Epoxidized Hemp Seed Oil Vitrimers and Hierarchical Bio-Composites: Dynamic Covalent Networks, Viscoelasticity, and Circular Engineering

Fundamental Chemistry of Bio-Based Vitrimer Networks

The widespread industrial deployment of conventional thermosetting polymers, such as diglycidyl ether of bisphenol A (DGEBA) crosslinked with amine hardeners, has long presented an environmental and processing dilemma. While petroleum-derived thermosets deliver high mechanical performance, elevated glass transition temperatures (T_g), and excellent chemical resistance, their permanent, irreversibly crosslinked covalent topologies prevent melt reprocessing, thermal welding, or post-cure reshaping. This structural permanence results in substantial landfill accumulation and composite waste at end-of-life. Covalent Adaptable Networks (CANs), specifically associative vitrimers, overcome this traditional thermoset-thermoplastic trade-off by introducing dynamic covalent bonds into the polymer architecture. Vitrimers undergo rapid, thermally stimulated bond exchange reactions above a characteristic topology freezing transition temperature (T_v), enabling macroscopic flow and stress relaxation while maintaining a constant crosslink density (ν_e) and structural integrity.
The associative transesterification dynamic exchange reaction proceeds via the nucleophilic attack of a hydroxyl group on an adjacent ester linkage, represented by the thermodynamic equilibrium:
$$\text{R-COO-R'} + \text{R''-OH} \xrightleftharpoons[\text{Catalyst}]{\Delta} \text{R-COO-R''} + \text{R'-OH}$$
Because the cleavage of an existing covalent bond is synchronized with the simultaneous formation of a new dynamic linkage, the total number of crosslinks across the macromolecular network remains constant throughout topological rearrangement.
Plant oils represent a versatile, highly scalable biomass platform for industrial vitrimer synthesis. Among agricultural feedstocks, industrial hemp seed oil (EHSO) possesses a favorable fatty acid profile characterized by high polyunsaturation—predominantly linoleic acid (C18:2, $\sim 55\text{-}60\%$) and α-linolenic acid (C18:3, $\sim 18\text{-}25\%$). This high concentration of non-conjugated double bonds yields iodine values exceeding $150\text{ g I}_2/100\text{ g}$, establishing numerous sites for chemical functionalization. Epoxidation via the Prileshajev reaction, utilizing peracetic acid generated in situ from hydrogen peroxide and acetic acid catalyzed by ion-exchange resins, converts these isolated double bonds into reactive oxirane rings. This process yields oxirane oxygen contents of $6.5\text{-}7.0\%$ and epoxy values of $5.5\text{-}6.0\text{ meq/g}$, among the highest reported for vegetable oil precursors.
The formulation framework for bio-based hydroxy-ester vitrimers typically relies on curing epoxidized plant oils (e.g., EHSO, epoxidized castor oil [ECO], or epoxidized linseed oil [ELO]) with polycarboxylic acids or anhydrides. Nucleophilic ring-opening of the oxirane rings by

carboxylic acid groups yields a secondary \beta-hydroxyl ester structure. This spatial pairing of \beta-hydroxyl groups adjacent to ester linkages constitutes the primary dynamic dynamic covalent motif responsible for transesterification exchange.

To optimize processing viscosity, elevate crosslink density, and mitigate the intrinsic flexibility of long fatty acid triglyceride backbones, reactive diluents such as furfuryl glycidyl ether (FGE) and rigid polycyclic co-monomers like maleopimaric acid (MPA) or maleinized hempseed oil (MHSO) are incorporated into the matrix formulation. FGE reduces overall resin viscosity during compounding while introducing rigid furan rings that facilitate interfacial compatibility with carbonaceous fillers. Catalytic transesterification is predominantly driven by metal salts such as zinc acetate (\text{Zn(OAc)}_2) or zinc acetylacetonate (\text{Zn(acac)}_2), typically loaded at 1.0-1.5\text{ wt\%}. Alternatively, metal-free organocatalysts like 1,5,7-triazabicyclo[4.4.0]dec-5-ene (TBD) or 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU) accelerate transesterification without metal leaching, though higher organic loadings (2-5\text{ wt\%}) are required.

Beyond single-bond transesterification networks, dual dynamic covalent networks (DCNs) integrate orthogonal exchange mechanisms to reduce the activation energy threshold for stress relaxation and impart multifunctional capabilities. Incorporating dynamic imine (Schiff base) bonds alongside hydroxy-esters yields rapid, dual-responsive exchange kinetics owing to the lower activation energy of imine metathesis compared to classical transesterification. Similarly, disulfide-ester hybrid vitrimers combine low-energy disulfide exchange with the thermal stability of ester networks, yielding sacrificial bond architectures that enhance material toughness, resilience, and chemical degradability. Cellulose-based vitrimers functionalized with acetoacetate groups and cured with bio-derived diamines generate dynamic enamine networks, enabling catalyst-free hot-pressing, acid-responsive degradation, and sub-micron surface patterning.

Vitrimer Matrix Backbone	Dynamic Covalent Linkage	Curing Agent / Hardener	Catalytic System	Key Performance Characteristics	Primary Sources
Epoxidized Hemp Seed Oil (EHSO)	Hydroxy-Ester (Transesterification)	Citric Acid (CA) / FGE Diluent	\text{Zn(OAc)}_2 / \text{Zn(acac)}_2 (1.0-1.5\text{ wt\%})	High tensile strength, thermal remodeling at \ge 100^\circ\text{C}, fast stress relaxation	
Epoxidized Hemp Seed Oil (EHSO)	Dual Hydroxy-Ester	Maleopimaric Acid (MPA) / MHSO	Zinc Acetate	Elevated T_g (110-125^\circ\text{C}), high specific modulus, structural metal replacement	
Epoxidized Castor Oil (ECO)	Dual Ester-Imine	Vanillin-derived Aromatic Schiff Base (ASB)	Catalyst-Free / Schiff Base Conjugation	Photothermal self-healing (\eta_{PT} = 6[span_32](star	

Vitrimer Matrix Backbone	Dynamic Covalent Linkage	Curing Agent / Hardener	Catalytic System	Key Performance Characteristics	Primary Sources
				t_span)[span_32](end_span)1.42\%), E_a = 37.25\text{ kJ/mol}, D_f = 0.025	
Epoxidized Vegetable Oil (EVO)	Dual Disulfide-Ester	Dicarboxylic Acid with Disulfide linkages	Zinc Acetate / Thiol-Disulfide Exchange	Sacrificial bonding, high resilience, chemical degradability	
Cellulose Acetoacetate (CAA)	Dynamic Enamine	Plant Oil-Derived Diamine	Catalyst-Free	Acid-responsive degradability, surface micro-patterning	

Thermodynamics, Viscoelasticity, and Stress Relaxation Kinetics

The thermo-mechanical profile of a bio-based vitrimer matrix is defined by two key thermal transitions: the glass transition temperature (T_g) and the topology freezing transition temperature (T_v). The glass transition temperature marks the onset of long-range cooperative segmental motion of the polymer backbones, transitioning the material from a rigid, glassy state to an elastic rubbery regime. In contrast, T_v represents the critical threshold above which dynamic covalent exchange reactions become kinetically fast on the experimental timescale, allowing the crosslinked network to undergo macroscopic viscoelastic flow. Below T_v, covalent exchange reactions are kinetically suppressed, causing the vitrimer to exhibit the creep resistance, solvent stability, and dimensional permanence of a conventional thermoset. Above T_v, exchange reactions accelerate, enabling topological reorganization while maintaining structural integrity.

The viscoelastic stress relaxation behavior of vitrimer networks under a constant applied strain (γ_0) is quantified using Dynamic Mechanical Analysis (DMA) or shear rheometry. Fitting the normalized relaxation modulus $G(t)/G_0$ to a Maxwell viscoelastic model yields the characteristic relaxation time (τ^*):

$$\frac{G(t)}{G_0} = \exp\left(-\frac{t}{\tau^*}\right)$$

where τ^* is defined as the time required for the relaxation modulus to decay to $1/e$ ($\sim 37\%$) of its initial value.

Unlike un-crosslinked thermoplastic melts whose temperature-dependent viscosity is described by the Williams-Landel-Ferry (WLF) model, the relaxation kinetics of vitrimers above T_v strictly obey Arrhenius fluid dynamics:

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

Taking the natural logarithm yields a linear relationship between the relaxation time and inverse absolute temperature:

\ln \tau(T) = \ln \tau_0 + \frac{E_a}{RT}
where \tau_0 is the pre-exponential factor, E_a is the activation energy of the dynamic exchange reaction, R is the universal gas constant (8.314\text{ J}/(\text{mol}\cdot\text{K})), and T is absolute temperature. Plotting \ln \tau^* against 1/T produces a linear Arrhenius slope equal to E_a/R, confirming that macroscopic flow is governed directly by catalyst-mediated covalent bond exchange kinetics. The topology freezing transition temperature T_v is mathematically defined as the temperature at which the extrapolated characteristic relaxation time reaches a high viscosity threshold, typically standardized to \tau = 10^2\text{ s} or \tau = 10^6\text{ s}.

Vitrimer System Composition	Glass Transition T_g (^\circ\text{C})	Topology Freezing T_v (^\circ\text{C})	Activation Energy E_a (\text{kJ/mol})	Relaxation Time \tau^* (seconds)	Rheological Characterization Method	Primary Sources
EHSO / Citric Acid / \text{Zn(acac)}_2 (Fixed Datum)	88.5 – 94.1	~100 – 150	84.3	95 s at 100$^\circ\text{C}$	Stress relaxation DMA (\gamma_0 = 1\%)	
EHSO / Maleopimaric Acid (MPA) / Zinc Acetate	110 – 125	150 – 175	80 – 120	100 s at 160$^\circ\text{C}$	Small-Amplitude Oscillatory Shear (SAOS)	
Castor Oil ASB-ECO (Dual Ester-Imine)	~40 – 65	123.13	37.25	Rapid photothermal relaxation	Torsional Shear Rheometry	
Epoxidized Linseed Oil (ELO) / Hydroxy-Ester	39 – 64	~140 – 160	95 – 110	300 s at 160$^\circ\text{C}$	Stress relaxation DMA	
Generic Epoxy-Acid (Zinc-Catalyzed)	Variable	~130 – 160	85 – 120	100 – 500 s at 160$^\circ\text{C}$	Normalized modulus fit G(t)/G_0	
Generic Epoxy-Anhydride (Zinc-Catalyzed)	Variable	~150 – 180	100 – 140	400 – 800 s at 160$^\circ\text{C}$	Creep-recovery / SAOS	

Stoichiometric balance plays a defining role in controlling viscoelasticity. Off-stoichiometric ratios alter crosslink density (\nu_e) and the concentration of unreacted functional groups. Maintaining an epoxy-to-carboxyl ratio near 1:0.8 provides an optimal balance between structural rigidity and dynamic exchange kinetics. Higher crosslink densities elevate T_g and mechanical strength but prolong \tau^* by restricting segmental mobility and limiting spatial collision frequencies between \beta-hydroxyl groups and esters. Conversely, excess unreacted hydroxyl groups act

as internal plasticizers—lowering T_g—while accelerating transesterification rates through local hydrogen bonding and self-catalysis.

Hierarchical Reinforcement Mechanisms: Fiber Hybridization and Biochar Nanostructures

Unreinforced plant-oil vitrimer matrices display moderate tensile strengths (12.0-82.4\text{ MPa}), which are often insufficient for load-bearing applications that demand parity with structural metals. Achieving aerospace- or automotive-grade mechanical properties requires hierarchical composite architectures that combine continuous high-modulus fibers with multi-scale carbonaceous fillers.

Hybridizing synthetic polyacrylonitrile-based carbon fibers (PAN-CF) with natural industrial hemp bast fibers balances structural efficiency with reduced environmental impact. Natural hemp fibers contribute low density (\sim 1.4\text{ g/cm}^3), cost efficiency, and high acoustic and mechanical damping. However, neat hemp fiber composites exhibit lower tensile moduli (\sim 6.18\text{ GPa}) and flexural strengths (\sim 64.85\text{ MPa}) compared to synthetic carbon fiber reinforced polymers (CFRPs). Strategic ply stacking sequences overcome these performance trade-offs. Placing high-modulus PAN-CF on the outer plies of a laminate absorbs peak flexural tensile and compressive loads, while embedding woven hemp fiber plies near the mid-plane maintains flexural stiffness while maximizing low-velocity impact energy dissipation. This core placement mitigates brittle failure modes, reduces component mass, and lowers lifecycle global warming potential (GWP).

Fiber Architecture / Reinforcement Scheme	Composite Density \rho (\text{g/cm}^3)	Tensile Strength (\text{MPa})	Flexural / Tensile Modulus (\text{GPa})	Interlaminar Shear Strength (ILSS) (\text{MPa})	Impact Toughness / Fracture Behavior	Primary Sources
Unreinforced EHSO Vitrimer Matrix	1.12 – 1.18	12.0 – 29.2	1.5 – 3.2	N/A	Elongation at break: 0.8\% - 300\%	
Neat Hemp Fiber / Bio-Epoxy (Un-hybridized)	~1.35 – 1.40	64.85	6.18	12.1 ± 3.1	High impact damping, lower static strength	
EHSO Vitrimer + Hybrid PAN-CF / Hemp Plies	~1.28 – 1.45	> 180.0	45.0 – 70.0	41.2 ± 0.8	Balanced quasi-plastic energy absorption	
EHSO Vitrimer + 5–9 wt% Hemp Biochar	~1.20	29.2	Increased vs neat	43.9 ± 0.6	Crack deflection, quasi-ductile fracture	

Fiber Architecture / Reinforcement Scheme	Composite Density \rho (\text{g/cm}^3)	Tensile Strength (\text{MPa})	Flexural / Tensile Modulus (\text{GPa})	Interlaminar Shear Strength (ILSS) (\text{MPa})	Impact Toughness / Fracture Behavior	Primary Sources
Bio-Epoxy + 20 wt% Biochar (Micro-particulate)	~1.25	Reduced (Agglomerated)	Increased Stiffening	Moderate	Impact energy drops to 10 J/m; 16.3 HRLS	
Bio-Epoxy + 50 wt% Biochar (Micro-particulate)	~1.32	Brittle failure	High modulus	Low	Impact energy drops to 9 J/m; 23.7 HRLS	

Sub-micron carbonaceous fillers derived from pyrolyzed agricultural waste—such as hemp hurd biochar, spruce biocarbon, or rice husk biochar—further enhance matrix properties. Pyrolysis at 450-500^\circ\text{C}, followed by KOH chemical activation, produces porous carbon particles with surface areas exceeding 2400\text{ m}^2/\text{g}. Adding moderate biochar loadings (5-9\text{ wt\%}) into the vitrimer resin alters performance through several interrelated mechanisms:

Surface oxygen groups (-\text{OH}, -\text{COOH}) on activated biochar particles react with oxirane rings and polycarboxylic acids during curing. This covalent anchoring creates a rigid interphase around the filler, restricting local chain mobility, elevating T_g, and increasing matrix tensile modulus. Furthermore, well-dispersed biochar particles force propagating crack fronts to tilt and twist around rigid obstacles. This crack deflection mechanism converts brittle cleavage into quasi-ductile fracture, increasing elongation at break (e.g., from 0.8\% in neat epoxy to 1.31\% at 9\text{ wt\%} biochar). Embedded biochar also acts as a thermal barrier, forming a protective char layer during decomposition . Low filler loadings (4\text{ vol\%}) can reduce flame spread rates to 5.31\t[span_151](start_span)[span_151](end_span)ext{ mm/min}, elevate mass retention to 96\%, and achieve UL-94 V-0 flame ratings .

However, filler content must be carefully controlled. Exceeding 15-20\text{ w[span_152](start_span)[span_152](end_span)t\%} biochar induces particle agglomeration, creating stress concentration sites that promote premature void formation. Consequently, impact toughness declines (e.g., dropping from 15\text{ J/m} in unfilled resin to 10\text{ J/m} at 20\text{ wt\%} biochar and 9\text{ J/m} at 50\text{ wt\%} biochar), even as surface indentation hardness increases from 5.6\text{ HRLS} up to 23.7\text{ HRLS} .

Hydrothermal carbonization (HTC) can also transform complex organic waste streams—such as confectionary residues—into monodisperse carbon microspheres. Autoclaving aqueous slurries at 190^\circ\text{C} produces microspheres rich in surface hydroxyl groups. When blended into the pre-cure vitrimer formulation, these functional microspheres suppress volatile outgassing during high-temperature curing (>140^\circ\text{C}), preventing void formation (maintaining composite void fractions below 0.5\%) and preserving interlaminar shear strength (43.9\text{ MPa}).

Multi-Cycle Reprocessing, Self-Healing Mechanisms,

and End-of-Life Circularity

The primary operational advantage of vitrimer-based composites over conventional thermosets is their complete circularity. Vitrimeric composites can be physically reprocessed in the solid state via compression molding, thermally or photothermally repaired to restore structural integrity, or chemically solvolyzed under mild conditions to recover high-value continuous fibers undamaged.

Solid-state physical recycling involves grinding end-of-life composites or manufacturing off-cuts into fine powders (25-120\text{ }\mu\text{m}). The powdered material is placed into a mold and heated above its topology freezing temperature (T = T_v + 30^\circ\text{C} to T_v + 50^\circ\text{C}) under applied pressure (0.5-10\text{ MPa}) for 10-30\text{ minutes}. Under these conditions, associative transesterification across particle boundaries reorganizes the crosslinked network. Contacting surfaces weld together, eliminating internal interfaces and fully restoring mechanical properties. Processing under an inert atmosphere (\text{N}_2 or \text{Ar}) minimizes oxidative side reactions such as chain scission or irreversible thermal crosslinking . This preserves glass transition stability (\Delta T_g < \pm 3^\circ\text{C}) and maintains over 90\% of baseline tensile strength across multiple recycling cycles.

Recycling Strategy	Operational Parameters (Temperature / Pressure / Time)	Mechanical Property Retention	Degradation Mechanisms / Technical Limitations	Primary Sources
Multi-Cycle Hot-Pressing	160-200^\circ\text{ C} / 0.5 - 10\text{ MPa} / 10 - 30\text{ min}	> 90\% tensile strength retained after 3–5 cycles	Thermal oxidation if exposed to air; mitigated under inert \text{N}_2	
Solvolytic Dissolution (Acidic)	0.5\text{ M HCl} in DMF at 50^\circ\text{C} / 48\text{ hours}	100\% structural recovery of clean reinforcing fibers	Complete cleavage of ester crosslinks; resin matrix fully dissolved	
Glycolysis Recycling	Ethylene Glycol / 160-180^\circ\text{ C} / 2 - 6\text{ hours}	High recovery of oligomeric/monomeric products	Excess glycol displaces crosslinks via dynamic exchange	
Alkaline Hydrolysis	Aqueous \text{NaOH} or basic alcohol / 80-100^\circ\text{C}	Moderate monomer yield recovered	Saponification of fatty acid ester backbones	

Damage repair in bio-vitrimers can be driven by direct thermal heating or photothermal activation. Conductive heating above T_v accelerates localized transesterification exchange across micro-crack interfaces, restoring load-bearing capability. Photothermal healing offers an energy-efficient alternative by converting light directly into localized thermal energy. Incorporating photothermal functional groups—such as conjugated aromatic Schiff base (ASB) hardeners, carbon nanotubes, or biochar—enables light-driven repair. For example, an ASB-conjugated Epoxidized Castor Oil network (ASB-ECO) achieves a photothermal conversion efficiency (\eta_{PT}) of 61.42\% under visible light. Photothermal heating elevates

local crack-tip temperatures above T_v, activating dual ester-imine exchange to achieve 100\% self-healing without requiring bulk heating of the structure.
When mechanical composite re-molding is unfeasible, vitrimeric CANs can be chemically degraded under mild solvolytic conditions. Unlike permanently crosslinked thermosets, the dynamic ester bonds of vitrimers are susceptible to controlled nucleophilic cleavage. Submerging EHSO vitrimers in an acidic organic solution (e.g., 0.5\text{ M HCl} in dimethylformamide at 50^\circ\text{C}) selectively hydrolyzes the ester crosslinks over 48 hours . This solvolysis process dissolves the polymer matrix into soluble oligomeric fragments while leaving embedded continuous carbon fibers intact, allowing clean fibers to be recovered and reused without degradation of their surface properties or tensile strength .

Advanced Industrial Applications and Smart Functionalization

The performance profile of bio-based vitrimer composites—combining high strength, thermo-mechanical reprocessability, and tailorable physical properties—supports applications in structural engineering, microelectronics, and anti-counterfeiting security.
In structural engineering, optimized EHSO-PAN-CF hybrid composites achieve specific strength and stiffness metrics capable of replacing traditional aluminum alloys (e.g., Al 6061-T6) and structural steels in automotive chassis panels, sports equipment, and aerospace fairings. Their mechanical damping capacity improves impact resistance and acoustic insulation compared to conventional synthetic CFRPs.
In electronic packaging, conjugated dynamic networks such as ASB-ECO serve as self-healing structural dielectrics. At high operating frequencies (10^6\text{ Hz}), ASB-ECO exhibits a low dielectric constant (D_k = 5.54) and a low dissipation factor (D_f = 0.025). These dielectric properties minimize signal loss in high-frequency circuit substrates, while photothermal self-healing repairs micro-cracks induced by thermal cycling, extending device operational lifespans.
Integrating covert anti-counterfeiting features into high-value composite components establishes supply-chain security and structural health tracking. Rare-earth-doped upconversion nanoparticles (UCNPs)—such as \text{NaYF}_4\text{:Yb}^{3+},\text{Er}^{3+} or \text{Mn}^{2+}-doped variants—can be uniformly dispersed into the EHSO vitrimer matrix during pre-cure blending. UCNPs convert near-infrared (NIR) laser excitation (980\text{ nm}) into visible RGB photoluminescence via anti-Stokes photon emission, producing overt visual authentication patterns.

Security Tagging Technique	Functional Marker / Dopant	Optical Spectral Mechanism	Authentication Pathway	Matrix Integration Method	Primary Sources
Upconversion Luminescence	\text{NaYF}_4\text{:Yb/Er/Tm} or \text{Mn}^{2+} Doped UCNPs	Anti-Stokes NIR-to-Visible emission (980\text{ nm} \to \text{RGB})	Overt visual or camera-detected luminescence pattern	In situ matrix dispersion during pre-cure blending	
Surface-Enhanced Raman Tags	Organic Dyes on Metallic Core-Shell	Vibrational Raman fingerprint	Covert spectroscopic matching of	Interfacial sizing on PAN-CF or	

Security Tagging Technique	Functional Marker / Dopant	Optical Spectral Mechanism	Authentication Pathway	Matrix Integration Method	Primary Sources
	Nanoparticles	scattering	sharp spectral lines	biochar fillers	
Dual-Mode Optical Tagging	Hybrid UCNP + SERS Particle Complexes	Simultaneous luminescence and vibrational Raman	Multi-level authentication for aerospace components	Embedded functional micro-spheres / CNC tags	

Combining UCNPs with covert Surface-Enhanced Raman Scattering (SERS) tags establishes a dual-mode security system . Raman-active molecules bonded to metallic nanoparticle cores generate unique vibrational spectra under spectroscopic inspection . Because transesterification processing temperatures (100-160^\circ\text{C}) remain well below the thermal decomposition limits of rare-earth UCNPs (>500^\circ\text{C}), these optical markers survive curing, thermal reshaping, and multiple hot-press recycling cycles. This thermal stability ensures continuous component authentication throughout the material lifecycle.

Synthesis and Technological Outlook

The development of epoxidized hemp seed oil vitrimers and their hierarchical carbon composites provides a viable path toward sustainable, high-performance structural materials. Replacing permanent petroleum-derived thermosets with bio-based Covalent Adaptable Networks resolves the historical compromise between mechanical integrity and end-of-life circularity.

Precise stoichiometric control governs the performance of these dynamic networks. Maintaining an epoxy-to-carboxyl ratio near 1:0.8 with 1.0-1.5\text{ wt\%} zinc catalyst balances mechanical rigidity (T_g > 90-125^\circ\text{C}) with fast stress relaxation ($\tau^* < 100\text{ s}$ at 100-160^\circ\text{C}). In composite architectures, placing continuous high-modulus PAN-CF on outer plies while embedding natural hemp fibers near the mid-plane optimizes flexural strength while increasing low-velocity impact energy absorption. Incorporating 5-9\text{ wt\%} activated biochar further elevates matrix stiffness, promotes quasi-ductile crack deflection, and enhances flame retardancy.

Thermally reprocessable and photothermally self-healable vitrimer matrices enable solid-state physical recycling across multiple processing cycles without mechanical degradation. Under conditions where physical remolding is unfeasible, selective chemical solvolysis cleaves dynamic ester linkages, recovering continuous reinforcing fibers intact . Finally, embedding rare-earth upconversion nanoparticles and Raman-active tags establishes lifetime component traceability. Together, these advances establish bio-based vitrimer composites as a scalable platform for sustainable manufacturing across the aerospace, automotive, and microelectronics industries.

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