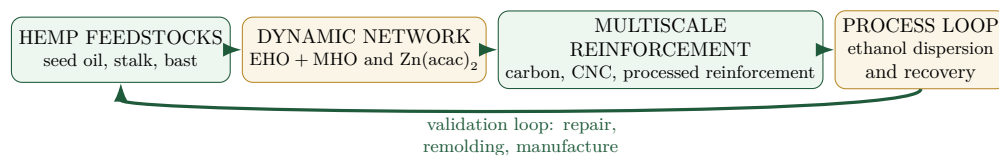

Hempoxies

A Hemp-Derived Multiscale Vitrimer Composite Platform

Epoxidized and maleinized hempseed-oil networks reinforced with hierarchical hemp-derived carbon and cellulose materials



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Open-source position: Hempoxies platform released as open source; see Section 5.3

Important status statement. This is a conceptual development proposal, not a validated product specification or experimental report. No performance data, replicated batch data, or independent qualification data were supplied with the source materials. Established vitrimer mechanisms, formulation hypotheses, target values, and required validation evidence are identified separately. The terms “biobased carbon,” “bio-derived mass,” and “hemp-derived mass” are used deliberately and are not treated as interchangeable.

This document does not provide: an executable laboratory recipe; home, kitchen, garage, or consumer-use instructions; exact synthesis quantities, addition rates, temperatures, pressures, residence times, quench recipes, or equipment dimensions; a validated manufacturing SOP; a product specification or certificate of analysis; measured or independently replicated performance data; a certified safety case, operating permit, SDS, exposure assessment, or emergency plan; regulatory, organic, vegan, environmental, food-contact, medical, aerospace, or other application approval; a freedom-to-operate or patent-clearance opinion; a complete life-cycle assessment; a guaranteed “greater than 99% hemp-derived” claim; a guarantee of biodegradability, compostability, non-toxicity, or infinite recyclability; or authorization to construct, sell, scale, or commercialize Hempoxies.

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1 Authorship, AI Assistance, and Guiding Principles

1.1 Authorship and AI-assisted research note

This proposal is authored by **Marie-Soleil Seshat Landry** of LandryIndustries.ca, MarieLandrySpyShop.com, and SearchForOrganics.com. Manus AI was used as an AI-assisted research and drafting system for literature discovery, source comparison, document organization, consistency checking, and editorial support. AI assistance does not constitute experimental observation, authorship of scientific judgment, laboratory supervision, regulatory approval, or verification of any claim. The named author and qualified project personnel remain responsible for source checking, experimental decisions, safety, data integrity, and all public statements.

1.2 Author principles and design constraints

The platform is developed under the following author-directed principles. They are design requirements and governance commitments, not certifications or completed life-cycle assessments.

Table 1: Author-directed principles and verification requirements.

Principle	Required interpretation and evidence
Green chemistry	Prefer prevention of waste, safer solvents and auxiliaries, energy efficiency, renewable feedstocks, catalysis, real-time monitoring, and inherently safer process conditions. Each substitution shall be evaluated for hazard, yield, performance, and total life-cycle burden rather than by a “green” label alone.
Sustainability	Report renewable content, hemp-derived mass, energy, water, emissions, solvent losses, waste, transport, and end-of-life limitations separately. No sustainability claim shall rely on feedstock origin alone.
Organic-certification principles	Where agricultural inputs are described as organic, document the applicable certification, chain of custody, allowed processing aids, segregation, residues, and certifier requirements. Organic certification of a crop does not automatically certify an industrial resin.
Vegan principles	Exclude intentionally animal-derived ingredients, processing aids, binders, testing materials, and animal-derived auxiliaries unless a declared exception is approved. Verify supplier declarations and avoid representing the resin as vegan until the complete supply chain is reviewed.
No-petrol requirement	The design target is no petroleum-derived feedstocks or auxiliaries. Epichlorohydrin, conventional FGE routes, catalysts, surfactants, coatings, and processing aids shall be origin-verified; any petroleum-derived input is a documented nonconformance to the strict no-petrol target, not silently counted as hemp-derived.

1.3 Non-negotiable laboratory boundary

Do not fabricate Hempoxies at home. Kitchen-made Hempoxies is prohibited. The platform may involve exothermic oxidation, peroxides, strong acids, reactive epoxides, flammable anhydrous ethanol, metal catalysts, combustible powders, vacuum, pressure, and hazardous vapors. No formulation, substitution, heating, solvent recovery, carbonization, nanomaterial preparation, or curing experiment shall be attempted in a kitchen, garage, bedroom, domestic workshop, improvised outdoor setup, or other non-laboratory environment. Work requires a qualified laboratory or pilot facility, trained staff, current

SDS documents, engineering controls, approved waste routes, emergency planning, and formal process-safety review.

The document is a research and governance framework, not a home recipe or an operating procedure. It intentionally omits executable quantities, improvised substitutions, and unsupervised reaction instructions. Any future detailed method shall be issued only as a controlled laboratory SOP after hazard review, reaction calorimetry, equipment qualification, and institutional approval.

2 Scientific Method, Stage Prohibitions, and Result Recording

Every Hempoxies work package shall follow the scientific method: define a question; review prior evidence; state a falsifiable hypothesis; pre-register the formulation revision, controls, endpoints, and stop criteria; conduct the experiment in an approved facility; preserve raw data; analyze against the predeclared method; record uncertainty and deviations; decide whether the hypothesis is supported, rejected, or unresolved; and publish the evidence package with its limitations.

Table 2: Scientific-method checkpoints and prohibited shortcuts.

Checkpoint	Required record	NOT TO DO
Question and background	Literature sources, prior-art boundary, material-origin assumptions, and a specific question.	Do not begin with a desired marketing claim and retrofit evidence.
Hypothesis and controls	Falsifiable hypothesis, negative and positive controls, replicates, endpoints, and stop criteria.	Do not omit controls, change endpoints after seeing results, or treat technical repeats as independent batches.
Approved experiment	Versioned SOP, trained personnel, calibrated equipment, risk assessment, and waste route.	Do not improvise recipes, substitute chemicals, bypass interlocks, or scale by geometric multiplication alone.
Data and analysis	Raw instrument files, photographs, batch records, deviations, scripts, uncertainty, and failure modes.	Do not discard inconvenient results, conceal failed batches, or report averages without specimen count and scatter.
Decision and publication	Supported/rejected/unresolved decision, next gate, limitations, repository deposit, and manuscript plan.	Do not call a target a result, a screening result a qualification, or open publication a safety or freedom-to-operate clearance.

2.1 Stage-by-stage “do not do” rules

1. **Feedstock qualification:** Do not accept unidentified oil, biomass, catalyst, solvent, or reinforcement; do not mix certified and uncertified streams without traceability; do not claim organic, vegan, hemp-derived, or no-petrol status from supplier marketing alone.
2. **Chemical functionalization:** Do not perform peroxide, acid, epoxidation, maleinization, or glycidylation work without calorimetry, compatible equipment, temperature control, emergency quench planning, and trained supervision.
3. **Carbon and nanomaterial preparation:** Do not carbonize, activate, oxidize, reduce, mill, or aerosolize material without dust control, ventilation, ignition control, respiratory protection

program, and waste characterization.

4. **Ethanol dispersion and recovery:** Do not use open vessels, uncontrolled heat, household appliances, ungrounded equipment, or unapproved condensers. Do not distill or recover ethanol without flammable-liquid design, vapor control, grounding, bonding, and emergency shutdown.
5. **Mixing and cure:** Do not add catalyst or reactive components to an uncharacterized batch, exceed validated temperature or pressure limits, or cure a formulation with unknown residual solvent or exotherm.
6. **Testing and claims:** Do not compare Hempoxies with steel, titanium, Kevlar, or aerospace composites using unmatched geometry, density, orientation, conditioning, or failure criteria. Do not publish selective data.
7. **Scale-up:** Do not transfer a laboratory procedure to pilot scale without process hazard analysis, heat-transfer review, mixing and mass-transfer analysis, relief design, waste plan, supplier qualification, and management-of-change approval.

2.2 Guided experimental record

The following spaces are intentionally blank. They are not permission to conduct work without approvals; they are prompts for a controlled electronic laboratory notebook or validated paper record.

Question:

Hypothesis and acceptance criterion:

Controls and replicate plan:

Record here: batch ID, date, operator, formulation revision, instrument IDs, raw-data path, deviations, observations, and decision.

3 Executive Summary

HEMPOXIES is proposed as a family of dynamic covalent polymer networks based on epoxidized hempseed oil and maleinized hempseed oil, reinforced with hemp-derived carbonaceous and cellulosic materials across molecular, nano, micro, and processed-reinforcement length scales. The intended value proposition is a combination of renewable feedstock utilization, thermoset-like dimensional stability, thermal bond exchange, repairability, and reduced dependence on petroleum-derived matrix chemistry.

The proposal is scientifically credible as a *research platform*. Epoxy–anhydride reactions can generate β -hydroxy ester linkages, and Zn(II) catalysts are established in transesterification-based epoxy vitrimers [1, 2, 12]. Direct hemp-oil epoxy prior art also exists: Lerma-Canto et al. reported epoxidized

hemp oil systems using maleinized hemp oil and anhydride hardeners, with formulation-dependent stiffness, ductility, cure time, and bio-based content [13]. Reviews of bio-based vitrimers describe the field as promising but still subject to unresolved trade-offs among mechanical performance, exchange kinetics, durability, and industrial processing [2, 5, 6]. The central development challenge is not whether the mechanism is conceptually possible; it is whether a reproducible, processable, durable composite can be produced while preserving adequate network density, processed-reinforcement adhesion, moisture resistance, and service-temperature performance.

The revised proposal therefore adopts five principles. First, the formulation is defined on a final-mass and reactive-equivalent basis. Second, ASTM D6866 is used only for biobased-carbon measurement, while hemp-derived mass is established by a separate component-level mass balance. Third, “infinite reprocessability” is replaced by measurable cycle-retention targets. Fourth, benchmark claims against steel, titanium, Kevlar, and aerospace composites remain hypotheses until equivalent test conditions are met. Fifth, scale-up is gated by data rather than by technology-readiness labels alone.

Table 3: Development position of the rewritten proposal.

Dimension	Revised position
Core chemistry	Plausible and supported by established vitrimer literature.
Primary uncertainty	Reactive-equivalent stoichiometry, filler dispersion, catalyst activity, and durability.
Sustainability claim	Report biobased carbon, total bio-derived mass, and hemp-derived mass separately.
Performance status	Target values requiring measured, replicated, and independently reviewable data.
Recommended first market	Non-safety-critical molded, repairable, or semi-structural components rather than aerospace primary structure.

4 Platform Definition and Design Objectives

4.1 Platform concept

The platform converts multiple fractions of hemp biomass into a family of reactive, processing, and reinforcing materials. Hempseed oil provides the lipid-derived matrix feedstock. Stalk and bast fractions provide cellulose, hemicellulose-derived furans, char, nanosheets, engineered carbon reinforcements, and a proposed anhydrous ethanol processing medium. The ethanol is intended primarily as a recoverable dispersion and processing solvent rather than as a permanent resin constituent.

Fiber-use boundary. Hempoxies does *not* use raw, untreated, or merely chopped natural hemp fibers as reinforcement. Any fiber-like reinforcement must first undergo a defined conversion and engineering sequence—such as purification, stabilization, carbonization, sizing, chopping, surface treatment, or other qualification—before it is introduced into the resin. The proposal therefore refers to *processed hemp-derived carbon reinforcement*, not raw hemp fiber.

The proposed formulation is not a single immutable recipe; it is a controlled library in which matrix stoichiometry, reactive diluent content, catalyst loading, filler type, processed-reinforcement content,

and solvent usage are selected for a defined application.

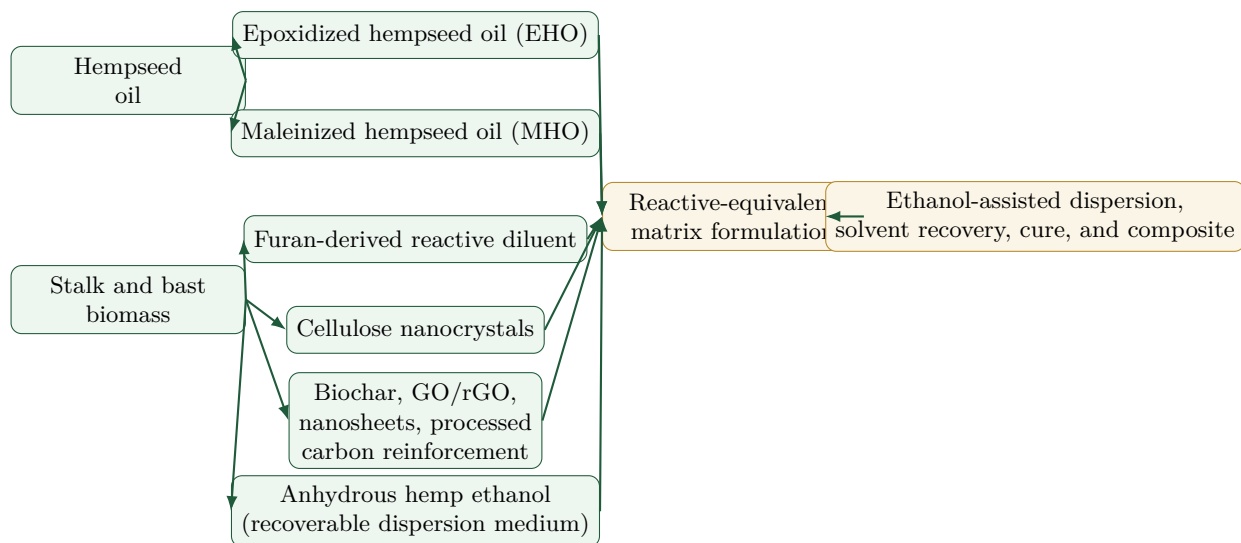


Figure 1: Conceptual, not-to-scale architecture. The diagram separates hemp feedstocks, derived components, reactive-equivalent formulation, and ethanol-assisted composite processing; it is not a validated process-flow diagram. All arrows represent proposed routes requiring yield, purity, recovery, and origin verification.

4.2 Design objectives

The development program shall optimize the following objective vector rather than a single tensile number:

1. reproducible reactive conversion and network formation;
2. adequate uncured viscosity and pot life for the selected process;
3. useful glass-transition and service-temperature margins;
4. tensile, flexural, fracture, fatigue, and impact performance at defined density;
5. measurable stress relaxation and pressure-assisted repair or welding;
6. resistance to moisture, solvents, thermal cycling, and hydrolysis;
7. retention of properties after repeated remolding cycles; and
8. defensible environmental and mass-balance accounting.

5 Prior Art, Open-Source Status, and Freedom-to-Operate Boundaries

5.1 Prior-art map

Table 4: Selected prior art relevant to Hempoxies. The table is a technical landscape review, not a legal opinion or freedom-to-operate determination.

Prior-art family	What it establishes	Relevance and limitation for Hempoxies
Foundational epoxy vitrimers	Montarnal et al. demonstrated epoxy networks whose topology rearranges by exchange reactions without depolymerization, with Arrhenius-like viscosity and thermal reshaping/welding [14].	Establishes the general vitrimer concept; does not establish hemp feedstocks, the proposed filler stack, ethanol processing, or the present formulation.
Zn-catalyzed epoxy vitrimers	Niu et al. studied Zn-containing catalysts for transesterification in epoxy vitrimers and compared catalyst efficiency through stress relaxation [12].	Supports Zn-mediated exchange as known art; does not validate $\text{Zn}(\text{acac})_2$ in Hempoxies or establish the proposed catalyst loading.
Hemp-oil epoxy resins	Lerma-Canto et al. developed EHO thermosetting resins using MHO and methyl nadic anhydride, reporting formulation-dependent mechanical and curing behavior [13].	Directly overlaps the broad EHO/MHO resin concept; Hempoxies must distinguish its dynamic-network, processed-reinforcement, solvent-loop, and open-source implementation claims.
Hemp cellulose nanocrystals	Bahsaine et al. extracted hemp CNCs using alkaline treatment and acid hydrolysis and evaluated their reinforcement in polymer films [15].	Supports hemp-CNC preparation precedent; does not demonstrate compatibility with EHO/MHO vitrimer matrices.
Hempseed-oil bio-epoxy commercialization prior art	ZILA BioWorks publicly describes hempseed-oil and other plant-oil bio-epoxy systems, application-specific formulation and cure-kinetics work, composites/coatings applications, and pilot-stage scale-up [24, 25, 26].	Establishes direct commercialization and disclosure prior art for hempseed-oil bio-epoxy. ZILA’s public statements are company or institutional reports, not independent validation of Hempoxies or a legal FTO conclusion.
Hemp-derived carbon nanosheets	Wang et al., including David Mitlin, reported interconnected partially graphitic nanosheets from hemp bast fiber and a hydrothermal-carbonization/activation route [27].	Establishes prior art for hemp-derived carbon nanosheet identity and preparation. The cited work concerns supercapacitor electrodes, not epoxy reinforcement; Hempoxies must not claim the nanosheet material or broad conversion route as wholly novel.
Hemp-derived carbon nanosheet patent	US10170251B2 lists David Mitlin and collaborators as inventors and the University of Alberta as assignee for carbon nanosheets [28].	Requires patent-family, jurisdiction, claim, assignment, and status review before any FTO conclusion. The Google Patents status is a locator only and not a legal opinion.
University of Washington attribution check	No authoritative University of Washington source was verified for the Mitlin hemp-nanosheet work in the current search. The verified primary record identifies the University of Alberta affiliation and assignee [27, 28].	Do not label the Mitlin nanosheet prior art as University of Washington work unless a specific UW publication, patent, researcher, or URL is supplied and independently verified.
Henry Ford and historical plant composites	The Henry Ford institutional record documents the 1941 soybean car, whose plastic panels were made from a historically uncertain plant-based formulation; accounts mention soybean fiber/phenolic resin and, in one account, hemp, flax, wheat, and ramie [29].	Establishes early plant-based composite and bio-resin precedent. The formulation is not reproducible from surviving records and does not establish Hempoxies chemistry, nanosheets, vitrimers, or modern performance.
Carbonized hemp filler in polymer composite	US10494501B2, “Nanocomposite hemp,” describes polymer composites containing carbonized hemp filler and lists Thomas Jefferson University as assignee [30].	Directly limits any absolute claim that hemp-derived carbon has never been proposed in polymer composites. Hempoxies must distinguish nanosheet morphology, EHO/MHO vitrimer matrix, multiscale stack, and processing route from the patent claims.
Biobased soybean-oil epoxy vitrimer composite	Liu et al. reported an epoxidized-soybean-oil/vanillin dynamic epoxy vitrimer used as a reprocessable and recyclable carbon-fiber composite matrix [31].	Establishes prior art for a biobased epoxy vitrimer combined with carbon-fiber reinforcement and recycling; it does not establish hemp-derived carbon nanosheets or the Hempoxies EHO/MHO/Zn/ethanol combination.

Prior-art family	What it establishes	Relevance and limitation for Hempoxies
Biobased vitrimer with carbon-fiber composite recycling	Liu et al. reported a biobased epoxy vitrimer with dynamic imine chemistry, UV shielding, and recyclable carbon-fiber reinforced composites [32].	Establishes additional prior art for biobased vitrimer matrices and carbon-fiber composite reprocessing; it does not validate the Hempoxies matrix or hemp-derived reinforcement claims.
Biocatalytic vitrimers	WO2020002904A1 describes vitrimer systems containing biomolecules with esterase activity and discusses metal catalysts including zinc acetylacetonate as prior art [16].	Relevant to catalyst and vitrimer landscape review; claim scope, status, and jurisdiction must be reviewed by patent counsel.
Vegetable-oil epoxy compositions	US20210371579A1 / US11945905B2 covers vegetable-oil-derived epoxy compositions and cured products [17].	Relevant to the broad plant-oil epoxy landscape; it is not a determination that Hempoxies infringes or avoids the patent family.

The prior-art review makes five boundaries explicit. First, the combination of hempseed-oil epoxy chemistry, anhydride curing, vitrimer exchange, nanofillers, processed hemp-derived carbon reinforcement, and ethanol-assisted processing should not be described as wholly unprecedented. Second, ZILA BioWorks is relevant commercial and technical prior art for hempseed-oil bio-epoxy systems and should be treated as a potential competitor, disclosure source, and patent-landscape subject rather than ignored. Third, Henry Ford’s soybean-car work establishes historical plant-based composite precedent, while US10494501B2 prevents an absolute statement that carbonized hemp has never been proposed in polymer composites. Fourth, David Mitlin’s hemp-derived nanosheet work and the related University of Alberta patent establish important prior art for hemp-derived carbon nanosheets, while Liu et al. establish biobased vitrimer/carbon-fiber composite prior art. These sources do not establish epoxy-composite performance for the Mitlin nanosheets or Hempoxies-specific novelty. Fifth, the requested University of Washington attribution remains unverified in the current source review and is not asserted. Open publication does not create freedom to operate. Patent claims, continuations, national-phase rights, assignments, expiration, prosecution history, and jurisdiction-specific enforceability require a professional patent search and legal opinion.

5.2 Qualified Hempoxies novelty and differentiation case

The proposal does not claim that hemp-derived carbon has never been used in a composite. The verified prior-art record includes historical plant-based panels associated with Henry Ford, a patent on polymer composites containing carbonized hemp filler, hemp-derived carbon nanosheets developed for supercapacitor electrodes, and biobased vitrimer matrices used with conventional carbon fiber. Those references are acknowledged rather than minimized.

The narrower novelty hypothesis is that, within the documented search scope, no verified source was identified that combines: (i) a measured EHO/MHO anhydride-linked epoxy vitrimer; (ii) Zn(II)-enabled associative exchange; (iii) hemp-derived carbon nanosheets used as reinforcement or interfacial filler in an epoxy, vitrimer, or structural polymer composite; (iv) a multiscale stack including processed hemp-derived carbon reinforcement, CNC, biochar, and optional nanosheets; (v) ethanol-assisted dispersion with solvent recovery and residual-solvent accounting; and (vi) the stated origin-accounting, laboratory-governance, and open-source release framework.

This is a search-based novelty hypothesis, not an absolute worldwide-first claim, legal opinion, or guarantee of patentability. The proposal may state that Hempoxies appears to propose a potentially novel use and combination, subject to expanded patent and literature searching, non-English database review, claim charting, prosecution-history review, enablement analysis, and professional freedom-to-operate advice. The proposal shall not state that hemp nanosheets have only ever

been used in supercapacitors; the defensible statement is that the Mitlin nanosheet publication focused on supercapacitor electrodes, while their use as reinforcement in the proposed Hempoxies epoxy/vitrimer system remains an open novelty and validation question.

5.3 Open-source platform status

The Hempoxies platform is designated by the project as **open sourced**. The open-source release should include the formulation hypotheses, process-development records, data schemas, validation protocols, mass-balance templates, safety assumptions, and versioned technical documentation needed for independent reproduction and critique. Each release shall identify the repository URL, version tag, license, authorship, contribution rules, provenance of data, and any third-party material or dependency.

The open-source designation applies to the project materials released under the selected license. It does not imply that every underlying chemical method, catalyst, process configuration, analytical method, software dependency, or third-party material is unpatented, royalty-free, or safe for unrestricted commercial use. The proposal therefore retains a mandatory freedom-to-operate review, safety review, and regulatory review before commercialization. Open-source publication also does not convert target values into measured results or waive applicable SDS, occupational-exposure, environmental, transport, or product-liability requirements.

6 Chemical Architecture

6.1 Dynamic matrix chemistry

The base network is formed from epoxidized hempseed oil (EHO) and maleinized hempseed oil (MHO). Hemp-oil epoxy resin formation has direct published precedent, but the present proposal extends that chemistry into a dynamic-network and processed-reinforcement platform rather than claiming the base EHO/MHO chemistry as new [13]. The proposed reaction is an epoxide–anhydride ring-opening process that generates ester and secondary hydroxyl groups. Under thermal activation and Zn(II) catalysis, the hydroxyl and ester groups can participate in associative transesterification. In a vitrimer, the network topology changes while the total number of covalent links remains approximately constant; this distinguishes bond exchange from simple reversible bond dissociation [1, 2].

The formulation shall be calculated using measured reactive equivalents:

$$R_{\text{epoxy}} = \frac{m_{\text{EHO}}}{EEW_{\text{EHO}}}, \quad R_{\text{anhydride}} = \frac{m_{\text{MHO}}}{AEW_{\text{MHO}}}, \quad (1)$$

where EEW is epoxy equivalent weight and AEW is anhydride equivalent weight. A nominal 1:1 oil mass ratio is not sufficient to establish stoichiometry. The target ratio shall be reported as $R_{\text{epoxy}}/R_{\text{anhydride}}$ with measured batch values and allowable tolerances.

6.2 Catalyst function

Zn(acac)₂ is proposed as a dual-function catalyst for cure acceleration and transesterification. Literature demonstrates that Zn(II) can coordinate oxygen-containing groups, activate ester carbonyls, and facilitate transesterification in epoxy vitrimer networks [1, 12]. The exact catalyst loading for Hempoxies must nevertheless be determined experimentally because nanofillers may adsorb

catalyst and because excessive catalysis may alter cure profile, creep, color, thermal degradation, or long-term stability.

6.3 Reactive diluent

Furfuryl glycidyl ether (FGE) is proposed as a reactive diluent and as a source of furan rings. The furfuryl fraction may originate from hemp-derived furfural, but glycidylation using epichlorohydrin means that the final molecule is not automatically 100% hemp-derived. The proposal shall therefore classify FGE as “partly bio-derived” unless the full precursor origin and system boundary are documented. ZILA BioWorks’ public materials likewise demonstrate that hempseed-oil bio-epoxy is an active commercial-development field; Hempoxies must distinguish its own formulation, processed-reinforcement, solvent-ledger, open-source, and validation claims from this prior art [24, 25].

7 Multiscale Reinforcement Architecture

Table 5: Indicative starting formulation window. All phr values are relative to the combined EHO+MHO resin basis and must be normalized to final mass for product specifications.

Component	Starting window	Function and control variables
EHO	Equivalent-based	Epoxy-bearing matrix precursor; measure oxirane oxygen and viscosity.
MHO	Equivalent-based	Anhydride-bearing network precursor; measure acid/anhydride number.
Zn(acac) ₂	1.0–3.0 wt% of final mass	Cure and exchange catalyst; verify catalyst availability after filler addition.
FGE	8–12 phr	Reactive diluent; monitor Tg, viscosity, conversion, and network density.
Hemp GO/rGO/nanosheets	<2.5 phr total	Interfacial, barrier, electrical, and thermal functions; characterize dispersion and ash.
CNC	1.0–2.0 phr	Crack pinning and modulus modification; hemp-CNC extraction by alkaline treatment and acid hydrolysis has published precedent, but matrix compatibility remains to be established [15].
Hemp biochar	3.0–5.0 phr	Microfiller and resin-pocket reduction; control ash, porosity, and adsorption.
Processed hemp-derived short carbon reinforcement	15–20 phr starting window	Primary reinforcement; measure carbonization history, length distribution, orientation, sizing, surface treatment, and retained strength.
Anhydrous hemp ethanol	50–100 phr process basis	Recoverable dispersion and processing medium; measure water content, solvent recovery, residual ethanol, and flammability controls.

7.1 Development bill of materials

The following bill of materials defines the development formulation and the reason each component is present. It is a controlled research BOM, not a commercial product specification. All masses shall be normalized to the selected final-product basis and reconciled against measured reactive equivalents, purity, moisture, solvent recovery, and origin documentation.

Table 6: Hempoxies development bill of materials and component rationale.

Component	Development basis	Why it is included	Required qualification and accounting treatment
EHO	Measured epoxy equivalents; starting formulation library	Hemp-derived epoxy-bearing matrix precursor; contributes renewable lipid backbone and reactive epoxide groups.	Oxirane oxygen/EEW, viscosity, moisture, oxidation, acid value, purity, origin, and storage stability. Incorporated matrix mass.
MHO	Measured acid/anhydride equivalents; starting formulation library	Hemp-derived anhydride/acid-bearing network precursor; supplies cure functionality and ester-forming sites.	Acid/anhydride number, FTIR/NMR, viscosity, moisture, cure response, purity, origin, and storage stability. Incorporated matrix mass.
FGE or qualified alternative	8–12 phr screening window, subject to origin review	Reactive diluent and potential furan functionality; lowers processing viscosity and may modify network density.	Epoxy equivalent, purity, water, residuals, origin of every precursor and auxiliary. Classify as hemp-derived, partly bio-derived, or nonconforming; incorporated mass.
Anhydrous hemp-derived ethanol	50–100 phr process basis; recoverable	Temporary dispersion and processing medium; improves handling of selected fillers and is not automatically a final resin ingredient.	Ethanol assay, water, denaturants, impurities, recovery, residual solvent, flammability controls, and origin. Charge and recovery in a separate solvent ledger; only residual product mass is incorporated.
Zn(acac) ₂	1.0–3.0 wt% screening window; external input	Cure and transesterification catalyst; zinc is intentionally not synthesized from hemp.	Supplier identity, purity, water, metal content, storage, catalyst loading, and compatibility. External/inorganic catalyst mass; not hemp-derived.

Hemp CNC	1–2 phr screening window	Nanoscale cellulose component for crack pinning, rheology, barrier effects, and interfacial modification.	Size, morphology, crystallinity, moisture, ash, purity, surface chemistry, dispersion, and contamination. Incorporated hemp-derived or bio-derived mass only after origin review.
Hemp biochar	3–5 phr screening window	Microfiller and potential resin-pocket, shrinkage, electrical, or thermal modifier.	Carbonization history, ash, porosity, particle size, moisture, PAHs/metals or other contaminants, and adsorption behavior. Incorporated processed carbon mass.
Processed hemp-derived carbon reinforcement	15–20 phr screening window	Primary micro/macro reinforcement; provides load transfer only if morphology, sizing, adhesion, and retained strength are qualified.	Raw or untreated hemp fibers are prohibited. Require carbonization history, length/particle distribution, orientation, sizing, surface chemistry, ash, moisture, strength, and COA. Incorporated processed carbon mass.
Hemp-derived carbon nanosheets or GO/rGO-type material	< 2.5 phr total screening window	Interfacial, barrier, electrical, and thermal functions; inclusion is optional and must be justified by application data.	Structural/surface chemistry, layer or particle distribution, ash, metals, moisture, conductivity, dispersion, and nanomaterial exposure controls. Incorporated processed carbon mass.
Process aids and cleaning materials	Facility-specific; minimized	Support filtration, transfer, cleaning, calibration, and safe handling.	Each aid must be listed, origin-classified, included in waste and life-cycle accounting, and excluded from hemp-derived claims unless documented.
Packaging and labels	Facility-specific	Preserve moisture, traceability, hazard communication, and lot identity.	Compatible packaging, SDS/label status, lot code, storage temperature, expiry/retest date, and chain-of-custody record. Not resin mass unless intentionally incorporated.

The BOM shall be version-controlled. A formulation revision is not valid until the responsible

chemist and quality manager approve the component identities, reactive-equivalent calculations, origin classifications, solvent ledger, hazard review, and release-test plan. Zinc remains an external catalyst input and is not included in the hemp-synthesis SOPs.

Anhydrous hemp ethanol shall be treated as a processing aid unless analytical testing demonstrates that a defined residual fraction remains intentionally incorporated in the final product. It may be used to prepare filler slurries, lower temporary processing viscosity, and support solvent-assisted dispersion. The process shall include closed handling, recovery by distillation or an equivalent method, water-content control, and a residual-solvent specification. Recovered ethanol shall not be counted as incorporated product mass, and unrecovered losses shall be reported in the process mass balance.

Raw or untreated hemp fiber shall not appear as an uncontrolled substitute in any formulation or test. All fiber-like reinforcement shall be traceable to a defined processed-material specification and certificate of analysis.

The full multiscale architecture shall not be presumed to be synergistic. A staged formulation program shall compare the neat matrix, single-filler systems, processed-reinforcement-only systems, ethanol-assisted and solvent-free dispersion routes, and the complete stack. The accepted formulation shall be the one that provides the best application-level balance of mechanical performance, processability, durability, solvent recovery, and cost—not necessarily the one containing the largest number of filler families.

8 Sustainability and Origin Accounting

8.1 Three separate claims

The project shall use three separate metrics:

1. **Biobased carbon content:** the percentage of new organic carbon relative to total organic carbon measured by ASTM D6866 or an equivalent recognized method [3, 4].
2. **Total bio-derived mass fraction:** the mass fraction of all ingredients obtained from renewable biological feedstocks, calculated from a declared system boundary.
3. **Hemp-derived mass fraction:** the mass fraction specifically traceable to hemp biomass, with chemical reagents, catalysts, solvents, process losses, and recovered streams identified separately.

ASTM D6866 is a radiocarbon method for distinguishing contemporary carbon from fossil carbon; it is not, by itself, a gravimetric assay of total product mass or proof that every component originated from hemp [3, 4]. The project shall therefore never use a D6866 result alone to substantiate a “greater than 99% hemp-derived mass” claim.

8.2 Proposed mass-balance statement

For each batch, the project shall report:

The ledger is maintained separately from the incorporated-product formulation. Recovered ethanol is not included in final product mass, residual ethanol is included only if analytically detected in the product, and unrecovered loss is included in process-emissions and environmental accounting.

Table 7: Illustrative ethanol solvent ledger for a 100-unit process charge. The values are accounting placeholders, not measured process results.

Ledger item	Illustrative mass units
Anhydrous hemp ethanol charged to dispersion	50.0
Ethanol recovered before cure	48.5
Ethanol remaining in concentrated formulation	1.0
Unrecovered process loss requiring emissions accounting	0.5
Check: recovered + residual + loss	50.0

For each batch, the project shall report:

$$M_{\text{final}} = \sum_i M_i - M_{\text{volatile loss}} + M_{\text{process additions}}, \quad (2)$$

with each M_i assigned to one of the following origin classes: hemp-derived, other bio-derived, fossil-derived organic, inorganic/mineral, catalyst, or unassigned pending verification. Anhydrous hemp ethanol shall be tracked in a dedicated solvent ledger that records charge, recovered quantity, residual quantity in the product, and process loss. Recovered ethanol shall not be counted as incorporated product mass unless it remains in the final article; unrecovered ethanol shall be included in process emissions and environmental accounting.

The present proposal retains an internal design target of approximately 98.5% renewable or hemp-derived incorporated mass in a representative formulation, subject to verification; this is not a measured result or an approved external claim. The target excludes recovered ethanol that does not remain in the cured product and separately reports any residual ethanol. The public claim shall be revised only after independent mass-balance review and a certified biobased-carbon measurement.

9 Stoichiometric Calculation and Cure-Schedule Specification

The current formulation library is not complete until every batch is converted from screening phr values to measured reactive equivalents and a validated thermal schedule. The following calculation framework is mandatory for each formulation revision. All numerical values in the worked example below are hypothetical and instructional; they are not measured Hempoxies values, not a production recipe, and not an approved operating schedule.

9.1 Reactive-equivalent calculation

Let m_E denote the mass of EHO, m_A the mass of MHO, EEW_E the measured epoxy-equivalent weight of EHO, and AEW_A the measured anhydride-equivalent weight of MHO. The reactive equivalents are

$$n_E = \frac{m_E p_E f_E}{EEW_E}, \quad n_A = \frac{m_A p_A f_A}{AEW_A}, \quad (3)$$

where p is the purity fraction and f is the validated functionality or active-equivalent correction factor. If the target anhydride-to-epoxy ratio is $\lambda = n_A/n_E$, the required MHO mass for a selected

EHO mass is

$$m_A = \frac{\lambda m_E p_E f_E AEW_A}{p_A f_A EEW_E}. \quad (4)$$

The batch record shall report EEW_E , AEW_A , purity, moisture, active-equivalent corrections, target λ , measured λ , and the permitted deviation. A nominal 1:1 EHO:MHO mass ratio is not an acceptable substitute for this calculation.

For any additive specified in phr relative to the EHO+MHO matrix basis $B = m_E + m_A$, the additive mass is

$$m_j = \frac{phr_j}{100} B. \quad (5)$$

For a catalyst specified as a final-product mass fraction w_c , calculate

$$m_c = \frac{w_c}{1 - w_c} M_{\text{pre-catalyst}}, \quad (6)$$

where $M_{\text{pre-catalyst}}$ includes all incorporated non-catalyst components and excludes recoverable ethanol. If the catalyst percentage is instead specified relative to matrix basis, that convention must be stated explicitly and must not be mixed with the final-mass convention.

The final incorporated mass is

$$M_{\text{final}} = m_E + m_A + m_{FGE} + m_{CNC} + m_{\text{biochar}} + m_{\text{carbon}} + m_{\text{nano}} + m_c + m_{\text{residual ethanol}} \quad (7)$$

while the process charge additionally includes ethanol charged to dispersion. Recovered ethanol is excluded from M_{final} ; unrecovered ethanol is a process loss; residual ethanol is included only when analytically measured in the cured article. The batch must close within the predeclared mass-balance uncertainty.

9.2 Illustrative calculation only

The following example shows the arithmetic structure using hypothetical measured values. Suppose $EEW_E = 250 \text{ g eq}^{-1}$, $AEW_A = 500 \text{ g eq}^{-1}$, both active-equivalent corrections equal one, purity is 100%, and $\lambda = 1.00$. Selecting $m_E = 100.0 \text{ g}$ gives $n_E = 0.400 \text{ eq}$ and therefore requires $m_A = 200.0 \text{ g}$ to give $n_A = 0.400 \text{ eq}$. The matrix basis is then $B = 300.0 \text{ g}$. A hypothetical 10 phr FGE addition is 30.0 g; 1.5 phr CNC is 4.5 g; 4.0 phr biochar is 12.0 g; 17.5 phr processed carbon reinforcement is 52.5 g; and 1.0 phr nanosheet material is 3.0 g. Before catalyst, the incorporated mass is 402.0 g. If catalyst is specified as 2.0 wt% of final incorporated mass, the calculated catalyst mass is $0.020/(1 - 0.020) \times 402.0 = 8.204 \text{ g}$ and the hypothetical final incorporated mass is 410.204 g before any measured residual ethanol. A separate 75.0 g ethanol charge is recorded in the solvent ledger and is not added to the product mass unless residual solvent is measured. This example must be replaced by actual batch values before any claim or scale-up decision.

9.3 Cure and post-cure schedule specification

No cure schedule in this proposal is a validated production schedule. The approved schedule shall be derived from DSC, rheology, gel-time, exotherm, residual-solvent, and mechanical-property data for the exact formulation, batch size, mold geometry, and equipment. Each schedule shall specify: (i) initial material and mold temperature; (ii) ramp rate; (iii) each hold temperature and duration; (iv) atmosphere and pressure; (v) maximum measured internal temperature; (vi) exotherm margin; (vii) demold criterion; (viii) post-cure temperature and duration; (ix) cool-down rate; and (x) conditioning temperature, humidity, and duration before testing.

For laboratory screening only, a non-authorizing staged schedule template may be used to organize DSC and small-coupon work: low-temperature flow and solvent-release hold; intermediate network-formation hold; higher-temperature conversion/exchange hold; controlled cool-down; and a separate post-cure hold only if DSC and DMA show residual reaction or inadequate network development. The actual temperatures, times, ramp rates, pressure, and maximum batch mass shall remain blank until approved by the responsible chemist, EHS reviewer, and process engineer.

Table 8: Mandatory cure-schedule record and approval fields.

Parameter	Facility-approved value and evidence reference
Formulation revision, batch size, mold geometry	
Initial material and mold temperature	
Ramp rate and atmosphere	
Stage 1 flow/solvent-release temperature and time	
Stage 2 network-formation temperature and time	
Stage 3 final-conversion/exchange temperature and time	
Maximum internal temperature and exotherm margin	
Pressure, demold criterion, and cooldown rate	
Post-cure temperature, time, and evidence basis	
Conditioning and release-test timing	
Approvals and deviation disposition	

9.4 Cure-schedule acceptance gates

A schedule is not released unless DSC or equivalent data show the selected hold sequence captures the required conversion, rheology confirms processability and gelation behavior, internal thermocouples demonstrate acceptable exotherm margin, residual-solvent testing passes, and cured specimens meet predeclared conversion, T_g, gel fraction, void, dimensional, and mechanical criteria. A schedule must be requalified when formulation composition, catalyst loading, filler morphology, ethanol residual, batch mass, mold thickness, heat-transfer coefficient, equipment, or ambient conditions change materially.

NOT TO DO. Do not copy a cure schedule from DGEBA, soybean-oil epoxy, or another vitrimer into Hempoxies without formulation-specific evidence. Do not scale time or temperature by geometric multiplication, assume oven setpoint equals specimen temperature, demold by appearance alone, post-cure to conceal incomplete conversion, or report a schedule as validated when it is only a screening hypothesis.

10 Manufacturing Development Plan

11 Controlled SOP Frameworks for Hemp-Derived Components

The following SOPs define the minimum structure for controlled laboratory work. They are not kitchen recipes, not executable home instructions, and not substitutes for facility-specific SOP approval. Exact reagent quantities, addition rates, temperatures, pressures, residence times, quench recipes, equipment dimensions, and emergency actions shall be specified only in a controlled document after SDS review, reaction calorimetry, compatibility review, EHS approval, and operator training. Zinc is intentionally excluded from this section and remains a qualified external catalyst input.

Every SOP shall carry a unique ID, revision, owner, approver, effective date, training requirement, hazard classification, equipment list, materials list, process-boundary diagram, pre-start checklist, in-process controls, stop-work criteria, release tests, waste route, deviation form, and change-control history.

11.1 SOP-H01: Hempseed-oil qualification and preparation

Purpose. Establish a traceable, clean, oxidation-controlled hempseed-oil feedstock suitable for downstream functionalization. **Sequence.** Receive and quarantine the lot; verify identity and chain of custody; inspect packaging and storage history; sample under an approved plan; test moisture, density, viscosity, acid value, peroxide value, iodine value, fatty-acid profile, contaminants, and origin documentation; filter or condition only by an approved method; release, reject, or place the lot on hold. **Controls.** Oxygen exposure, light, temperature, water, cross-contamination, allergen or contaminant status, organic-certification status, vegan supply-chain declaration, and no-petrol origin classification. **Release tests.** COA reconciliation, FTIR/NMR or chromatographic identity, moisture, oxidation indices, and batch-to-batch specification. **Waste.** Segregate off-spec oil, contaminated wipes, filters, and analytical residues. **NOT TO DO.** Do not blend unidentified lots, mask rancidity with additives, or treat food-grade labeling as proof of industrial suitability.

11.2 SOP-H02: Epoxidized hempseed oil (EHO) functionalization

Purpose. Convert qualified hempseed oil into an epoxy-functional intermediate under a controlled oxidation process. **Sequence.** Approve the reaction calorimetry and compatible-equipment review; verify reagent identity and concentration; establish controlled feed and heat-removal capability; conduct the reaction under monitored conditions; sample for conversion and residual oxidant; complete an approved quench and phase/work-up sequence; dry, filter, package, and quarantine the intermediate pending release. **Controls.** Exotherm, peroxide accumulation, acid corrosion, oxygen compatibility, dosing interlocks, cooling failure, venting, pressure, residual oxidant, and waste neutralization. **Release tests.** Epoxy equivalent weight or oxirane oxygen, acid value, residual peroxide, moisture, viscosity, density, FTIR/NMR, color, and storage stability. **Waste.** Treat oxidizing, acidic, aqueous, and organic streams as characterized hazardous waste until EHS-approved classification. **NOT TO DO.** Do not improvise peroxide chemistry, use household containers, exceed validated heat-removal capacity, or proceed without reaction calorimetry and emergency controls.

11.3 SOP-H03: Maleinized hempseed oil (MHO) functionalization

Purpose. Prepare or qualify an anhydride/acid-functional hempseed-oil intermediate for network formation. **Sequence.** Verify oil and maleinizing reagent identity; confirm vessel compatibility

and venting; conduct a controlled addition and reaction under the approved thermal envelope; monitor acid/anhydride functionality, viscosity, color, and side reactions; cool, sample, package, and quarantine pending release. **Controls.** Exotherm, fume control, reagent exposure, pressure, water exclusion, polymerization or gelation, and corrosion. **Release tests.** Acid/anhydride number, FTIR/NMR, epoxy-equivalent compatibility, moisture, viscosity, density, color, cure response, and storage stability. **Waste.** Segregate acidic organic residues and contaminated absorbents. **NOT TO DO.** Do not define MHO by oil mass ratio alone, use an unvented vessel, or release material without measured reactive equivalents.

11.4 SOP-H04: Hemp-derived furan intermediate and reactive diluent

Purpose. Establish whether furfural or another hemp-derived furan intermediate can support a reactive diluent route that satisfies the no-petrol design target. **Sequence.** Qualify the hemp-derived precursor; document fractionation and purification; perform route-specific functionalization only under an approved chemical SOP; isolate and purify the intermediate; verify origin of every reagent and processing aid; and classify the product as hemp-derived, partly bio-derived, or nonconforming. **Controls.** Flammability, corrosivity, reactive epoxide hazards, residual chlorinated or halogenated species where applicable, catalyst residues, and origin accounting. **Release tests.** Epoxy equivalent, purity, water, residual reagents, FTIR/NMR, chromatographic profile, viscosity, color, and no-petrol chain-of-custody review. **NOT TO DO.** Do not label conventional FGE as hemp-derived merely because the furfuryl portion is bio-derived; do not conceal fossil-derived glycidylation reagents or auxiliaries.

11.5 SOP-H05: Processed hemp-derived carbon reinforcement and biochar

Purpose. Convert qualified hemp biomass into engineered carbon reinforcement or biochar; raw, untreated, and merely chopped hemp fibers are prohibited. **Sequence.** Qualify and dry the precursor; perform controlled stabilization and carbonization in engineered equipment; cool under the approved atmosphere; mill, classify, or size only in contained systems; apply any approved surface treatment or sizing; package under dust-controlled conditions; and release only against a certificate of analysis. **Controls.** High-temperature operation, combustible dust, carbon monoxide and volatile emissions, oxygen ingress, ignition, particle aerosolization, ash, metals, PAHs or other contaminants, and retained mechanical integrity. **Release tests.** Carbonization history, particle/length distribution, ash, moisture, surface chemistry, bulk density, porosity, electrical properties where relevant, contamination screen, and reinforcement strength or retained integrity. **Waste.** Characterize char fines, filters, contaminated PPE, and off-spec carbon before disposal. **NOT TO DO.** Do not carbonize in ovens, kilns, grills, or improvised equipment; do not handle powders in open air; do not substitute raw hemp fiber for processed reinforcement.

11.6 SOP-H06: Hemp-derived cellulose nanocrystals (CNC)

Purpose. Isolate and qualify CNC from hemp cellulose under a contained laboratory process. **Sequence.** Qualify and pre-clean the cellulose precursor; conduct approved delignification, purification, and hydrolysis steps in compatible equipment; separate and wash under a validated method; neutralize or recover process streams; concentrate or dry using an approved method; characterize size and surface chemistry; and package with moisture and aerosol controls. **Controls.** Strong acid or base exposure, heat, pressure, corrosive waste, aerosol generation, nanomaterial inhalation, contamination, and aggregation. **Release tests.** Size distribution, morphology, crystallinity, surface chemistry, moisture, ash, purity, dispersion stability, and matrix-compatibility screening. **Waste.**

Neutralization and disposal shall follow the facility waste plan; nanomaterial-containing liquids and filters shall not enter drains without approval. **NOT TO DO.** Do not assume that nanoscale cellulose is harmless, use open sonication without exposure controls, or release material without particle and contamination characterization.

11.7 SOP-H07: Hemp-derived carbon nanosheets, GO/rGO-type materials

Purpose. Establish a qualified route for any hemp-derived nanosheet, graphene-oxide-like, or reduced-carbon material proposed for Hempoxies. The route must explicitly review the hemp-bast carbon nanosheet precedent reported by Wang et al. and the related University of Alberta patent family before making novelty, ownership, or freedom-to-operate statements [27, 28]. **Sequence.** Qualify the carbon precursor; define the selected oxidation, exfoliation, reduction, or alternative route in a facility-specific SOP; operate in closed or contained equipment; monitor oxidation state and heat release; separate and wash under approved controls; dry or disperse under dust and aerosol containment; and release only after structural and contamination testing. **Controls.** Strong oxidants, corrosive media, gas evolution, pressure, exotherm, nanopowder exposure, residual metals, and electrical-conductivity hazards. **Release tests.** Raman/FTIR/XPS or equivalent surface chemistry, microscopy, layer or particle distribution, ash, residual metals, moisture, conductivity where relevant, and dispersion stability. **Waste.** Oxidizing, acidic, metal-containing, and nanocarbon waste streams require separate EHS classification. **NOT TO DO.** Do not synthesize or reduce nanosheets in an unventilated room, use uncontrolled ultrasonication, or describe an uncharacterized black powder as graphene, GO, or rGO.

11.8 SOP-H08: Anhydrous hemp-derived ethanol

Purpose. Produce, purify, or qualify ethanol derived from hemp biomass for use as a recoverable processing aid. **Sequence.** Qualify the fermentation feedstock and origin; perform approved conversion, separation, and purification in a permitted flammable-liquid facility; verify water content and denaturant status; store in compatible grounded containers; use in closed dispersion equipment; recover and test the solvent; and maintain a charge/recovery/residual/loss ledger. **Controls.** Flammable vapor, ignition sources, static, pressure, ventilation, vapor detection, denaturants, water content, storage temperature, and recovery-system integrity. **Release tests.** Ethanol assay, water by Karl Fischer, denaturants and impurities, odor/color where relevant, residual-solvent performance, and origin documentation. **Waste.** Distillation bottoms, contaminated solvent, wipes, and spill residues shall be managed as flammable or chemically contaminated waste as directed by EHS. **NOT TO DO.** Do not distill ethanol in a kitchen, use open flames or household heating, operate ungrounded equipment, or count recovered solvent as incorporated product mass.

11.9 SOP approval and release record

No component may enter Hempoxies formulation work until the responsible chemist, EHS reviewer, quality manager, and facility authority have signed the release record. The record shall include the SOP ID and revision, operator training, feedstock lot, origin and certification status, equipment IDs, calibration status, deviations, analytical results, waste manifest, storage conditions, expiry or retest date, and disposition. Zinc remains outside these hemp-component SOPs and shall be purchased, qualified, stored, and handled under its own supplier and catalyst-management SOP.

SOP ID: _____

Component and route: _____

Release decision and approvers: _____

Record here: batch ID, date, operator, formulation revision, instrument IDs, raw-data path, deviations, observations, and decision.

11.10 Laboratory synthesis

The laboratory program shall establish reproducible procedures for EHO epoxidation, MHO maleinization, FGE preparation, carbon-material preparation, CNC preparation, anhydrous hemp-ethanol preparation or purification, solvent-assisted dispersion, and composite compounding. Each procedure shall include material specifications, temperature and pressure profiles, addition rates, heat-removal requirements, solvent-recovery efficiency, residual-solvent limits, yield, purity, and waste classification.

Peracetic-acid epoxidation requires particular process-safety attention because hydrogen peroxide, acetic acid, and sulfuric acid form an exothermic oxidizing system. Before pilot operation, the project shall complete reaction calorimetry, peroxide-compatible equipment review, dosing interlocks, emergency quench design, venting analysis, and HAZOP/LOPA review.

11.11 Controlled mixing, dispersion, solvent-recovery, and curing SOP

This SOP is a laboratory-controlled process framework. It is intentionally parameterized: facility-approved values for batch size, mixing speed, shear history, temperature, vacuum, time, mold pressure, cure schedule, and post-cure schedule shall be entered in the controlled SOP record only after the relevant safety and materials gates are passed. The framework does not authorize kitchen, home, garage, or improvised fabrication.

Pre-start release. Confirm approved BOM revision; verify EHO and MHO reactive equivalents; release FGE or alternative diluent; inspect catalyst identity; release every filler against its COA; measure filler moisture; confirm ethanol water content and flammable-liquid controls; verify equipment calibration, grounding, bonding, ventilation, interlocks, emergency shutdown, spill response, waste containers, and trained personnel. Record batch ID, formulation revision, operator, equipment IDs, and environmental conditions.

Stage 1—drying and conditioning. Dry or condition hygroscopic fillers using an approved method that does not degrade the material. Cool and store in sealed, labeled containers. Record mass before and after conditioning, moisture result, and hold time. **NOT TO DO:** Do not use household ovens, open heating, unverified temperatures, or uncontained nanopowder handling.

Stage 2—matrix preparation. Charge the qualified EHO and MHO components according to measured reactive equivalents, not nominal oil mass ratio. Mix until uniform under the approved temperature and shear envelope. Add FGE or the qualified alternative only after its identity, origin classification, and compatibility are released. Record viscosity, temperature, appearance, and pot-life baseline. **NOT TO DO:** Do not add catalyst to an uncharacterized or out-of-specification matrix.

Stage 3—filler pre-dispersion. Prepare separate slurries or concentrates for CNC, biochar, nanosheets, or other approved fillers using the selected solvent route. Where ethanol is used, operate in closed, grounded, ignition-controlled equipment. Establish the mixing sequence from low-risk single-filler controls before attempting the full stack. Measure dispersion quality by microscopy,

rheology, and sedimentation or stability observations. **NOT TO DO:** Do not use open vessels, open flames, ungrounded equipment, uncontrolled ultrasonication, or an unqualified filler blend.

Stage 4—combination and catalyst addition. Combine the qualified matrix and filler concentrate under the approved shear and temperature history. Add $\text{Zn}(\text{acac})_2$ only after dispersion is documented and only at the approved external-catalyst loading. Sample for homogeneity, viscosity, pot life, and cure-response screening. **NOT TO DO:** Do not compensate for poor dispersion by arbitrarily increasing catalyst, diluent, solvent, or temperature.

Stage 5—ethanol recovery and degassing. Recover ethanol using the validated closed solvent-recovery system. Record charge, recovered quantity, residual solvent, and process loss. Degas the concentrated formulation under an approved pressure and temperature envelope, monitoring foaming, boiling, temperature rise, and mass loss. Residual ethanol shall be measured before cure. **NOT TO DO:** Do not distill in a kitchen, use household vacuum equipment, vent solvent to occupied space, or proceed when residual solvent or exotherm is unknown.

Stage 6—processed-reinforcement addition. Add the qualified processed hemp-derived carbon reinforcement at the approved low-shear condition to minimize length loss and agglomeration. Verify orientation or distribution where relevant. Raw, untreated, or merely chopped hemp fibers shall not be added. **NOT TO DO:** Do not substitute raw hemp fiber, use an unqualified carbon powder, or exceed the validated mixing torque, temperature, or residence-time envelope.

Stage 7—molding and cure. Transfer the formulation to compatible molds or test fixtures using the approved process. Apply the validated cure schedule from the controlled record, including ramp, hold, pressure, atmosphere, and any post-cure. Monitor temperature, pressure, exotherm, deformation, and release behavior. Stop work for uncontrolled temperature rise, gas evolution, pressure increase, loss of cooling or ventilation, solvent-vapor alarm, visible decomposition, mold failure, or suspected ignition. **NOT TO DO:** Do not extrapolate a cure schedule to larger mass without thermal modeling and calorimetry.

Stage 8—conditioning and release. Condition specimens under the approved temperature, humidity, and time. Measure mass, dimensions, density, voids, residual solvent, T_g , conversion, DMA, DSC, TGA, mechanical properties, stress relaxation, and microscopy as applicable. Assign lot disposition: release, hold, rework only under approved procedure, or reject. Preserve failed material and raw data. **NOT TO DO:** Do not release material based on appearance, hardness, or one successful coupon.

Record here: batch ID, date, operator, formulation revision, instrument IDs, raw-data path, deviations, observations, and decision.

Existing process note. Nanofillers shall be dried and characterized before use. Where anhydrous hemp ethanol is used, the filler slurry shall be processed in closed, grounded, ignition-controlled equipment, and the solvent shall be recovered before cure. Dispersion shall be evaluated by microscopy, rheology, and cured-section imaging. The project shall measure whether GO, rGO, CNC, and biochar adsorb $\text{Zn}(\text{acac})_2$ or otherwise alter cure kinetics. Catalyst compensation may be explored as a hypothesis, but the final rule shall be based on stress-relaxation and conversion data.

Table 9: Controlled mixing-and-curing record fields.

Field	Facility-approved entry
BOM and SOP revision	_____
Batch size and target final mass	_____
Reactive-equivalent ratio and tolerances	_____
Mixing equipment, speed/shear, and temperature limits	_____
Ethanol charge, recovery, residual, and loss	_____
Catalyst loading and addition point	_____
Cure and post-cure schedule	_____
Release decision and reviewer	_____

12 Hypotheses and Falsifiable Acceptance Criteria

The proposal shall be treated as a set of testable hypotheses rather than as a statement of achieved performance. Each hypothesis must be evaluated against a predeclared control, a defined test method, replicate specimens, and a pass/fail rule. A result that contradicts a hypothesis is a useful development result and shall not be hidden by changing the claim after testing.

Table 10: Core hypotheses and minimum falsification tests.

ID	Hypothesis	Control and measurement	Indicative acceptance rule
H1	Measured EHO/MHO reactive-equivalent balance produces a reproducible ester-linked network.	Three independent batches; FTIR/NMR, DSC, gel fraction, and cure conversion.	Conversion and gel fraction meet the frozen formulation specification with no unexplained batch trend.
H2	Zn(II) catalysis enables measurable associative exchange without unacceptable loss of service-temperature performance.	Catalyst-free and catalyzed controls; stress relaxation, DMA, creep, and TGA.	Catalyzed material shows statistically distinguishable exchange while retaining the predefined Tg and creep limits.
H3	Ethanol-assisted dispersion improves filler distribution without unacceptable residual solvent or process emissions.	Solvent-free and ethanol-assisted controls; microscopy, rheology, recovery ledger, residual-solvent assay.	Dispersion benefit exceeds the predefined threshold and recovery, residual, and emissions limits are met.

ID	Hypothesis	Control and measurement	Indicative acceptance rule
H4	Processed hemp-derived carbon reinforcement improves application-level properties relative to the neat matrix.	Neat matrix, single-reinforcement, and full-stack controls; density-normalized mechanical and fracture tests.	Improvement is replicated and remains after conditioning, not merely present in one screening test.
H5	Repair or remolding retains useful properties for a finite number of documented cycles.	Untreated control and cycles 0, 1, 3, 5, and 10; microscopy and mechanical testing.	Retention remains above the application-specific threshold, with failure modes recorded.
H6	The declared hemp-derived mass fraction survives independent origin and mass-balance review.	Component origin matrix, solvent ledger, yield records, and independent D6866 where relevant.	No unassigned mass remains above the predeclared uncertainty allowance.

13 Experimental Governance and Data Quality

Every experiment shall have a controlled identifier, approved formulation revision, operator, date, equipment identifier, raw-data location, calibration status, environmental conditions, and deviation record. Raw instrument files shall be retained together with processed data and analysis scripts. Figures shall show the number of independent batches and specimens; pooled technical repeats shall not be represented as independent material batches.

The project shall predefine exclusion rules before testing. Specimens may be excluded only for documented manufacturing or test-method failures, never solely because a result is unfavorable. Outliers shall be reported with and without exclusion, and any post hoc change to a formulation, test method, or acceptance threshold shall be version-controlled and justified. Statistical comparisons shall report sample count, central tendency, scatter, confidence intervals where appropriate, and effect size—not only a pass/fail label.

No claim shall be promoted from hypothesis to demonstrated result without a signed evidence package containing the formulation record, method, raw data, calculations, photographs or microscopy where relevant, deviations, and independent technical review. A claim matrix shall map every public statement to its evidence status: proposed mechanism, literature context, internal target, measured result, independently replicated result, or qualified application claim.

14 Process Safety and Laboratory Warnings

Safety warning. This proposal contains hazardous-chemical and flammable-solvent development concepts. Ethanol handling shall be designed as flammable-liquid service; OSHA ventilation criteria and applicable local fire codes shall be reviewed during facility design [18]. It is not a laboratory procedure, operating permit, safety case, or substitute for current Safety Data Sheets (SDS), occupational-exposure limits, local regulations,

institutional approvals, or direction from a qualified process-safety professional. Work shall be performed only by trained personnel in an appropriately equipped facility after documented hazard review.

14.1 Hazard boundaries

The proposed chemistry may involve epoxidizing and maleinizing reagents, peroxides, organic acids, strong acids, reactive epoxides, metal catalysts, combustible organic materials, nanocarbon powders, cellulose powders, and anhydrous ethanol. These hazards can include corrosivity, oxidizing behavior, exothermic reaction, sensitization, respiratory exposure, dust explosion potential, flammability, pressure generation, thermal runaway, and hazardous waste formation. The actual hazard classification shall be determined from the selected chemicals, concentrations, impurities, equipment, and scale; it shall not be inferred from the name “bio-based” or “hemp-derived.”

14.2 Mandatory controls before experimental work

Before any synthesis or compounding campaign, the responsible facility shall complete the following controls:

1. obtain and review current SDS documents and exposure limits for every reagent, intermediate, catalyst, filler, cleaning agent, and waste stream;
2. perform a written risk assessment and, for scale-up, reaction calorimetry and formal HAZOP/LOPA or equivalent process-safety review;
3. verify engineering controls, including suitable fume extraction, closed solvent handling, grounding and bonding, ignition-source control, pressure relief, temperature monitoring, and emergency shutdown;
4. establish approved storage segregation for oxidizers, acids, flammable liquids, catalysts, nanomaterials, and waste;
5. define PPE, respirator policy, spill response, exposure response, fire response, first aid, evacuation, and waste-labeling procedures with the site safety officer; and
6. prohibit unattended reactions, improvised quenching, open-vessel solvent evaporation, and scale-up based only on successful small-scale behavior.

14.3 Laboratory safety, calibration, and PPE checklist

This checklist implements the hierarchy of controls expected for laboratory use of hazardous chemicals: recognize hazards, assess risk, minimize exposure through engineering and administrative controls, and prepare for emergencies. It is a planning and verification aid, not a substitute for the site Chemical Hygiene Plan, current SDSs, exposure limits, local fire code, or qualified EHS approval [19, 18, 21, 22].

14.3.1 A. Facility and pre-start safety gate

No Hempoxies synthesis, filler preparation, solvent recovery, or cure campaign may begin until every applicable item is checked, documented, and accepted by the responsible supervisor and EHS authority.

Table 11: Pre-start laboratory safety checklist.

Check	Requirement	Record or acceptance evidence
☐	Current SDSs, hazard classifications, exposure limits, incompatibilities, storage requirements, and waste classifications are available for every reagent, intermediate, filler, catalyst, cleaning agent, and waste stream.	SDS revision dates and chemical inventory ID
☐	Written risk assessment and task-specific SOP are approved; operators are trained and authorized.	Risk assessment, SOP ID, training record
☐	Chemical Hygiene Plan, emergency plan, spill plan, fire plan, exposure-response plan, and waste plan are accessible.	Plan revision and location
☐	Fume hood or local-exhaust system is operating, has current performance verification, and is appropriate for corrosive, oxidizing, flammable, and nanopowder operations.	Face-velocity or capture-verification record
☐	Flammable-liquid storage, grounding and bonding, ignition-source control, vapor monitoring, and compatible closed containers are available for ethanol.	Facility inspection and vapor-alarm test
☐	Peroxide/oxidant work has approved reaction calorimetry, cooling capacity, dosing interlocks, compatible materials, venting, and emergency-quench design.	Calorimetry and process-safety approval
☐	Nanomaterial and fine-powder work uses containment, HEPA-rated exhaust or equivalent exposure control, controlled transfer, and approved spill cleanup.	Containment certification and cleanup SOP
☐	Eyewash, safety shower, first-aid supplies, fire extinguisher, spill kit, emergency exits, alarms, and communication methods are unobstructed and inspected.	Inspection dates and drill record
☐	Waste containers are compatible, labeled, closed, segregated by hazard, and have secondary containment.	Waste labels and accumulation log
☐	No unattended reaction, open-vessel solvent evaporation, improvised quench, unapproved scale increase, or home/kitchen fabrication is permitted.	Supervisor sign-off

14.3.2 B. Equipment calibration and readiness

Calibration intervals shall be set by the facility quality system, manufacturer instructions, risk, usage, and historical drift. “Calibrated” means that the instrument has an in-date certificate or verification record traceable to an appropriate standard; it does not mean merely that the display turns on.

Table 12: Equipment calibration and readiness checklist.

Equipment	Minimum verification before use	Failure response
Balances and scales	Calibration check across the intended mass range; level, clean pan; certified check weights; record drift.	Stop weighing; quarantine affected batches; recheck prior data.
Thermometers, RTDs, thermocouples	Compare against a traceable reference at relevant points; inspect probes, insulation, and placement.	Stop heating or reaction work if temperature is uncertain.
Pressure, vacuum, and differential-pressure gauges	Zero check, range suitability, leak check, and traceable calibration; confirm relief path.	Do not operate pressurized or evacuated equipment.
Dosing pumps and flow meters	Verify delivered mass or volume over the intended range; confirm tubing compatibility and alarm/interlock operation.	Do not begin peroxide or reactive addition.
Stirrers, mixers, homogenizers, and sonicators	Verify speed or power indication, torque/load behavior, guards, cooling, containment, and emergency stop.	Do not compensate for unverified shear by changing formulation.
Fume hoods and local exhaust	Current capture/face-velocity or performance test; sash, alarms, filters, and exhaust path verified.	Stop volatile, corrosive, oxidizing, or powder work.
Vapor and oxygen monitors	Bump test or functional check, sensor status, alarm setpoints, and calibration date.	Stop flammable-solvent work on failed alarm.
Vacuum pumps and solvent-recovery system	Leak test, compatible seals, cold-trap/condenser capacity, grounding, temperature and pressure monitoring.	Stop recovery; contain solvent; do not vent to occupied space.
Ovens, hot plates, baths, and furnaces	Independent temperature verification, over-temperature protection, electrical condition, and appropriate atmosphere.	Do not use household or unclassified heating equipment.
Reaction vessels and fittings	Material compatibility, inspection for cracks/corrosion, seals, clamps, venting, relief path, and containment.	Quarantine vessel; do not improvise repairs.
DSC, DMA, TGA, GC, FTIR, NMR, Karl Fischer, rheometer	Method-specific calibration/verification, standards, blank, sample conditioning, and software/version record.	Mark data as invalid or qualified pending correction.

Table 12: Equipment calibration and readiness checklist.

Mechanical-test frames and environmental chambers	Load-cell, displacement, temperature, humidity, and chamber verification; fixture inspection.	Do not report performance data from out-of-calibration equipment.
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14.3.3 C. PPE matrix

PPE shall be selected from the actual SDS, hazard assessment, permeation data, task duration, concentration, splash/impact risk, and respiratory-protection program. PPE is the last line of defense; it does not replace containment or ventilation. Nanomaterial guidance emphasizes engineering controls, controlled transfer, and appropriate PPE, with respirators governed by the applicable respiratory-protection standard rather than chosen informally [21, 22, 20].

Table 13: Task-based PPE checklist.

Task or exposure	Minimum PPE subject to site hazard assessment	Additional controls
Routine liquid handling	Chemical splash goggles; lab coat or chemical-resistant coat; compatible chemical-resistant gloves; long pants and closed shoes.	Work in suitable containment; inspect gloves and change when contaminated.
Corrosive acids, bases, or oxidizing reagents	Goggles plus face shield for splash risk; chemical-resistant apron or coat; gloves selected by permeation data; closed footwear or boot covers as required.	Fume hood, compatible tray, no lone work, emergency shower available.
Peroxide/epoxidation operation	Eye/face protection, chemical-resistant clothing, gloves selected for oxidant compatibility, and any additional protection specified by the reaction-specific assessment.	Engineered cooling, interlocks, remote or shielded addition where warranted, no improvised quench.
Anhydrous ethanol charging or recovery	Splash goggles; flame-resistant lab coat as required; compatible gloves; closed footwear.	Grounding/bonding; closed system; ignition control; vapor monitor; flammable-liquid area.
Dry carbon, CNC, or nanosheet powders	Goggles, dedicated coat/coveralls, compatible gloves, and respirator only under the approved site program.	HEPA enclosure or local exhaust; damp cleanup; never use compressed air.
Nanomaterial spill cleanup or equipment maintenance	Gloves and protective clothing specified by EHS; eye/face protection; fit-tested respirator only under the site program.	Restrict access; use the spill SOP; use HEPA or damp methods; characterize waste.
High-temperature carbonization or furnace work	Eye protection, heat-resistant gloves for the task, flame-resistant clothing where required, and respiratory protection only under an approved program.	Guarding, atmosphere control, gas monitoring, heat-resistant tools, cooldown and lockout controls.
Molding, cure, and post-cure	Eye protection, gloves compatible with uncured resin, lab coat, and heat protection for hot molds or fixtures.	Monitor exotherm and pressure; use shields where splash or rupture is credible.

14.3.4 D. Emergency, stop-work, and closeout checklist

Stop work immediately for an uncontrolled temperature rise, unexpected gas evolution, pressure increase, loss of cooling or ventilation, solvent-vapor alarm, ignition, visible decomposition, peroxide

contamination, damaged containment, failed calibration, exposure incident, or spill beyond the approved response capacity. Do not improvise neutralization, rescue, or cleanup. Evacuate and contact the facility emergency response team when required.

Table 14: Emergency and closeout checklist.

Check	Action	Record
☐	Reaction or process is placed in a safe state; heating, addition, mixing, and solvent transfer are stopped according to the emergency SOP.	Time and operator
☐	Area is isolated, personnel are accounted for, and emergency services/EHS are contacted when required.	Incident or near-miss ID
☐	Exposures receive immediate first aid and occupational-health evaluation under the site plan.	Exposure report
☐	Waste and contaminated PPE are packaged, labeled, and segregated; no drain or ordinary-trash disposal occurs without approval.	Waste manifest
☐	Raw data, instrument status, photographs, deviations, and affected lot identities are preserved.	Data package location
☐	Equipment is inspected, decontaminated or quarantined, and returned to service only after authorization.	Maintenance/release record
☐	A documented review identifies root cause, corrective action, retraining, and conditions for restart.	CAPA or restart approval
☐	The batch is dispositioned as released, held, reworked under approval, or rejected; no result is quietly discarded.	Quality disposition

14.4 Specific process warnings

Peroxide-based epoxidation shall be treated as a potentially exothermic oxidizing operation. Addition rate, temperature, agitation, cooling capacity, peroxide decomposition, gas evolution, and emergency quench behavior shall be characterized before increasing batch size. Incompatible materials and contamination routes shall be controlled, and peroxide residues shall not be assumed harmless because the reaction appears complete.

Anhydrous ethanol is a flammable volatile solvent. It shall be handled in closed, grounded, ventilated equipment with ignition-source control and suitable vapor monitoring. Solvent recovery shall use equipment designed for flammable service; vacuum operation shall account for boiling, bumping, pressure excursions, and condenser capacity. Residual ethanol shall be measured before release of cured material into testing or storage. Ethanol shall never be treated as harmless simply because it is bio-derived.

Dry carbon materials, nanosheets, CNC, and other fine powders may create inhalation and combustible-dust hazards. Powder handling shall minimize airborne release, use appropriate containment and housekeeping, avoid uncontrolled compressed-air cleaning, and evaluate dust-hazard controls with the facility safety professional. Nanomaterial-specific exposure controls shall be applied where applicable.

14.5 Emergency and stop-work criteria

Work shall stop immediately for uncontrolled temperature rise, unexpected gas evolution, pressure increase, loss of cooling, loss of ventilation, solvent-vapor alarm, visible decomposition, peroxide contamination, ignition, spill beyond the approved response capacity, or any exposure incident. The response shall follow the facility emergency plan; personnel shall not improvise neutralization or rescue operations. Near misses and stop-work events shall be documented and reviewed before restarting.

15 Waste, Exposure, and Lifecycle Boundaries

All liquid, solid, contaminated absorbent, filter, and cleaning waste shall be segregated by hazard class and managed under applicable waste rules. Recovery efficiency shall not be equated with zero emissions. The environmental ledger shall report solvent charge, recovered solvent, residual solvent, fugitive or unrecovered loss, energy use, water use, process yield, rejected material, and waste treatment route.

The proposal shall not claim biodegradability, compostability, non-toxicity, food contact suitability, marine safety, or benign end-of-life behavior without dedicated testing. A hemp-derived feedstock can still produce a durable crosslinked network, hazardous intermediates, persistent additives, or difficult-to-recycle composite waste. End-of-life evaluation shall distinguish mechanical recycling, thermal treatment, chemical recovery, landfill behavior, and release of catalyst, carbon, or residual organics.

Before any worker, customer, or environmental claim is made, the project shall complete an exposure and lifecycle review for the actual formulation and process. “Bio-based,” “hemp-derived,” and “low-carbon” shall not be used as synonyms for safe, non-toxic, biodegradable, or low-impact.

16 Additional Validation, Quality, Sustainability, and Commercialization Controls

This section closes the principal evidence and governance gaps identified during self-critique. It does not convert targets into results. Every value, threshold, or decision rule below remains proposed until supported by controlled data, calibrated instrumentation, documented uncertainty, and independent review.

16.1 Analytical-method validation and uncertainty

Every release or research method shall have a method sheet specifying analyte or measurand, matrix, sample preparation, instrument configuration, calibration model, standards, blanks, replicates, acceptance limits, uncertainty estimate, analyst, software version, and data-retention location. Method suitability shall be demonstrated before results are used for a gate or public claim.

16.2 Worked formulation-accounting example

The following is an illustrative calculation structure only. It must be populated with measured values for a real batch. Suppose a development batch contains m_E grams of EHO with measured epoxy equivalent weight EEW_E , and m_M grams of MHO with measured anhydride equivalent

Table 15: Minimum analytical-method validation package.

Method family	Minimum validation or verification elements
Reactive equivalents and acid/anhydride values	Reference standards, blank, duplicate or triplicate titrations, endpoint rule, recovery or comparison standard, repeatability, and uncertainty.
Moisture and residual ethanol	Karl Fischer or validated GC method, matrix spike or recovery, repeatability, reporting limit, storage-time study, and solvent-ledger reconciliation.
Conversion and cure kinetics	DSC/rheology method, baseline correction, heating-rate study, replicate runs, onset/peak/integral definitions, model residuals, and sensitivity to specimen mass.
Molecular and surface characterization	FTIR/NMR/Raman/XPS or equivalent method ID, spectral preprocessing, reference materials, peak-assignment rules, and independent interpretation.
Particle, fiber, and nanosheet morphology	Sampling plan, dispersion protocol, imaging magnification, number of fields and particles, segmentation method, analyst blinding where practical, and uncertainty in size distribution.
Mechanical and durability testing	ASTM/ISO method, specimen geometry, conditioning, fixture verification, strain rate, failure rule, batch and specimen count, environmental conditions, and density normalization.
Mass and origin accounting	Calibrated mass records, lot traceability, solvent ledger, origin matrix, loss estimates, allocation rule, independent arithmetic review, and sensitivity to missing data.

weight AEW_M . The reactive-equivalent ratio is:

$$R_E = \frac{m_E}{EEW_E}, \quad R_M = \frac{m_M}{AEW_M}, \quad \rho = \frac{R_E}{R_M}. \quad (8)$$

The batch record shall report the target ratio, measured ratio, permitted tolerance, and disposition if ρ is outside the approved range. FGE, catalyst, CNC, biochar, nanosheets, and processed carbon reinforcement shall be reported separately on a final-mass basis. Ethanol shall be reported in a separate solvent ledger and excluded from incorporated product mass unless residual ethanol is analytically detected and intentionally specified.

The completed calculation shall include: input mass; measured purity; water; reactive equivalents; incorporated mass; recovered solvent; residual solvent; unrecovered loss; waste; rejected or reworked material; and closing mass-balance error. An independent reviewer shall reproduce the calculation from raw batch records without relying on a manually typed summary.

16.3 Wetted-material and compatibility matrix

Before any reaction or recovery operation, the facility shall approve a materials-compatibility matrix covering oxidants, acids, epoxides, anhydrides, ethanol, zinc catalyst, carbon powders, CNC suspensions, cleaning agents, and waste. The matrix shall include vessel body, seals, gaskets, tubing, pumps, filters, sensors, sample vials, storage containers, and spill-kit materials. Compatibility shall be confirmed from manufacturer data, SDS information, literature, or a controlled coupon test; an apparently inert material shall not be assumed compatible at temperature, pressure, or under oxidizing conditions.

16.4 Cure kinetics, exotherm, and moisture-control plan

The cure schedule shall be derived from measured cure kinetics rather than copied from another epoxy system. The work package shall include DSC or equivalent screening at multiple heating rates,

Table 16: Compatibility-review matrix to be completed before operation.

Service	Candidate material	Required review	Status
Peroxide/acid epoxidation	Vessel, seals, dosing line, probe, tray	Oxidizer, acid, temperature, contamination, and pressure compatibility; supplier evidence or coupon test.	_____
MHO functionalization	Vessel, condenser, vent, seals, transfer line	Acid/anhydride, temperature, fume, corrosion, and gelation compatibility.	_____
Anhydrous ethanol	Tank, pump, tubing, condenser, vacuum system	Flammable-service rating, static control, seal swelling, grounding, and vapor containment.	_____
Nanocarbon/CNC slurry	Mixer, sonicator, filter, enclosure, waste container	Abrasion, adsorption, aerosol containment, HEPA compatibility, and cleaning method.	_____
Cure and post-cure	Mold, liner, fixture, thermocouple, release system	Temperature, pressure, resin adhesion, thermal degradation, and contamination.	_____

isothermal conversion studies, rheological gelation tracking, exotherm measurement at representative and bounding batch masses, and a documented rule for selecting ramp, hold, post-cure, and maximum allowable mass. The model shall be checked against an independent batch and shall report its valid temperature and conversion range.

A moisture budget shall be maintained for EHO, MHO, FGE, ethanol, CNC, biochar, nanosheets, processed carbon reinforcement, vessels, compressed gases, and storage air. The plan shall specify sampling location, Karl Fischer or equivalent method, maximum allowable water, drying method, sealed hold time, re-test interval, and action if water exceeds specification. Moisture excursions shall trigger a disposition review rather than an informal drying adjustment.

16.5 Exposure monitoring and occupational health

The facility shall perform an exposure assessment for ethanol vapor, acid and peroxide aerosols, reactive epoxide or anhydride vapors, carbon monoxide and volatile carbonization products, respirable dust, and nanoscale aerosol. The assessment shall identify task-based and full-shift sampling, worker groups, sampling locations, analytical methods, action levels, medical-surveillance triggers, and corrective actions. Respirator selection, fit testing, cartridge change-out, medical clearance, and program administration shall follow the site respiratory-protection program and applicable law; respirators shall not be selected informally.

The exposure program shall include baseline monitoring before routine work, monitoring after process changes, monitoring during transfer and cleanup, and review of near misses or symptoms. Results shall be communicated to affected workers and retained with the batch and facility records. No assertion of safe exposure may be made from the renewable origin of a component.

16.6 Quality system, data integrity, and management of change

The project shall operate a proportionate quality system with controlled documents, unique batch and specimen identifiers, audit-trailed electronic records, raw-file retention, instrument status, reference-standard control, deviation and CAPA records, supplier qualification, sample retention, and independent review of safety-critical and claim-critical results. Research-use-only work shall not be represented as GLP, GMP, ISO 17025, aerospace qualification, or another regulated quality status unless that system has actually been implemented and audited.

Management of change is mandatory for any change to feedstock lot or supplier, catalyst, solvent grade, filler morphology, vessel volume, mixing equipment, sensor, heating or cooling rate, recovery system, cure schedule, test method, waste route, or public claim. Each change shall be risk-ranked, reviewed for comparability, assigned a validation plan, and approved before use. Failed batches and unfavorable results shall remain in the data record.

16.7 Quantitative LCA and green-chemistry scorecard

The sustainability package shall include a screening life-cycle assessment with a declared functional unit, system boundary, allocation rule, geography, electricity mix, transport assumptions, water use, solvent recovery, fugitive loss, energy, process yield, rejected batches, waste treatment, catalyst fate, and end-of-life pathway. The package shall report both point estimates and uncertainty ranges. It shall not infer low impact from hemp origin alone.

The green-chemistry scorecard shall score the actual route against waste prevention, atom economy, less hazardous synthesis, safer solvents, energy efficiency, renewable feedstocks, fewer derivatives, catalysis, degradability where relevant, accident prevention, and real-time analysis. Ethanol recovery, peroxide hazards, acid waste, zinc content, nanomaterial exposure, and carbonization emissions shall be included rather than hidden as upstream details.

Organic-certification, vegan, and no-petrol principles shall be treated as claim-governance requirements. Agricultural organic status does not automatically certify a chemically modified resin. Vegan status requires supply-chain review of processing aids, filters, membranes, antifoams, lubricants, adhesives, and outsourced services. The no-petrol requirement requires a prohibited-substance list and a declared system boundary covering reagents, catalysts, auxiliaries, packaging, utilities, and outsourced processing.

16.8 Uncertainty-based TEA and supply-chain qualification

The TEA shall progress from point sensitivity to scenario and probabilistic uncertainty analysis. It shall include feedstock price and quality, yield, batch rejection, utilization, downtime, commissioning losses, maintenance, calibration, EHS staffing, waste disposal, insurance, permitting, analytical outsourcing, inventory carrying cost, working capital, logistics, depreciation, taxes, and the cost of producing and qualifying processed hemp-derived carbon reinforcement. Each critical input shall have at least two qualified supply options or an explicit single-source mitigation plan.

Supplier qualification shall document identity, specification, COA history, change-notification policy, lead time, minimum order, payment terms, storage life, transport classification, geographic concentration, business-continuity plan, and audit rights. A construction or investment gate shall require supplier quotes, pilot yield data, independent cost review, uncertainty ranges, and a downside case that includes quality failures and temporary solvent or feedstock unavailability.

16.9 Regulatory and permitting matrix

The project shall maintain a jurisdiction-specific matrix covering laboratory chemical use, flammable-liquid storage and recovery, hazardous waste, air emissions, carbonization, nanomaterial handling, worker exposure, transportation, environmental marketing claims, product labeling, and any sector-specific qualification. The matrix shall identify competent authority, permit or notification, responsible owner, evidence required, renewal date, and status. The proposal does not itself constitute regulatory approval, an operating permit, or a product authorization.

Table 17: Regulatory and permitting matrix template.

Topic	Possible authority or standard	Required evidence	Owner/status
Chemical hygiene and worker exposure	OSHA or local equivalent	Chemical Hygiene Plan, SDS, exposure assessment, training, medical provisions.	_____
Flammable liquids and ethanol recovery	Fire authority, OSHA, local code	Area classification, storage, grounding, ventilation, vapor detection, emergency response.	_____
Hazardous waste and emissions	Environmental authority	Waste characterization, manifests, air/water permit review, solvent-loss accounting.	_____
Nanomaterials and carbonization	EHS and environmental authority	Exposure controls, dust assessment, gas monitoring, waste classification.	_____
Product and environmental claims	Consumer/product and advertising authorities	Substantiation dossier, LCA, certification evidence, label review.	_____

16.10 Open-source license, repository, and publication policy

The open-source designation shall be made operational through a selected license and a versioned repository. The release package shall identify code, documentation, data, hardware or CAD files where applicable, contribution rules, issue tracking, third-party dependencies, data license, authorship, provenance, and safety notice. A suggested implementation is an OSI-approved software/documentation license for code and text, a separately selected license for data, and a clear statement that chemical safety, patent rights, regulatory duties, and third-party materials are not waived by publication.

The repository record shall include a version tag, release date, checksum or immutable archive, machine-readable metadata, license files, a README, a change log, a data dictionary, raw and processed-data directories, analysis scripts, calibration records, deviations, negative results, and the permitted claim language. Zenodo or an equivalent repository shall receive immutable releases with DOI; GitHub shall host versioned collaboration materials; peer-reviewed publication shall follow internal technical review and patent-counsel timing review. Authors shall be credited by documented contribution, and conflicts of interest or AI assistance shall be disclosed.

16.11 Component decision tree

The platform shall use a remove-or-qualify decision tree rather than forcing every component into the final stack. If a component fails identity, purity, origin, compatibility, exposure, performance, durability, cost, or end-of-life criteria, it shall be removed, replaced, or held for a new hypothesis. If ethanol does not produce a demonstrated dispersion benefit after recovery and residual-solvent testing, use a solvent-free route or remove it. If CNC increases moisture sensitivity, remove or reformulate it. If nanosheets create unacceptable exposure, contamination, cost, or reproducibility, remove them. If processed hemp-derived carbon reinforcement fails morphology or retained-strength requirements, do not substitute raw or untreated hemp fiber. If FGE cannot meet the no-petrol or origin boundary, reclassify it or remove it. If zinc catalyst performance or leaching is unacceptable, stop the route rather than silently increasing loading.

16.12 Sample retention and human-factors controls

Each experiment shall retain representative feedstock, intermediate, final formulation, cured specimen, failed specimen, and waste sample where safe and legally permitted. Retention records shall specify quantity, container, storage conditions, expiry or review date, chain of custody, and destruction authorization. Human-factors review shall address labeling, ergonomic transfer, alarm visibility, operator workload, shift handover, fatigue, language accessibility, supervision, lone-worker restrictions, two-person rules, contractor access, and emergency communication.

17 Twelve-Experiment Research Program

The experiments below are a staged research portfolio, not a home protocol. Each experiment requires an approved risk assessment, a controlled SOP, qualified operators, appropriate blanks and controls, raw-data retention, and a supported/rejected/unresolved decision. Experiments shall proceed sequentially where a preceding result is a safety or material-quality gate.

Table 18: Twelve experiments required before strong platform or commercialization claims.

ID	Question and hypothesis	Controls and primary measurements	NOT TO DO / gate
E1	Can qualified hempseed-oil feedstock meet repeatable identity, oxidation, moisture, and reactive-equivalent specifications?	Multiple lots; NMR/FTIR, acid value, iodine value, peroxide value, moisture, viscosity, density, chromatographic profile, and supplier COA comparison.	Do not blend unidentified lots or claim organic/vegan/no-petrol status without chain-of-custody evidence. Gate: feedstock specification approved.

E2	Can the EHO functionalization route achieve reproducible conversion without unacceptable exotherm or residual oxidant?	Reagent blanks, conversion controls, reaction calorimetry, heat-release profile, residual peroxide/acidity, yield, and waste characterization.	Do not scale or operate without calorimetry, cooling capacity, compatible materials, and emergency quench design. Gate: thermal and chemical safety review.
E3	Can MHO be produced or qualified with reproducible anhydride/acid functionality?	Lot-to-lot titration, FTIR/NMR, acid/anhydride number, viscosity, water, cure response, and storage stability.	Do not use nominal oil ratios as a substitute for reactive-equivalent measurement. Gate: MHO specification.
E4	Can furan-derived reactive diluent meet the no-petrol design target or be removed from the formulation?	Compare bio-derived and conventional routes; origin audit, purity, epoxy equivalent, residuals, toxicity, and cure contribution.	Do not call FGE hemp-derived if glycidylation reagents or auxiliaries are fossil-derived or undocumented. Gate: origin classification and route decision.
E5	Can processed hemp-derived carbon reinforcement be made with stable morphology and surface chemistry without raw-fiber use?	Qualified batches; particle/length distribution, carbonization history, ash, moisture, surface chemistry, strength retention, and COA reproducibility.	Do not introduce raw, untreated, or merely chopped hemp fibers; do not aerosolize powders outside engineered containment. Gate: reinforcement COA.
E6	Can hemp-derived CNC and other nanoscale components be produced with controlled size, moisture, purity, and dispersion compatibility?	Extraction blanks and controls; microscopy, particle sizing, surface chemistry, moisture, ash, endotoxin/contaminant screen where relevant, and dispersion stability.	Do not assume CNC compatibility from a different polymer matrix or describe nanoscale material as harmless. Gate: nanomaterial handling and compatibility review.
E7	Does anhydrous hemp-derived ethanol improve dispersion and recover within the solvent ledger?	Solvent-free, commercial-ethanol, and hemp-ethanol controls; water content, recovery, residual solvent, rheology, microscopy, vapor monitoring, and mass balance.	Do not use open flames, household heating, ungrounded equipment, or uncontrolled distillation. Gate: flammable-service and recovery review.

E8	Does measured reactive-equivalent stoichiometry produce a reproducible vitrimer network?	Stoichiometric matrix, catalyst-free control, cure conversion, DSC/DMA, gel fraction/solvent resistance, Tg, rheology, and replicate batches.	Do not infer network formation from appearance or hardness alone. Gate: network-formation evidence package.
E9	Does Zn(II) catalyst loading enable associative exchange without unacceptable creep, toxicity, discoloration, or durability loss?	Catalyst loading series, catalyst-free control, stress relaxation, Arrhenius analysis, creep, DMA, TGA, leachable/metal screen, and aged specimens.	Do not claim “self-healing” or “infinite” recyclability from one relaxation curve. Gate: finite cycle-retention target.
E10	Does the multiscale reinforcement stack improve application-relevant properties after conditioning?	Neat matrix, single-filler, partial-stack, and full-stack controls; tensile, flexural, fracture, impact, fatigue, density-normalized properties, microscopy, moisture and thermal cycling.	Do not compare unmatched architectures or use raw-fiber benchmarks for processed carbon reinforcement. Gate: application-specific property threshold.
E11	Can repair, welding, and remolding retain properties over a finite number of cycles?	Cycles 0, 1, 3, 5, and 10; unprocessed control; joint strength, fracture, microscopy, creep, mass loss, and failure modes.	Do not call a material infinitely recyclable; do not reprocess material with unknown degradation or residual solvent. Gate: documented cycle-retention window.
E12	Can the process, supply chain, origin accounting, safety case, and TEA survive independent review?	Pilot mass balance, solvent ledger, LCA screening, supplier dual-source audit, HAZOP/LOPA, cost model, uncertainty analysis, D6866 where relevant, and external technical review.	Do not authorize construction or market claims from an unreviewed spreadsheet or single supplier quote. Gate: investment and publication package.

17.1 Equipment and analytical capability

The minimum capability set includes a qualified chemical laboratory with fume hoods, explosion-aware flammable-liquid handling, temperature-controlled reactors, calibrated balances, controlled addition and cooling systems, compatible glass or metal vessels, vacuum and inert-gas capability, closed solvent recovery, grounding and bonding, fire detection and suppression, chemical storage, spill control, and approved waste segregation. Pilot work requires engineered process vessels, heat-transfer and relief design, vapor monitoring, hazardous-area review, documented commissioning, and management of change.

Analytical capability should include FTIR, NMR access, acid/anhydride and epoxy-equivalent

titration, Karl Fischer moisture, peroxide and acid-value testing, viscosity and rheology, DSC, DMA, TGA, thermogravimetric ash, microscopy and image analysis, particle-size measurement, density and void measurement, mechanical test frames, impact and fracture fixtures, environmental conditioning, thermal cycling, fatigue and creep equipment, residual-solvent GC, elemental or ICP metal analysis, and access to accredited external laboratories for ASTM/ISO testing and radiocarbon analysis where relevant.

17.2 Staffing and facilities

The program requires, at minimum, a principal investigator or technical lead; polymer or organic chemist; process-safety engineer; analytical chemist; composite/materials engineer; technician trained in hazardous chemicals and nanomaterials; quality and data manager; EHS professional; supply-chain and procurement lead; and an external reviewer or qualified testing laboratory. Pilot operation additionally requires maintenance, instrumentation and controls, fire-protection, waste-management, and operations personnel. No single researcher should be the sole approver, operator, analyst, and claimant for a safety-critical or commercialization-critical result.

Facilities shall provide controlled access, training records, SDS management, chemical inventory, exposure-control plans, emergency drills, eyewash and shower facilities, appropriate fire protection, spill response, respiratory-protection governance where required, medical and occupational-health provisions, secure data storage, calibration management, and a documented waste contractor. The facility must be legally permitted for its chemical inventory and process hazards.

17.3 Testing and publication matrix

Every experiment shall specify the applicable ASTM, ISO, USP, OECD, or internal validated method before work begins. The project shall publish raw data where legally and ethically appropriate, with sensitive supplier, personal, security, and safety information redacted. Recommended release sequence is: versioned protocols and metadata on [GitHub](#); immutable data packages, analysis scripts, and releases on [Zenodo](#) with DOI; preprints only after internal review; and peer-reviewed manuscripts in appropriate polymer, composites, green-chemistry, process-safety, or life-cycle journals. Patent counsel shall review publication timing before any potentially patentable implementation is disclosed.

Table 19: Minimum public data package for a completed experiment.

Data layer	Required contents
Identity and provenance	Material name, supplier, lot, COA, origin classification, certification evidence, chain of custody, and storage history.
Method and safety	SOP version, approvals, operator training, equipment IDs, calibration status, hazard review, deviations, and waste route.
Raw observations	Instrument-native files, images, specimen maps, batch records, environmental conditions, and failed or excluded observations with reasons.
Analysis	Versioned scripts, calculations, uncertainty, statistical model, replicate structure, outlier policy, and independent review record.
Decision and release	Hypothesis status, acceptance criterion, limitations, repository URL/DOI, manuscript status, and claim-language permitted by the evidence.

17.4 Experiment record pages

Experiment ID and title:

Question, hypothesis, and acceptance criterion:

Approved SOP and risk assessment IDs:

Record here: batch ID, date, operator, formulation revision, instrument IDs, raw-data path, deviations, observations, and decision.

Data-release location and DOI:

Record here: batch ID, date, operator, formulation revision, instrument IDs, raw-data path, deviations, observations, and decision.

18 Validation and Stage-Gate Program

Table 20: Development gates and minimum evidence package; all gates remain future work unless supported by a separate validation report.

Gate	Objective	Minimum evidence for passage
G0	Freeze claims and boundaries	Controlled formulation sheet; reactive-equivalent calculation; origin matrix; final-mass convention.
G1	Validate feedstocks and processed reinforcement	Three independent batches; NMR/FTIR; oxirane and anhydride values; filler ash, moisture, morphology, carbonization history, surface treatment, and processed-reinforcement strength data.
G2	Validate neat vitrimer matrix	Conversion, gel fraction, DSC/DMA, tensile, fracture, solvent resistance, creep, and stress-relaxation data.
G3	Validate fillers individually	Viscosity, dispersion, cure conversion, catalyst activity, density, void content, and mechanical effect for each filler family.
G4	Validate full composite	Replicated mechanical, thermal, moisture, impact, fatigue, fracture, and microscopy results against commercial controls.
G5	Validate repair and remolding	Defined repair/weld protocol; strength retention after cycles 0, 1, 3, 5, and 10; documented failure modes.

Gate	Objective	Minimum evidence for passage
G6	Validate pilot scale	Reaction calorimetry, heat transfer, mass yield, impurity control, dispersion throughput, quality-control plan, and safety review.
G7	Application qualification	Application-specific aging, fatigue, fire/smoke/toxicity, damage tolerance, traceability, and supplier-quality evidence.

18.1 Required test methods

The test matrix shall include tensile and flexural properties, compression, fracture toughness, interlaminar shear where applicable, density, void content, DMA, DSC, TGA, solvent resistance, water uptake, hydrolytic aging, thermal cycling, creep, fatigue, and impact. ASTM or ISO methods shall be selected according to the intended product geometry and application. Every reported value shall include specimen count, mean, standard deviation, conditioning history, and failure-mode documentation.

For vitrimer behavior, the project shall report stress-relaxation curves rather than a single relaxation time. The reported τ^* shall include temperature, applied strain, specimen geometry, initial modulus normalization, catalyst loading, and replicate scatter. A proposed initial target is $\tau^* \leq 300$ s at 180 °C, but this is a development target rather than an established property.

19 Performance Targets and Claim Discipline

Table 21: Status of major platform claims.

Claim	Status	Required qualification
Dynamic β-hydroxy ester vitrimer	Mechanistically plausible	Must be demonstrated by conversion, rheology, and relaxation data.
Greater than 99% hemp-derived	Not established	Separate D6866 carbon, bio-derived mass, and hemp-derived mass metrics.
Tg of 60–80 °C	Target	Must be measured by DSC/DMA after defined conditioning.
Reprocessable in 10–30 minutes	Target	Must specify geometry, pressure, temperature, heating rate, and property retention.
Infinite reprocessability	Rejected wording	Replace with measured retention after a defined number of cycles.
Outperforms steel, titanium, or Kevlar	Unverified hypothesis	Require equivalent density, architecture, orientation, and application-specific test basis.
Aerospace-ready	Premature	Requires qualification, durability, damage tolerance, fire, traceability, and quality-system evidence.

The proposal contains no supplied experimental dataset. Every numerical performance value in this document is therefore a target, screening hypothesis, or literature-context statement unless explicitly identified as measured in a future validation report. The project shall avoid presenting calculated specific properties as proof of component-level superiority. Specific strength and specific

modulus are useful screening metrics, but they do not establish fatigue life, impact tolerance, creep resistance, environmental durability, manufacturability, or safety-factor performance.

20 Commercialization Strategy

The first commercial target should be a non-safety-critical or semi-structural product where renewable content, repairability, low density, and moderate-temperature processing have direct value. Candidate applications include molded panels, tooling, fixtures, repairable housings, interior components, and selected marine or automotive parts. Aerospace primary structure, ballistic protection, and safety-critical structural components shall remain long-term qualification targets rather than launch markets.

Table 22: Recommended market-entry sequence.

Stage	Product position	Evidence required
1	Renewable-content dynamic resin or filled compound	Reproducibility, viscosity, cure, Tg, stress relaxation, and verified origin accounting.
2	Processed-carbon-reinforcement molded composite for noncritical components	Mechanical, thermal, moisture, impact, fatigue, and remolding data.
3	Repairable or weldable composite system	Joint strength, repair-cycle retention, aging, and process-window data.
4	Regulated structural application	Full application-specific qualification, quality systems, traceability, fire and damage-tolerance evidence.

The financial model shall be rebuilt from measured yields and process data. Cost estimates must include feedstock variability, reagent recovery, energy, waste treatment, labor, catalyst loss, filler preparation, dispersion throughput, quality control, scrap, and facility safety systems. Revenue projections shall be presented as scenario ranges with explicit assumptions rather than as a single deterministic trajectory.

21 Techno-Economic and Supply-Chain Scale-Up Analysis

21.1 Scope and functional-unit boundary

This section adds an early-stage screening techno-economic analysis (TEA) and supply-chain assessment for the Hempoxies resin platform. The functional unit is **1 kg of saleable Hempoxies resin** before downstream molding, prepregging, or finished-composite conversion. The model includes EHO/MHO functionalization, FGE or an equivalent reactive diluent, catalyst, process chemicals, energy, labor, quality assurance, packaging, waste, and ethanol make-up. It does not include a fully costed production line for processed hemp-derived carbon reinforcement, carbon nanosheets, GO/rGO, CNC, or downstream composite conversion.

This boundary is deliberate. The proposal combines resin chemistry, processed reinforcement, biomass fractionation, ethanol production, and composite manufacturing. These are separate

businesses with different equipment, permits, quality systems, and cost structures. A resin-only TEA must not be presented as a complete composite TEA.

Table 23: TEA system boundary and separately gated activities.

Boundary	Included in this screening TEA	Excluded or separately gated
Resin platform	Hempseed oil, EHO/MHO functionalization, FGE, catalyst, process chemicals, ethanol circulation and make-up, energy, labor, QA, packaging, and waste.	–
Processed reinforcement	Demand indication based on the 15–20 phr proposal window.	Full carbonization, activation, oxidation/reduction, sizing, qualification, and yield economics.
Composite conversion	None.	Milling, prepregging, molding, machining, scrap, tooling, and customer qualification.
Upstream agriculture	Seed and land-equivalent requirement.	Farm profit, crop insurance, contracts, storage, regional taxes, and land-use economics.
Financial scope	EBITDA screening and simple payback.	Tax, depreciation, financing, subsidies, carbon credits, FX hedging, working capital, and insurance.

21.2 Recommended scale-up configuration

The lowest-risk Phase 1 configuration is a modular specialty-chemicals plant that buys and qualifies hempseed oil or a qualified hempseed-oil intermediate, maleic anhydride, catalyst, FGE, and selected processed reinforcement. The plant would perform EHO/MHO functionalization, blending, ethanol-assisted dispersion, solvent recovery, degassing, packaging, and release testing. This avoids making the first resin facility simultaneously responsible for agricultural aggregation, decortication, high-temperature carbonization, KOH activation, graphene chemistry, CNC production, fermentation, distillation, wastewater treatment, and nanomaterial qualification.

Selective integration may be considered in Phase 2 for the operations that create a demonstrated cost or quality advantage, especially EHO/MHO functionalization, closed-loop ethanol recovery, or processed-carbon finishing. Full integration of stalk and bast fractionation into ethanol, carbon, nanosheets, CNC, and furan intermediates should be treated as a separate Phase 3 investment case.

21.3 Screening assumptions

The following assumptions are planning values, not supplier quotes or measured Hempoxies results. They shall be replaced by pilot yields, vendor quotations, process-safety data, and customer-backed pricing before financing or construction authorization.

The maleic-anhydride base assumption is close to a public U.S. assessment of approximately USD 953/t reported by Intratec for November 2025 [9]. The ethanol assumption is more conservative than a commodity-fuel reference because Hempoxies requires anhydrous, traceable, potentially hemp-derived ethanol rather than ordinary fuel ethanol; the U.S. Grains Council reported a Midwest rack reference of 57.04 cents/L in April 2026 [10]. EIA publishes industrial electricity price tables by state and sector; the model uses a range rather than treating one national value as universal [11].

Table 24: Screening TEA scenarios in 2026 USD.

Assumption	Conservative	Base	Upside
Nameplate capacity (t/y)	1,000	5,000	10,000
Utilization	60%	75%	85%
Saleable output (t/y)	600	3,750	8,500
Overall saleable yield	92%	95%	97%
Hempseed-oil planning price (USD/kg)	12.60	6.00	4.50
Maleic-anhydride planning price (USD/kg)	1.20	0.95	0.80
FGE planning price (USD/kg)	8.00	5.00	3.00
Zn(acac) ₂ planning price (USD/kg)	35.00	22.00	15.00
Energy intensity (kWh/kg)	5.0	3.0	2.0
Electricity price (USD/kWh)	0.14	0.10	0.08
Ethanol recovery	90%	95%	98%
Selling price (USD/kg)	11.00	14.00	15.00
Installed capital (USD million)	18	35	60

21.4 Mass balance and capacity consequences

The base-case model uses the following planning factors per kg saleable resin before yield correction: 0.85 kg hempseed oil, 0.10 kg maleic anhydride, 0.09 kg FGE, 0.02 kg catalyst, and 0.03 kg other reagents. Ethanol is charged at 0.75 kg/kg product and recovered; only make-up ethanol is costed.

Table 25: Base-case annual material requirements at 3,750 t/y saleable resin.

Material or flow	Requirement
Hempseed oil	3,355 t/y
Maleic anhydride	395 t/y
FGE	355 t/y
Catalyst	79 t/y
Ethanol circulation charge	2,961 t/y
Ethanol make-up at 95% recovery	148 t/y
Processed carbon reinforcement at 15 phr	563 t/y
Processed carbon reinforcement at 20 phr	750 t/y
Biochar at 3–5 phr	113–188 t/y
CNC at 1–2 phr	38–75 t/y

The ethanol circulation quantity drives tankage, vapor control, recovery capacity, condenser duty, fire protection, and solvent-quality management even though only make-up ethanol is consumed. A 30-day inventory policy would imply approximately 280 t of hempseed oil, 33 t of maleic anhydride, 30 t of FGE, and 247 t of ethanol circulation capacity before safety stock and lead-time adjustments.

Table 26: Screening economics before tax, depreciation, financing, and excluded reinforcement/composite costs.

Scenario	Output (t/y)	Variable cost (USD/kg)	Price (USD/kg)	EBITDA (USD M/y)	Payback
Conservative	600	17.22	11.00	−7.7	Not achieved
Base	3,750	8.40	14.00	15.0	2.3 years
Upside	8,500	5.80	15.00	68.2	0.9 years

21.5 Scenario economics

The conservative case is EBITDA-negative at low utilization and premium oil pricing. The base case appears attractive only under meaningful operating leverage, high utilization, and a selling price that customers accept. These outputs are a screening envelope, not a forecast, because the model excludes the full cost of processed carbon reinforcement, downstream composite conversion, qualification, technical service, insurance, and working capital.

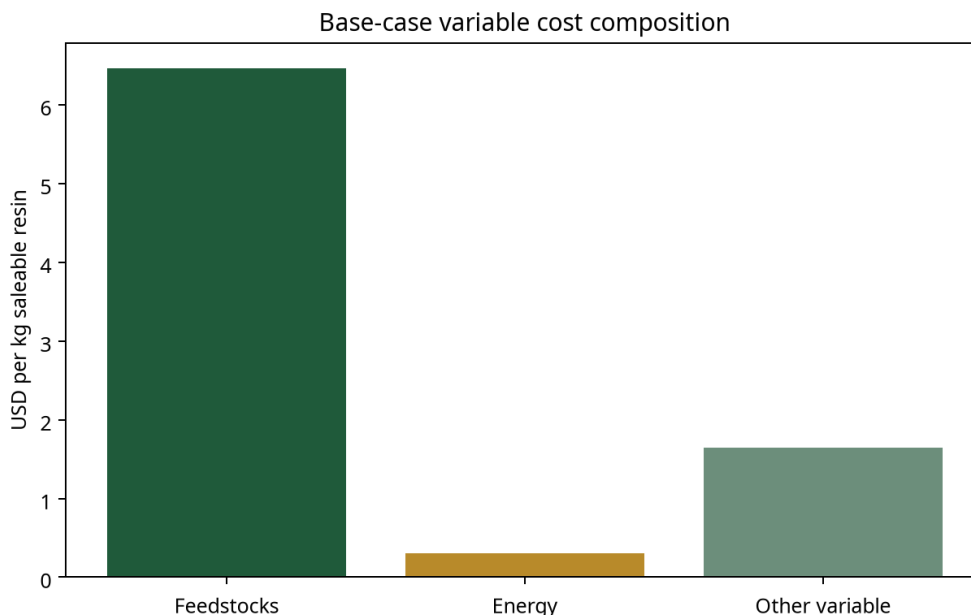


Figure 2: Base-case variable-cost composition. Feedstocks dominate the screening cost structure; the chart excludes downstream processed-reinforcement and composite-conversion costs.

21.6 Sensitivity and economic breakpoints

The model indicates that hempseed-oil price and overall yield dominate energy cost. This is expected for a bio-based oil platform: heat integration matters, but feedstock quality, oxidation losses, batch yield, and release rate are economically more important than small changes in electricity price. FGE is a strategic bottleneck because it is both a reactive diluent and a potential origin-claim component.

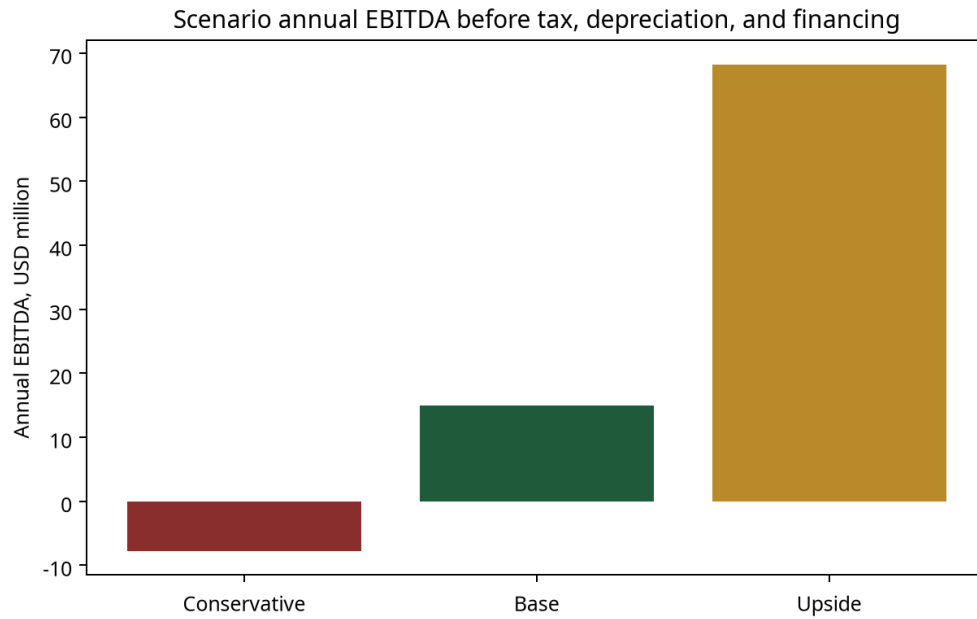


Figure 3: Scenario EBITDA before tax, depreciation, and financing. The result is highly assumption-dependent and is not a validated financial forecast.

Table 27: Base-case one-at-a-time sensitivity of variable cost.

Variable	Low-case cost (USD/kg)	High-case cost (USD/kg)	Base (USD/kg)
Hempseed-oil price	7.06	14.30	8.40
FGE price	8.21	8.68	8.40
Overall yield	8.61 at 92%	8.26 at 97%	8.40 at 95%
Ethanol recovery	8.42 at 90%	8.38 at 98%	8.40 at 95%
Energy intensity	8.30 at 2 kWh/kg	8.60 at 5 kWh/kg	8.40
Electricity price	8.34 at 0.08/kWh	8.52 at 0.14/kWh	8.40
Variable labor	8.05	9.30	8.40

21.7 Supply-chain requirements and resilience

Hempseed oil is the dominant supply-chain exposure. USDA background material reports approximately 29–34% oil content in hempseed and notes that the oil is highly unsaturated and susceptible to oxidation and rancidity unless preserved [7]. The Ohio State techno-economic analysis reports U.S. 2022 hemp grain production of 1,104 Mg and fiber production of 9,545 Mg, with production concentrated in specific states [8]. The base-case requirement of approximately 3,355 t/y oil implies approximately 9,900–11,600 t/y seed before extraction loss and therefore requires multi-year grower contracts, broader geographic sourcing, harvest-season storage, or a controlled contingency for non-hemp bio-oil.

The proposal does not use raw or untreated fibers. At 5,000 t/y saleable resin, the 15–20 phr window corresponds to approximately 563–750 t/y processed hemp-derived carbon reinforcement. The reinforcement line is therefore a material business in its own right and requires precursor qualification, drying, stabilization or carbonization, inert-gas supply, high-temperature furnaces, chopping or sizing, surface treatment, dust control, and retained-strength testing.

Table 28: Critical inputs and minimum supply-chain controls.

Input	Primary risk	Minimum control
Hempseed oil	Seasonal supply, oxidation, limited scale, origin variability	Multi-year contracts, regional diversification, oxygen-control protocol, and 60–120 days safety stock.
Hempseed	Crop failure, THC/compliance variability, seed quality	Approved varieties, grower network, contracted acreage, and harvest-season storage.
Processed carbon reinforcement	Furnace/finishing bottleneck, morphology variability, dust hazard	Two qualified processors or redundant trains, COA with carbonization history and strength, and 90-day buffer.
Maleic anhydride	Commodity-price and heated/solid-handling exposure	Dual distributors, storage design, and price-index clauses.
FGE	Specialty supply and origin uncertainty	Buy-versus-make decision, dual qualification, and substitution protocol.
Zn(acac) ₂	Specialty catalyst price and filler adsorption	Supplier agreements and catalyst–filler compatibility testing.
Anhydrous ethanol	Flammability, water specification, origin premium, recovery loss	Closed loop, dual supplier, vapor controls, and water/residual-solvent release tests.

21.8 Capital strategy and stage gates

The USD 35 million base-case installed-capital assumption is an order-of-magnitude placeholder. It may be low if the scope includes carbonization, inert-gas systems, nanomaterial finishing, ethanol recovery, hazardous-waste treatment, and redundant safety systems; it may be high if the operation is a toll-manufactured resin line with purchased fillers. DOE/NETL guidance distinguishes rough factored estimates from detailed equipment-based estimates and cautions that insufficiently defined novel processes do not justify construction-grade accuracy [23].

Table 29: Recommended capacity and investment sequence.

Stage	Scale and purpose	Decision gate
0	10–100 kg campaigns	Reactive-equivalent control, yield, viscosity, catalyst effect, ethanol recovery, and safety envelope.
1	1–10 t/y pilot	Repeatability, closed ethanol recovery, reinforcement COA consistency, and QC release.
2	100–500 t/y demonstration	Customer samples, labor, cycle time, quality cost, waste treatment, and supply contracts.
3	1,000–5,000 t/y specialty plant	72-hour campaign, heat-transfer validation, batch release, anchor customers, and feedstock contracts.
4	10,000 t/y or integrated biorefinery	Separate proof of demand, margin, safety, and supply resilience for each upstream business.

21.9 Financing gates and minimum data package

Before financing or construction authorization, the project shall obtain three or more independent EHO/MHO campaigns; a complete mass balance including solvent, waste, wastewater, off-spec product, and unaccounted mass; a reinforcement-only pilot balance; supplier quotations and contracts; a pilot operating model; a formal process-safety package; customer qualification evidence; and an integrated TEA that separates resin, processed reinforcement, and composite conversion economics.

The recommended financing structure is staged. Release the next tranche only if the resin-only case remains positive under a conservative oil-price and yield stress case, at least two suppliers are qualified for each critical input, processed-carbon capacity and COA consistency are demonstrated, ethanol recovery and flammable-service controls are validated, and customer evidence supports the assumed selling price.

22 Risk Register

23 Conclusion and Investment Recommendation

HEMPOXIES should proceed as a gated materials-development program. The platform has a credible chemical foundation and a potentially differentiated sustainability and reparability proposition. It is not yet justified to market the material as universally stronger than steel, titanium, Kevlar, or conventional aerospace composites, nor to claim more than 99% hemp-derived total mass without a formal and independently reviewed accounting basis.

The next investment tranche should be released against five hard milestones: a reproducible neat vitrimer matrix; a reproducible filled composite; verified biobased-carbon and hemp-derived-mass measurements; measured stress relaxation and defined remolding performance; and a transparent comparison against commercial controls. If those milestones are passed, the project can rationally advance toward pilot-scale manufacturing and a focused first application. If they are not passed, the platform should be simplified by removing filler families, reducing claim scope, or selecting a different market where the measured property balance is genuinely competitive.

Recommended external positioning: “Hempoxies is a hemp-derived, dynamic-network composite platform under development. Its formulation library is designed

Table 30: Priority technical and commercial risks.

Risk	Priority	Mitigation
Mass-accounting ambiguity	Critical	Publish system boundary, final-mass formulation, component origin matrix, ethanol solvent ledger, and independent review.
Reactive-equivalent imbalance	Critical	Measure EEW and AEW for every batch; formulate on equivalents, not oil mass.
Processed-reinforcement quality and breakage	High	Specify precursor purification, stabilization and carbonization, sizing or surface treatment, length distribution, orientation, and retained strength; prohibit raw-fiber substitution.
Nanofiller agglomeration	High	Use staged dispersion, microscopy, rheology, moisture control, and filler-by-filler screening.
Catalyst sequestration	High	Measure cure and relaxation with increasing filler loading; test compensation only experimentally.
Moisture and hydrolysis	High	Drying protocol, water uptake, hydrothermal aging, and post-aging mechanical testing.
Low service-temperature margin	High	Measure Tg, creep, DMA, and long-term stress retention before structural claims.
Peroxide and acid process hazards	Critical	Reaction calorimetry, interlocks, venting, emergency quench, and formal process-safety review.
Ethanol flammability and residual solvent	High	Closed, grounded equipment; vapor control; recovery efficiency; residual-ethanol specification; ignition-source control; and solvent-emissions accounting.
Uncertain scale economics	Medium-High	Use measured yields, energy, waste, labor, and throughput in scenario-based costing.

to combine renewable feedstocks, processed hemp-derived carbon reinforcement, and thermally activated repair or reprocessing. No performance or origin claim is considered validated until supported by defined analytical, mass-balance, and mechanical testing.”

A Expanded Laboratory and Scale-Up Record Templates

This appendix converts the proposal into a recordable development system. Blank fields are intentional. They are not permission to proceed without approvals, and they shall be completed only in the controlled laboratory or pilot-facility record. Every value shall carry a unit, instrument ID, calibration status, operator, timestamp, batch ID, method revision, and uncertainty or detection-limit statement where applicable.

A.1 Batch identity and chain of custody

Table 31: Minimum batch-identification record.

Record field	Entry
Project, experiment, and batch IDs	_____
Formulation and BOM revision	_____
SOP IDs and revisions	_____
Operator, reviewer, EHS release	_____
Feedstock lot and supplier	_____
Component receipt, quarantine, and release dates	_____
Equipment IDs and calibration due dates	_____
Room, hood, enclosure, and environmental conditions	_____
Deviation, incident, or change-control numbers	_____
Final disposition and archive location	_____

A.2 Expanded stoichiometric worksheet

For each formulation, record both the measured input data and the calculated output. The calculation must be independently checked before any reactive component is combined.

Table 32: Reactive-equivalent calculation worksheet.

Quantity	EHO	MHO	Units/notes
Charged mass	_____	_____	g
Purity or active fraction	_____	_____	mass fraction
Moisture	_____	_____	mass fraction or ppm
Measured EEW/AEW	_____	_____	g eq ⁻¹

Functionality correction	_____	_____	dimensionless
Calculated equivalents	_____	_____	eq
Target ratio λ	_____	_____	n_A/n_E
Measured ratio	_____	_____	n_A/n_E
Deviation from target	_____	_____	percent or absolute
Independent calculation check	_____	_____	name/date

The same worksheet shall list each additive, its phr basis, charged mass, moisture correction, active fraction, origin class, and whether it is incorporated or removed. For every filler, report both as-received mass and dry-basis mass. For ethanol, record charge, recovered mass, residual measured mass, unrecovered loss, water content before and after recovery, and the instrument method used.

A.3 Uncertainty and error propagation

The project shall not report a mass fraction, reactive-equivalent ratio, or cost estimate without an uncertainty statement. For independent quantities x_i with standard uncertainties u_i , a first-order combined uncertainty may be reported as

$$u_c^2(y) = \sum_i \left(\frac{\partial y}{\partial x_i} \right)^2 u_i^2(x_i) + 2 \sum_{i < j} \frac{\partial y}{\partial x_i} \frac{\partial y}{\partial x_j} \text{cov}(x_i, x_j). \quad (9)$$

The report shall identify whether uncertainties are repeatability, calibration, sampling, purity, moisture, yield, or model uncertainties. Correlated inputs shall not be treated as independent. When distributions are used in the TEA, the distribution, parameter source, correlation assumptions, and number of simulations shall be documented.

For the hemp-derived mass fraction $H = M_H/M_{\text{final}}$, report H , standard uncertainty, expanded uncertainty, coverage factor, system boundary, and all unassigned mass. A claim shall be blocked when the upper uncertainty boundary crosses the claim threshold or when any significant mass remains unassigned.

A.4 Component release specifications

Table 33: Component release-test planning matrix.

Component	Identity and composition	Physical and reactive tests	Release decision
EHO	FTIR/NMR or validated identity; origin and purity	EEW/oxirane oxygen, acid value, moisture, viscosity, peroxide value, density, storage stability	Release / hold / reject
MHO	FTIR/NMR; acid/anhydride functionality	AEW or acid/anhydride number, moisture, viscosity, cure response, storage stability	Release / hold / reject
FGE	Identity, precursor-origin matrix, purity	EEW, water, viscosity, residuals, color, compatibility	Release / hold / reject
Ethanol	Assay, water, denaturants, impurities, origin	Karl Fischer water, vapor/flammability controls, recovery performance	Release / hold / reject
Zinc catalyst	Supplier identity and lot	Assay, metal content, moisture, particle size, storage history	External catalyst release
CNC	Cellulose origin and process history	Morphology, size, crystallinity, surface chemistry, moisture, ash, contamination	Release / hold / reject
Biochar	Feedstock and carbonization history	Ash, moisture, porosity, particle distribution, contaminants, adsorption	Release / hold / reject
Carbon reinforcement	Conversion history and sizing	Length/particle distribution, surface chemistry, retained strength, ash, moisture, orientation suitability	Release / hold / reject
Nanosheets	Carbon precursor and route	Raman/FTIR/XPS, microscopy, layer distribution, ash, metals, conductivity, dustiness	Release only after EHS and analytical review

A.5 Controlled mixing and cure run sheet

The run sheet below expands the mixing-and-curing SOP into an auditable record. It intentionally leaves facility-approved values blank.

Table 34: Mixing, solvent-recovery, and curing run sheet.

Stage	Required record	Acceptance or stop condition
Pre-start	BOM/SOP revision, releases, calibration, ventilation, grounding, waste, personnel	Stop if any release, calibration, or control is missing
Drying	Starting mass, method ID, endpoint moisture, cooling and storage time	Stop if material degrades, overheats, or moisture is out of specification
Matrix preparation	EHO/MHO masses, EEW/AEW, ratio, temperature, viscosity, appearance	Stop if ratio, temperature, viscosity, or identity is out of range
Reactive diluent	Identity, origin class, charged mass, water, compatibility, addition record	Stop if origin, purity, or compatibility is unresolved
Filler pre-dispersion	Filler lot, dry mass, solvent charge, shear history, temperature, microscopy sample	Stop if open flammable handling, aerosol release, or unstable dispersion occurs
Catalyst addition	Catalyst lot, basis, mass, addition point, mixing torque and temperature	Stop if catalyst basis or homogeneity is uncertain
Ethanol recovery	Charge, recovered, residual, loss, water before/after, vapor controls	Stop if recovery, grounding, condenser, vapor, or residual-solvent control fails
Degassing	Pressure, temperature, time, foam height, mass loss, endpoint evidence	Stop if boiling, uncontrolled foaming, pressure instability, or solvent vapor escapes
Reinforcement addition	Lot, morphology, low-shear settings, torque, distribution, sample location	Stop if breakage, agglomeration, overheating, or raw-fiber substitution occurs
Molding	Mold ID, geometry, release agent, fill mass, pressure, thermocouples	Stop if mold compatibility, fill, pressure, or temperature monitoring fails
Cure/post-cure	Approved schedule revision, setpoint, internal temperature, exotherm, pressure, cooldown	Stop for uncontrolled exotherm, gas, pressure, decomposition, or interlock failure
Conditioning/release	Conditioning environment, test timing, mass, dimensions, residual solvent, disposition	Hold if release tests or records are incomplete

A.6 Analytical method and acceptance-record template

For each test, record the method name and revision, instrument ID, calibration standard, sample preparation, number of independent batches, number of specimens, raw-data path, processing script version, result, uncertainty, acceptance threshold, reviewer, and deviation number. The following minimum matrix should be completed before testing:

Table 35: Minimum analytical and performance test matrix.

Question	Primary method	Required companion evidence	Status
Were EHO and MHO converted as intended?	FTIR/NMR, EEW, AEW, acid/anhydride number	Mass balance, moisture, replicate lots	_____
Did curing occur?	DSC, FTIR, gel fraction, rheology	Internal temperature and cure record	_____
Is the vitrimer exchange active?	Stress relaxation, creep, DMA	Catalyst-free control and temperature history	_____
Is dispersion acceptable?	Microscopy, rheology, sedimentation, cured-section imaging	Filler moisture and shear history	_____
Is solvent controlled?	GC or validated residual-solvent method; Karl Fischer	Recovery ledger and emissions record	_____

Does reinforcement improve performance?	Tensile, flexural, fracture, fatigue, impact, density-normalized tests	Neat matrix and single-filler controls	_____
Does durability survive exposure?	Moisture, hydrothermal, solvent, thermal-cycle and UV conditioning	Pre/post mass, Tg, microscopy, mechanics	_____
Does reprocessing retain utility?	Cycle 0, 1, 3, 5, 10 mechanical and DMA testing	Processing history, defects, mass loss, microscopy	_____

A.7 Scale-up and heat-transfer record

Scale-up shall be based on measured heat release, heat-transfer coefficient, mixing power, viscosity evolution, fill level, and solvent-removal rate rather than volume multiplication alone. For a batch with heat-generation rate q_{gen} and heat-removal rate q_{rem} , the operating envelope shall maintain a positive margin $q_{rem} - q_{gen}$ under credible cooling-loss and mixing-loss cases. The batch record shall state vessel working volume, jacket area, agitation geometry, torque limit, residence time, maximum credible temperature, pressure boundary, vent/relief basis, thermocouple locations, solvent-vapor control, and maximum allowed batch mass.

The scale-up gate shall include a laboratory-to-pilot comparison of conversion, viscosity, mixing time, temperature gradients, residual solvent, cure exotherm, filler distribution, yield, waste, and operator exposure. A pilot batch shall be rejected for comparison when the equipment, heat-transfer regime, solvent-recovery configuration, or material specification is materially different without a documented equivalence analysis.

A.8 Data-release and publication package

Each public release shall contain a versioned README, formulation and BOM revision, raw data or an access statement, processed data, analysis scripts, calibration records, batch metadata, deviations, negative results, uncertainty calculations, safety boundaries, and a machine-readable data dictionary. A Zenodo release shall receive a DOI; the GitHub repository shall contain version tags and an issue history; and manuscripts shall identify the exact dataset and code release used for every figure and table.

Authorship shall follow documented intellectual contribution, experimental contribution, analysis, writing, supervision, and accountability. AI assistance shall be disclosed for literature triage, drafting, code support, and editing, while human authors retain responsibility for source verification, safety decisions, calculations, interpretation, and final approval. Conflicts of interest, supplier relationships, sponsored work, patent interests, and negative results shall be disclosed.

A.9 Decision-gate worksheet

Table 36: Stage-gate decision record.

Gate	Evidence required	Failure response	Decision
Feedstock gate	Identity, origin, moisture, purity, certification, supplier qualification	Quarantine, reject, or requalify lot	_____
Chemistry gate	Conversion, reactive equivalents, residual oxidant, waste and calorimetry	Stop, investigate, revise SOP	_____
Matrix gate	Cure conversion, Tg, gel fraction, viscosity, stress relaxation	Remove catalyst/diluent or revise balance	_____
Reinforcement gate	Morphology, dispersion, adhesion, retained strength, exposure controls	Remove or replace filler family	_____
Process gate	Mixing, recovery, exotherm, residual solvent, yield, waste	Do not scale; perform hazard review	_____
Application gate	Conditioning, density-normalized properties, durability, controls	Narrow claim or change market	_____
Scale gate	Supplier redundancy, TEA, LCA, permits, customer evidence, FTO review	Hold financing or reduce scope	_____

A.10 Final pre-publication checklist

Before any external release, the project shall confirm that every factual statement has a source or is labeled as an assumption; every numerical result has raw-data provenance; every image has an origin and license; every performance comparison uses matched conditions; every safety statement is reviewed by qualified EHS personnel; every patent statement is labeled as a landscape observation rather than legal advice; every sustainability claim has a system boundary; every “hemp-derived” claim

has a mass and origin ledger; every AI-assisted contribution is disclosed; and every unsupported claim has been removed or rewritten as a hypothesis.

Record here: batch ID, date, operator, formulation revision, instrument IDs, raw-data path, deviations, observations, and decision.

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