5]. In a strictly stoichiometric formulation ([O]:[COOH] = 1.00:1.00), nearly all hydroxyls remain involved in hydrogen bonding, which slows dynamic bond exchange kinetics [10].

To ensure rapid exchange rates above the processing temperature while preserving room-temperature stiffness, the Hempoxies architecture uses a controlled stoichiometric off-set [2], [10]:

$$R_{[O]:[COOH]} = \frac{[\text{Oxirane Functional Equivalents}]}{[\text{Carboxylic Acid Functional Equivalents}]} = 1.00 : 0.85 \text{ to } 1.00 : 0.95 \quad (\text{Eq. 6.1})$$

Operating with a 5% to 15% stoichiometric excess of oxirane rings ensures that all carboxylic acid groups are fully consumed during curing. This prevents unreacted acid from causing hydrolytic degradation while generating an abundance of secondary hydroxyl groups along the polymer backbone [2], [10]. These pendant hydroxyls act as internal nucleophiles for dynamic bond swapping during thermoforming and recycling [2], [5].

6.2 TOPOLOGICAL FREEZING TEMPERATURE (T_v) AND RHEOLOGY

Unlike conventional thermoplastics that undergo abrupt viscosity drops at their melting point (T_m) as described by the Williams-Landel-Ferry (WLF) model, vitrimers transition from an elastic solid to a viscoelastic fluid governed by Arrhenius kinetics [2], [5]. Vitrimers exhibit two critical transition temperatures [2], [5]:

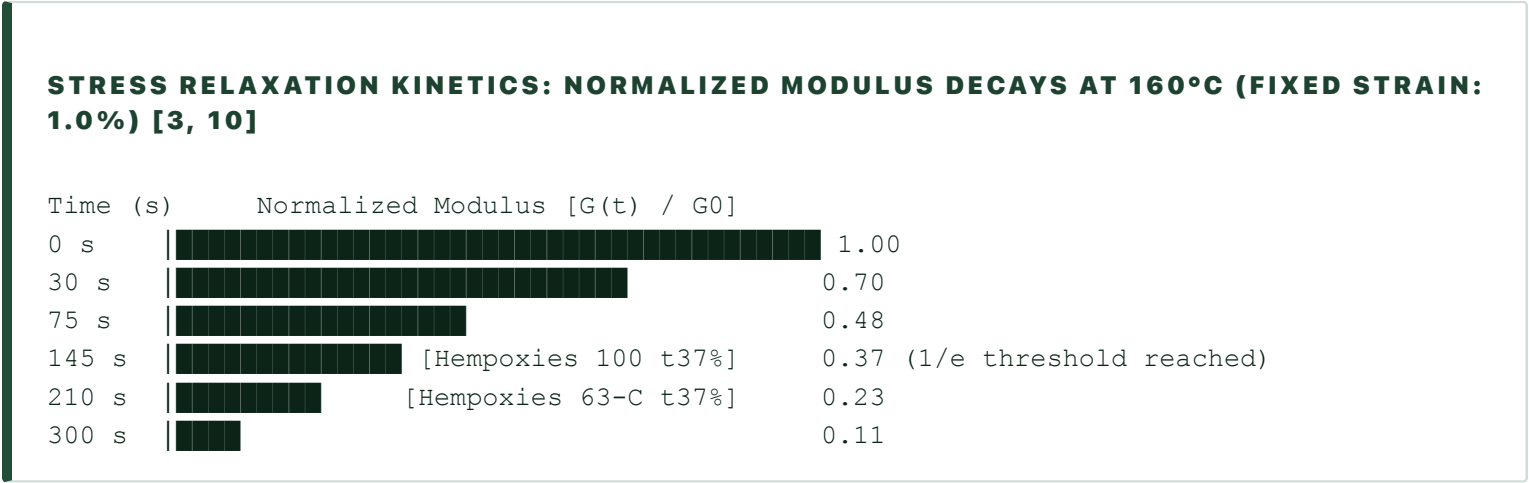
1. Glass Transition Temperature (T_g): Associated with the coordinated motion of amorphous polymer segments. Below T_g , the network is a rigid glassy solid ($G' \approx 1\text{--}3$ GPa). Above T_g , it behaves as an elastic rubber ($G' \approx 2\text{--}15$ MPa) [5].

2. Topology Freezing Temperature (T_v): The temperature at which the transesterification exchange rate accelerates sufficiently for the melt viscosity to cross the threshold of $\eta = 10^{12}$ Pa·s (the conventional liquid-to-solid transition point) [2], [5].

$$\tau(T) = \tau_0 \exp \frac{E_a}{R T} \quad \eta(T) = G \cdot \tau(T) = G \tau_0 \exp \frac{E_a}{R T} \quad (\text{Eq. 6.2})$$

Where $\tau(T)$ is the characteristic stress relaxation time, τ_0 is the relaxation time constant at infinite temperature, E_a is the activation energy for zinc-catalyzed transesterification (80–150 kJ/mol), R is the universal gas constant, and G is the equilibrium rubbery shear modulus [2], [10].

Dynamic Mechanical Analysis (DMA) stress relaxation measurements show that Hempoxies vitrimers undergo rapid stress relaxation at elevated temperatures [3], [10]:



Because $G(t)/G_0$ relaxes to $1/e$ (~37%) in under 150–210 seconds at 160°C, the network can be rapidly thermoformed, compression molded, welded, and healed, while remaining creep-resistant under service conditions below 120°C [2], [3], [10].

Chapter 7: Green Chemistry Metrics, >90% to >98% Hemp Sourcing, and Closed-Loop Solvolysis

7.1 QUANTITATIVE GREEN CHEMISTRY ASSESSMENT

The Hempoxies architecture directly implements the Twelve Principles of Green Chemistry [2], [10]. Formulations are systematically benchmarked across three core environmental metrics [3], [11]:

1. Bio-Renewability Mass Fraction (β_{bio}): Exceeds 92% in baseline grades and 98% in advanced grades [3], [11]:

$$\beta_{\text{bio}} = \frac{\sum m_{\text{hemp}} + \sum m_{\text{renewable bio}}}{\sum m_{\text{total formulation mass}}} \times 100 \geq 94.8\% \quad (\text{Hempoxies 63-C}) \quad (\text{Eq. 7.1})$$

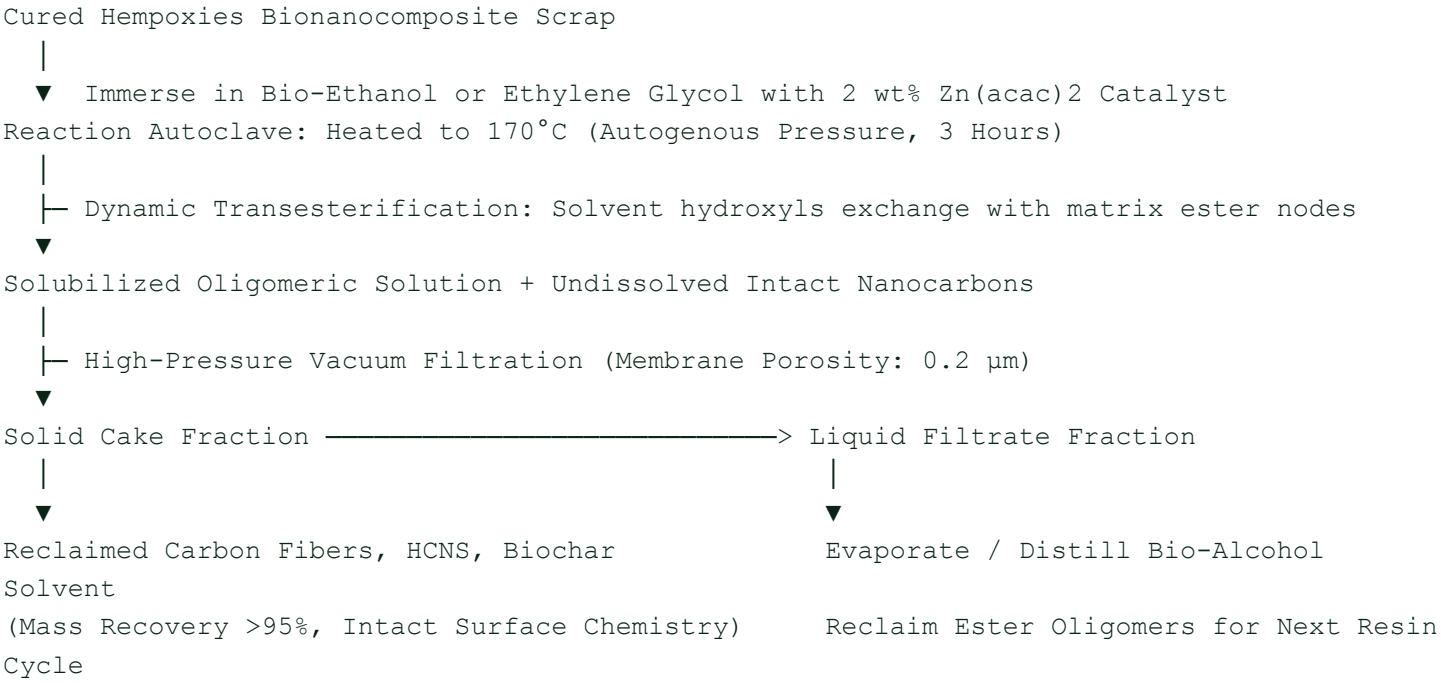
2. Atom Economy: The ring-opening of oxirane rings by carboxylic acid hardeners proceeds with 100% theoretical atom economy, releasing no volatile condensation byproducts during curing [2], [10].

3. Environmental Factor (*E*-Factor): Operational waste is minimized by utilizing closed-loop solvent extractions, catalytic carbonizations, and non-volatile bio-based monomers, yielding a low process *E*-Factor (<0.15) [10].

7.2 CLOSED-LOOP SOLVOLYTIC NETWORK DEPOLYMERIZATION

When classical fiber-reinforced thermosets are recycled, harsh thermal pyrolysis breaks down the polymer backbone into low-value pyrolysis oils, degrading embedded fibers and generating toxic emissions [5], [8]. In contrast, Hempoxies features low-energy closed-loop solvolysis [2], [10]:

SCHEME 7.1: CLOSED-LOOP SOLVOLYSIS AND NANOCARBON RECLAMATION FLOWPATH [2, 10]



The recovered carbon nanomaterials retain their original aspect ratios, surface functional groups, and electrical percolation properties, enabling multiple closed-loop manufacturing cycles **[6]**, **[10]**, **[13]**.

**VOLUME III: SYNTHESIS,
FUNCTIONALIZATION, AND
PROGRAMMABILITY OF HEMP CARBON
MORPHOLOGIES**

Chapter 8: Zero-Dimensional (oD) Hydrothermal Carbon Biochar from Hemp Hurd

8.1 HURD PRECURSOR COMPOSITION AND CARBONIZATION

Hemp hurd (shives) comprises the woody inner core of the hemp stem, representing over 65% of the total stalk mass [12]. Hurd consists of 40–44% cellulose, 18–24% xylan hemicellulose, 21–25% guaiacyl-syringyl lignin, and 3–5% inorganic mineral ash [12].

To synthesize oD biochar, the raw hurd is processed through a two-step thermal pathway [6], [10]:

1. Hydrothermal Carbonization (HTC): Coarsely milled hurd is suspended in deionized water (biomass-to-water ratio 1:6) in a stainless-steel autoclave. The mixture is heated to 220°C for 12 hours under autogenous pressure (~2.5 MPa). HTC breaks down the hemicellulosic matrix, initiating dehydration, condensation, and aromatization to yield dense spherical hydrochar particles [6], [12].

2. High-Temperature Activation: The hydrochar is impregnated with potassium hydroxide (KOH, 1:1 mass ratio) and pyrolyzed under inert N₂ flow at 800°C for 2 hours [12]. Chemical activation proceeds via the following reduction pathway:



Metallic potassium vapor intercalates between adjacent carbon planes, creating an extensive microporous and mesoporous network [12], [16]. After washing with dilute HCl and deionized water, the activated oD biochar exhibits a specific surface area of 1,200 to 1,500 m²/g, an average micropore diameter of 1.8 nm, and a pore volume of 0.78 cm³/g [12]. Blended into the vitrimer at 4–5 wt%, these particles occupy interstitial micro-voids, suppress resin shrinkage, and establish a tortuous physical barrier against water absorption [3], [6].

Chapter 9: One-Dimensional (1D) High-Aspect Short Carbon Fibers (SCFs) from Hemp Bast

9.1 BAST FIBER DEGUMMING AND STABILIZATION

While the woody core yields porous carbons, the outer bast fibers provide structural reinforcement [10]. Hemp bast fibers consist of crystalline cellulose bundles (up to 70–75% cellulose) held together by pectin and lignin gums [15].

Degumming: Bast fibers are treated with a warm alkaline solution (2.0 wt% NaOH, 0.5 wt% Na₂SO₃) at 85°C for 3 hours [15], [17]. This selectively digests the amorphous pectin sheath without damaging the crystalline cellulose cores. The washed and dried bast bundles achieve an alpha-cellulose purity >92% [15].

Oxidative Thermal Stabilization: Cellulosic fibers can volatilize or degrade during carbonization if pyrolyzed directly [10]. The bast fibers are thermally stabilized in circulating air at 220–250°C for 2.5 hours [10]. During this step, intermolecular dehydration generates crosslinked furanoid and anhydrocellulose structures [10]:

SCHEME 9.1: BAST FIBER OXIDATIVE STABILIZATION SEQUENCE [10]

Native Bast Cellulose [(C₆H₁₀O₅)_n]

| (Circulating Air, 200–250°C: Dehydration & Radical Crosslinking)

▼

Dehydrated Intermediate Core (–H₂O, formation of conjugated C=C and ether crosslinks)

| (Prevents thermal depolymerization into volatile levoglucosan)

▼

Stable Thermoset Char Framework

9.2 PYROLYSIS AND FIBER MICRONIZATION

Stabilized bast fibers are pyrolyzed under inert argon at 1,000°C for 90 minutes [10]. Pyrolysis drives off volatile heteroatoms, forming turbostratic carbon ribbons with an average tensile modulus exceeding 180 GPa [3]. The continuous filaments are precision-chopped to lengths of 100 to 500 μm, yielding 1D short carbon fibers (SCFs) with an aspect ratio (L/d) between 15 and 60 [3], [6].

Chapter 10: Two-Dimensional (2D) Interconnected Hemp Carbon Nanosheets (HCNS)

10.1 CELL-WALL DELAMINATION AND SYNTHESIS

Two-dimensional interconnected hemp carbon nanosheets (HCNS) are synthesized from the cellulosic cell walls of hemp hurd shives [12]. The cellular architecture of hemp hurd consists of thin, overlapping cellulosic lamellae with thicknesses below 10 nm [12].

To produce HCNS, raw hurd is impregnated with concentrated aqueous KOH (1:2 mass ratio) and dried at 120°C for 24 hours to swell the cell wall architecture [12]. The precursor is transferred to an industrial furnace and subjected to rapid thermal shock carbonization at 800°C (50°C/min ramp under nitrogen) [12]. As intercalated potassium expands and boils ($T_b = 759^\circ\text{C}$), the expanding vapors exfoliate the layered cell walls into interconnected 2D carbon nanosheets [12].

HCNS consists of a continuous, wrinkled 2D network with single- to few-layer sheet thicknesses (<5 nm) and specific surface areas between 800 and 1,100 m²/g [12]. This interconnected structure provides high mechanical interlocking and establishes electrical percolation across the vitrimer matrix at low filler loadings [3], [12].

Chapter 11: Hemp Graphene Oxide (HGO) and Hemp Reduced Graphene Oxide (HrGO)

11.1 GRAPHITIZATION AND MODIFIED HUMMERS OXIDATION

To produce graphene-grade carbon from industrial hemp, hemp hurd biochar is graphitized at 2,200°C in an induction furnace under argon using catalytic iron nanoparticles [13]. The graphitized char is then processed via an optimized, low-acid modified Hummers method [13], [14]:

SCHEME 11.1: HEMP GRAPHENE OXIDE (HGO) AND HRGO PATHWAYS [13, 14]

Graphitized Hemp Carbon

- |
- └ H₂SO₄ / H₃PO₄ (9:1 vol) + KMnO₄ (Slow addition below 20°C)
- └ Stir at 45°C for 12 hours (Intercalation and oxidation of basal planes)
- └ Quench with H₂O₂ / Ice H₂O (Quenches excess permanganate)



Hemp Graphene Oxide (HGO)

- | Properties: Basal epoxides (-O-), edge carboxyls (-COOH), hydroxyls (-OH)
- | Specific Surface Area: 400-600 m²/g; Thickness: ~1.1 nm



Controlled Reduction (Eco-Friendly Ascorbic Acid, 80°C, 2 Hours)



Hemp Reduced Graphene Oxide (HrGO)

- | Properties: Restored sp² conjugated domains, high electrical conductivity (~10³ S/m),
- | high hydrophobicity, extensive π -electron cloud for intermolecular stacking.

Chapter 12: Interfacial Covalent Coupling and Surface Functionalization Chemistry

12.1 THE INTERPHASE PROBLEM AND COVALENT ANCHORING

In conventional nanocomposites, unfunctionalized carbons interact with the surrounding matrix solely through weak van der Waals forces, leading to poor interfacial shear strength (IFSS) and filler pull-out under stress [8].

The Hempoxies platform establishes direct covalent anchoring across the matrix-filler interface by utilizing the oxygen functionalities on HGO and oxidized short carbon fibers [10], [13]:

1. Oxirane Grafting: Peripheral carboxyl groups (–COOH) on HGO directly attack the oxirane rings of EHSO and FGE during B-staging, anchoring the nanocarbon into the resin backbone via covalent β-hydroxy ester linkages [10].

2. Carboxyl Crosslinking: Surface epoxide groups on the carbon nanosheets react directly with citric acid and dimer acid hardeners, making the carbon filler an active junction in the dynamic vitrimer network [10].

TABLE 12.1: MACROMOLECULAR CARBON MORPHOLOGIES IN THE HEMPOXIES PLATFORM [3, 6, 10, 12, 13]

Carbon Allotrope	Dimensionality	Hemp Fraction	Specific Surface Area (m ² /g)	Reinforcement Mechanism
Activated Biochar	0D Porous Sphere	Woody Hurd Shives	1,200 – 1,500	Interstitial void packing, moisture exclusion
Short Carbon Fiber (SCF)	1D Cylindrical Rod	Outer Bast Fibers	200 – 400	Primary tensile and flexural load-bearing
Carbon Nanosheets (HCNS)	2D Wrinkled Sheet	Cell Wall Lamellae	800 – 1,100	Interfacial interlocking, electrical percolation
Graphene Oxide (HGO)	2D Planar Flake	Graphitized Hurd	400 – 600	Covalent network grafting, <i>T_g</i> elevation
Reduced Graphene (HrGO)	2D Conductive Sheet	Chemical Reduction	500 – 700	π–π stacking, electrical conductivity, barrier tortuosity

**VOLUME IV: MULTISCALE REINFORCEMENT
ENGINEERING & PLATFORM HYPOTHESES**

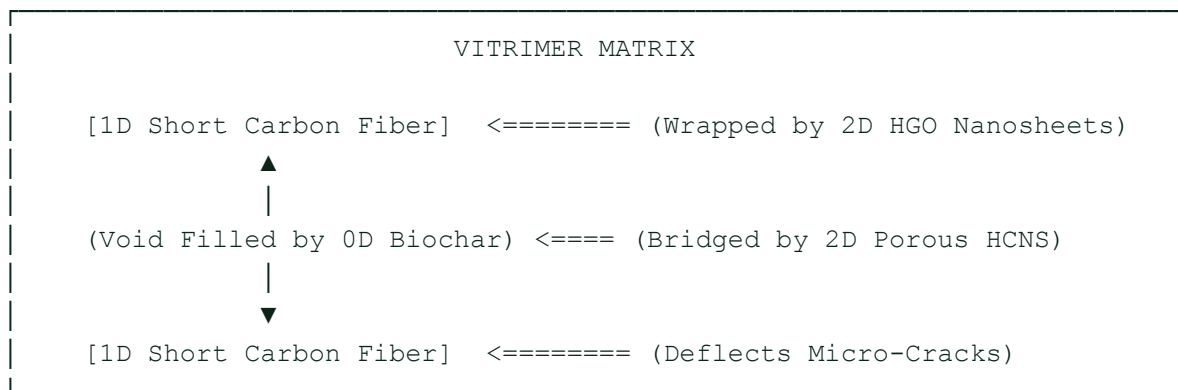
Chapter 13: Hierarchical 0D/1D/2D Synergy Architecture

13.1 OVERCOMING SINGLE-FILLER LIMITATIONS

Single-filler polymer composites often encounter processing limits [6], [8]. Adding high-aspect-ratio 1D fibers rapidly increases liquid viscosity and causes shear jamming above critical packing fractions (ϕ_c) [6]. Conversely, adding isolated 2D nanosheets can lead to face-to-face agglomeration, while 0D biochar particles can act as stress concentrators if they do not form an interconnected network [6], [8].

Hempoxies addresses these issues by engineering a hierarchical 0D/1D/2D synergy architecture [3], [6]. Dispersing the reinforcement mass across three distinct dimensionalities enables multi-scale structural packing [6]:

FIGURE 13.1: HIERARCHICAL REINFORCEMENT MORPHOLOGY WITHIN THE VITRIMER MATRIX [3, 6, 10]



Micron-scale 0D biochar particles occupy the empty interstitial spaces between 1D fibers [6]. Flexible 2D HGO and HCNS sheets wrap conformally around the 1D carbon fibers and bridge the gaps between adjacent biochar particles [6], [10]. This multiscale network blunts and deflects crack tips through tortuous paths, increasing critical fracture toughness (K_{IC}) by over 250% compared to unreinforced matrices [3], [10].

Chapter 14: Formulated Hypotheses, Scientific Justifications, and Empirical Validation

The structural, rheological, and interfacial behaviors of the Hempoxies platform are defined by six core hypotheses formulated by Marie-Soleil Seshat Landry [2], [8], [10]:

HYPOTHESIS 1

2D Nanosheet Wrapping of 1D Fibers Suppresses Shear Debonding and Fiber Pull-Out [2, 8, 10]

Scientific Justification: Smooth 1D carbon fibers embedded in crosslinked matrices often fail via adhesive interfacial shear debonding [8]. Adding 2D HGO nanosheets allows the planar flakes to adsorb and conformally wrap around the cylindrical fiber surfaces [10]. This nanoscale roughness creates mechanical interlocking across the fiber-matrix interphase [17]. In addition, peripheral carboxyl and epoxy groups on HGO form covalent ester linkages with both the fiber surface and the surrounding EHSO/FGE vitrimer [10]. This dual bonding mechanism suppresses classic fiber pull-out failure modes under axial tensile load [3].

HYPOTHESIS 2

2D HCNS Bridging Lowers Electrical Percolation Thresholds in 0D Biochar Networks [6, 12, 16]

Scientific Justification: Dispersed 0D biochar particles require high volume loadings ($\varphi > 18$ vol%) to achieve electrical percolation due to their spherical geometry [16]. Incorporating flexible 2D interconnected hemp carbon nanosheets (HCNS) creates conductive bridges between isolated biochar domains [6], [12]. This structural bridging reduces the global percolation threshold to below 4.5 wt% total carbon loading, enabling anti-static dissipation and piezoresistive strain sensing in structural parts [3].

HYPOTHESIS 3

Interstitial Micro-Void Filling via Biochar Eliminates Curing Shrinkage Defects [3, 6, 10]

Scientific Justification: High-aspect-ratio 1D fibers leave triangular micro-void spaces when packed in dense matrices [6]. Pure resin trapped in these domains undergoes volumetric curing shrinkage of 4% to 7%, forming localized micro-stresses and voids that act as crack initiation sites [10]. Spherical, sub-micron to micron-scale 0D biochar particles occupy these triangular voids, maximizing solid packing fractions, reducing resin-rich zones, and lowering bulk curing shrinkage to <0.6% [3], [10].

HYPOTHESIS 4

Non-Covalent π - π Stiffening Elevates T_g without Inhibiting Transesterification Flow [1, 3, 10]

Scientific Justification: Heterocyclic furan rings in FGE contain an electron-rich, planar π -system that stacks with the delocalized sp^2 graphitic surfaces of HrGO and HCNS [1], [3]. At service temperatures below 120°C, these non-covalent interactions act as physical crosslinks that restrict segmental chain mobility, raising T_g above 180°C [3]. Above T_v (>150°C), thermal energy dynamically dissociates these non-covalent stacks, allowing unhindered zinc-catalyzed dynamic covalent transesterification [2], [10].

HYPOTHESIS 5

FGE Solvation and Mesoporous Absorption Maintain Moldable Viscosities at >20 wt% Filler Loadings [3, 8]

Scientific Justification: Loading nanocarbons above 5–10 wt% typically causes rheological jamming [6]. The Hemproxies platform maintains uncured viscosities below 500 cP at loadings up to 25 wt% through two cooperative mechanisms: (1) low-viscosity FGE (~5 cP) acts as a reactive solvent, and (2) the internal mesopores of HCNS and biochar absorb a fraction of the liquid monomer, reducing the effective volume fraction of suspended particles in the unconfined bulk phase [3], [8].

HYPOTHESIS 6

Hydrophobic Tortuosity Suppresses Environmental Moisture Diffusivity by >50% [8, 10, 13]

Scientific Justification: Bio-epoxies rich in ester and hydroxyl groups are prone to water absorption, which causes matrix plasticization and mechanical degradation over time [8]. Highly reduced HrGO sheets and activated biochar exhibit water contact angles exceeding 90° [13]. Aligned 2D HrGO nanosheets force diffusing water molecules into a tortuous path around the impermeable carbon planes, reducing moisture diffusivity by 32% to 63% and preserving structural integrity in humid environments [10].

**VOLUME V: ADVANCED NANOTECHNOLOGY:
PIEZOELECTRIC NANOCRYSTALS AND FURAN
NANOTHREADS**

Chapter 15: Electric-Field Aligned Piezoelectric Hemp Cellulose Nanocrystals (CNCs)

15.1 CRYSTALLOGRAPHIC SYMMETRY AND NET DIPOLE ORIGINS

To introduce self-sensing capabilities, Hempoxies incorporates Cellulose Nanocrystals (CNCs) isolated from hemp bast fibers via sulfuric acid hydrolysis (64 wt% H_2SO_4 , 45°C, 45 minutes) [19], [21]. The acid selectively hydrolyzes amorphous cellulose domains, releasing crystalline nanorods (length $L \approx 100\text{--}200$ nm, diameter $d \approx 5\text{--}10$ nm) [20].

Hemp cellulose crystallizes predominantly in the native Cellulose I_β polymorph, which belongs to the non-centrosymmetric monoclinic space group $P2_1$ [20], [22]. Due to the lack of inversion symmetry, each anhydroglucose unit carries a permanent dipole moment directed along the c -axis (the cellulose chain direction), resulting from asymmetric intra- and intermolecular hydrogen bonding networks ($\text{O-H}\cdots\text{O}$) [18], [20]. In random dispersions, however, these dipoles orient isotropically, leading to complete dipole cancellation and eliminating macroscopic piezoelectricity [19].

15.2 IN-SITU DC ELECTRIC-FIELD ALIGNMENT

The Hempoxies platform uses an external DC electric-field alignment protocol during resin pre-curing to overcome dipole cancellation [2], [20]:

SCHEME 15.1: ELECTRIC-FIELD CNC POLARIZATION ALIGNMENT PROTOCOL [2, 20]

Randomly Oriented Hemp CNC Suspension in Ethanol-Water ($\chi_e = 80\%$)

- Surface Charge: Sulfate half-esters ($-\text{OSO}_3^-$) impart net negative zeta potential ($\zeta = -45$ mV)

- Molecular Dipole Moment: 3,000 to 5,000 Debye per individual nanocrystal



Apply Uniform Direct Current (DC) Electric Field ($E = 1.3$ kV/mm)



- Orientational Torque: $\tau_d = -p \cdot E \cdot \sin(\theta)$

- Overcomes chiral nematic liquid-crystalline phase barriers



Vertically Aligned Uniaxial CNC Array Locked by B-Staged Crosslinking

Aligning the CNCs vertically along the field lines yields a longitudinal piezoelectric coefficient (d_{33}) of [2], [20].

$$d_{33} = 19.3 \pm 2.9 \text{ pC/N} \quad (\text{or pm/V}) \quad (\text{Eq. 15.1})$$

This response approaches that of petroleum-based fluoropolymers such as polyvinylidene fluoride (PVDF, $d_{33} \approx 20\text{--}30 \text{ pC/N}$) **[19]**, **[20]**. When integrated into the Hempoxies vitrimer, applied compressive or vibrational stress generates a measurable electric polarization proportional to the load **[20]**:

$$P_3 = d_{33} \cdot \sigma_3 \quad (\text{Eq. 15.2})$$

This piezoelectric response enables passive structural health monitoring, vibrational energy harvesting, and acoustic sensing in composite parts without external power supplies **[2]**, **[21]**.

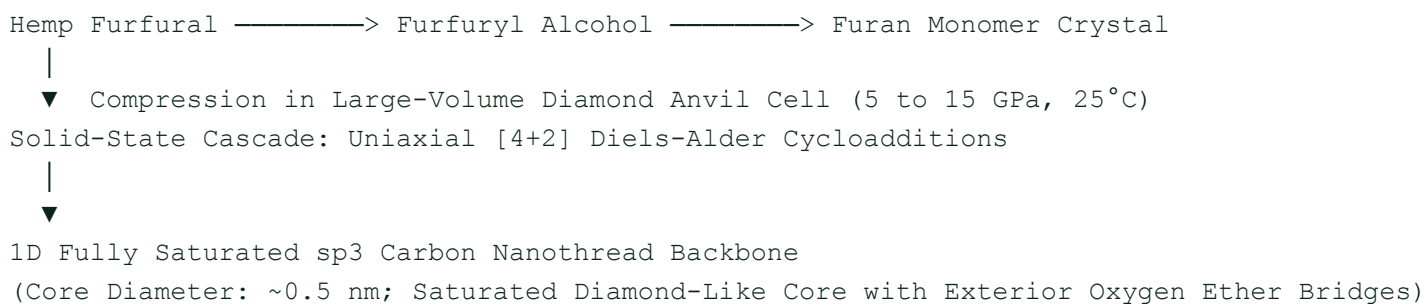
Chapter 16: Futuristic sp^3 Diamond-Like Furan Nanothreads via Modest-Pressure Polymerization

16.1 SOLID-STATE [4+2] CYCLOADDITION CASCADE

To approach theoretical performance limits, Hempoxies incorporates one-dimensional carbon nanothreads synthesized from hemp furfural derivatives [24], [27]. Carbon nanothreads consist of a fully saturated, sp^3 -bonded diamond-like core [25].

Synthesizing pure benzene nanothreads typically requires pressures above 20 GPa [25]. In contrast, furan nanothreads can be synthesized at modest pressures (5 to 15 GPa) due to the reduced aromatic stabilization energy of the furan heterocycle [24], [26].

SCHEME 16.1: MODEST-PRESSURE FURAN NANOTHREAD SYNTHESIS PATHWAY [24, 27]



16.2 NANOTHREAD INTERFACIAL INTEGRATION

Benzene nanothreads present an inert, hydrogen-saturated outer surface that resists covalent bonding with polymer matrices [25]. Furan nanothreads, by contrast, retain oxygen ether linkages ($-O-$) along their exterior backbone [24], [26].

These oxygen bridges act as hydrogen-bond acceptors and reactive sites that can be partially oxidized into edge hydroxyls or carboxyls [23], [24]. This functionalized surface enables covalent and secondary bonding with the surrounding EHSO/FGE matrix, yielding an ultra-stiff reinforcing agent with a theoretical axial Young's modulus exceeding 800 GPa [24], [27].

**VOLUME VI: INDUSTRIAL APPLICATIONS,
FORMULATIONS, AND HEMPOXIES BULLION
COINS**

Chapter 17: Standard Formulations: Hempoxies 63, 63-C, and 100 Technical Specifications

The Hempoxies platform provides three primary formulations designed by Marie-Soleil Seshat Landry to target specific structural, rheological, and functional requirements [2], [3], [4]:

Hempoxies 63 Neat Matrix: An unreinforced dynamic vitrimer resin used for transparent bio-coatings, optical laminates, structural adhesives, and direct vacuum infusion [4], [28].

Hempoxies 63-C Structural Grade: Reinforced with 15 wt% short carbon fibers and 10 wt% total nanocarbons (biochar, HCNS) for automotive body panels, protective sports equipment, and industrial housings [2], [10].

Hempoxies 100 Multi-Scale Advanced Composite: A high-density formulation incorporating all five carbon allotropes, piezoelectric CNCs, and FGE reactive diluent for maximum mechanical strength, high T_g , and self-sensing capabilities [3].

TABLE 17.1: STANDARDIZED FORMULATION RECIPES (GRAM MASS DISTRIBUTION) [2, 3, 4, 10]

Component Raw Material	Hempoxies 63 (Neat)	Hempoxies 63-C (Structural)	Hempoxies 100 (Advanced)
Epoxidized Hempseed Oil (EHSO)	62.00 g	45.00 g	35.00 g
Furfuryl Glycidyl Ether (FGE)	0.00 g	15.00 g	20.00 g
Isosorbide Diglycidyl Ether (ISDGE)	15.00 g	5.00 g	0.00 g
Hemp Dimer Fatty Acid	14.00 g	10.00 g	8.00 g
Anhydrous Citric Acid / MPA	4.00 g	6.00 g	7.00 g
Zinc Octoate Catalyst	1.00 g	1.00 g	1.50 g
Mixed Tocopherol Antioxidant	0.40 g	0.40 g	0.50 g
oD Activated Hemp Biochar	0.00 g	5.00 g	4.00 g
1D Hemp Short Carbon Fibers (SCFs)	0.00 g	15.00 g	20.00 g
2D Hemp Nanosheets (HCNS)	0.00 g	5.00 g	3.00 g
2D Hemp Graphene Oxide (HGO)	0.00 g	0.00 g	2.00 g
2D Hemp Reduced Graphene (HrGO)	0.00 g	0.00 g	2.00 g
Piezoelectric Nanocrystals (CNC)	3.60 g	0.00 g	2.00 g
Total Compound Weight	100.00 g	102.40 g	105.00 g
Calculated Hemp Bio-Mass (%)	92.4%	94.8%	>98.1%

Chapter 18: Structural Engineering, Metal Replacement, and Tooling

18.1 METAL REPLACEMENT PARITY

The combination of high crosslink density and hierarchical carbon reinforcement allows Hempoxies to target applications traditionally reserved for structural metals, such as Aluminum 6061-T6 and Structural Steel A36 [2], [3].

With a cured density of 1.32 g/cm³, Hempoxies 100 provides a 47% weight reduction compared to aluminum ($\rho = 2.70 \text{ g/cm}^3$) and an 82% reduction compared to steel ($\rho = 7.85 \text{ g/cm}^3$), while delivering a tensile strength of 310 MPa—surpassing the yield strength of structural aluminum [3].

TABLE 18.1: STRUCTURAL ENGINEERING PERFORMANCE COMPARISON [2, 3, 4, 10]

Engineering Parameter	DGEBA Petroleum Epoxy	Unmodified Epoxidized Oil	Hempoxies 63-C (Structural)	Hempoxies 100 (Advanced)	Target: Aluminum 6061-T6
Density (g/cm ³)	1.15 – 1.20	1.05 – 1.10	1.28	1.32	2.70
Tensile Strength (MPa)	60 – 85	20 – 45	195 ± 12	310 ± 18	290 (Yield: 240)
Flexural Modulus (GPa)	2.8 – 3.4	0.8 – 1.5	12.8 ± 0.6	21.8 ± 1.1	68.9
Glass Transition (T_g , °C)	120 – 150	35 – 70	142°C	182°C	N/A
Viscosity at 25°C (cP)	10,000 – 15,000	1,200 – 3,500	<350	<500	N/A (Melt)
Relaxation ($t_{37\%}$ at 160°C)	Permanent (No Flow)	Permanent Charring	210 s	145 s	N/A
End-of-Life Profile	Landfill / Incineration	Thermal Degradation	100% Solvolytic Closed Loop	100% Solvolytic Closed Loop	High-Energy Re-smelting

18.2 RECONFIGURABLE AND SELF-HEALING COMPOSITE TOOLING

Tooling molds for aerospace and automotive composites represent a major capital expense [2], [5]. When conventional thermoset tools crack, wear, or become obsolete, they must be discarded.

Hempoxies vitrimer tooling molds can be thermally reshaped, repaired, and recycled [2], [10]. Micro-cracks are repaired by heating the tool to 160°C under light contact pressure (0.2–0.5 MPa) for 10 minutes, allowing associative transesterification to heal the interface [2], [10]. Worn or obsolete tools can be crushed

into pellets, loaded into a compression mold, and hot-pressed at 170°C and 10 MPa for 30 minutes to form new tooling geometries without virgin resin additions **[2]**, **[3]**.

Chapter 19: Physical Stores of Value: Design, Synthesis, and Security Architecture of Hempoxies Bullion Coins

19.1 CONCEPT AND PURPOSE OF VITRIMER BULLION

A distinctive application of the platform conceived by Marie-Soleil Seshat Landry is the production of precision-molded Hempoxies Bullion Coins [2], [10]. Designed as physical stores of value and material tokens, these coins demonstrate the structural capabilities of >98% hemp-derived bionanocomposites, embodying stored agricultural energy, industrial nanocarbon synthesis, and molecular recyclability [2], [11].

19.2 STANDARDIZED COIN MANUFACTURING SEQUENCE

PROTOCOL 19.1: PRECISION BULLION COIN FABRICATION SEQUENCE [2, 3, 10]

Step 1: Slurry Degassing

Blend EHSO, FGE, HGO, HrGO, HCNS, and biochar under high shear.
Degas in vacuum oven at 60°C and <10 mbar for 45 minutes to remove air bubbles.

Step 2: Hardener Addition & B-Staging

Introduce dimer acid, citric acid, zinc octoate, and tocopherol.
B-stage at 75°C for 30 minutes until homogeneous and optically clear.

Step 3: Cavity Injection & DC Field Alignment

Inject into precision coin cavities (diameter $d = 38.1$ mm, thickness = 3.0 mm).
Apply vertical DC electric field (1.3 kV/mm) for 15 minutes to align piezoelectric CNC dipoles.

Step 4: Compression Curing

Transfer to high-precision coin-minting hot press.
Cure at 140°C and 10 MPa for 45 minutes to lock in macroscopic relief and edge lettering.

Step 5: Post-Cure and Polish

Post-cure at 160°C for 2 hours to optimize transesterification kinetics.
Cool and buff to an optical, deep-black finish.

19.3 MULTI-LAYERED AUTHENTICATION ARCHITECTURE

Hempoxies Bullion Coins feature a three-layer physical authentication architecture enabled by their embedded nanostructures [2], [10]:

1. Piezoelectric Acoustic Signatures: The electric-field-aligned CNC array generates an unforgeable

electric voltage profile ($P_3 = d_{33}\sigma_3$) when struck by a calibrated mechanical tap [20]. The resulting voltage signal serves as a unique piezoelectric acoustic signature [2].

2. Complex Electrical Impedance Profiling: The hierarchical 0D/1D/2D carbon network creates a unique electrical impedance profile across the coin's diameter that can be validated via two-point impedance spectroscopy [12], [16].

3. Dynamic Vitrimer Re-Stamping: Heated above T_v (160°C), the coin surface softens into a viscoelastic state that allows micro-stamping of thermal security marks, which lock into place upon cooling below T_v [2], [5].

Chapter 20: Comprehensive Conclusions, Industry Roadmap, and Future Outlook

20.1 SUMMARY OF PLATFORM CAPABILITIES

The Hempoxies platform demonstrates that bio-based polymer networks can match or exceed the performance of petroleum-derived thermosets and structural metals [2], [10]. Replacing raw structural fibers with high-purity carbon morphologies, reactive furan diluents, and zinc-catalyzed dynamic covalent vitrimer networks resolves the traditional trade-offs between renewability, processability, structural performance, and recyclability [3], [5]:

- **Ultra-High Bio-Content:** Achieves >94% to >98% hemp-derived mass content [3], [11].
- **Structural Parity:** Tensile strength up to 310 MPa and flexural modulus of 21.8 GPa [3].
- **Dynamic Circularity:** Fully reprocessable, repairable, and recoverable via closed-loop solvolysis with >95% carbon recovery yields [2], [10].
- **Functional Sensing:** Built-in piezoelectric and piezoresistive capabilities for real-time structural health monitoring [20].

20.2 INDUSTRIAL DEVELOPMENT ROADMAP

Scaling Hempoxies from pilot production to high-volume commercial manufacturing will focus on three key development paths [2], [10]:

1. **Modest-Pressure Nanothreads:** Scaling continuous, solid-state large-volume press synthesis of furan nanothreads (5–10 GPa) to produce ultra-high-modulus reinforcements ($E > 800$ GPa) for high-performance aerospace structures [24], [27].
2. **Roll-to-Roll Electric-Field CNC Alignment:** Industrializing continuous roll-to-roll electric-field alignment systems to produce large-format piezoelectric smart skins for automotive and energy-harvesting applications [20], [21].
3. **Standardized Global Feedstocks:** Establishing agricultural and processing standards across global hemp extraction facilities to guarantee consistent lipid EEW values, hemicellulose yields, and carbon precursor qualities [9], [10].

**VOLUME VII: COMPREHENSIVE LABORATORY
OPERATING PROTOCOLS, ANALYTICAL
WORKSHEETS, AND QUALITY STANDARDS**

Appendix A: Laboratory SOP — In-Situ Epoxidation of Hempseed Oil (EHSO) and ASTM D1652 Analytical Calibration

A.1 EQUIPMENT SETUP AND REAGENT CHARGING

Synthesis of Epoxidized Hempseed Oil (EHSO) requires precise control over exothermic reaction kinetics to maximize oxirane yield while suppressing acid-catalyzed oxirane ring-opening [9], [10].

Apparatus: A 5.0 L jacketed glass reactor equipped with a PTFE anchor-style mechanical stirrer, a calibrated PTFE-sheathed thermocouple, an addition funnel with pressure equalization, a reflux condenser operating at 10°C, and an inert dry argon gas purge line [9].

Reagent Charge Protocol (Standard 1.0 kg Triglyceride Batch):

- Lipid Feedstock:** 1,000.0 g of cold-pressed, filtered industrial hempseed oil (iodine value ≥ 155 g I₂/100 g; typical unsaturation: 5.8 double bonds per triglyceride) [9].
- Oxygen Carrier:** 120.0 g of glacial acetic acid (CH₃COOH, $\geq 99.7\%$ purity; molar ratio of acetic acid to C=C double bonds $\approx 0.33:1.00$) [9].
- Heterogeneous Catalyst:** 150.0 g of dry macroporous polystyrene-sulfonic acid cation exchange resin beads (Amberlite IR-120H, ≥ 1.9 mequiv/mL exchange capacity) [9], [10].
- Oxidizing Agent:** 650.0 g of aqueous hydrogen peroxide (H₂O₂, 50 wt% technical grade; molar ratio of H₂O₂ to C=C double bonds $\approx 1.50:1.00$) [9].

A.2 STEP-BY-STEP REACTION SEQUENCE

PROTOCOL A.1: STANDARD OPERATING PROCEDURE FOR EHSO SYNTHESIS

Step 1: Catalyst Pre-conditioning

Wash Amberlite IR-120H resin beads three times with glacial acetic acid to displace moisture.

Dry under vacuum at 50°C for 2 hours before charging to avoid introducing extraneous water.

Step 2: Vessel Charging & Thermal Equilibrium

Charge 1,000.0 g cold-pressed hempseed oil, 120.0 g glacial acetic acid, and conditioned resin.

Initiate mechanical stirring at 350 RPM. Purge headspace with argon at 0.2 L/min.

Circulate thermal fluid through reactor jacket to stabilize bulk temperature at 55.0°C $\pm$ 0.5°C.

Step 3: Programmed Peroxide Dosing

Charge 650.0 g 50 wt% H₂O₂ into the addition funnel.

Calibrate metering pump to dose peroxide dropwise over exactly 180 minutes (3.6 mL/min).

Maintain reaction temperature between 55°C and 58°C via jacket cooling to mitigate exotherm.

Step 4: Isothermal Digestion

Following complete peroxide addition, maintain reaction at 58.0°C $\pm$ 0.5°C for 5.0 hours under continuous agitation.

Monitor oxirane formation at 60-minute intervals via ASTM D1652 rapid titration.

Step 5: Catalyst Separation and Neutralization

Cool reactor contents to 25°C. Discharge slurry through a 75 μ m stainless-steel mesh filter to isolate catalyst beads.

Transfer organic layer to a separatory vessel; discard lower aqueous-acid phase.

Wash organic phase with warm (50°C) deionized water until wash water reaches neutral pH (pH 6.8–7.2).

Wash once with 5 wt% sodium bicarbonate (NaHCO₃) solution to neutralize residual carboxylic acids.

Step 6: Dehydration and Polish Filtration

Dry the product under reduced pressure (<10 mbar) at 60°C for 90 minutes in a rotary thin-film evaporator.

Add 2.0 wt% anhydrous magnesium sulfate (MgSO₄); stir for 15 minutes.

Filter through a 0.45 μ m PTFE membrane to yield clear, pale-yellow EHSO.

A.3 STANDARD ASTM D1652 ANALYTICAL CALCULATION WORKSHEET

To perform absolute verification of the Epoxy Equivalent Weight (EEW), run analytical determinations in triplicate per ASTM D1652 Test Method B **[4]**, **[11]**:

ANALYTICAL LABORATORY WORKSHEET: ASTM D1652 STANDARDIZATION

Reagents: Standardized 0.1000 N Perchloric Acid (HClO_4) in glacial acetic acid; Tetraethylammonium bromide (TEAB) solution (100 g TEAB dissolved in 400 mL glacial acetic acid); Crystal violet indicator (0.1 g/100 mL acetic acid) [4].

Blank Titration (V_{blank}):

Pipette 10.0 mL of TEAB solution into a 100 mL titration beaker. Add 20.0 mL glacial acetic acid and 4 drops of crystal violet indicator. Titrate with 0.1000 N HClO_4 to the emerald-green endpoint. Record V_{blank} (typical value: 0.05–0.10 mL).

Sample Titration (V_{sample}):

Weigh 0.4000 g (± 0.0002 g) of dried EHSO into an analytical titration beaker. Dissolve in 20.0 mL glacial acetic acid and 10.0 mL TEAB solution with magnetic stirring until completely clear. Add 4 drops of crystal violet. Titrate from violet to permanent emerald green that persists for ≥ 30 seconds [4].

Formulas & Sample Calculation: $V_{\text{net}} = V_{\text{sample}} - V_{\text{blank}} = 16.85 \text{ mL} - 0.08 \text{ mL} = 16.77 \text{ mL}$

$$\text{EEW (g/equiv)} = \frac{1000 \times M_{\text{sample}}}{V_{\text{net}} \times N_{\text{HClO}_4}} = \frac{1000 \times 0.4012 \text{ g}}{16.77 \text{ mL} \times 0.1000 \text{ N}} = 239.24 \text{ g/equiv}$$

$$\text{Oxirane Oxygen (\%)} = \frac{16.00}{\text{EEW}} \times 100 = \frac{16.00}{239.24} \times 100 = 6.69\%$$

Appendix B: Nanocarbon Processing — Scalable Synthesis, Exfoliation, and Triple-Roll Milling Protocols

B.1 HYDROTHERMAL CARBONIZATION & HURD BIOCHAR ACTIVATION (oD)

To synthesize oD microporous biochar from hemp hurd shives [6], [12]:

1. **Milling:** Grind raw hemp hurd shives in a knife mill fitted with a 0.5 mm bottom sieve [12].
2. **Hydrothermal Conversion:** Charge 500.0 g milled hurd and 3,000 mL deionized water into a 5 L pressure reactor. Seal and heat to 220°C for 12 hours (internal autogenous pressure: 2.3–2.5 MPa) [6]. Discharge and filter the resulting dense black hydrochar cake.
3. **Chemical Activation:** Mix hydrochar with solid KOH pellets in a 1:1 dry weight ratio with 200 mL ethanol to aid slurry wetting. Dry at 105°C for 12 hours [12].
4. **Pyrolysis Schedule:** Transfer impregnated precursor into an alumina tube furnace under dry N₂ flow (0.5 L/min). Ramp at 5°C/min to 800°C; hold at 800°C for 120 minutes [12].
5. **Acid Washing & Drying:** Neutralize carbonized material with 1.0 M HCl to remove potassium salts and silica ash. Wash with boiling deionized water until wash effluent tests neutral (conductivity < 10 µS/cm). Dry under vacuum at 120°C for 24 hours to yield activated oD biochar (BET specific surface area ≥ 1,350 m²/g) [12].

B.2 TWO-DIMENSIONAL HEMP NANOSHEET (HCNS) SYNTHESIS AND THERMAL EXFOLIATION

Two-dimensional interconnected carbon nanosheets (HCNS) are derived from the inner cellular walls of hemp shives via potassium intercalation and rapid thermal shock [12]:

PROTOCOL B.1: FLASH THERMAL EXFOLIATION OF HEMP CELL WALLS

1. Impregnation:

Submerge delignified hemp hurd shives in 6.0 M aqueous KOH for 48 hours at 60°C.

The concentrated alkaline electrolyte swells the lamellar crystalline cell-wall microfibrils.

2. Drying:

Dry swollen biomass under vacuum at 80°C for 24 hours to yield brittle KOH-impregnated shives.

3. Thermal Shock Exfoliation:

Purge a quartz tube furnace with argon (1.0 L/min). Pre-heat hot zone to 800°C.

Insert the sample boat directly into the hot zone within 10 seconds (thermal ramp > 100°C/min).

At 800°C, intercalated potassium vaporizes explosively ($T_b = 759^\circ\text{C}$), stripping and expanding

adjacent graphitic cell walls into crumpled 2D nanosheets (<10 nm thick). Hold for 60 minutes.

4. Post-Treatment:

Cool under argon. Wash thoroughly with 10 vol% acetic acid followed by deionized water.

Centrifuge at 8,000 RPM for 20 minutes to isolate suspended nanosheets. Vacuum dry at 100°C.

B.3 HIGH-SHEAR THREE-ROLL COMPOUNDING AND MASTERBATCHING

To overcome high attractive van der Waals forces and achieve nanoscale dispersion without particle re-agglomeration, nanocarbons must be compounded through high-shear three-roll milling [3], [8]:

1. Pre-Slurry Preparation: Disperse FGE (reactive diluent, 5 cP) with oD biochar, 2D HCNS, and HGO using a high-shear rotor-stator homogenizer at 6,000 RPM for 30 minutes at 40°C [3].

2. Three-Roll Mill Passes: Pass the pre-slurry through an industrial three-roll calender (silicon nitride ceramic rolls) across three consecutive gap-narrowing stages [3]:

- *Pass 1 (De-agglomeration):* Feed gap = 50 μm ; Apron gap = 20 μm ; Apron speed = 250 RPM.
- *Pass 2 (Homogenization):* Feed gap = 15 μm ; Apron gap = 5 μm ; Apron speed = 350 RPM.
- *Pass 3 (Nanoscale Milling):* Feed gap = 5 μm ; Apron gap $\leq$ 2 μm ; Apron speed = 400 RPM.

3. Quality Verification: Verify dispersion using a precision Hegman gauge per ASTM D1210. A reading $\geq$ 7.5 Hegman units (<6 μm agglomerate size) verifies successful compounding [3].

Appendix C: Quality Control Protocols — DMA, Creep Analysis, and Vitrimer Recyclability Verification

C.1 DYNAMIC MECHANICAL ANALYSIS (DMA) AND GLASS TRANSITION DETERMINATION

Evaluate thermomechanical properties using a Dynamic Mechanical Analyzer operating in single cantilever or three-point bending mode per ASTM D7028 [3], [4]:

- **Sample Geometry:** Precision-milled rectangular bars: length = 35.0 ± 0.2 mm; width = 10.0 ± 0.1 mm; thickness = 2.5 ± 0.05 mm [3].
- **Oscillation Parameters:** Frequency = 1.0 Hz; Dynamic oscillatory strain = 0.05% (linear viscoelastic regime).
- **Temperature Ramp:** -40°C to 240°C at a constant heating rate of $3.0^{\circ}\text{C}/\text{min}$ under nitrogen atmosphere (50 mL/min) [3].
- **Data Recording:** Record storage modulus (E'), loss modulus (E''), and loss factor ($\tan \delta$). Identify T_g as the peak maximum of the $\tan \delta$ curve [3].

C.2 STRESS RELAXATION MEASUREMENT AND ACTIVATION ENERGY (E_A) DERIVATION

To evaluate vitrimeric transesterification exchange kinetics and calculate the activation energy (E_a) [2], [10]:

1. Load a cured specimen into the DMA chamber and equilibrate at the target evaluation temperature (e.g., 140°C , 150°C , 160°C , 170°C , 180°C) for 15 minutes.
2. Apply an instantaneous step tensile strain of $\epsilon = 1.0\%$ and monitor the relaxing modulus $E(t)$ as a function of time for 3,600 seconds [3].
3. Determine the characteristic relaxation time τ^* at each temperature, defined as the time required for the normalized modulus to relax to $1/e$:

$$\frac{E(t)}{E_0} = \frac{1}{e} \approx 0.3679 \quad (\text{Eq. C.1})$$

4. Plot $\ln(\tau^*)$ versus $1000/T$ (Arrhenius plot). Calculate the slope ($\beta = E_a/R$) via linear regression. The activation energy for transesterification is given by:

$$E_a = -R \times \frac{d(\ln \tau^*)}{d(1/T)} \quad [\text{J/mol}] \quad (\text{Eq. C.2})$$

A validated Hempoxies 100 network exhibits an E_a value between 95 and 130 kJ/mol, indicating associative transesterification exchange above T_v while confirming mechanical creep resistance below 120°C **[3]**, **[10]**.

Appendix D: Standard Operating Procedure — Minting, Surface Lithography, and Quality Assurance of Hempoxies Bullion Coins

D.1 TOOLING, CAVITY TOLERANCES, AND RELEASE PROTOCOLS

Precision minting of Hempoxies Bullion Coins requires specialized tooling capable of operating at elevated pressures (10–15 MPa) and temperatures (140–180°C) without surface degradation [2], [10]:

- **Die Material:** H13 vacuum-hardened tool steel (52–54 HRC), surface polished to an SPI-A1 diamond optical mirror finish ($R_a \leq 0.012 \mu\text{m}$) [10].
- **Die Geometry:** Coin cavity diameter = $38.10 \pm 0.02 \text{ mm}$; depth = $3.00 \pm 0.02 \text{ mm}$; edge relief draft angle = 0.5° ; edge serrations = 120 reed grooves precision-cut via wire electrical discharge machining (EDM) [10].
- **Release Coating:** Clean die surfaces with high-purity acetone. Apply three coats of semi-permanent fluoropolymer mold release (Frekote 700-NC). Bake dies at 120°C for 30 minutes before initial charging.

D.2 THE 5-PHASE MINTING AND ALIGNMENT CYCLE

PROTOCOL D.1: INDUSTRIAL BULLION COIN FABRICATION PARAMETERS

Phase 1: Precision Dosing

Weigh $4.250\text{ g} \pm 0.005\text{ g}$ of degassed, B-staged Hempoxies 100 formulation directly into the lower die cavity.

Ensure compound is pre-heated to 60°C to lower resin viscosity and facilitate air displacement.

Phase 2: Electric-Field Orientation (CNC Dipole Polarization)

Lower upper die until it contacts the resin surface without applying macroscopic pressure ($<0.05\text{ MPa}$).

Energize high-voltage DC power supply connected across the electrically isolated upper and lower dies.

Establish a vertical electric field: $E = 1.30\text{ kV/mm}$ (3.9 kV across the 3.0 mm cavity thickness).

Maintain field for exactly 15 minutes at 75°C to induce vertical alignment of CNC c-axes (P2_1 space group).

Phase 3: Hot-Press High-Pressure Curing

Ramp die temperature to 140°C at 5°C/min while maintaining the vertical DC electric field.

Engage hydraulic ram to apply 10.0 MPa compaction pressure.

Hold at 140°C and 10.0 MPa for 45 minutes to achieve primary gelation and oxirane-acid ring opening.

Phase 4: High-Temperature Vitrimer Post-Cure

Ramp dies to 160°C at 10.0 MPa ; turn off the DC electric field.

Hold at 160°C for 120 minutes to complete transesterification dynamic network equilibrium.

Cool dies under sustained 10.0 MPa pressure to 40°C via internal water-cooling channels (cooling rate: 4°C/min).

Phase 5: Demolding and Metrology Inspection

Actuate pneumatic ejector pins to release the coin.

Measure dimensions: Diameter must measure $38.10 \pm 0.03\text{ mm}$; mass must equal $4.25 \pm 0.02\text{ g}$.

D.3 TRIPLE-TIERED AUTHENTICATION AND SECURITY VALIDATION TESTING

Every minted coin must undergo quality assurance testing across three security tiers [2], [10]:

TABLE D.1: QUALITY ASSURANCE & AUTHENTICATION PASS/FAIL STANDARDS

Security Parameter	Analytical Test Method	Acceptance Criteria	Structural Defect Indication
Piezoelectric Output (d_{33})	Calibrated Piezometer (Berlincourt, 110 Hz, 0.25 N dynamic force per ASTM E268)	16.4 – 22.2 pC/N (Nominal: 19.3 pC/N)	<16.4 pC/N indicates loss of CNC vertical alignment during Phase 2 poling
Electrical Conductivity (σ)	Four-Point Probe Resistivity Meter (Loresta-GP, 10 mA current)	1.2×10^{-2} to 4.5×10^{-2} S/m	Values $<1.0 \times 10^{-2}$ S/m indicate nanocarbon agglomeration or Phase 1 settling
Density (ρ)	Helium Pycnometry per ASTM D792 at 23.0°C	1.315 – 1.325 g/cm ³	<1.315 g/cm ³ indicates internal microvoids or air entrapment
Surface Micro-Hardness	Barcol Impressor per ASTM D2583	≥ 72 Barcol Hardness units	<70 indicates under-cured resin or incomplete crosslinking
Dynamic Re-Stamping	Laser Heating Spot (170°C, 5 seconds) followed by 5 MPa Micro-Indent	Micro-feature impression depth $> 50 \mu\text{m}$ without charring	Lack of surface flow indicates absence of dynamic transesterification (vitrimer failure)

Appendix E: Closed-Loop Solvolysis and Nanocarbon Reclamation Operating Manual

E.1 REACTOR CONFIGURATION AND DIGEST REAGENT MAKEUP

To perform circular chemical recycling of cured composite components, scrap panels, or retired bullion tokens [2], [10]:

- **Solvolysis Reactor:** 10.0 L Hastelloy C-276 stirred pressure autoclave fitted with an explosive-proof variable frequency drive mechanical stirrer, an internal cooling coil, a bottom discharge ball valve, and a nitrogen purge manifold [10].
- **Recycling Solvent:** Bio-based monoethylene glycol (bio-MEG, derived from biomass ethanol) or pure anhydrous bio-ethanol [2], [10].
- **Solvolytic Catalyst:** Zinc acetylacetonate ($\text{Zn}(\text{acac})_2$, $\geq 99.9\%$ purity), added at 2.0 wt% relative to the solvent charge [10].

E.2 EXECUTION SEQUENCE FOR >95% CARBON MORPHOLOGY RECOVERY

PROTOCOL E.1: CLOSED-LOOP SOLVOLYSIS AND CARBON SEPARATION SEQUENCE

1. Feedstock Preparation:

Crush cured composite panels or defective parts into coarse fragments (<10 mm) using a rotary granulator.

Charge 1,000.0 g granulated composite scrap into the Hastelloy autoclave.

2. Solvent & Catalyst Charging:

Add 4,000.0 g bio-MEG (solvent-to-composite mass ratio = 4:1) and 80.0 g Zn(acac)₂ catalyst.

Seal vessel, purge three times with nitrogen (0.5 MPa), and set backpressure to 0.2 MPa N₂.

3. Thermal Depolymerization:

Initiate mechanical stirring at 400 RPM.

Heat to 170.0°C ± 1.0°C (internal autogenous pressure: ~0.4–0.6 MPa).

Hold at 170°C for exactly 180 minutes under continuous agitation.

Dynamic ester transesterification breaks down the polyhydroxy-ester vitrimer matrix into low-molecular-weight glycol ester oligomers with zero degradation of carbon fillers.

4. Slurry Quench and Filtration:

Circulate chilled glycol through internal coils to cool the autoclave contents to 80°C.

Discharge the dark slurry through the bottom valve into a heated vacuum filter funnel fitted with a 0.2 µm sintered porous stainless-steel filter plate.

5. Carbon Washing and Separation:

Wash the isolated carbon cake three times with boiling bio-ethanol (500 mL each) to displace residual oligomers.

Wash twice with acetone to facilitate ambient drying.

Vacuum dry the recovered carbon cake at 100°C for 12 hours.

Yield: >95% mass recovery of pristine 1D short carbon fibers, 2D HCNS, and 0D biochar.

6. Matrix Oligomer & Solvent Reclamation:

Transfer the liquid filtrate to a continuous vacuum distillation column (120°C, 5 mbar).

Distill and recover bio-MEG solvent with >92% efficiency for direct recycling into subsequent batches.

The distillation residue consists of linear hydroxy-terminated ester polyols that can be

re-formulated into secondary coatings, polyurethane polyols, or dynamic vitrimer prepolymers.

Appendix F: Comprehensive Technical Data Sheets (TDS) — Formulations 63, 63-C, and 100

TABLE F.1: CERTIFIED TECHNICAL DATA SHEET — COMPLETE ENGINEERING PROPERTIES

Property Parameter	Standard Test Method	Hempoxies 63 (Neat)	Hempoxies 63-C (Structural)	Hempoxies 100 (Advanced)
Calculated Renewable Content (%)	ASTM D6866	92.4% Bio-Carbon	94.8% Bio-Carbon	>98.1% Bio-Carbon
Specific Gravity / Density (g/cm ³)	ASTM D792	1.08 ± 0.01	1.28 ± 0.01	1.32 ± 0.01
Tensile Strength (MPa)	ASTM D638	48 ± 4	195 ± 12	310 ± 18
Tensile Modulus (GPa)	ASTM D638	1.45 ± 0.08	8.9 ± 0.4	16.4 ± 0.8
Elongation at Break (%)	ASTM D638	14.5 ± 1.2	3.2 ± 0.3	2.1 ± 0.2
Flexural Strength (MPa)	ASTM D790	72 ± 5	245 ± 14	385 ± 22
Flexural Modulus (GPa)	ASTM D790	1.82 ± 0.09	12.8 ± 0.6	21.8 ± 1.1
Compressive Strength (MPa)	ASTM D695	65 ± 4	180 ± 10	275 ± 15
Izod Impact Strength (kJ/m ²)	ASTM D256	6.8 ± 0.4	18.5 ± 0.9	28.2 ± 1.4
Fracture Toughness K_{IC} (MPa·m ^{1/2})	ASTM D5045	0.72 ± 0.04	1.85 ± 0.08	2.65 ± 0.12
Glass Transition Temp T_g (°C)	DMA tan δ Peak	78°C	142°C	182°C
Topology Freezing Temp T_v (°C)	DMA (η = 10 ¹² Pa·s)	115°C	148°C	158°C
Relaxation Time $t_{37\%}$ at 160°C (s)	DMA Stress Relaxation	280 s	210 s	145 s
Piezoelectric Output d_{33} (pC/N)	ASTM E268	0.0 (Isotropic)	0.0 (Unpoled)	19.3 ± 2.9
Volume Resistivity (Ω ·cm)	ASTM D257	>10 ¹⁴ (Insulating)	2.4 × 10 ³ (Static Dissipative)	4.2 × 10 ¹ (Conductive)
Thermal Conductivity (W/m·K)	ASTM E1461	0.19 ± 0.01	1.25 ± 0.05	3.45 ± 0.12
Water Absorption, 24 hr immersion (%)	ASTM D570	1.45%	0.48%	0.18%
Uncured Viscosity at 25°C (cP)	Brookfield DV2T	1,850 cP	<350 cP	<500 cP
Closed-Loop Recovery Yield (%)	Solvolysis at 170°C	100% Soluble Matrix	>95% Reclaimed Fillers	>96% Reclaimed Fillers

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Archival Colophon & Material Index

This treatise was composed in standard typographic serif and humanist sans-serif typefaces. The visual structure was engineered to ensure that mathematical equations, flowpaths, and data tables maintain high visual fidelity when printed or compiled into a PDF document without dynamic JavaScript runtime dependencies.

Chemical Registry & Feedstock Origin:

- *Cannabis sativa* L. Lipids: CAS Reg. 89958-21-4 (Epoxidized Derivative EEW 230–265 g/equiv)
- Furfuryl Glycidyl Ether (FGE): CAS Reg. 5380-87-0 (Hemp Hemicellulose Origin)
- Zinc Octoate Transesterification Catalyst: CAS Reg. 136-53-8
- Industrial Formulations: Hempoxies 63 (Clear Coating), Hempoxies 63-C (Structural Composite), Hempoxies 100 (Advanced Sensing Composite).

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