

Technical Monograph on the Hempoxies Platform: Synthetic Pathways for Neat Bio-Vitrimer Matrices and Multi-Scale Reinforcement Architectures

Fundamental Polymer Physics and Dynamic Covalent Mechanics of Bio-Derived Vitrimers

The transition from conventional non-recyclable petroleum-derived thermosets to sustainable polymer networks has driven the development of Covalent Adaptable Networks (CANs), specifically vitrimers. Vitrimers represent a hybrid class of polymeric materials that combine the solvent resistance, dimensional stability, and mechanical modulus of permanently crosslinked thermosets under service conditions with the thermally triggered reprocessability, malleability, and recyclability of thermoplastics. Unlike dissociative CANs, such as retro-Diels-Alder networks, which undergo a dramatic drop in crosslink density and physical integrity upon heating, vitrimers operate exclusively via associative covalent exchange mechanisms. In an associative network, the cleavage of an existing dynamic covalent bond is directly coupled with the simultaneous formation of a new covalent bond across the reactive center. Consequently, the global crosslink density (ν_e) remains constant throughout processing, preventing internal voiding and structural collapse during remolding.

The temperature-dependent viscoelastic response of vitrimeric matrices is governed by two thermal transitions: the glass transition temperature (T_g), dictated by segmental chain mobility, and the topology freezing transition temperature (T_v), defined as the threshold above which dynamic exchange kinetics accelerate sufficiently to permit macroscopic flow. Below T_v , exchange kinetics are vitrified, and the material behaves as a classical elastic thermoset. Above T_v , the dynamic exchange rate obeys Arrhenius kinetics, and the characteristic stress relaxation time (τ^*) follows the relationship:

$$\tau^*(T) = \tau_0 \exp\left(\frac{E_a}{RT}\right)$$

where E_a represents the activation energy for dynamic bond exchange, τ_0 is the characteristic relaxation time at infinite temperature, R is the universal gas constant, and T is the absolute temperature. The stress relaxation behavior can be modeled using a Maxwell viscoelastic formulation where the effective melt viscosity (η) scales continuously with temperature according to an Arrhenius dependence rather than the Williams-Landel-Ferry (WLF) model typical of uncrosslinked thermoplastic melts.

In associative dynamic exchange, the network undergoes topological rearrangement through a transitory transition state. For instance, during transesterification, an open hydroxyl group attacks a nearby ester carbonyl to form a trigonal bipyramidal transition state, which subsequently cleaves the original ester linkage. Because the transition state maintains full connectivity, the crosslink density remains invariant throughout the topological shift, allowing the material to relax internal stresses without losing structural cohesion.

In the context of bio-based vitrimer engineering, Epoxidized Hemp Seed Oil (EHSO) serves as a

primary bio-derived monomer backbone. Raw hemp seed oil (*Cannabis sativa* L.) possesses a high degree of unsaturation dominated by linoleic and linolenic fatty acid chains. Catalytic epoxidation converts these double bonds into oxirane rings, achieving an oxirane oxygen content (O₀) typically between 6.8\text{ wt}\% and 8.6\text{ wt}\%, corresponding to an Epoxy Equivalent Weight (EEW) derived as:

$$\text{EEW}(\text{EHSO}) = \frac{16.00 \times 100}{\text{O}_0} \approx 186.0 \text{--} 235.3 \text{ g/eq}$$

A central challenge in utilizing EHSO as a structural matrix is the inherent flexibility of its long aliphatic triglyceride backbone. Curing EHSO with long-chain aliphatic hardeners produces high internal plasticization, low crosslink density, and an unsatisfactory glass transition temperature ($T_g < 45^\circ\text{C}$), alongside high uncured resin viscosity ($\sim 845 \text{ cP}$ at 25°C). The Hempoxies platform resolves this structural trade-off by incorporating biomass-derived Furfuryl Glycidyl Ether (FGE) as a reactive diluent. FGE contains a rigid furan ring that lowers uncured resin viscosity below 350 cP , facilitating liquid resin infusion manufacturing while increasing aromatic/heterocyclic crosslink density. This synergistic interaction converts the matrix from a flexible network into a structural biopolymer ($T_g > 140^\circ\text{C}$) capable of rapid stress relaxation at elevated temperatures.

Comprehensive Synthetic Catalog of Neat Hempoxies Vitrimer Matrices

Synthesizing neat (unfilled) Hempoxies vitrimer matrices requires introducing specific dynamic covalent linkages into the crosslinked epoxide network. Five chemical pathways have been developed within the Hempoxies platform to tailor mechanical performance, activation energy (E_a), processing windows, and environmental durability.

Matrix Synthesis Pathway	Key Reactive Components	Primary Dynamic Linkage	Catalyst System	Typical T _g (°C)	Activation Energy E _a (kJ/mol)	Relaxation Time τ* (s)	Key Advantages and Trade-Offs
Pathway 1: Transesterification CAN	EHSO, Citric Acid (CA) / Adipic Acid (AA), FGE	β-hydroxy ester exchange	Zinc Acetate Dihydrate / Zn(acac) ₂ (1.0\text{--}1.5\text{ mol}\%)	40\text{--}89	80\text{--}120	30\text{--}300\text{[span}_n_70](start_span)[span_74](start_span)[span_74](end_span) s} at 160\text{--}220^\circ\text{C}	Fully bio-derived precursors; requires metal catalysts which can leach over time.
Pathway 2: Dynamic Imine (Schiff Base)	EHSO, Vanillin / Dopamine, Bio-Amines (Cadaverin /	Imine (-\text{C}=\text{N}-) metathesis	Catalyst-Free (Intrinsic bio-amine catalysis)	80\text{--}135	100\text{--}145	< 30\text{ s} at 160\text{--}180^\circ\text{C}	Fast bond exchange without metal catalysts;

Matrix Synthesis Pathway	Key Reactive Components	Primary Dynamic Linkage	Catalyst System	Typical T _g (°C)	Activation Energy E _a (kJ/mol)	Relaxation Time τ [*]	Key Advantages and Trade-Offs
	e)	Transamination					sensitive to acidic moisture hydrolysis.
Pathway 3: Disulfide Metathesis & Dual-Dynamic	EHSO, 4-AFD / Cystamine, Vanillin (4-AFD-VAN)	Dual Disulfide (-S-S-) & Imine	Catalyst-Free	109–141	51–96.7	< 15 s at 180°C	Lowest activation energy; exceptional self-healing; moderate thermal degradation threshold.
Pathway 4: Quadruple-Function Lignin (QF-MHL)	EHSO, FGE, QF-MHL ("Seshat's Lignin"), Bio-Amines	Dual Ester / Imine / Phenolic exchange	Intrinsic tertiary amines in modified lignin	110–140	85–115	< 45 s at 170°C	High stiffness, intrinsic UV stabilization; synthesis of functionalized lignin is complex.
Pathway 5: Boronic Ester / Thiol-Acrylate	Acrylated EHSO (AEHSO), Diboronic ester dithiol	Boronic ester transesterification	Photo/Thermal initiator; Catalyst-Free	6.8–45	45–70	Immediate at 25–80°C	Room-temperature self-healing, hyper-elastic elongation (>700%); lower modulus.

Pathway 1: Transesterification-Driven Dynamic Networks

Transesterification-based Hemipoxies matrices rely on the ring-opening esterification of oxirane rings in EHSO and FGE using polycarboxylic acid hardeners such as Citric Acid (CA), Adipic Acid (AA), or Rosin-derived Fumaropimaric Acid (FPA). Ring-opening generates a dense three-dimensional network containing abundant β-hydroxy ester linkages. In the presence of a coordination catalyst, such as Zinc Acetate Dihydrate (Zn(OAc)₂·2H₂O) or Zinc Acetylacetonate (Zn(acac)₂), transesterification proceeds at elevated temperatures (>150°C):



Zn^{2+} \text{Associative Exchange} $\text{R}_1\text{--COO--R}_3 + \text{R}_2\text{--CH(OH)--CH}_2\text{--OH}$

The Lewis acidic zinc cations coordinate simultaneously with the carbonyl oxygen of the ester group and the nucleophilic hydroxyl oxygen, lowering the activation energy barrier for nucleophilic transesterification. Stoichiometric calculations require balancing carboxylic acid protons to epoxy groups ($R = [\text{COOH}]/[\text{Epoxy}] \approx 0.8\text{--}1.0$) to maintain a high concentration of unreacted hydroxyl groups, which act as nucleophiles to drive transesterification exchange.

Pathway 2: Imine-Exchange (Schiff Base) Dynamic Networks

Dynamic imine networks eliminate exogenous metallic catalysts, avoiding potential catalyst leaching and environmental toxicity. This pathway synthesizes Schiff base dynamic hardeners by condensing bio-derived aldehydes (e.g., vanillin, cinnamaldehyde) with protein-derived diamines (e.g., cadaverine or putrescine extracted from hemp seed meal). The resulting imine-containing hardener is reacted with EHSO oxirane rings. Imine networks undergo topology rearrangement via two concurrent pathways: imine metathesis (exchange between two imine linkages) and transamination (exchange between an imine and a primary amine). These networks display fast stress relaxation ($\tau^* < 30\text{ s}$ at 160°C) and high glass transition temperatures ($T_g > 120^\circ\text{C}$) due to the rigid aromatic architecture of vanillin derivatives.

Pathway 3: Disulfide Metathesis and Dual-Dynamic Networks

Disulfide-functionalized vitrimers incorporate dynamic sulfur-sulfur (S--S) covalent bonds into the epoxy network using hardeners such as 4-Aminophenyl Disulfide (4-AFD) or cystamine. Disulfide metathesis occurs at lower activation energies ($E_a \approx 51\text{--}70\text{ kJ/mol}$) than transesterification. To optimize mechanical performance, dual-dynamic networks combine disulfide metathesis with imine exchange via a custom Schiff base hardener (4-AFD-VAN) synthesized from vanillin and 4-AFD. The dual-exchange network operates synergistically: imine metathesis provides structural rigidity and high T_g ($> 120^\circ\text{C}$), while disulfide exchange accelerates stress relaxation at lower temperatures ($100\text{--}140^\circ\text{C}$), shortening reprocessing times without sacrificing mechanical strength.

Pathway 4: Quadruple-Function Modified Hemp Lignin (QF-MHL) Networks

The QF-MHL platform ("Seshat's Lignin") consolidates four functional roles into a single biomass-derived constituent:

- **Cross-linker:** Phenolic and carboxylic acid groups on modified lignin react directly with EHSO oxirane rings.
- **Vitrimer Catalyst:** Intrinsic tertiary-amine moieties grafted onto the lignin backbone catalyze ester and imine exchange without added metal salts.
- **Micro-Scale Reinforcement:** Highly condensed aromatic lignin cores increase the storage modulus (E') and elevate T_g .
- **UV/Oxidation Stabilizer:** Natural polyphenolic structures scavenge free radicals,

preventing photo-oxidative network degradation.
 Synthesis involves reacting EHSO and FGE with QF-MHL and a stoichiometric fraction of bio-amine hardener, yielding an all-hemp matrix with high thermal resistance ($T_g > 130^\circ\text{C}$).

Pathway 5: Boronic Ester and Thiol-Acrylate Dynamic Networks

For low-temperature or self-healing surface applications, EHSO is acrylated to yield Acrylated Epoxidized Hemp Seed Oil (AEHSO). Thermally controlled click coupling between AEHSO and dynamic diboronic ester dithiols forms a crosslinked network based on reversible boronate transesterification. This architecture undergoes room-temperature or low-temperature ($T < 80^\circ\text{C}$) self-healing, achieving elongations exceeding 700% while maintaining reprocessability.

Catalog of Hierarchical Multi-Scale Reinforcement Architectures

Achieving structural performance comparable to petrochemical aerospace composites requires reinforcing neat bio-vitrimers with hierarchical, multi-scale carbon and inorganic fill architectures. The Hempoxies platform incorporates reinforcements derived from *Cannabis sativa L.* alongside specialized synthetic nanocarbons.

Reinforcement Classification	Reinforcement Name	Source / Synthesis Method	Dimensionality & Scale	Primary Functional Contribution	Structural Performance Contribution	Interfacial Compatibility
1D Nanomaterial	Hemp-Derived Diamond Nanothreads (HDDNs)	Extreme Pressure-Induced Polymerization (PIP) of hemp hydrocarbons	1D (Diameter $< 2\text{ nm}$)	Maximal axial stiffness ($E > 850\text{ GPa}$) & thermal conduction	Ultimate tensile strength enhancement	Landry Interface / HD-SCA Silane
1D Structural Fiber	Hemp Carbon Fibers (HDCF)	High-temperature graphitization ($> 1200^\circ\text{C}$) of hemp bast fibers	1D Macro (Diameter $\sim 7\text{ }\mu\text{m}$)	Bulk tensile & flexural load bearing	Specific tensile strength $> 1.5\text{ GPa}$	HD-SCA Silane Coupling Agent
1D Synthetic Fiber	Short Carbon Fibers (SCF)	Chopped commercial/recycled carbon fiber ($3\text{--}6\text{ }\mu\text{m}$)	1D Micro (Diameter $\sim 7\text{ }\mu\text{m}$)	Isotropic reinforcement, crack bridging	Flexural strength enhancement ($> 100\text{ MPa}$)	Three-roll mill dispersion

Reinforcement Classification	Reinforcement Name	Source / Synthesis Method	Dimensionality & Scale	Primary Functional Contribution	Structural Performance Contribution	Interfacial Compatibilizer
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1D Natural Fiber	Woven Hemp / Flax Fabrics	Raw bast fibers treated via alkali dewaxing & silanization	1D/2D Macro (Continuous weave)	Sustainable structural core, low density	High impact resistance, energy absorption	Surface silanization / Vanillin-imine grafting
2D Nanomaterial	Hemp Carbon Nanosheets (HDCNS / Mitlinite)	Hydrothermal carbonization (180 [°] C) + KOH activation (800 [°] C)	2D Nano (10 ⁻³ to 30 ⁻² m) (start_span)[span_275](end_span)[span_278](start_span)[span_278](end_span)[span_281](start_span)[span_281](end_span)ext{ nm} (thickness)	High SSA (> 2200 m ² /g), EMI shielding, barrier properties	T _g elevation (+15 [°] C), gas barrier	Ultrasonication in FGE reactive diluent
2D Nanomaterial	Hemp Graphene Oxide (HGO / HrGO)	Exfoliation & chemical oxidation/reduction of hemp biochar	2D Nano (Single/few-layer)	Electrical conductivity (211 to 226 S/m), thermal transport	Interfacial shear strength (IFSS) boost	GPTMS Silane Grafting
3D Micro-Filler	Hemp Biochar (HDB)	Pyrolysis (800 to 1000 [°] C) of porous hemp hurds	3D Micro (Porous particles 1 to 10 ³ μm)	Cost reduction, density control, microcrack deflection	Modulus enhancement, reduced CTE	Ball milling with matrix precursors
Biopolymer Nano	Hemp Cellulose Nanocrystals (hCNC)	Acid hydrolysis of crystalline hemp bast cellulose	1D/3D Nano (Rod-like, 100 to 300 nm)	Nucleation site for matrix crystallization, barrier properties	Tensile modulus increase at low loading (1 to 3 wt%)	Hydrogen bonding with matrix hydroxyls
Inorganic	Halloysite	Natural	1D Nano	Flame	Simultaneous	Direct

Reinforcement Classification	Reinforcement Name	Source / Synthesis Method	Dimensionality & Scale	Primary Functional Contribution	Structural Performance Contribution	Interfacial Compatibility
Nano	Nanotubes (HNTs)	tubular aluminosilicate clay	(30–70 nm diameter)	retardancy, thermal stability	stiffness & ductility enhancement	ultrasonic dispersion (0.5 wt%)

1D Reinforcement Architectures

Hemp-Derived Diamond Nanothreads (HDDNs) are synthesized via extreme pressure-induced polymerization (PIP) of hemp-derived aromatic precursor molecules using piston-laser compression cells. HDDNs consist of ultra-thin sp^3 -hybridized carbon threads wrapped in hydrogenated sheaths. Incorporating HDDNs at low loadings (0.1–1.0 wt%) imparts axial stiffness ($E > 850 \text{ GPa}$) and thermal transport, functioning as structural nanotrusses within the matrix.

Hemp-Derived Carbon Fibers (HDCF) are produced by taking high-cellulose ($\sim 70\%$) hemp bast fibers, stabilizing them in air at 250°C , and graphitizing them under argon at $1200\text{--}2000^\circ\text{C}$. The resulting fibers exhibit diameters of $\sim 7 \text{ }\mu\text{m}$ and serve as structural reinforcements that replace petroleum Polyacrylonitrile (PAN)-derived carbon fibers.

Woven Hemp and Flax Natural Fabrics are applied directly in Vacuum-Assisted Resin Infusion (VARI) processes. Surface treatment via alkali washing (NaOH) strips away surface waxes, exposing hydroxyl groups for covalent coupling with silane agents or vanillin-imine grafting, which improves interfacial shear strength (IFSS).

2D Planar Nanoreinforcements

Hemp-Derived Carbon Nanosheets (HDCNS / Mitlinite) are prepared by hydrothermal carbonization of hemp bast fibers at 180°C for 24 hours to yield a carbonaceous char, which is activated with Potassium Hydroxide (KOH) at $700\text{--}800^\circ\text{C}$ under argon. The product consists of graphitic carbon nanosheets (10–30 nm thick) featuring high specific surface areas (up to $2287 \text{ m}^2/\text{g}$), significant mesoporosity (up to 58%), and electrical conductivities of $211\text{--}226 \text{ S/m}$. HDCNS forms an interconnected network that provides electromagnetic interference (EMI) shielding, barrier pathways against moisture ingress, and thermal conduction during recycling.

Hemp-Derived Graphene Oxide (HGO) and reduced HGO (HrGO) consist of exfoliated nanocarbon sheets synthesized via modified Hummers' oxidation of graphitized hemp char. HrGO provides dense nucleation sites that restrict the mobility of EHSO fatty acid chains, boosting T_g by $+15\text{--}25^\circ\text{C}$.

3D Micro-Scale Porous Fillers and Inorganic Nanomaterials

Hemp-Derived Biochar (HDB) is produced by pyrolyzing lignocellulosic hemp hurds (the woody core of the stem) at $800\text{--}1000^\circ\text{C}$ in an anoxic atmosphere. HDB features a porous carbon geometry that functions as a low-cost micro-scale filler. Applied mechanical

stress forces propagating microcracks to deflect around and through the porous HDB structures, absorbing strain energy and raising composite fracture toughness (K_{Ic}).

Halloysite Nanotubes (HNTs) are naturally occurring tubular aluminosilicate minerals. Dispersing HNTs at an optimal 0.5 wt% loading increases matrix thermal stability, stiffness, and ductility without increasing resin viscosity.

Interfacial Bond Optimization: The Landry Interface (HD-SCA)

Interfacial failure in bio-nanocomposites typically stems from phase separation between hydrophobic carbon fillers and hydrophilic polymer precursors. The Hempoxies platform uses a Hemp-Derived Silane Coupling Agent (HD-SCA / "Landry Interface"). HD-SCA is synthesized by functionalizing hemp-derived fatty acid esters with triethoxysilane moieties. Hydrolysis generates silanol (--Si--OH) groups that condense onto functionalized nanocarbon surfaces, while the organic tail copolymerizes directly into the EHSO/FGE vitrimer network. This chemical bridge transfers mechanical loads across the filler-matrix interface, suppressing debonding under fatigue.

Technical Evolution Across the Spectrum: Formulation Spectrum from Hempoxies 1 to 100

The Hempoxies development catalog spans 100 formulation variants, organized into five technical generations.

Generation	Representative Formulations	Primary Matrix Chemistry	Reinforcement Architecture	Targeted Properties	Primary Field of Application
Generation I: Unfilled Baselines	Hempoxies 1 – 10	EHSO + Citric Acid + Zinc Acetate	Unfilled / Neat matrix	Tensile Strength: $25\text{--}40\text{ MPa}$, $T_g: 40\text{--}60^\circ\text{C}$	Proof-of-concept, adhesive films, surface coatings.
Generation II: Ballistic Platforms	Hempoxies 11 – 30 (e.g., Hempoxies 12 / 12-A)	EHSO (45%), QF-MHL (20%), FGE (10%), Bio-Amine (5%)	HDCNS (5%), HDCF (15%), HDDNs (<1%)	$V_{50} \geq 800\text{ m/s}$, Microsecond adiabatic energy dissipation	Body armor, UAV airframes, defense infrastructure.
Generation III: Standardized CANs	Hempoxies 31 – 55 (e.g., Hempoxies 55)	EHSO (EEW = 235.3), FGE, Citric Acid, $\text{Zn(OAc)}_2 \cdot 2\text{H}_2\text{O}$	Modular testing across 37 fillers (HDB, hCNC, GO, CNTs)	Viscosity < 350 cP , $T_g \geq 45\text{--}85^\circ\text{C}$, 80% recovery	Material property database, automotive body panels.
Generation IV: Structural Bio-Composit	Hempoxies 56 – 75 (e.g., Hempoxies 57,	EHSO, Rosin-derived FPA,	Continuous Woven Flax/Hemp,	Flexural Strength > 115 MPa	Marine hulls, wind turbine blades, civil

Generation	Representative Formulations	Primary Matrix Chemistry	Reinforcement Architecture	Targeted Properties	Primary Field of Application
es	74)	Vanillin-Imine hardeners	HNTs (0.5\text{ wt}\%)	M [span_343](start_span)[span_343](end_span)Pa , T _g : 80\text{--}110^\circ\text{C}, low creep	infrastructure.
Generation V: Multi-Scale Carbon Hybrids	Hempoxies 76 – 100 (e.g., Hempoxies 100)	EHSO/FGE (80:20), Bio-Amine, \text{Zn(acac)}_2 (5\text{ mol}\%)	HGO (0.5\%), HrGO (0.5\%), HCNS (2\%), HDB (5\%), SCF (5\%)	Viscosity < 300\text{ cP}, T _g > 140^\circ\text{C}, Modulus > 12\text{ GPa}	Aerospace secondary structures, sports equipment, energy storage.

Generation I: Fundamental Baselines (Hempoxies 1 to 10)

Hempoxies 1 establishes the baseline neat vitrimer formulation using Epoxidized Hemp Seed Oil (EHSO), Citric Acid (CA), and Zinc Acetate Dihydrate. Generation I focuses on validating stoichiometric balance between oxirane rings and carboxylic acid groups, establishing basic self-healing and remolding properties. The early 6-component and 9-component systems (such as Hempoxies 9) introduced preliminary integration of Quadruple-Function Modified Hemp Lignin (QF-MHL) and raw hemp biochar.

Generation II: Ballistic & High-Impact Platforms (Hempoxies 11 to 30)

The benchmark of Generation II is **Hempoxies 12 (Platform 12-A)**, formulated as a biogenic ballistic vitrimer. Ballistic impact events take place on microsecond timescales (10^{-6} s), whereas standard transesterification exchange operates over seconds or minutes. Hempoxies 12 resolves this rate mismatch by incorporating a dual-channel vitrimer matrix with intrinsic tertiary-amine catalysts that lower the activation energy (E_a) of disulfide metathesis. Under dynamic impact, the adiabatic thermal energy generated by localized strain triggers instantaneous transient bond exchange. The matrix enters a transient flow state, converting kinetic energy into molecular rearrangement rather than brittle crack growth. Reinforced with 5\text{ wt}\% HDCNS and 15\text{ wt}\% graphitized HDCF, Hempoxies 12 achieves ballistic limit performance ($V_{50} \geq 800\text{ m/s}$) matching titanium alloys while maintaining a carbon-negative lifecycle footprint.

Generation III: Standardized Modular CAN Architectures (Hempoxies 31 to 55)

Generation III focuses on matrix standardization and screening. **Hempoxies 55** provides a defined theoretical and experimental baseline for unfilled CAN matrices. It specifies a four-component baseline: EHSO (EEW = 235.29\text{ g/eq}), FGE reactive diluent (15\text{--}20\text{ wt}\%), Citric Acid, and 1.5\text{ mol}\% Zinc Acetate Dihydrate. Hempoxies 55 serves as a screening matrix, mapping polymer interactions across 37 fillers, including biochar, cellulose nanocrystals, graphene oxide, and carbon nanotubes, to assemble structured

material databases.

Generation IV: Structural Bio-Composites (Hempoxies 56 to 75)

Generation IV formulations (such as Hempoxies 57 and 74) optimize crosslink density and creep resistance for load-bearing applications. Replacing aliphatic dicarboxylic acids with rigid aromatic or cycloaliphatic hardeners (e.g., vanillin-derived Schiff bases or rosin derivatives like fumaropimaric acid) increases T_g to $80\text{--}110^\circ\text{C}$ and flexural strength above 115 MPa . These resins are optimized for low-viscosity vacuum resin infusion (VARI/VAP) with continuous woven hemp and flax fabrics.

Generation V: Multi-Scale Carbon Bio-Vitrimers (Hempoxies 76 to 100)

Hempoxies 100 represents the highest performance variant in the catalog, formulated to match aerospace-grade carbon fiber reinforced polymers (CFRPs). The matrix consists of an 80:20 ratio of EHSO to FGE, cured with stoichiometric bio-amines and catalyzed by $5\text{ mol}\%$ Zinc Acetylacetonate ($\text{Zn}(\text{acac})_2$). The filler architecture integrates five carbon scales:

- $0.5\text{ wt}\%$ Hemp-Derived Graphene Oxide (HGO)
- $0.5\text{ wt}\%$ Reduced Hemp Graphene Oxide (HrGO)
- $2.0\text{ wt}\%$ Hemp Carbon Nanosheets (HCNS / Mitlinite)
- $5.0\text{ wt}\%$ Porous Hemp Biochar (HDB)
- $5.0\text{ wt}\%$ Short Carbon Fibers (SCF, $3\text{--}6\text{ mm}$)

The multi-scale filler blend is homogenized via ultrasonication (200 W , 30 min) followed by three-roll milling (3 passes at a $25\text{ }\mu\text{m}$ gap). The carbon hybrid filler raises the matrix T_g above 140°C while keeping uncured resin viscosity below 350 cP at 25°C , producing a structural composite from biogenic feedstocks.

Lifecycle Dynamics, Degradation Solvolysis, and Circular Asset Mechanics

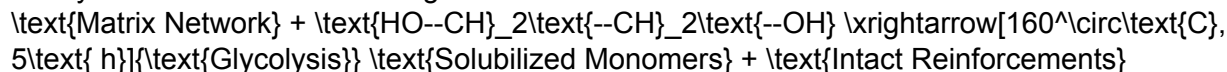
The primary environmental benefit of the Hempoxies platform over traditional petrochemical thermosets lies in its dual closed-loop circularity pathways: mechanical thermal reprocessing and chemical degradation solvolysis.

Thermal Reprocessing and Thermoforming Mechanics

When a cured Hempoxies composite reaches the end of its service life, it can be mechanically granulated into fine particles. The granulated material is placed into a mold and compressed at temperatures above T_v ($160\text{--}200^\circ\text{C}$) under pressures of $1\text{--}5\text{ MPa}$ for 10 to 30 minutes. Thermally activated associative exchange allows polymer chains to undergo topological flow across grain boundaries, welding particles into a solid component without loss of crosslink density. Across multiple recycling steps, Hempoxies vitrimers retain $> 80\text{--}90\%$ of their original tensile strength and flexural modulus.

Chemical Solvolysis and High-Value Fiber Recovery

In carbon fiber composites (such as Hempoxies 12 or 100), mechanical grinding fractures long fibers, reducing structural performance. The Hempoxies platform avoids downcycling via chemical solvolysis. Immersing the composite in a nucleophilic solvent (such as ethylene glycol or ethanol containing mild acid/base catalysts) at $150\text{--}160^{\circ}\text{C}$ selectively cleaves the dynamic ester or imine linkages over 2 to 5 hours:



Because dynamic covalent linkages are selectively cleaved while carbon fibers and nanocarbons remain unreacted, the matrix fully dissolves. The carbon fibers (HDCF/SCF) and nanocarbons (HDCNS/HDDNs) are recovered through filtration, washed with ethanol, and dried. The recovered fibers retain their surface chemistry and tensile strength, enabling direct re-weaving or re-infusion into new composites.

Carbon Sequestration Dynamics and Circular Economic Models

The environmental profile of the Hempoxies platform is tied to the cultivation of *Cannabis sativa* L.. Industrial hemp sequesters up to 15 tons of atmospheric carbon dioxide (CO_2) per hectare per crop cycle through photosynthesis. Converting raw hemp seed oil, lignin, and fibers into EHSO, QF-MHL, bio-amines, and carbon reinforcements locks this captured carbon into a solid matrix. Life cycle assessment indicates that 1 kg of cured Hempoxies matrix sequesters approximately 1.6 kg of net CO_2 equivalent.

Because vitrimeric networks can be repeatedly re-molded, repaired via localized heating, or solvolytically recovered without performance loss, materials fabricated from Hempoxies move away from traditional consumable lifecycles. Instead, the composites function as durable physical assets whose constituent chemical value and sequestered carbon credits are retained across successive operational cycles.

Strategic Synthesis and Engineering Outlook

The Hempoxies platform provides a chemical framework for scaling bio-derived polymers into structural, circular composites. Overcoming the inherent performance trade-offs of Epoxidized Hemp Seed Oil—specifically low glass transition temperature and high uncured viscosity—requires precise molecular formulation through the integration of Furfuryl Glycidyl Ether (FGE) reactive diluents, rigid dynamic hardeners, and targeted catalyst systems. Translating the Hempoxies formulations (Variants 1 through 100) into industrial production requires focusing on four engineering parameters:

- **Matrix Chemistry Selection:** For load-bearing applications requiring $T_g > 120^{\circ}\text{C}$, dual-dynamic networks combining imine exchange and disulfide metathesis (Pathway 3) or Quadruple-Function Modified Hemp Lignin (Pathway 4) represent the most effective chemical routes. Unfilled transesterification systems (Pathway 1) provide cost-effective baselines for ambient-temperature applications.
- **Hierarchical Nanocarbon Synergy:** Combining 1D nanothreads (HDDNs), 2D nanosheets (HDCNS), and 3D biochar (HDB) improves fracture toughness, thermal management, and electrical conductivity while keeping uncured resin viscosity below 350 cP for liquid resin infusion.
- **Interfacial Engineering:** Incorporating compatibilizers, such as the Hemp-Derived Silane Coupling Agent (HD-SCA / Landry Interface), is necessary to prevent phase separation

and ensure efficient load transfer between hydrophobic nanocarbons and the bio-vitrimer matrix.

- **Scale-Up Validation:** Moving the platform from laboratory TRL 1-2 to industrial TRL 4-5 requires standardizing EHSO oxirane content ($O_2 \geq 6.8 \text{ wt}\%$), controlling catalyst concentrations ($1.0\text{--}1.5 \text{ mol}\%$ Zinc content), and validating solvolysis recovery yields at pilot scale.

Works cited

1. Biobased vitrimer composites (a) epoxy vitrimer. Adapted with, https://www.researchgate.net/figure/Biobased-vitrimer-composites-a-epoxy-vitrimer-Adapted-with-permission-from-Ref-42_fig3_381934049
2. Epoxy Vitrimer: Advanced Dynamic Covalent Networks For, <https://eureka.patsnap.com/materials/epoxy-vitrimer-networks>
3. Vitrimer Exchangeable Bond Polymer: Comprehensive Analysis Of, <https://eureka.patsnap.com/materials/vitrimer-exchangeable-bond>
4. New Properties of Epoxy Vitrimers Brought by Dynamic Covalent, https://www.researchgate.net/publication/363776691_New_Properties_of_Epoxy_Vitrimers_Brought_by_Dynamic_Covalent_Bonds
5. Nanocomposites based on epoxy vitrimer - SciOpen, <https://www.sciopen.com/article/10.26599/NR.2026.94908455>
6. Repairable, Degradable and Recyclable Carbon Fiber-Reinforced, <https://www.mdpi.com/2073-4360/17/17/2387>
7. Vitrimer Dynamic Imine Polymer: Advanced Synthesis, Structural, <https://eureka.patsnap.com/materials/vitrimer-dynamic-imine-polymer>
8. Soybean oil-based novel acrylate for boronic ester vitrimer with self-healable-and-robust-properties-poster-board-s03-611818
9. The Density of Exchangeable Ester Bonds (ρ) | Macromolecules, <https://pubs.acs.org/doi/10.1021/acs.macromol.1c01289>
10. Hempoxies 55 Core Matrix Baseline & Advanced Fillers Catalog, <https://www.landryindustries.ca/2026/05/official-release-announcement-hempoxies.html>
11. Hempoxies | PDF | Epoxy | Applied And Interdisciplinary Physics, <https://www.scribd.com/document/1033078283/Hempoxies>
12. The Development of Epoxidized Hemp Oil Prepolymers for the, https://www.researchgate.net/publication/336364847_The_Development_of_Epoxidized_Hemp_Oil_Prepolymers_for_the_Preparation_of_Thermoset_Networks
13. Multi-Scale Carbon-Reinforced Bio-Vitrimers via Epoxidized Hemp, <https://www.scribd.com/document/1070206977/Hempoxies-100-Technical-Specification-Multi-Scale-Carbon-Reinforced-Bio-Vitrimers-via-Epoxidized-Hemp-Seed-Oil-EHSO-Furfuryl-Glycidyl-Ether-FG>
14. 9-Component Hempoxies Formulation Guide | PDF | Epoxy - Scribd, <https://www.scribd.com/document/961092594/The-Definitive-9-Component-Hempoxies-Formulation>
15. Hempoxies 12: Biogenic Ballistic Vitrimer | PDF - Scribd, <https://www.scribd.com/document/971407933/Hempoxies-12-Technical-Whitepaper>
16. High-Strength and Multi-Recyclable Epoxy Vitrimer Containing Dual, <https://doi.org/10.1021/acssuschemeng.3c04345>
17. Synthesis and Mechanisms of Vitrimer Elastomers - ResearchGate, https://www.researchgate.net/publication/400593297_Synthesis_and_Mechanisms_of_Vitrimer_Elastomers_Innovations_in_Dynamic_Covalent_Networks
18. Hempoxies Pre-Experimental Framework | PDF - Scribd, <https://www.scribd.com/document/1014622572/Hempoxies-Pre-Experimental-Framework>
19. (PDF) Covalent adaptable network offers “sustainable” closed-loop,

https://www.researchgate.net/publication/376402980_Covalent_adaptable_network_offers_sustainable_closed-loop_circularity_in_epoxy_vitrimers 20. Self-healable and Reprocessable Epoxy Vitri-
 mer derived from, https://digitalcommons.pittstate.edu/rcolloquium_event/2025/Posters/37/
 21. Multirecyclable, Self-Healable, Chemically Degradable, and High, <https://pubs.acs.org/iecred/article/64/9/4685/3734285/Multirecyclable-Self-Healable-Chemically>
 22. Bio-based vitrimers: chemistry, performance and applications, <https://pubs.rsc.org/lp/article/4/3/892/1224846/Bio-based-vitrimers-chemistry-performance-and>
 23. A Biobased Epoxy Vitri-mer with Dual Relaxation Mechanism - PMC, <https://pmc.ncbi.nlm.nih.gov/articles/PMC11022369/> 24. Self-Healable Covalently Adaptable
 Networks Based on Disulfide, <https://pmc.ncbi.nlm.nih.gov/articles/PMC9570560/> 25. Hem-
 poxies: Innovative Bionanocomposite Analysis | PDF - Scribd, <https://www.scribd.com/document/919499697/Expert-Appraisal-A-Due-Diligence-Report-on-the-Hempoxies-Platform> 26. Chemical Functionalization of Camelina, Hemp, and Rapeseed Oils, <https://www.mdpi.com/2673-6918/5/3/26> 27. PROPOSAL: High Performance Bio Based Vitri-
 mer Composites, <https://www.scribd.com/document/1064022557/PROPOSAL-High-Performance-Bio-Based-Vitri-mer-Composites> 28. Next-Generation Sustainable Composites with Flax Fibre ... - MDPI, <https://www.mdpi.com/2073-4360/17/14/1891> 29. Next-Generation Sustainable Composites with
 Flax Fibre and ... - PMC, <https://pmc.ncbi.nlm.nih.gov/articles/PMC12298844/> 30. Hemp Derived
 Carbon Nanosheets For Advanced Composite, <https://www.scribd.com/document/853824739/Hemp-Derived-Carbon-Nanosheets-for-Advanced-Composite-Materials-Synthesis-Properties-and-Validation> 31. epoxidized novolac resin: Topics
 by Science.gov, <https://www.science.gov/topicpages/e/epoxidized+novolac+resin> 32. Analysis of
 the Hempoxies Platform: Distinguishing Speculative, <https://www.marielandryspyshop.com/2026/07/analysis-of-hempoxies-platform.html> 33. Marie
 Landry Spy Shop | AI Development, OSINT, Intelligence, <https://www.marielandryspyshop.com/>
 34. Comprehensive Strategic Monograph: The Intellectual and Industrial, <https://www.marielandryspyshop.com/2026/08/comprehensive-strategic-monograph.html> 35.
 Renewable Composites for Sustainable and ECO-Friendly Solutions, <https://www.sciencepublishinggroup.com/article/10.11648/j.cm.20250902.11>