

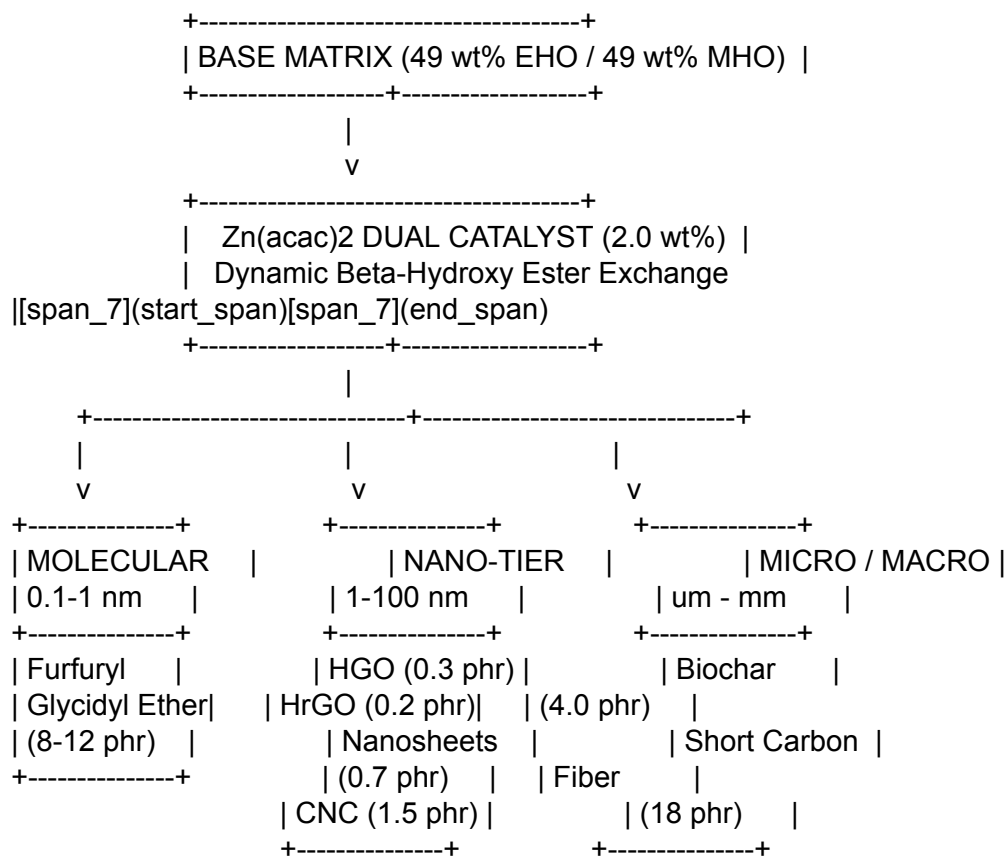
10-Page Standard Operating Protocol: >99% Hemp-Monoculture Multiscale Vitrimers Composite

Document ID: SOP-HEMPOX-2026-v1.0 **Organization:** Hempoxies Division, Landry Industries, Moncton, NB, Canada **Author:** Marie-Soleil Seshat Landry **Date:** August 2026 **Core Standard:** ASTM D6866 / ISO 16620 (>99% Bio-based Carbon Content)

SECTION 1: System Overview & Theoretical Framework

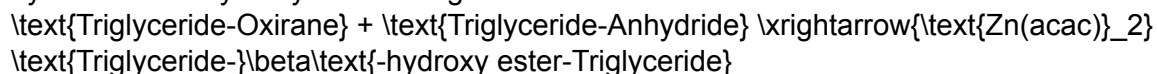
1.1 Executive Summary

This document provides the standard operating protocol for formulating, synthesizing, and processing a >99% hemp-derived multiscale vitrimer composite. The material system integrates an epoxidized and maleinized hempseed oil matrix cross-linked dynamically with a zinc catalyst, reinforced across five distinct spatial length scales using hemp-derived carbon and cellulose nanomaterials.



1.2 Vitrimer Cross-Linking Mechanics

The network relies on the epoxide ring-opening reaction by cyclic anhydride groups, forming dynamic β -hydroxy ester linkages:



In the presence of zinc acetylacetonate (Zn(acac)_2), these ester linkages undergo thermally activated transesterification exchange at elevated temperatures ($180\text{--}200^\circ\text{C}$), allowing stress relaxation ($\tau^* < 300\text{ s}$), full reprocessability, self-healing, and mechanical welding.

SECTION 2: Material Specifications & Chemical Inventories

2.1 Reagent & Raw Material Specifications

Component	Function / Role	Target Specification	Derivation Route	Source
Epoxidized Hempseed Oil (EHO)	Base Epoxy Resin	Oxirane Oxygen: 7.0–7.5%; EEW: 220–230 g/eq	Cold-pressed hempseed oil + peracetic acid	
Maleinized Hempseed Oil (MHO)	Anhydride Cross-linker	Acid Number: 100–110 mg KOH/g; Viscosity: <10 dPa·s	Hempseed oil + maleic anhydride (ene/Diels-Alder)	
Furfuryl Glycidyl Ether (FGE)	Reactive Diluent / π -Stacking	Vacuum Distilled (bp 80°C at 1 mbar)	Hemp hemicellulose $\rightarrow$ Furfural $\rightarrow$ Glycidylation	
Hemp Graphene Oxide (HGO)	Covalent Interfacial Nanofiller	C/O ratio: 2.0–2.5; XRD spacing: 0.8–1.0 nm	Modified Hummers oxidation of hemp biochar	
Reduced Hemp GO (HrGO)	Electrical/Thermal Percolation	Thermal shock (1000°C) or ascorbic acid	Reduction of HGO	
Hemp Carbon Nanosheets	2D High-Aspect Barrier	BET Surface Area: $>1500\text{ m}^2/\text{g}$; Thickness: 2–10 nm	KOH chemical activation (800°C) of char	
Cellulose Nanocrystals (CNC)	1D Crack Pinning / Modulus	Length: 100–300 nm; Crystallinity: >80%	Acid hydrolysis (64 wt% H_2SO_4)	

Component	Function / Role	Target Specification	Derivation Route	Source
			4) of bast	
Hemp Biochar	Micro 0D Interstitial Filler	Fixed Carbon: $>70\text{ wt}\%$; BET Area: $>200\text{ m}^2/\text{g}$	Slow pyrolysis (550°C , N_2) of stalk	
Short Hemp Carbon Fiber	Macro 1D Load Bearing	Length: 3–6 mm; Single-fiber strength: $>1\text{ GPa}$	Bast carbonization (1200°C , Ar) + chopping	
Anhydrous Ethanol	Dispersion Medium	Water content: $<0.5\text{ wt}\%$ (Karl Fischer)	Hemp fermentation, distillation, 3 μm sieves	
Zinc Acetylacetonate	Cure & Exchange Catalyst	Purity: $>98\%$ (HPLC)	Chemical synthesis (Non-hemp origin, $\sim 1.5\text{ wt}\%$ total)	

SECTION 3: Feedstock Derivation Procedures (SOP-001 through SOP-011)

3.1 SOP-EHO-001: Epoxidized Hempseed Oil Synthesis

- Charge 500 g cold-pressed hempseed oil and 150 g glacial acetic acid (30 wt% rel. to oil) into a 2 L three-neck round-bottom flask.
- Add 2.5 g concentrated H_2SO_4 (0.5 wt% rel. to oil) as catalyst.
- Heat contents to 40°C with mechanical stirring at 400 rpm.
- Add 300 g H_2O_2 (30 wt% aqueous, 60 wt% rel. to oil) dropwise via a dropping funnel over 2 hours, keeping internal temperature at $40\text{--}50^\circ\text{C}$.
- Elevate batch temperature to 70°C and hold for 6 hours under continuous stirring.
- Cool to room temperature and transfer contents into a separatory funnel.
- Wash organic layer with warm deionized water (3 $\times$ 200 mL) until aqueous discharge reaches $\text{pH} > 5$.
- Dry over 50 g anhydrous Na_2SO_4 for 2 hours, filter, and strip residual moisture/volatiles via rotary evaporation (60°C , 20 mbar, 1 hour).
- Target Metrics:** Oxirane oxygen 7.0 $\text{--}7.5\%$; Epoxy Equivalent Weight (EEW) 220 $\text{--}230\text{ g/eq}$. Yield: 520 $\text{--}540\text{ g}$.

3.2 SOP-MHO-001: Maleinized Hempseed Oil Synthesis

- Charge 500 g filtered hempseed oil into a 1 L three-neck flask and purge with N_2 gas (99.999%) for 15 minutes.
- Add 100 g finely ground maleic anhydride (20 wt% rel. to oil).

3. Heat to 100°C with stirring at 300 rpm under constant N_2 purge.
4. Maintain reaction at 100°C for 4 hours.
5. Cool system to 60°C and strip any unreacted volatile species under vacuum.
6. **Target Metrics:** Acid number $100\text{--}110\text{ mg KOH/g}$; Viscosity $<10\text{ dPa}\cdot\text{s}$ at 20°C . Yield: $580\text{--}600\text{ g}$.

3.3 SOP-FGE-001: Furfuryl Glycidyl Ether

1. **Furfural:** React 200 g ground hemp stalks with 1 L of 3 M H_2SO_4 in a stainless steel autoclave at 180°C for 30 min. Filter, extract liquid with toluene ($3 \times 200\text{ mL}$), and evaporate solvent. Yield: 30–35 g furfural.
2. **Furfuryl Alcohol:** Combine 30 g furfural, 3 g Raney-Ni, and 100 mL ethanol in a Parr reactor. Pressurize with H_2 to 2 MPa and heat at 80°C for 2 hours. Filter and evaporate ethanol. Yield: 28–30 g.
3. **Glycidylation:** Mix 25 g furfuryl alcohol (0.255 mol) and 28.3 g epichlorohydrin (0.306 mol) at 0°C . Add 20.4 g of 50 wt% NaOH dropwise over 1 hour. Warm to 50°C for 4 hours. Extract with diethyl ether, wash with brine, dry over MgSO_4 , and vacuum distill at 80°C (1 mbar). Yield: 22–25 g.

3.4 SOP-HGO-001: Hemp-Derived Graphene Oxide

1. Mix 90 mL H_2SO_4 and 10 mL H_3PO_4 (9:1 v/v) in an ice bath.
2. Slowly add 1 g hemp biochar ($<75\text{ }\mu\text{m}$) under constant magnetic stirring.
3. Add 9 g KMnO_4 in small increments over 15 minutes to prevent exotherm spikes.
4. Remove ice bath, heat to 50°C , and maintain stirring for 12 hours.
5. Quench reaction by pouring onto 200 g crushed ice containing 3 mL of 30 wt% H_2O_2 .
6. Centrifuge (4000 rpm, 10 min) and wash sequentially with 1 M HCl ($2 \times 100\text{ mL}$) and deionized water until supernatant reaches $\text{pH } 5\text{--}6$.
7. Dialyze against DI water for 3 days and freeze-dry at -50°C (0.1 mbar) for 48 hours.
8. **Target Metrics:** C/O ratio 2.0–2.5; XRD layer spacing 0.8–1.0 nm. Yield: 1.5–2.0 g.

3.5 SOP-HrGO-001: Hemp-Derived Reduced Graphene Oxide

- **Method A (Thermal):** Load 0.5 g HGO into a quartz boat inside a tube furnace. Purge with Argon (100 sccm) for 30 minutes. Rapidly heat to 1000°C (20°C/min), hold for 30 seconds, and cool under continuous Ar flow. Yield: 0.25–0.30 g.
- **Method B (Chemical):** Disperse 0.5 g HGO in 500 mL DI water via 30 min sonication. Add 2.0 g L-ascorbic acid, heat to 80°C , and stir for 2 hours. Filter through a $0.22\text{ }\mu\text{m}$ PVDF membrane, wash with ethanol/water, and dry at 60°C under vacuum. Yield: 0.30–0.35 g.

3.6 SOP-HCNS-001: Hemp Carbon Nanosheets

1. Mix 5 g ground biochar ($<75\ \mu\text{m}$) with 20 g KOH pellets (4:1 w/w) in a mortar using minimal ethanol to form a uniform paste. Dry at 80°C overnight.
2. Place mixture in a quartz boat within a tube furnace and purge with N_2 for 30 minutes.
3. Ramp temperature to 800°C (5°C/min), hold for 1 hour under N_2 (100 sccm), and cool to room temperature.
4. Wash product with 1 M HCl (200 mL) followed by DI water centrifugation until neutral pH. Dry at 120°C under vacuum.
5. **Target Metrics:** BET Surface Area $>1500\ \text{m}^2/\text{g}$; Thickness 2–10 nm. Yield: 3.0–3.5 g.

3.7 SOP-CNC-001: Cellulose Nanocrystals from Hemp Bast

1. **Alkaline Pulping:** Treat 50 g dew-retted hemp bast fibers in 1 L of 2 M NaOH at 80°C for 2 hours. Filter and wash to neutral pH.
2. **Bleaching:** Suspend 30 g alkali cellulose in 500 mL water with 6 g NaClO_2 and acetic acid (pH 4.5–5.0) at 80°C for 1 hour. Filter, wash, and dry.
3. **Acid Hydrolysis:** Cool 300 mL of 64 wt% H_2SO_4 to 45°C . Add 20 g bleached cellulose under high-shear stirring and maintain at 45°C for 45 minutes.
4. Quench reaction with 3 L ice-cold DI water. Centrifuge (10,000 rpm, 10 min) repeatedly to eliminate acidic supernatant. Dialyze against DI water until neutral, concentrate via rotary evaporation, and spray-dry.
5. **Target Metrics:** Length 100–300 nm; Diameter 5–20 nm; Crystallinity $>80\%$. Yield: 8–10 g.

3.8 SOP-BIO-001: Hemp Biochar Production

1. Load 500 g air-dried, chopped hemp stalks (2–5 cm) into a stainless steel retort.
2. Purge system with N_2 (100 sccm) for 30 minutes.
3. Ramp furnace temperature to 550°C (5°C/min) and hold for 2 hours.
4. Cool under nitrogen atmosphere to ambient room temperature.
5. Ball-mill solid pyrolyzate to pass a $<250\ \mu\text{m}$ sieve.
6. **Target Metrics:** Fixed carbon $>70\ \text{wt}\%$; BET surface area $>200\ \text{m}^2/\text{g}$. Yield: 125–150 g.

3.9 SOP-SCF-001: Short Hemp Carbon Fiber

1. Align 50 g dew-retted hemp bast fibers inside a quartz boat.
2. Insert into tube furnace and purge with Argon for 30 minutes.
3. Heat to 1200°C (5°C/min), maintain target for 2 hours under Ar flow, and cool down.
4. Precision-chop carbonized strands into 3–6 mm lengths.
5. Sieve through fine mesh screens to eliminate dust and particulate fraction ($<1\ \text{mm}$).
6. **Target Metrics:** Tensile strength $>1\ \text{GPa}$. Yield: 10–13 g.

3.10 SOP-ETOH-001: Anhydrous Ethanol Dispersion Solvent

1. **Pretreatment:** Autoclave 500 g ground stalks in 2 L of 1 wt% H_2SO_4 at 121°C for 30 min. Neutralize to pH 4.8 using Ca(OH)_2 .
2. **Enzymatic Hydrolysis:** Add cellulase enzyme cocktail (15 FPU/g glucan) in citrate buffer (pH 4.8, 2 L). Incubate at 50°C , 150 rpm for 72 hours.
3. **Fermentation:** Inoculate hydrolysate liquid with *Saccharomyces cerevisiae* (0.5 g/L). Ferment at 30°C for 48 hours.
4. **Distillation & Dehydration:** Distill at 78°C to recover 95 wt% ethanol. Pass distillate through a packed column of pre-dried 3 Å molecular sieves at 25°C (residence time: 30 min).
5. **Target Metrics:** Moisture <0.5 wt% via Karl Fischer titration. Yield: 25–35 g.

3.11 SOP-CAT-001: Zinc Acetylacetonate Catalyst

1. Dissolve 10 g $\text{Zn(NO}_3)_2 \cdot 6\text{H}_2\text{O}$ in 50 mL DI water.
2. Add 12 mL acetylacetone dropwise under continuous stirring.
3. Adjust solution pH to 7–8 using 2 M NaOH to precipitate product.
4. Stir suspension for 1 hour, filter, wash with ethanol (3 $\times$ 50 mL) and water (2 $\times$ 50 mL).
5. Vacuum-dry at 80°C overnight. Recrystallize from hot ethanol if purity <98%. Yield: 8–9 g.

SECTION 4: Standard Baseline Formulation Table

Tier	Component	Specific Loading	Functional Role
Matrix Base	Epoxidized Hempseed Oil (EHO)	49.0 wt%	Epoxide Matrix Monomer
Matrix Base	Maleinized Hempseed Oil (MHO)	49.0 wt%	Anhydride Cross-linking Agent
Matrix Base	Zinc Acetylacetonate	2.0 wt%	Cure Accelerator & Dynamic Exchange Catalyst
Molecular Scale	Furfuryl Glycidyl Ether (FGE)	8–12 phr	Viscosity Reduction; Filler Interfacial π - π Stacking
Nano 2D Scale	Hemp-Derived GO (HGO)	0.3–0.5 phr	Interfacial Covalent Coupling & Crack Deflection
Nano 2D Scale	Hemp-Derived rGO (HrGO)	0.2–0.3 phr	Electrical/Thermal Percolation Network
Nano 2D Scale	Hemp Carbon Nanosheets	0.5–1.0 phr	Gas/Moisture Barrier; High Aspect Ratio Stiffness
Nano 1D Scale	Cellulose Nanocrystals	1.0–2.0 phr	Rod-like Crack Pinning

Tier	Component	Specific Loading	Functional Role
	(CNC)		& Intersegmental Modulus
Micro 0D Scale	Hemp Biochar	3.0–5.0 phr	Interstitial Micro-filler & Compressive Support
Macro 1D Scale	Short Hemp Carbon Fiber	15–20 phr	Primary Structural Load-Bearing Reinforcement
Processing Aid	Anhydrous Hemp Ethanol	50–100 phr	Solvent Medium for Nanofiller Dispersion (Stripped)

Note: Parts per hundred resin (phr) values calculated relative to combined EHO + MHO mass.

SECTION 5: Master Processing & Curing Protocol

[Phase 1: Solvent Dispersion]

- |-- Bath Sonicate (30 min) HGO/HrGO/Nanosheets/CNC in Anhydrous Ethanol
- |-- Probe Sonicate (10 min, 30% amplitude)
- +-- Add Micro Biochar --> Bath Sonicate (10 min)



[Phase 2: Desolvation & Milling]

- |-- Rotary Evaporate Solvent (60 deg C, 50 mbar)
- |-- Vacuum Oven Drying (80 deg C, 12 hours)
- +-- Blend Dry Filler Paste with EHO + FGE via Three-Roll Mill (3000 rpm, 10 min)



[Phase 3: Activation & Integration]

- |-- Incorporate MHO and Zn(acac)₂ Catalyst
- |-- Degas Under Vacuum (80 deg C, 30 min, <5 mbar)
- +-- Fold in Short Carbon Fibers via Planetary Mixer (Low Speed)



[Phase 4: Stepped Thermal Cure Cycle]

- |-- 120 deg C for 2 Hours (Gelation & Initial Network Formation)
- |-- 150 deg C for 2 Hours (Advanced Cross-linking)
- +-- 180 deg C for 2 Hours (Post-Cure Density Optimization)

SECTION 6: Network Preservation & Catalyst Compensation Rules

6.1 Catalyst Surface Adsorption Rules

Oxygenated functional groups on HGO and HrGO surfaces adsorb Zn^{2+} coordination sites, starving the vitrimer matrix of active transesterification centers.

Catalyst Compensation Rule: If Total Nanofiller Loading > 2.0 phr, Increase Zn(acac)_2 to 2.5 – 3.0 phr

Alternatively, pre-passivate HGO/HrGO surfaces by stirring nanofillers in a 0.5 wt% Zn(acac)_2 ethanol solution for 1 hour prior to primary resin blending.

6.2 Stress Relaxation Protocol

Every production batch must pass Stress Relaxation Rheology to verify dynamic network preservation:

- **Instrument Parameter:** Parallel plate rheometer (25 mm plate, 1.0 mm gap).
- **Test Conditions:** Constant shear strain $\gamma = 1.0\%$, temperature $T = 180^\circ\text{C}$.
- **Acceptance Criterion:** Normalized relaxation modulus must decay below $1/e$ ($\approx 37\%$) within $\tau^* < 300$ seconds.

SECTION 7: Material Property Tuning & Sensitivity Analysis

7.1 Stoichiometric Sensitivity

- **Anhydride Excess ($\text{MHO:EHO} = 55:45$ wt%):** Increases cross-link density, pushing T_g up to 100 – 115°C . Increases τ^* to >600 s at 180°C , degrading thermal reprocessability.
- **Epoxide Excess ($\text{EHO:MHO} = 55:45$ wt%):** Lowers T_g to 60 – 75°C , increases elongation at break ($>15\%$), and reduces uncured resin viscosity to improve fiber wetting.

7.2 FGE Rheological & Dynamic Tuning

- **<8 phr FGE:** Uncured viscosity remains high (>5000 mPa $\cdot$ s) at 80°C , preventing complete fiber wet-out.
- **8 – 12 phr FGE:** Drops viscosity to 2000 – 3000 mPa $\cdot$ s, increases nanofiller dispersion by 30–50% via furan π - π stacking, and accelerates stress relaxation.
- **>12 phr FGE:** Reduces network density, dropping T_g by 10 – 20°C and causing thermal-oxidative instability above 200°C .

7.3 HGO:HrGO Electrical Percolation Switch

- **HGO Only (0.5 phr):** Electrical conductivity $< 10^{-8}$ S/cm (Insulator).
- **HrGO Only (0.5 phr):** Electrical conductivity 10^{-4} – 10^{-2} S/cm (Semiconductor), but degrades tensile strength by 10–15% due to filler agglomeration.
- **Hybrid (2:1 to 3:1 HGO:HrGO):** Achieves conductive percolation (10^{-3} – 10^{-1} S/cm) while retaining 90% of maximum mechanical strength.

SECTION 8: Application-Specific Testing Variants

(Variants 1 through 8)

The table below summarizes eight engineered formulations designed to meet or exceed specific properties of common engineering materials.

Variant ID	Target Incumbent	Key Formulation Changes	Target Performance Metrics	Test Protocol Standard
HEMP-AL	Aluminum 6061-T6	MHO 55 wt%; 25 phr aligned short carbon fiber; 2.5 phr catalyst	$\rho = 1.35 \text{ g/cm}^3$; $E = 38 \text{ GPa}$; Specific Modulus = $28.1 \text{ GPa} \cdot \text{cm}^3/\text{g}$ (+9.8% vs. Al)	ASTM D3039 / ASTM D6641
HEMP-STEEL	Mild Steel	MHO 52 wt%; 22 phr random-in-plane carbon fiber; 4 phr biochar	$\rho = 1.32 \text{ g/cm}^3$; $\sigma_{\text{tensile}} = 220 \text{ MPa}$; Specific Strength = $167 \text{ MPa} \cdot \text{cm}^3/\text{g}$ (+193% vs. Steel)	ASTM D3039 / ASTM D6110
HEMP-PLAST	ABS Plastic	EHO 55 wt%; 12 phr FGE; 8 phr biochar; 10 phr carbon fiber	$\rho = 1.18 \text{ g/cm}^3$; $\sigma = 85 \text{ MPa}$; $E = 5.5 \text{ GPa}$; Elongation at break $\approx 12\%$	ASTM D638 / ASTM D256
HEMP-CRETE	C30 Concrete	15 phr fine biochar + 30 phr coarse biochar (1–3 mm aggregate); 12 phr fiber	$\rho = 1.45 \text{ g/cm}^3$; $\sigma_{\text{compressive}} = 55 \text{ MPa}$ (+83%); $\sigma_{\text{tensile}} = 35 \text{ MPa}$ (+1067%)	ASTM C39 / ASTM C496
HEP-OXY	Petroleum DGEBA Epoxy	EHO:MHO 49:49 stoichiometric; 15 phr carbon fiber; 1.5 phr CNC	$\rho = 1.28 \text{ g/cm}^3$; $\sigma = 140 \text{ MPa}$; $E = 12 \text{ GPa}$; Fully reprocessable	ASTM D3039 / ASTM D5868

Variant ID	Target Incumbent	Key Formulation Changes	Target Performance Metrics	Test Protocol Standard
HEMP-KEV	Kevlar-49	MHO 60 wt%; 30 phr aligned short carbon fiber; 2 phr CNC	$\rho = 1.42 \text{ g/cm}^3$; $\sigma_{\text{tensile}} = 420 \text{ MPa}$; $E = 52 \text{ GPa}$; Omnidirectional impact toughness	ASTM D3039 / NIJ Level IIA
HEMP-TITAN	Ti-6Al-4V Titanium	MHO 55 wt%; 28 phr aligned fiber; 3.6 phr total nanofillers	$\rho = 1.38 \text{ g/cm}^3$; $E = 42 \text{ GPa}$; Specific Modulus = $30.4 \text{ GPa} \cdot \text{cm}^3/\text{g}$ (+18% vs. Ti)	ASTM D3039 / ASTM E831
HEMP-GFRP	E-Glass / Epoxy	MHO 52 wt%; 20 phr random-in-plane carbon fiber; 1.5 phr CNC	$\rho = 1.30 \text{ g/cm}^3$; $\sigma = 200 \text{ MPa}$; $E = 26 \text{ GPa}$; Reprocessable, 28% lighter	ASTM D3039 / ASTM D2344

SECTION 9: Thermal Reprocessing & Circularity Protocols

9.1 Compression Molding Reprocessing (Recycling) Protocol

1. Granulate cured vitrimer scrap into fine particles ($1\text{--}3 \text{ mm}$) using a mechanical composite grinder.
2. Load granulated scrap into a matched metal compression mold pre-heated to 180°C .
3. Apply 3.0 MPa pressure for 20 minutes to allow dynamic β -hydroxy ester transesterification bond exchange across granule boundaries.
4. Cool mold under pressure to $<60^\circ\text{C}$ before demolding.

9.2 Lap-Shear Thermal Welding Protocol

1. Surface-clean two cured vitrimer composite plaques using anhydrous hemp ethanol.
2. Overlap plaque ends by 12.5 mm inside a heated lap-shear welding fixture.
3. Clamp joint at 2.0 MPa pressure and heat joint interface to 190°C for 15 minutes.
4. Cool under pressure. Joint strength must exceed 90% of monolithic lap-shear strength when evaluated under ASTM D5868.

SECTION 10: Quality Control, ASTM Standards & Safety Data

10.1 Quality Control Test Matrix

BATCH QUALITY CONTROL MATRIX					
V		V		V	
CHEMICAL QC		PHYSICAL QC		RHEOLOGY QC	
Oxirane Oxygen (AOCS Cd 9-57)		Archimedes Density (ASTM D792)		Stress Relaxation (180 deg C) $\tau^* < 300$ s	
Acid Number (ASTM D6641)		Void Content (ASTM D2734)			

10.2 Bio-Based Carbon Verification Standard

Pursuant to ASTM D6866 / ISO 16620 radiocarbon (^{14}C) testing, all matrix monomers and carbon nanofillers qualify as 100% modern biological carbon. The non-renewable mass fraction is limited to $\approx 1.5\%$, originating exclusively from the zinc acetylacetonate catalyst core.

10.3 Laboratory Safety & Handling

- **Nanofiller Handling:** Handle dry HGO, HrGO, nanosheets, and CNC inside a HEPA-filtered ISO Class 5 laminar flow hood with certified N95 or P100 respirator protection to avoid inhalation risks.
- **Thermal Hazards:** High-temperature processing ($180\text{--}200^\circ\text{C}$) during curing and vitrimer thermoforming requires heat-resistant Kevlar gloves and face protection.