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Beyond Biodegradability: Engineering Reprocessable Epoxidised Palm Oil Vitrimers Through Dynamic Covalent Networks, Self-Healing and Circular Polymer Design—A Critical Review

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Abstract

Renewable composition cannot, by itself, establish that an epoxy thermoset is environmentally sustainable or appropriate for repeated industrial use. This critical qualitative literature review examines epoxidised palm oil (EPO) as a precursor for covalent adaptable polymer networks, focusing on the molecular and engineering conditions under which repairability, structural integrity and circularity might coexist. Recent EPO-specific work is critically assessed alongside mechanistic evidence from soybean-, tung- and other bio-derived vitrimer systems, without treating the latter as direct validation of palm-derived performance. The synthesis identifies six interdependent themes: precursor functionality and curing stoichiometry; exchange chemistry and relaxation kinetics; filler–matrix interactions; healing and reprocessing; long-term environmental durability; and material recovery and life-cycle consequences. A particular contradiction emerges between reinforcement that improves stiffness and solvent resistance and the molecular mobility required for efficient welding and topology rearrangement. The proposed Molecular Adaptability–Structural Integrity–Circularity (MASIC) framework reframes formulation selection as application-specific multi-objective optimization, subject to durability and life-cycle qualification. The review distinguishes visual crack closure, recovered mechanical strength, thermal reshaping and chemical recycling as different outcomes and proposes a staged assessment protocol covering reproducible precursor chemistry, exchange behaviour, retained performance across processing cycles, accelerated ageing and comparative environmental performance. EPO vitrimers are promising candidates for repairable coatings, detachable adhesives and selected composite matrices, but current laboratory demonstrations do not establish general industrial readiness. Progress requires standardized metrics, credible counterfactual materials, and transparent reporting of failures as well as successes.

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JEL classification: L65; O32; Q53; Q55; Q56.

Introduction

The Problem with a Renewable but Permanent Network

Industrial thermosets are valued because densely interconnected polymer chains preserve shape, transfer stress and resist many chemicals under conditions that defeat less strongly connected materials. Epoxy matrices have consequently become deeply embedded in coatings, bonded joints, fibre composites and electronic protection systems. Their strongest advantage is simultaneously their end-of-life weakness: an ordinary permanent network cannot be heated into a molecularly mobile melt without bond scission, nor can a damaged joint easily be restored by the simple interdiffusion processes available to thermoplastics. Solvent swelling, grinding and energy-intensive waste management may remain possible, but these routes rarely return an equivalent virgin thermoset. The recent expansion of vitrimer research responds to this structural problem rather than merely replacing a fossil carbon source with biomass [1-4].

The designation 'bio-based' describes the origin of some feedstock carbon; 'biodegradable' describes breakdown under specified biological and environmental conditions; 'reprocessable' describes the ability to reshape or join an existing network; and 'chemically recyclable' refers to obtaining useful chemical fractions through controlled transformation. These concepts are neither interchangeable nor hierarchically guaranteed. A palm-oil-containing resin may remain environmentally persistent after curing, and a network that relaxes stress under heat may still resist depolymerization to its original constituents. Conversely, maintaining a coating or composite in service through credible repair can reduce demand for replacement even when biodegradation is undesirable. Sustainable materials design must therefore address durability, material recovery and comparative environmental burdens together [5-9].

Epoxidised palm oil (EPO) offers a distinctive renewable triglyceride platform because carbon–carbon double bonds in suitable palm oil fractions can be converted into oxirane groups and subsequently reacted with multifunctional curing agents. These modifications produce useful thermoset precursors without assuming that untreated vegetable oil already has the functional density, rigidity or cure rate of commercial aromatic epoxies. Palm feedstocks differ in their fatty-acid profiles, degree of unsaturation, impurities and processing history; any robust EPO programme must measure rather than assume precursor functionality. More flexible aliphatic segments can aid deformation and segmental motion but often lower glass-transition temperature and stiffness relative to rigid aromatic systems. These relationships are central to existing epoxidised vegetable-oil reviews and recent formulation analyses [8,10-12].

Why Epoxidized Palm Oil Vitrimers now Warrant Critical Appraisal

Vitrimers are covalent adaptable networks in which suitably activated exchange reactions rearrange the position of crosslinks while ideally preserving network connectivity during the exchange event. Their properties can combine solid-like dimensional integrity in one operating window with weldability and remouldability in another. For an EPO network containing β-hydroxy esters, transesterification provides a particularly relevant mechanism: an alcohol participates in exchanging ester connections while the crosslinked material maintains an associative pathway. Importantly, the presence of ester bonds alone does not establish measurable vitrimer behaviour, and appreciable relaxation requires suitable access, catalysts or intrinsic catalysis, temperature and network architecture. In that sense, exchange chemistry must be demonstrated kinetically, not inferred from a synthetic scheme [1,2,4,13,14].

The 2026 study by Lee and colleagues directly connects this mechanism with a renewable EPO matrix reinforced using nanofibrillated cellulose and palm-kernel-shell-derived activated carbon. The authors reported an instructive distinction between a composite containing 4 wt.% of each filler, which displayed complete strain recovery in the measured experiment, and a higher-loading composition containing 5 wt.% of each filler,

which was stiffer but showed incomplete recovery. This result supports the plausibility of an optimum reinforcement region within the tested formulation set. It does not prove complete tensile-strength restoration, universal fatigue resistance, full chemical recyclability or a commercially appropriate processing temperature. A separate study of palm-kernel-shell activated carbon in an epoxy vitrimer offers relevant interphase information but must not be misrepresented as establishing an EPO backbone in that system [15,16].

These distinctions matter because current enthusiasm sometimes translates a successful heating demonstration directly into claims about sustainability or industrial relevance. A repaired sample can retain an invisible weak interface; a moulded object may lose tensile toughness across cycles; and a formulation that relaxes rapidly above its glass transition may creep under long-term service loads. Heat-driven shape recovery, reversible bonding, crack closure and chemically assisted material recovery require different evidence. Existing research on soybean-oil matrices, crosslink density, fibre reclamation and processability offers promising analogues while warning against extrapolation across chemistry and processing histories [14,17-21].

Research Purpose and Questions

This review asks how the molecular structure of EPO can be engineered so that exchangeable connectivity provides useful repair and reprocessing without sacrificing service-conditioned strength, stability and environmental value. Eight connected questions guide the analysis: how do triglyceride composition and epoxidation determine network formation; which exchange chemistries are transferable to EPO; what is the effect of fillers on mobility and stress transfer; when does crack repair restore load-bearing performance; how do processing cycles alter the network; what distinguishes reshaping from chemical recycling; which qualification evidence is essential; and how can these findings be translated into coherent design decisions? The questions are addressed through a qualitative synthesis and the original Molecular Adaptability–Structural Integrity–Circularity (MASIC) framework, rather than a new experimental campaign or quantitative meta-analysis [3,11,12,22].

The principal contribution is an engineering interpretation of an emerging materials family. It deliberately ranks direct EPO studies above related vegetable-oil analogues when drawing palm-specific conclusions, interprets reinforcement and exchange rate as coupled variables, and connects laboratory measurements to end-use failure modes. It also proposes a practical reporting architecture in which the evidence needed for a coating differs from that for a structural bonded joint or an electronic encapsulant. The paper first establishes molecular and polymer-physics foundations, explains the qualitative review approach, presents six thematic findings, and then evaluates the MASIC framework, proposed design propositions and an industrial qualification roadmap [9,23-25].

Literature Review: Molecular, Network and Circularity Foundations

Palm Triglycerides, Epoxidation and Cure-State Heterogeneity

Palm oil is not a single molecular building block. It is a population of triglycerides assembled from fatty acids with different lengths and degrees of unsaturation, and the effective number of epoxy groups obtainable per molecule depends on the subset of double bonds accessible to epoxidation. Once oxirane groups are introduced, successful synthesis must characterize actual oxirane conversion, residual unsaturation, epoxide equivalent weight and side reactions rather than reporting only nominal reagent ratios. Hydrolysis, ring-opening impurities or oxidative by-products can change curing behaviour and create a network different from the intended architecture. Because these characteristics also vary across palm fractions and processing batches, reporting only the generic label EPO obscures relevant materials variation [8,10,11,26,27].

Network formation requires more than a high measured oxirane content. Acid or anhydride hardeners, selected amines, hydroxyl donors and multifunctional co-monomers differ in cure reaction pathways and in whether they create exchangeable groups. A network built through epoxy–acid opening may incorporate β-hydroxy esters suited to transesterification; an epoxy–amine network can instead prioritize different covalent linkages and exchanges. Off-stoichiometric formulation may leave additional hydroxyl, epoxide or carboxyl functionalities that alter the exchange rate, swelling and mechanical consistency. Controlled departure from

stoichiometry can be a strategy, but residual groups can also increase moisture sensitivity or hinder reproducibility. Formulation therefore demands measurements of conversion, gel fraction, dynamic mechanical properties and soluble extractables alongside chemical spectroscopy [9,11,28-30].

Epoxidised soybean oil provides a valuable comparator because its often greater unsaturation can yield a different average functionality from many palm-oil-derived fractions. Studies using epoxidised soybean oil with rigid vanillin-derived hardeners, natural sugar alcohols, divanillic acid and tartaric acid demonstrate that backbone flexibility can be modified by aromatic structure, hydrogen bonding, acid functionality and network density. Those studies do not imply that an identical mass ratio will deliver an equivalent EPO network; reaction-equivalent ratios and functional-group availability must be recalculated for each precursor. A particularly important formulation principle is to distinguish the fraction of nominal renewable precursor from the fraction of dynamically active crosslinks actually incorporated [19,28,29,31,32].

Figure 1 illustrates the design pathway at a molecular rather than an atom-by-atom synthetic level. Unsaturated palm triglycerides are epoxidised, reacted with a selected hardener, and then endowed with demonstrable exchange kinetics. The figure intentionally separates cure chemistry from dynamic bond exchange: a crosslinked resin is not considered a vitrimer solely because it contains ester or hydroxyl groups. For EPO, establishing this distinction with rheological evidence and appropriate non-dynamic controls is particularly important because the literature base is still modest compared with epoxidised soybean-oil materials [15,17,27,33].

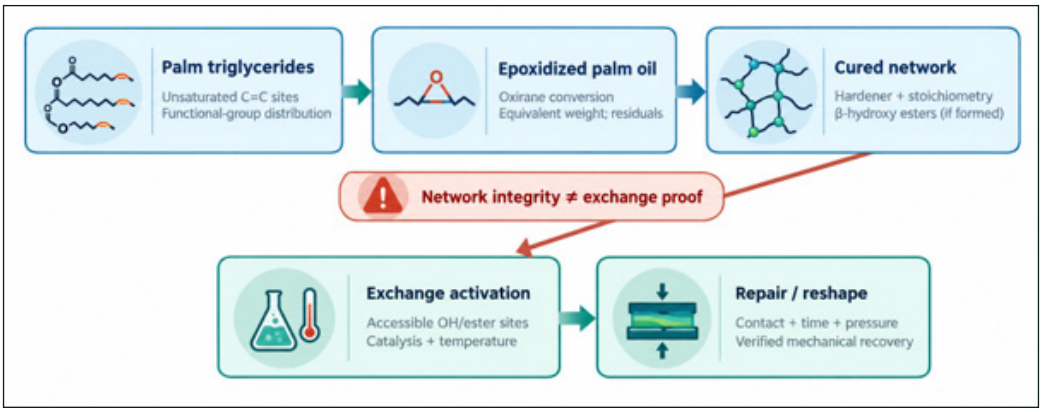


Figure 1: Conceptual Chemical Design Pathway from Epoxidised Palm Triglycerides to Exchange-Capable Networks. Not a Detailed Stoichiometric Reaction Scheme; Exchange Must be Verified Experimentally.

The sequence in Figure 1 clarifies that the presence of a cured three-dimensional network and the verification of bond exchange represent separate scientific claims. Oxirane conversion and the chosen hardener determine which hydroxyl and ester functions are formed, whereas thermal activation and dynamic testing determine whether topological rearrangement actually occurs. The final repair or reshaping step must be validated through the recovery of an explicitly specified function, not inferred from the presence of potentially exchangeable groups [11,15].

Associative Exchange, Dissociative Adaptation and Topology

The distinction between associative and dissociative adaptable networks is mechanistic rather than semantic. In an ideal associative process, a new connection forms during exchange before the previous connection is released, limiting temporary changes in the number of effective crosslinks. Dissociative chemistry instead allows a bond to break and later reform, potentially decreasing connectivity at intermediate stages. Both classes can yield repairable thermosets, yet only the associative family belongs to the stricter vitrimer concept. Diels–Alder remending systems, for example, may offer excellent thermal reversibility but should not automatically be counted as associative transesterification vitrimers. Using these definitions consistently prevents misleading comparisons

of viscosity, gel fraction, reaction pathways and failure risk [1,4,22,23].

Transesterification of β-hydroxy esters has received attention because the reactant hydroxyls and esters can be generated directly during epoxy curing. The rate depends on accessible reactive groups, catalyst activity, segmental mobility and temperature. Imidazoles, metal salts and other catalytic systems can increase reprocessing rate but introduce concerns about cost, long-term chemical compatibility and unintended reactions. Catalyst-free routes have also been described, including vegetable-oil systems using sugar alcohols, tartaric acid or tung-oil-derived epoxides. Here 'catalyst-free' is a formulation statement, not proof of negligible reaction energy or superior environmental performance, since intrinsic catalysis and elevated processing temperature may remain necessary [13,29,32,33,34].

Alternative chemistries broaden the design palette while introducing new failure modes. Disulfide exchange has been used for weldable soybean-oil networks and for chemical recovery strategies; imine exchange contributes reprocessability to vanillin-derived hardeners but can be sensitive to water and local chemistry; boronic or borate esters offer dynamic adhesion and rapid exchange but raise hydrolytic-resistance questions. Hybrid networks may seek to distribute function among exchangeable covalent bonds, permanent scaffold connections and reversible noncovalent associations. It is essential to distinguish evidence from each route and to avoid assuming a processing protocol suitable for one chemistry will transfer to another [17,19,35-37].

Relaxation, Glass Transition and the Meaning of a Processing Window

Vitrimer characterization typically combines dynamic mechanical analysis, temperature-dependent stress relaxation and creep-recovery tests. A common descriptive quantity is a characteristic relaxation time, tau, sometimes operationally defined by the time required for normalized stress to reach 1/e of its starting value. Under a simplified Arrhenius approximation, ln(tau) varies linearly with reciprocal absolute temperature with an apparent activation energy; real networks may deviate because of heterogeneous exchange, catalysts, changing mobility or concurrent degradation. Temperature-dependent rheology thus establishes a conditional processing regime rather than a universal intrinsic constant. The glass transition describes segmental dynamics, while a topology-related timescale describes connectivity rearrangement; the two should not be conflated [4,13,14,38].

For an approximately Arrhenius exchange-controlled interval, the characteristic relaxation time may be expressed through the following operational relation. Here $\tau(T)$ is a specified relaxation time measured at absolute temperature T, τ_0 is the apparent prefactor, E_a is the apparent activation energy and R is the universal gas constant. Departures from a straight-line dependence of $\ln \tau$ on reciprocal temperature should be documented rather than hidden by extrapolation [14,39].

$$\ln \tau(T) = \ln \tau_0 + \frac{E_a}{RT} \quad (1)$$

An apparent topology-freezing temperature is commonly obtained by extrapolating an operational viscosity criterion, but neither the chosen criterion nor the exchange distribution is automatically unique. A sample may have different practical weld and compression-moulding thresholds, and an apparent flow temperature can depend on observation time. Successful joining also requires molecular contact across the interface; chain mobility cannot heal a contaminated, oxidized or poorly pressed surface without adequate wetting. Moreover, rates measured under small strain may not predict large-strain forming, crack-tip mechanics or delayed creep. Rheological studies identify the physical complexity of this translation, including nonlinear deformation around conditions associated with network flow [2,4,14,40].

More explicit rheological interpretation is required because the apparent relaxation timescale depends on the deformation protocol and the relative rates of bond exchange and segmental motion. Meng, Saed and Terentjev demonstrated that both linear and nonlinear vitrimer responses require treatment beyond simplified thermoplastic analogies, while the apparent topology-freezing transition is sensitive to its operational definition[39]. For EPO formulations, reporting the complete stress-relaxation response, applied strain, temperature equilibration and time-dependent creep is therefore more informative than publishing a single extrapolated transition temperature. This methodological distinction is particularly important when different

reports use unlike loading histories and catalyst systems [39].

Service Durability, Reinforcement and Circular Material Value

Fillers are added for mechanically sound reasons: they can carry load, limit swelling, alter fracture pathways and introduce functions such as conductivity, barrier properties or char formation. Cellulose nanofibrils may form hydrogen-bonded bridging pathways; carbonaceous particles can increase tortuosity and resist solvent penetration. But large surface areas can also immobilize nearby matrix segments, alter catalyst distribution or promote agglomeration at higher loadings. Interphase strength is therefore not an independent bonus; it changes the molecular freedom needed for exchange at an interface. The appropriate filler concentration is the one that satisfies both structural and repairability requirements under realistic conditions, not the concentration giving the highest initial modulus [15,16,41-43].

In a circular economy, remoulding, reuse of a repaired component, recovery of intact carbon fibres and depolymerization into building blocks occupy different positions in a resource-preservation hierarchy. Mechanically reprocessed vitrimer may still include shortened reinforcement and accumulated oxidized segments. Chemical disassembly may recover valuable fibres but require hazardous solvents, energy or conversion steps that offset some benefits. An LCA must therefore compare equivalent service delivered, not merely equal masses of products at the factory gate. Research on fibre-reinforced vitrimers, adhesives, printed-circuit-board materials and environmental impacts demonstrates that performance requirements and end-of-life pathways are application-specific [6,44-48].

Table 1 organizes the evidence according to the degree to which a reported mechanism or measured result can legitimately support an EPO-specific conclusion. The central distinction is that experiments on soybean, tung or general epoxy systems identify plausible design mechanisms but do not establish performance thresholds for palm-derived matrices. This hierarchy determines how the subsequent thematic results are interpreted and prevents the overstatement of findings from neighbouring materials families [10,15,39].

Table 1: Evidence Hierarchy and Limits to Transferability Between Material Families.

System / chemistry	Observed or transferable design insight	Evidence status
EPO + NFC + PKS activated carbon	Intermediate filler loading balanced recovery and reinforcement in a defined test series [15].	Direct EPO study
Epoxy + PKS activated carbon	Cure ratio and filler content interact, but backbone not presumed EPO [16].	Palm-biomass filler analogue
ESO + dynamic imine hardener	Rigid hardener improves tunability and reversible processing [19].	Other vegetable-oil network
ESO + sugar alcohol / tartaric acid	Catalyst-free or intrinsically promoted exchange is possible [29,32].	Other vegetable-oil network
General vitrimers /dynamic composites	Stress relaxation, service creep, ageing and recovery depend strongly on protocol [38,49].	Contextual methodology

The evidence classes in Table 1 cannot be merged into a single pooled performance estimate without controlling for the underlying chemistry and test methods. Direct EPO studies anchor palm-specific conclusions, whereas comparable vegetable-oil formulations and general vitrimer studies inform mechanisms and qualification procedures. This tiered interpretation is maintained in the Results and Discussion to distinguish measured outcomes from design hypotheses [10,15].

Method: Critical Qualitative Literature Review

Rationale, Scope and Study Design

The study applies a critical qualitative literature review (QLR) using theory-guided thematic synthesis. A QLR is appropriate when the problem is not simply how many studies report a performance value but why different molecular architectures produce conflicting engineering outcomes and which interpretations are transferable across material families. The study does not claim a registered protocol, exhaustive screening, PRISMA flow diagram, statistical effect-size pooling or quantitative meta-analysis. Instead it integrates established mechanisms, contrasting observations and unresolved assumptions to construct an analytical framework intended to guide subsequent experimental validation. Relevant peer-reviewed materials-science literature published between 2020 and October 2026 forms the main evidence window [1-3,9].

Source Identification and Critical Relevance Criteria

The literature was assembled around interconnected search concepts covering 'epoxidised palm oil', 'epoxidised vegetable oil', 'vitrimer', 'covalent adaptable network', 'transesterification', 'stress relaxation', 'creep', 'self-healing', 'reprocessability', 'aging', 'filler', 'life-cycle assessment' and 'chemical recycling'. Publisher and journal records, scholarly indexing information and DOI-linked article pages were used to assess relevance. Priority was assigned to studies describing both network chemistry and measurable performance under specified test conditions. Reviews were used to clarify evolving theoretical debates, but experiment-specific assertions were attributed to the relevant original article. Citation chasing was purposive rather than exhaustive; it was used to investigate contradictions and identify application-related exceptions [3,10-12].

An evidence hierarchy was applied throughout the synthesis. Tier A comprises direct EPO network investigations; Tier B comprises other epoxidised vegetable-oil and closely related renewable epoxy vitrimer experiments; Tier C comprises general vitrimer mechanics, ageing, composite repair and circularity methods. Tier B findings were considered mechanistically informative only when the implicated chemistry, functionality, filler system and testing conditions were described. Tier C was used to identify potential failure modes and evaluation practices, not to assign unmeasured material properties to EPO. This distinction responds to the disparity between a relatively small EPO-specific experimental base and the broader, rapidly expanding bio-based vitrimer literature [15,16,18,33,50].

Thematic Interpretation, Evidence Strength and Limitations

Six themes were developed iteratively: precursor and cure chemistry; dynamic exchange and kinetic measurement; mechanical reinforcement and interphase effects; healing and cyclic reprocessing; ageing and load-bearing durability; and material recovery with environmental impacts. For each theme, reported mechanisms, relevant experimental observations and limitations were compared. Claims were treated as stronger when experiments reported controls, chemistry characterization, standardized mechanical data, multiple temperature points, reproducibility and more than a single reprocessing event. Claims based only on appearance, theoretical schemes or one favourable processing condition were assigned a narrower interpretive scope [2,9,12,25].

The approach does not supply numerical pooled effect estimates, and comparisons across experiments remain vulnerable to differences in resin composition, sample thickness, catalyst concentration, healing temperature, pressure, test speed and reporting terminology. Industrial performance projections therefore appear below as propositions and recommended validation steps, rather than achieved EPO outcomes. The term 'research gap' is used to describe evidence not established within the reviewed work; it does not necessarily prove that no unpublished or unlocated experiment exists. This interpretive restraint is especially important for 2026 work, for which indexing and follow-up replication remain in progress [15,23,24,49].

Results: Six Interdependent Themes

Theme I: Precursor Functionality and Stoichiometric Design

A first convergent finding is that the number, accessibility and location of reactive groups are as consequential as the renewable identity of the oil. Epoxidised oils differ in their distributions of epoxy groups per triglyceride, and their cured networks consequently differ in opportunities for forming elastically effective

junctions. Recent reviews synthesize evidence that higher epoxide functionality can improve tensile properties and glass-transition temperature under otherwise compatible cure conditions. However, neither property necessarily rises monotonically with nominal functionality: intramolecular reactions, network defects and incomplete conversion can intervene. This point matters particularly when EPO is compared with more highly unsaturated vegetable oils, because using equal masses of precursor can conceal unequal functional equivalents [8,10,11,51].

The hardener is not simply a passive complement to the epoxy. Rigid aromatic segments can increase modulus and thermal resistance; sugar alcohols and multifunctional acids can simultaneously create hydroxyl-rich exchange pathways; and vanillin, divanillic acid, fumaropimaric-acid-derived and other bio-derived motifs can change mechanical and dynamic responses. Zhao et al demonstrated the adjustability of soybean-oil networks cured with a vanillin-derived imine hardener, whereas Yang et al employed a different bio-derived chemistry to obtain shape memory and thermal reprocessing[19,20]. Later work varied starch-based, sugar-alcohol and citric- or tartaric-acid-derived components. The common transferable principle is intentional functionality and rigidity management, not a claim that every curing agent is compatible with all EPO precursors [19,20,28,29,32].

A second finding concerns stoichiometric and cure-state control. Hydroxyl availability can accelerate exchange, yet a high unreacted hydroxyl concentration also affects hydrogen bonding, water uptake and modulus. Curing agent excess may strengthen a hydrogen-bonded phase while reducing network uniformity; apparent improvement in relaxation can partly arise from a softer matrix instead of solely from faster reaction kinetics. The direct comparison of acid-to-epoxy ratios and catalyst efficiency should therefore include gel fraction, soluble content, cure conversion and a chemically justified estimate of network junctions. Jing et al and Lee et al place stoichiometric calculations at the centre of reproducible epoxy vitrimer interpretation, while recent studies demonstrate that bio-derived rigid functionality can change strength–recycling relationships in ways that are not adequately captured by renewable-content percentages [11,30,52].

Theme II: Exchange Mechanisms and Kinetic Comparability

The literature supports a family of workable exchange routes, not one universal chemical solution. Epoxy–acid systems offer transesterification when the required β-hydroxy ester motifs exist; disulfide-based soybean-oil networks exploit another molecular pathway; imine-containing hardeners enable rearrangement of vanillin-containing networks; and borate-based adhesives exhibit dynamic bond exchange under relevant conditions. Each approach embodies a different activation barrier, environmental sensitivity and opportunity for irreversible side reactions. An apparent fast relaxation process is desirable during joining but can be counterproductive near service temperature. Thus, catalyst concentration and exchange mechanism should be selected with an identified operating interval in mind [9,13,17,19,35].

Evidence of catalyst-free transesterification is significant but easily overinterpreted. A reported absence of deliberately added external catalyst is not equivalent to catalyst-independent exchange, because internal hydroxyl groups, neighbouring functional groups and cure chemistry can promote reactions. Li J et al report sugar-alcohol-based soybean-oil vitrimers capable of welding, crack healing and repeated mechanical recycling without added conventional transesterification catalysts; Nepomuceno et al emphasize the functional role of tartaric acid in related networks; and Xu et al examine tung-oil systems employing intrinsic exchange pathways [30,32,33]. Transferring these routes to palm chemistry requires direct measurement of relaxation at more than one temperature and evaluation of thermal stability throughout the processing window [29,32,33].

The kinetic results also demonstrate why a relaxation curve should not be treated as a universal proxy for healing. Stress relaxation is a bulk measurement under a particular strain and temperature history. Crack healing requires intimate interfacial contact and exchange across a damaged plane; moulding additionally requires sufficient bulk shape accommodation; and adhesive debonding depends on local stress fields and substrate interactions. Networks with an appealing short relaxation time may exhibit unacceptable creep, and networks with slow bulk relaxation may still support local surface healing under appropriate pressure and

chemistry. Rheological work by Fang et al. and separate strategies reported by Wu et al illustrate why dynamic measurements should be interpreted together with strength and transition data [14,34,40,45].

Theme III: Reinforcement Produces both Strength and Constraints

The clearest EPO-specific result is that filler content alters more than simple composite stiffness. Lee et al. observed a synergistic response from nanofibrillated cellulose and palm-kernel-shell-derived activated carbon, interpreting the nanofibrils as bridging the interface between the carbon particles and EPO network[15]. In the reported experimental series, moderate loading improved structural response and recovery, while a higher combined loading increasingly restricted rearrangement. The composite at 4 wt.% of each filler achieved 100% strain recovery in the study's reported creep-recovery test. That value should be described precisely: it is strain recovery under defined conditions and not a measured 100% restoration of fracture toughness or tensile strength after an arbitrary crack [15].

The observed reinforcement–adaptability compromise can be explained by several coupled, not mutually exclusive processes. Rigid inclusions take up deformation, interfacial hydrogen bonds constrain nearby segmental movement, filler agglomerates amplify local stress and transport barriers slow solvent penetration. At the same time, dispersion and crack bridging may reduce damage and permit more reliable welding if the interface remains continuous. There is therefore no reason to assume that fillers are universally harmful to adaptation; rather, their effect depends on the spatial organization of mobile and constrained regions. Related work on palm-kernel-shell activated carbon in another epoxy vitrimer found that changing both curing ratio and activated carbon loading changed mechanical and healing characteristics, reinforcing the importance of the interphase rather than validating an identical optimum for EPO [15,16,41].

Figure 2 summarizes this trade-off as a conceptual, non-empirical design map. The curves are illustrative and do not represent measured data, fitted models or universal critical filler concentrations. At low reinforcement, the network may rearrange but carry insufficient service load; at excessive reinforcement, modulus may increase while interfacial defects and restricted exchange make repair inefficient. Between these extremes lies a feasible region defined jointly by minimum mechanical requirements, maximum tolerated creep and adequate recovery after multiple cycles. The location and shape of that region must be measured for each EPO chemistry, filler morphology and end use [15,38,42,43].

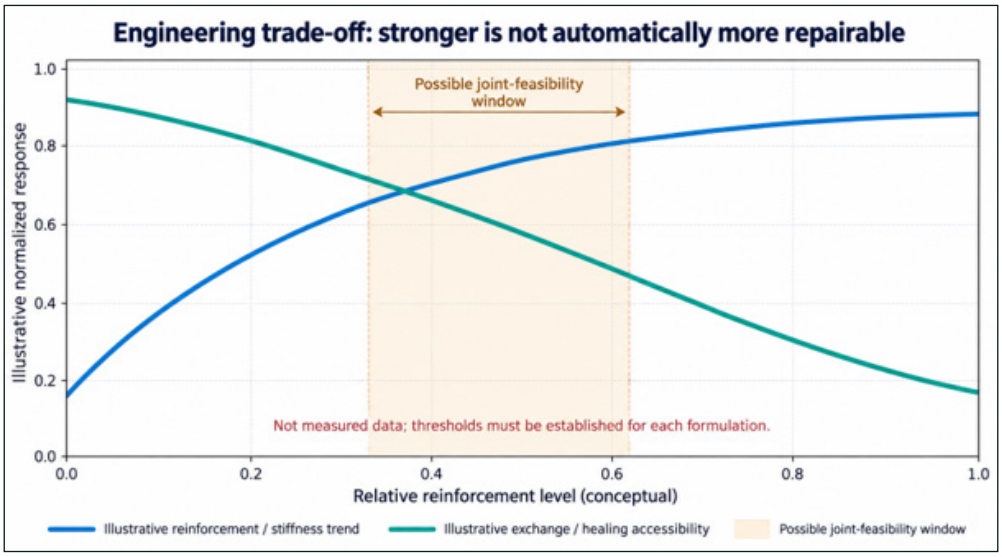


Figure 2: Illustrative Reinforcement–Adaptability Trade-off. Curves and Feasibility Region are Conceptual, With no Empirical Datapoints or Estimated Optimum.

Figure 2 should be read as a hypothesis-generating map rather than an experimentally calibrated property diagram. It places a possible design window between inadequate structural reinforcement and inhibited molecular exchange, while indicating that its location depends on the chosen application threshold. The crossing of the illustrative curves is not an estimated optimum and should not be used to choose an EPO filler loading without a controlled experimental series and property-specific recovery measurements [15,38].

The ability to improve mechanical properties without simply suppressing exchange has motivated more complex design strategies. Rigid and reactive biomass-derived ingredients, dual-dynamic systems, hydrogen-bonded stickers and tailored aliphatic/aromatic ratios offer different ways to redistribute stiffness and molecular mobility. Research on glycyrrhizic-acid-modified vitrimers, hydrogen-bond-enriched network architectures and dihydromyricetin-derived formulations indicates that some combinations can improve more than one property simultaneously. These are valuable counterexamples to a fatalistic trade-off model, but any claim of 'decoupling' must be conditional on temperature, observation time and the property used to measure mechanical integrity [34,38,52,53].

Relevant counterexamples in the broader network literature suggest that hybrid architecture and interphase design can preserve useful mechanical integrity without simply suppressing every rearrangement pathway. Lorenz, Dyer and Kumru demonstrated a hybrid epoxy vitrimer using a renewable reactive diluent and controlled permanent crosslink content to preserve low-temperature creep resistance while allowing elevated-temperature reprocessing [54]. This non-EPO system does not validate an EPO-specific optimum, but it supports the hypothesis that controlled phase architecture may widen its feasible mechanical–dynamic processing window [54].

Theme IV: Healing, Welding and Reprocessing are Distinct Experimental Outcomes

A self-healing claim becomes meaningful only when the initial damage, treatment and recovery metric are explicitly defined. Optical disappearance of a scratch verifies surface levelling or crack closure but cannot alone verify a repaired load-bearing network. A credible experiment should compare virgin, damaged and repaired specimens, including thermal-treatment controls that were never damaged. Measurements may include lap-shear strength for adhesives, fracture energy for bulk specimens, coating barrier performance, and retained fatigue life after repeated damage. A recovered tensile strength percentage should not be equated with recovered elongation, interfacial toughness or corrosion resistance. The soybean-oil, castor-oil and furandicarboxylic-acid vitrimer literature provides multiple repair and reuse demonstrations but also differs markedly in the characterization endpoints reported [17,27,55,56].

Mechanical recovery also needs to be interpreted as a property-specific, temperature-dependent outcome rather than an intrinsic percentage attached to a resin name. Luo et al reported an epoxy vitrimer cured with a disulfide-containing diamine that combined substantial tensile strength with recyclability under relatively mild laboratory processing conditions [57]. The result illustrates a credible strategy for balancing relaxation with load-bearing behaviour, but it concerns a non-palm epoxy chemistry and cannot be transferred directly to EPO. Reporting treatment temperature, reprocessing conditions, virgin baseline and failure mode is essential when using such studies as engineering comparators [57].

Thermal welding requires two surfaces to contact while exchangeable chemical groups remain accessible. Applied pressure can help close microscopic gaps, but too much pressure can squeeze a coating, damage a porous filler network or distort dimensions. The optimum treatment duration is thus constrained by both exchange kinetics and degradation. Thermal reprocessing adds further complexity: a ground vitrimer may need elevated temperature and pressure to fuse particle surfaces, and the remoulded specimen can contain interparticle interfaces absent from the pristine moulding. Repeated cycles may change molecular weight distribution of soluble fractions, filler orientation, residual stress and oxidation state even when overall gel content remains high. Epoxidised soybean-oil and carbon-fibre composite studies establish technical feasibility for some systems but leave EPO-specific cycle retention to be demonstrated separately [18,21,33,41].

Figure 3 provides a measurement-oriented distinction

between four pathways. Repair restores a damaged component for its existing function; welding joins previously separate surfaces; reprocessing changes macroscopic geometry while retaining a crosslinked network; chemical recycling deliberately recovers reusable molecules or constituent materials. One network may enable several routes, yet each must be verified with independent evidence and life-cycle boundaries. Png et al demonstrate an especially relevant alternative involving reversible vitrimerisation of commodity polymer systems, showing that a material's circular pathway is not restricted to repeated hot pressing [58]. Conversely, Guggari et al examine closed-loop disulfide chemistry, a more specific chemical-recovery proposition than simply reporting remouldability [25,36,58].

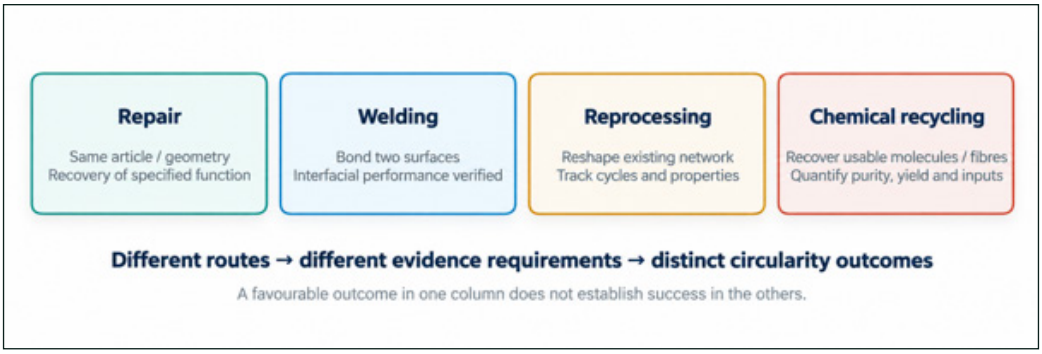


Figure 3: Repair, Welding, Reprocessing and Chemical Recycling are Distinct Experimental and Industrial Outcomes.

The four routes summarized in Figure 3 differ in what is preserved or recovered and consequently in the experimental evidence that must be gathered. Repair and welding primarily concern recovered article or interfacial function, whereas reprocessing changes geometry and chemical recycling seeks usable constituent materials. A successful result for one route cannot be substituted for another, especially when the proposed environmental benefit depends on recovery purity, energy use and actual reuse of the product [36,47].

Theme V: Ageing and Service Conditions Remain the Largest Qualification Gap

The available work strongly suggests that accelerated ageing is essential before comparing EPO networks with industrial thermosets. Temperature and oxygen exposure can create irreversible oxidation, embrittlement or altered relaxation times. Moisture may plasticize a network, weaken an interface, extract residual ingredients or hydrolyse susceptible bonds; UV and weathering can change exposed coatings without immediately producing a visible crack. Not all changes are monotonic: post-curing may initially increase stiffness before degradation dominates, and swelling may temporarily accelerate exchange while damaging long-term barrier performance. As Jewell and Sain emphasize for epoxy vitrimers, ageing chemistry and mechanical brittleness cannot be understood from initial tensile data alone [37,49].

Thermal history creates an additional source of uncertainty, even when test specimens have not experienced visibly aggressive environmental ageing. Sharma, Patel and Rana investigated the effect of thermal cycling on stress relaxation and self-healing in epoxy vitrimers [59], providing relevant evidence that repeated thermal exposure must be treated as an experimental variable rather than a neutral preparation step. Characterization after each cycle should therefore separate continued cure, reversible rearrangement and irreversible deterioration. EPO studies require analogous experiments under specified oxygen exposure and moisture conditions before cyclic property retention can be generalized [59].

Creep deserves treatment as a qualification variable rather than an incidental dynamic response. Associative exchange permits network stress relaxation, which helps reshaping but can also enable irreversible strain under load. A structural adhesive carrying a constant load near a warm service temperature must resist this deformation for much longer than the typical laboratory stress-relaxation test. Research on doubly crosslinked

networks and nitroxide-mediated or siloxane-based dynamic chemistries provides conceptual ways to address creep while retaining remouldability, but these mechanisms are not direct proof of comparable EPO performance. The significance of such studies lies in exposing an engineering design possibility: separate the low-temperature load-bearing mechanism from the high-temperature exchange mechanism as much as chemistry permits [38,40,53].

Thermal processing windows must also be constrained by irreversible degradation kinetics. A nominally reprocessable resin may need temperatures sufficiently high that oxidation, chain scission or filler damage accumulate within repeated cycles. Sanchez-Rodriguez et al explicitly connect processability and reprocessability maps with degradation and temperature gradients, helping explain why a successful small heated coupon does not guarantee equivalent behaviour in a thick composite or large adhesive joint[21]. Composite thermal gradients can allow surface repair while leaving internal regions insufficiently exchanged, or conversely can overheat the surface while the interior reaches the target temperature. These conflicts justify mapping not a single 'healing temperature' but the coupled temperature–time–pressure domain for an application [21,45].

Theme VI: Practical Circularity Depends on Preserved Function

The literature provides meaningful precedents for material reuse, fibre recovery and new product geometries, but the term 'recyclable' must be anchored to the retained value of what is recovered. A ground and hot-pressed resin that becomes a lower-grade filler has been reprocessed, though it may not have achieved closed-loop material recycling. Chemical treatment that liberates carbon fibres can preserve valuable reinforcement while consuming solvents and potentially destroying resin value. Recovery of a usable polymer fraction can be attractive, but scale-up, purification, contamination and transport must be included before asserting net benefit. Reports on industrial-grade carbon-fibre composites, reversible adhesives and printed-circuit-board materials demonstrate the breadth of potential routes while underscoring how differently end-of-life success can be defined [44,45,47,48].

A consequential life-cycle comparison also needs to account for the upstream production of palm oil, including sourcing, land-use conditions, farming inputs and traceability. A biobased formulation containing added catalysts, petroleum-derived co-monomers or carbon-intensive fillers should not be counted as fully renewable unless material inventories justify the claim. Furthermore, using an edible oil feedstock may have opportunity costs relative to using residual streams. For EPO derived from responsibly sourced palm material, a credible LCA can compare the environmental burdens of producing and maintaining equivalent coating area, adhesive joint performance or composite service over a specified lifetime. Research on vitrimer composite environmental assessment and broader circular network design provides the necessary analytical starting point, but EPO-specific comparative inventories remain an important gap [6,44,46].

The distinctions summarized in Table 2 are not merely terminological because they require different performance baselines and end-of-life system boundaries. A repair experiment should document property recovery in the original article, while chemical recycling requires quantifiable recovery and identification of useful fractions. These criteria help prevent lab-scale processing demonstrations from being misrepresented as evidence of reduced life-cycle burdens [36,47].

Table 2 translates the principal circularity terms into independently testable evidence requirements and identifies shortcuts that would misclassify a result. For example, a thermally flattened scratch does not establish restored fracture performance, while remoulding does not identify a recoverable monomer stream. Consequently, studies should define the relevant outcome before experimentation and report the corresponding recovery metric, test controls and functional requirements, rather than using a generic recyclability label [36,47,48].

Table 2: Operational Definitions and Verification Requirements for Commonly Conflated Claims.

Claim	Evidence needed	Incorrect shortcut to avoid
Self-healing	Identical virgin/damaged/repaired functional tests, controls, cycle history	Crack visually disappears
Reprocessability	Repeated shaping with original-property retention and process conditions	One heated remoulding photograph
Chemical recyclability	Identified output chemistry, purity, usable recovery yield, solvent input	Material swells or dissolves
Industrial durability	Creep, fatigue, ageing, barrier/adhesion and exposure envelope	High initial modulus or single tensile test
Environmental benefit	Comparable functional unit, feedstock burden, repair uptake, end of life	Renewable input fraction alone

Discussion and Analysis

Interpreting the Six Themes Through the MASIC Framework

The six thematic findings collectively challenge the assumption that more exchangeable bonds, greater renewable content or higher initial tensile strength individually defines the 'best' vitrimer. Molecular Adaptability comprises chemically accessible exchange reactions, controlled relaxation kinetics and interfacial welding potential. Structural Integrity comprises retained mechanical, thermal, barrier and dimensional functions throughout realistic service and ageing. Circularity comprises verified maintenance of material value, environmental impacts of repair and reprocessing, recovery yields and the possibility of returning useful constituents to production. The MASIC framework treats the three dimensions as linked design objectives, not independent checkboxes. A candidate is qualified only when it meets application-specific thresholds in each domain [3,4,6,23].

Figure 4 illustrates the framework as an engineering decision structure. Precursor chemistry, stoichiometry, catalyst system and reinforcement define a network architecture. That architecture influences mobility and strength, while processing and service exposures progressively modify both. Reprocessing outcomes then interact with environmental metrics: a faster repair process can improve durability benefits but may require higher operating energy or catalysts that increase burdens elsewhere. The MASIC perspective therefore rejects one-dimensional rankings based on a single healing percentage. Its distinctive contribution is to make the dependencies explicit and to require a documented counterfactual conventional material for each proposed end use [11,15,21,44].

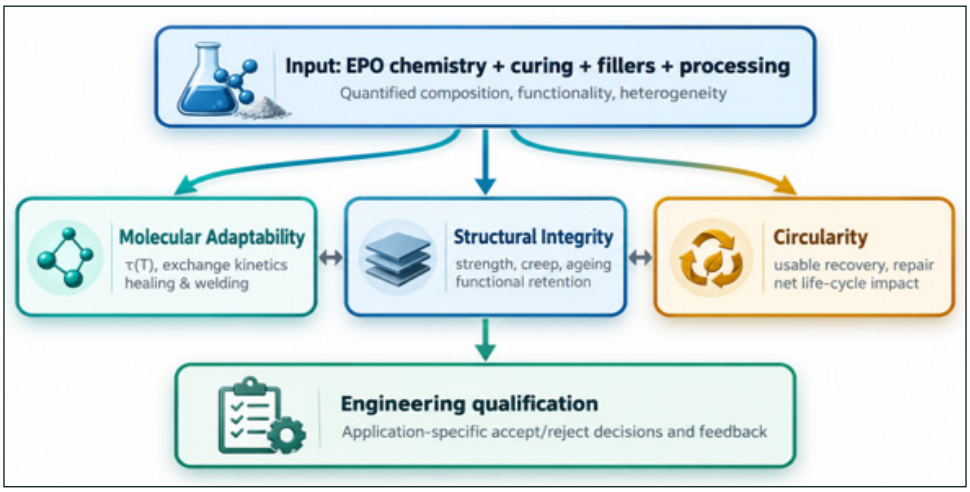


Figure 4: The Proposed Molecular Adaptability–Structural Integrity–Circularity (MASIC) Framework. Original Conceptual Synthesis.

Figure 4 formalizes MASIC as a decision framework rather than a numerical model already validated for EPO. The three domains are interdependent: a formulation alteration that improves exchange kinetics may lower long-term integrity, and a repair method that preserves a component may increase the energy burden of circularity. Application-specific qualification therefore requires simultaneous, independently measured thresholds rather than a single composite score with arbitrary weights [6,54].

The framework also identifies an important asymmetry of evidence. A favourable initial experiment may be obtained under a specific, optimized condition, whereas a negative service outcome can arise from many combinations of moisture, temperature, exposure duration and load. It is therefore easier to establish that an EPO sample can be welded at a chosen temperature than to establish that it will remain dimensionally stable through years of intermittent heat and humidity. Claims of industrial readiness need a pre-specified operating envelope and preferably failure-oriented test conditions. Such a requirement is not unusually severe for vitrimers; it is the ordinary burden placed on protective materials intended to be trusted in service [2,45,46,49].

A Multi-Objective and Time-Dependent Optimization Problem

The engineering objective is better represented by a feasible region than by a maximized scalar property. Let M denote an exchange-related adaptability descriptor, S a service-conditioned integrity descriptor and C a verified circularity descriptor. A conceptual selection problem is to maximize a vector (M, S, C) subject to application thresholds for creep, strength retention, chemical resistance, processing temperature and cost. These descriptors are not proposed as measurements on a common numerical scale; they become meaningful only after each is operationalized for a specified product. A Pareto frontier can then identify formulations for which one objective cannot improve without loss in another under the selected tests. The concept is consistent with evidence that cure ratio, rigid co-monomers and filler concentration can change these properties jointly [16,30,43,52].

A particularly useful hypothesis is that EPO networks will exhibit an application-specific adaptation window bounded below by ineffective bond exchange and above by unacceptable load-induced rearrangement. For a non-load-bearing repairable coating, relatively rapid surface healing may be useful even if creep properties are modest. For a structural adhesive, the allowable creep and environmental degradation thresholds are more demanding; faster exchange can only be accepted when the activation window remains well separated from likely service conditions. Electronic encapsulation introduces additional requirements, including low ionic contamination, dimensional control, dielectric stability and compatibility with delicate components. In each setting, optimal properties are conditional on time: a sample that withstands a one-hour test may fail an exposure measured in months [37,38,48,53].

Reinforcement illustrates why monotonic assumptions are particularly dangerous. Increasing activated-carbon concentration can reduce permeation or raise modulus, but simultaneously increase viscosity during fabrication, produce clusters and restrict molecular contact during thermal welding. Nanofibrillated cellulose may distribute load yet create moisture-sensitive domains if poorly protected. In principle, interface-specific functionalization could let a filler provide stress transfer at service temperature while facilitating local exchange at repair temperature. That proposal is chemically plausible but remains a hypothesis requiring matched formulations, microscopy, rheology and repaired fracture measurements; it cannot be claimed as an experimentally demonstrated EPO solution merely from the existing 2026 filler study [15,16,42].

Separating Healing Efficiency, Reprocessing Efficiency and Recycling Yield

Three property-specific metrics should be reported separately rather than combined into a single measure of sustainability. Mechanical healing efficiency must compare a repaired specimen with the identically tested virgin reference for a pre-specified property P; the property may be tensile strength, lap-shear strength or fracture energy. For repeated processing, retention must be measured against the original virgin property rather than the immediately preceding weakened cycle. Useful material recovery yield is a mass balance, not proof that recovered material has sufficient purity or functional value [18,29,36,45].

$$H_p\ (\%) = 100 \times \frac{P_repaired}{P_virgin} \quad (2)$$

$$R_{p,n}\ (\%) = 100 \times \frac{P_after,n}{P_initial} \quad (3)$$

$$Y_m\ (\%) = 100 \times \frac{m_usable}{m_input} \quad (4)$$

In Equations (2)–(4), P is one consistently defined and identically tested mechanical or functional property, n identifies a specified reprocessing cycle, and m refers to a measured mass rather than a nominal resin fraction. Healing and retention ratios greater than 100% may occur if further curing changes the material, but this should be investigated rather than automatically interpreted as superior restoration. All reported percentages should be accompanied by the absolute initial and recovered values, replicate counts, variability and the full processing history [47,57].

The metrics must also be complemented by mechanisms. A high healing ratio without microscopy or fracture-surface characterization may hide changed failure location, post-cure effects or substrate adhesion. A high mass yield without compositional analysis may describe a contaminated mixture rather than recoverable constituents. A repeated processing series should record absolute properties, not only percentages referenced to a progressively weakened prior cycle. If the original tensile property is P0, the nth-cycle retention must be compared with P0, while the incremental n-to-(n−1) change may be supplied as secondary information. Similar reporting discipline should apply to glass transition, soluble fraction, gel fraction, chemical spectra and stress-relaxation behaviour [12,25,47,56].

Studies that introduce thermal conductivity, fire performance or water resistance reveal a further reason for multidimensional reporting. A reinforced vitrimer used in electronics must meet electrical and thermal requirements in addition to being recyclable; a fire-retarding composite must retain fire behaviour after repair rather than merely showing a respectable initial limiting oxygen index. Research on inherently fire-retarding bio-based epoxies, flame-retardant network structures and thermally conductive vitrimer composites identifies multiple additional application attributes. These should be tested before and after reprocessing because chemical recovery alone will not recreate a product that has lost its required safety performance [37,42,60,61].

What an Industrial EPO Qualification Protocol Should Contain

A staged qualification protocol can convert the MASIC idea into a reproducible experimental programme. Gate 1 verifies the feedstock and reaction chemistry with fatty-acid analysis, oxirane characterization, cure stoichiometry, residual functionality and batch-to-batch variation. Gate 2 establishes network integrity and exchange using spectroscopy, gel fraction, swelling, DMA, temperature-dependent rheology and appropriate controls. Gate 3 measures virgin mechanical and application-specific properties against a commercial reference, including fracture, adhesion and barrier performance where relevant. Gate 4 evaluates repair and reprocessing over a predeclared number of cycles while monitoring mass, emissions, energy and property retention. Gate 5 examines combined ageing, creep, fatigue and recovery under realistic environmental conditions; Gate 6 establishes comparative circularity through relevant life-cycle inventories and end-of-life demonstrations [10,11,21,46].

Figure 5 summarizes this progression and its stopping rules. Advancement between gates should depend on meeting explicit acceptance values agreed for the intended application, rather than on the availability of visually persuasive images. A formulation that fails creep testing should not proceed directly to claims of use in sustained-load structures, although it might remain promising for a repairable, non-load-bearing surface film. Similarly, a treatment that restores stiffness but sacrifices adhesion, chemical barrier properties or electrical reliability has not restored the original function. Gate-based assessment would make negative findings actionable and prevent overstating the maturity of the technology [2,45,48,49].

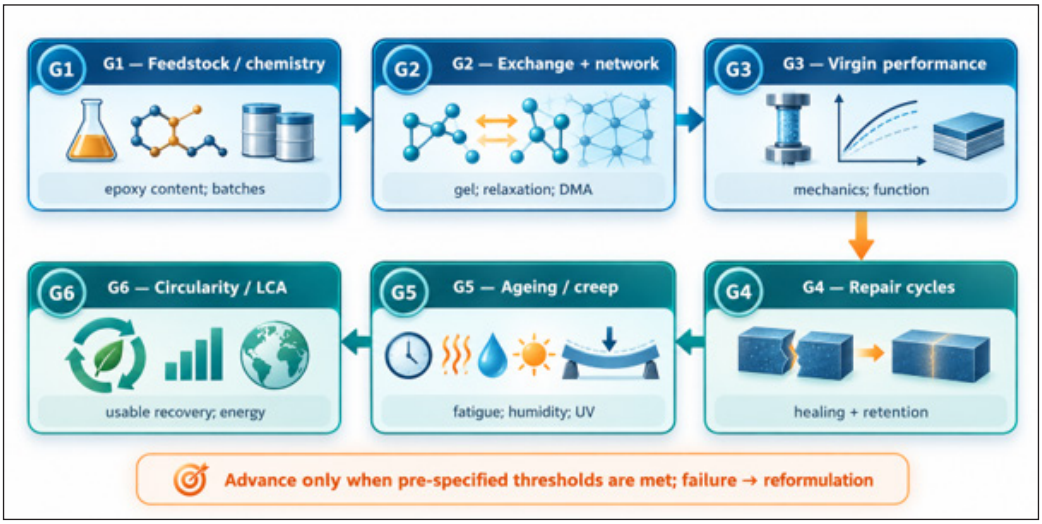


Figure 5: Proposed Stage-Gated Industrial Qualification of EPO-Derived Vitrimer Systems; Acceptance Thresholds Depend on Application.

Figure 5 translates the MASIC framework into six successive evidence gates, beginning with reproducible feedstock chemistry and ending with comparative life-cycle consequences. Each gate requires documented acceptance criteria, with rejection or reformulation permitted when critical properties fall below the specified application threshold. The diagram should therefore be interpreted as a proposed research and qualification pathway, not a claim that current EPO vitrimers have satisfied all six stages [2,21].

The reprocessing test plan should contain at least a modest serial-cycle programme, with five cycles serving as a practical exploratory target rather than an externally established sufficiency threshold. Replicate specimens should be tracked for each cycle, with the number chosen using expected experimental variation and the minimum meaningful property change. Processing temperature, pressure, dwell time, atmosphere, powder or coupon size and cooling profile should be reported fully. Different reprocessing techniques, such as compression remoulding, local welding and thermoforming, should not be placed in the same category unless their mechanical histories and expected performance are comparable. This discipline would help resolve the present inability to compare headline recycling percentages across publications [21,29,46,58].

Application-Specific Implications and Industrial Boundaries

Protective coatings provide an attractive early target because selected surface defects might be repairable without dismantling a whole product. However, a successful scratch-healing photograph is not an adequate surrogate for resistance to oxygen, water and ions or for retention of substrate adhesion following repeated thermal cycles. Barrier performance after damage and repair, electrochemical impedance where relevant, cross-hatch or pull-off adhesion and weathering should be combined with microstructural evidence. If a coating is applied to a heat-sensitive substrate, the activation temperature may become the decisive limitation rather than the initial resin chemistry. Related research on repairable adhesives and chemical-resistance design offers methods, but direct EPO coating qualification remains to be established [35,37,47].

A recent experimental study of epoxy-vitrimer coatings shows why coating functionality should be evaluated alongside chemical exchange. Marotta et al examined epoxy–anhydride coating formulations and found that transesterification catalyst addition and epoxide excess influenced relaxation; protective performance and thermally stimulated healing were also examined [62]. The work offers an experimentally grounded testing precedent for EPO-based protective films, but the study used a different epoxy precursor and does not demonstrate identical palm-derived coating behaviour. Future EPO coating research should combine rheological characterization with corrosion and adhesion tests performed before damage, after controlled damage and after each repair event [62].

Adhesives offer a different benefit: end-of-life debonding could simplify disassembly or allow replacement of components. Their critical tests include lap shear and peel at temperature, hydrothermal ageing, creep under constant load, fatigue under cyclic load and performance after deliberate debonding and rebonding. A reversible joint is valuable only when its adhesion is stable for the required service period and reversible under a deliberate, controlled intervention. Adhesive studies based on soybean oil and other epoxy vitrimers demonstrate promising adhesion and reuse, and carbon-fibre patch work illustrates how repair-oriented materials may restore damaged structures. These examples are important precedents, but their numerical strengths should not be transferred directly to EPO formulations without comparable substrates and test methods [35,47,56].

For fibre-reinforced composites, matrix reprocessability must be assessed in conjunction with fibre orientation, fibre–matrix shear transfer and ply integrity. A material that remoulds readily when ground into short-fibre fragments may be unsuitable for components requiring retained continuous-fibre stiffness. Chemical separation may recover continuous fibre but destroy or downgrade the polymer. Recent composite literature ranges from laboratory carbon-fibre networks to industrially relevant prepreg processing and reprocessing, confirming both opportunity and technological heterogeneity. The likely first EPO composite candidates are noncritical panels and selected repair elements rather than highly safety-critical structural components, pending stronger evidence of fatigue and environmental durability [18,41,45,46].

Electronic encapsulation and circuitry present perhaps the most stringent combination of environmental and property targets. A resin must resist moisture, electrical leakage and dimensional drift, while chemical recovery must not jeopardize contained devices or generate unacceptable residues. Recyclable printed circuit boards have been demonstrated using vitrimer concepts, yet this achievement should be interpreted as evidence for a device-specific polymer and process rather than ready validation of palm-derived formulations. Thermal conductivity, flame retardance and dielectric losses may become binding constraints on the choice of filler, catalyst and network chemistry. EPO-derived networks should be advanced here only when processing temperatures, outgassing and electrical properties satisfy device qualification protocols [48,60,61].

Sustainable Feedstocks, Life-Cycle Counterfactuals and the Value of Lifespan

Palm-derived feedstocks may create a circular materials opportunity when responsible sourcing, co-product utilization and material longevity are jointly considered. Palm-kernel-shell activated carbon is interesting partly because it can derive from a biomass residue rather than requiring a newly cultivated crop solely for filler manufacture. Nevertheless, assigning zero burden to such materials can be misleading if drying, carbonization, activation, washing or transport is energy-intensive. EPO resin and a conventional epoxy comparator should be assessed using a common functional unit, for example protection of a defined area to an agreed failure criterion over a specified time, not a kilogram of neat resin regardless of performance [15,44,46].

Palm oil production itself must remain inside the environmental system boundary whenever feedstock advantage is claimed. Anyaoha and Zhang compared technologies in the palm-oil industry through life-cycle assessment and showed the relevance of processing pathways and associated environmental burdens [63]. This does not supply a ready-to-use emission factor for EPO vitrimer synthesis, which adds epoxidation, hardeners, catalysts and possibly activated-carbon manufacture. Nevertheless, it demonstrates why feedstock origin, upstream processing and conversion technology should be documented explicitly in comparative cradle-to-service-and-recovery assessments [63].

Long-lived industrial polymers also challenge simplistic readings of biodegradability. Rapid biological degradation would be a disadvantage for a protective coating exposed to warm, humid conditions for years. From a life-cycle perspective, extending a component's verified service life can be more important than biodegradation under conditions the component should never encounter. The favourable scenario for an EPO vitrimer is therefore one in which it replaces a higher-impact material without increasing the failure rate, and its repairability actually reduces product

replacement or its end-of-life design meaningfully increases recovery. The result might depend on repair uptake, infrastructure, transport, energy source and the number of successful cycles. Circularity remains a measured systems outcome rather than a molecular property [3,6,44,46].

Research Agenda and Testable Propositions

Five research directions emerge from this synthesis. First, matched EPO series should separately vary epoxide functionality, acid-to-epoxy equivalent ratio and reactive hydroxyl content, using equivalent curing conversions to isolate chemical effects. Second, catalyst and dynamic-linker experiments should report absolute stress-relaxation time, degradation onset and temperature–time processing maps, not only a single apparent topology temperature. Third, factorial filler designs should separate concentration, dispersion, particle chemistry and interphase modification, then relate them to both virgin fracture behaviour and post-repair recovery. Fourth, multi-cycle studies should integrate oxidation, ageing, fatigue and realistic assembly constraints. Fifth, comparative cradle-to-service-and-recovery analyses should use measured rather than assumed repair frequency and material yields. These priorities arise from limitations common across many bio-based vitrimer studies and are especially pertinent to the more limited direct EPO literature [10,15,24,49].

Three falsifiable propositions can guide experimental programmes. Proposition A predicts that, at matched curing conversion, there will be a composition-dependent band of hydroxyl and ester functionality that gives faster repair without exceeding service creep limits. Proposition B predicts a non-monotonic relationship between filler loading and recovered fracture performance, mediated by interphase mobility and dispersion. Proposition C predicts that environmentally advantageous EPO reprocessing will require a minimum retained useful-service fraction sufficient to offset the energy and material burden of the repair operation. None is asserted as a proven universal law; each can be tested by matched controls, longitudinal property retention and comparative life-cycle modelling. Broader progress in catalyst-controlled composite recycling and closed-loop networks suggests useful methodological templates for these studies [36,44,52,58].

Two additional propositions concern chemistry-specific caution. Proposition D states that improvements in apparent stress relaxation obtained by softening the network will not necessarily improve tensile-property recovery or sustained-load performance. Proposition E states that a mixed permanent–dynamic network may reduce service creep at the cost of increased processing temperature or reduced chemical recoverability, so performance gains must be interpreted over the entire life cycle. The most important theoretical consequence is that MASIC does not recommend maximum adaptability. It recommends sufficient adaptability constrained by the required service function and a credible recovery route. Only that conditional design logic can transform palm-based vitrimer development from an attractive material demonstration into an engineering platform [34,38,40,53].

Conclusion and Future Directions

Epoxidized palm oil provides a promising renewable precursor for dynamic thermosetting polymer networks, but its long-term value does not follow automatically from palm origin, epoxidation or a visually successful repair demonstration. The critical synthesis identifies six connected determinants of performance: precursor functionality and stoichiometric control, accessibility and kinetics of dynamic exchange, reinforcement-driven changes in interphase mobility, mechanism-specific healing and reprocessing, service-conditioned ageing, and verified recovery of useful material value. Direct EPO experiments suggest that intermediate nanofibrillated-cellulose and activated-carbon loading can balance reinforcement with strain recovery in the tested composites. Their significance is strongest when the reported outcome is described precisely and not extrapolated to universal structural strength retention or chemical recyclability.

The proposed MASIC framework reframes vitrimer development as the simultaneous management of Molecular Adaptability, Structural Integrity and Circularity within an application-defined temperature, time and environmental window. The framework implies that future studies should report not only relaxation and initial tensile data but also damaged-versus-repaired strength, cycle-by-cycle property retention, creep under service loads, environmental exposure, processing energy, and the quality of material recovery. Molecular reversibility is a mechanism, not a

guarantee of product reversibility; the latter depends on geometry, interfaces, ageing and the industrial system in which repair or recycling actually occurs.

The strongest near-term opportunities are application-specific repairable coatings, controllably detachable adhesives and selected noncritical composite components, provided that their functional acceptance criteria can be met. More demanding uses such as sustained-load joints, high-performance structural composites and electronic encapsulation need independent durability and safety qualification. Research priorities include statistically controlled EPO formulations, chemically justified exchange measurements, functionalized residue-based fillers, multi-cycle mechanical and environmental testing, and transparent comparative life-cycle assessments. Only through this integrated approach can EPO vitrimers move beyond a narrow biodegradability narrative toward durable, repairable and demonstrably circular engineering polymers.

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