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From Palm Oleochemicals to Industrially Durable Non-Isocyanate Polyurethanes: Molecular Design, CO_2 Carbonation, Interfacial Performance and Circular Systems

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Abstract

Non-isocyanate polyurethanes (NIPUs) made by cyclic-carbonate aminolysis promise a route toward hydroxyurethane networks without conventional isocyanate precursors. Palm oleochemicals provide accessible triglyceride, fatty-acid and potentially lignocellulosic feedstocks, yet chemical renewability does not establish industrial durability or environmental superiority. This critical qualitative literature review synthesises journal evidence published in 2020-2026 across feedstock engineering, epoxidation and carbon dioxide carbonation, network formation, interfacial behaviour, foams and protective materials, reprocessing, and life-cycle assessment. It introduces a Feedstock-Carbonation-Network-Performance (FCNP) framework that connects feedstock functionality and batch consistency with carbonate conversion, cure kinetics, molecular topology, practical service-life requirements, and end-of-life options. The evidence supports chemical feasibility and several compelling analogies from soybean, linseed, lignin and hybrid polyhydroxyurethane systems, while revealing limited palm-specific qualification under realistic industrial exposure. Hydroxyl-rich networks can promote adhesion but may exacerbate water uptake; increased crosslink density can improve chemical resistance while impairing reprocessability. Carbon dioxide incorporation is a chemical transformation, not inherently permanent sequestration or a negative-carbon manufacturing route. The review proposes application-specific qualification gates, including comparative curing, wet adhesion, hydrothermal and ultraviolet ageing, repeatable pilot-scale processing, and functional-unit life-cycle and techno-economic evaluation. Palm-derived NIPUs are positioned as promising conditional candidates for selected coatings, adhesives, flexible systems and foams rather than proven general replacements for conventional polyurethanes.

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Introduction

Technological Importance and Sustainability Problem

Polyurethane is less a single material than a family of engineered polymer architectures whose functions range from soft cushioning to structural bonding, insulating foams, corrosion-control surfaces and mechanically demanding elastomers. Its industrial success reflects the tunability of polymer segments, functional-group density, phase distribution and curing pathways. The familiar route from diisocyanates and polyols is versatile and mature, but hazardous isocyanate exposure, precursor production, energy consumption and end-of-life challenges motivate a careful search for alternatives. The relevant research question is not whether a polymer can be synthesized without isocyanate, but whether an alternative can deliver comparable properties at the required production rate, service lifetime and cost under a demonstrably preferable environmental inventory [1-4].

The term non-isocyanate polyurethane encompasses chemically distinct routes, and indiscriminate treatment of them as one technology obstructs valid comparisons. The most widely investigated route for bio-derived raw materials couples cyclic carbonates with primary or secondary amines, generating urethane linkages and pendant hydroxyl groups. These products are often termed polyhydroxyurethanes, or PHUs. Avoiding free isocyanate in the polymer-forming step can remove a category of occupational exposure, but it does not eliminate risks connected with oxidants, amines, catalysts, solvents, volatile by-products or industrial heat. A responsible assessment therefore uses a process-wide inventory and distinguishes a change in hazardous substance profile from the stronger claim of inherently benign chemistry [1,3,5,6].

Synthetic feasibility has advanced rapidly: catalysed epoxy-carbon dioxide cycloaddition, novel cyclic-carbonate functionality, higher-molecular-weight hydroxyurethane synthesis, foam generation and adaptable network design offer a much wider processing repertoire than early proof-of-concept reactions. Nevertheless, improved tensile strength in a specimen or high carbonate conversion in a flask need not imply successful coating deposition, room-temperature curing, long-term wet adhesion or foam dimensional stability. These requirements are emergent properties of the full formulation and process, not isolated molecular descriptors. An industrially useful review must interrogate the transitions from monomer to network, from network to interface, and from fresh properties to aged service performance [5,7-10].

The Palm-Oil Opportunity and its Limits

Palm oil offers a broad oleochemical platform including triglyceride fractions, refined olein, fatty-acid methyl esters, fatty-acid derivatives, epoxidized intermediates and polyol products. Differences in unsaturation and chain composition affect the number and distribution of reactive sites available for epoxidation and subsequent carbonate formation. Those distinctions are technologically consequential. A feedstock richer in saturated fatty-acid chains may contribute flexible hydrophobic segments yet offer fewer intrinsic epoxidizable double bonds; a more unsaturated fraction may allow greater carbonate functionality but change oxidation stability, viscosity and resulting crosslink topology. Consequently, the label palm-based is insufficient to specify a NIPU precursor without analytical characterization of the actual fraction and its chemical transformations [1,11-13].

A small but strategically important body of directly relevant work confirms that palm-derived structures are not merely speculative sources for alternative polymer families. Research on palm-olein-derived non-isocyanate polyurethane-acrylate demonstrates the possibility of integrating palm chemistry with responsive or hybrid thermoplastic formulations. Additional research on oil-palm empty fruit bunch biomass examines lignin-containing bio-polyol approaches, illustrating a broader palm value-chain opportunity distinct from triglyceride carbonation. However, the existence of these routes does not mean they share the exact five-membered cyclic-carbonate

aminolysis pathway, nor that laboratory outcomes can be generalized across palm olein, stearin and mixed refinery streams. Explicit chemical-route classification is necessary before performance claims are transferred [11,12,14].

Feedstock origin also introduces environmental and commercial constraints independent of polymer chemistry. Palm fractions already participate in food and oleochemical markets, and diverting a chemically attractive stream to polymer manufacturing has opportunity costs. Waste or by-product claims require proof of the stream classification, recovery requirements and displaced uses; use of lignocellulosic residues may reduce direct food competition but can increase pretreatment complexity. Upstream land-use change, cultivation practices and refinery energy intensity can dominate an otherwise favorable laboratory carbon balance. Therefore, palm traceability, actual fractions, coproduct allocation, and supplier variability must be treated as design inputs rather than relegated to post-synthesis sustainability commentary [3,12,15,16].

The available palm-olein experiment is particularly informative because Lam et al [14]. report epoxidation followed by carbonation of epoxidized palm olein and subsequent non-isocyanate functionalization toward polyurethane-acrylate chemistry. In their reported route, carbonation was performed under relatively mild pressure, but the resulting material was investigated as a responsive thermoplastic modifier rather than as a qualified corrosion-resistant coating. Accordingly, this paper offers a direct chemistry precedent while leaving crucial questions about long-term wet adhesion, catalyst residues, and large-area coating production unresolved. Distinguishing a demonstrated precursor reaction from a demonstrated industrial end use is necessary to avoid overstating the palm-specific evidence [1,14].

Research Gap, Questions and Contribution

The central gap lies between demonstrated molecular synthesis and industrial qualification. Reports frequently establish functional-group formation with spectroscopy and characterize thermal or mechanical properties soon after curing. Fewer connect quantified palm feedstock variation to carbonate equivalent weight, gel-time predictability, coating application windows, wet interface retention, maintenance intervals or end-of-life recovery. The present article asks how palm oleochemicals should be selected; which carbonation and curing choices are technically credible; how interface and durability trade-offs arise; when carbon dioxide use offers net environmental gains; and what evidence thresholds define commercially meaningful performance. These questions are answered by a thematic critical synthesis rather than by pooled numerical effect sizes [2,5,15,17,18].

The contribution is a Feedstock-Carbonation-Network-Performance, or FCNP, framework. Its purpose is analytical rather than decorative: it requires every apparent performance advantage to be traced backward to molecular functionality and processing, while every environmental claim must be traced forward to service life and disposal. A network with excellent initial adhesion but premature wet failure may be environmentally worse per protected service-year than a less bio-based competitor with a longer lifetime. Conversely, a moderately performing palm-based coating might be valuable where moderate temperatures, repairable surfaces and low-hazard application provide an actual market niche. This application-conditioned interpretation avoids both premature dismissal of emerging chemistry and promotional assumptions that renewable monomers ensure superior products [2,15,19,20].

Literature Review: Chemical and Conceptual Foundations

Functional-Group Chemistry of Vegetable-Oil Precursors

Triglycerides contain three fatty-acid ester chains, but the relevant polymerization functionality is not fixed at three. Double bonds may occur zero, one or more times in individual acyl chains, producing a distribution of molecular species within each commercial oil fraction. Epoxidation adds an oxirane at accessible unsaturation sites, while side reactions can open epoxy rings and change hydroxyl content. Carbonation then incorporates carbon dioxide across an epoxide to form a cyclic carbonate; the number of carbonate groups per molecule helps determine whether aminolysis produces predominantly linear chains, branched architectures or network gels. Average functionality is useful for formulation calculations, but molecular distributions and conversion heterogeneity can govern real gel behavior [1,11,21-23].

In the archetypal five-membered cyclic-carbonate reaction, an amine attacks the carbonate carbon and ring opening generates a urethane group alongside a new hydroxyl group. This is a practical distinction from conventional urethane formation: each incorporated carbonate can introduce local polarity that affects hydrogen bonding, interphase wetting and water sorption. Chemoselectivity, steric accessibility and the ring structure govern kinetics; oligomer formation and viscosity feedback can further slow conversion near gelation. Polymers described collectively as NIPU may therefore differ considerably in chain architecture and residual functional groups even when they start from nominally similar renewable oils. Structural characterization should pair conversion data with molecular-weight or gel-fraction and functional-network analyses [1,24-26].

The catalyst problem consists of more than maximizing the percentage of cyclic-carbonate formation. Catalytic systems must balance carbon dioxide pressure, reaction temperature, catalyst loading, epoxide scope, separation and recycling, product color and residual catalyst compatibility with downstream aminolysis. Quaternary halide salts, heterogeneous catalysts, deep eutectic mixtures and alternative halide-free approaches have each been studied in broader epoxide chemistry. Yet results for small epoxides cannot be inserted directly into viscous, multifunctional triglycerides without addressing mass transfer, diffusion, epoxide accessibility and changing fluid rheology. The optimum catalyst in an academic reaction can be unsuitable for coatings when its removal is expensive or residual ions compromise corrosion resistance [21-23,27-30].

Measured precursor descriptors are especially important because vegetable-oil derivatives bring molecular heterogeneity that is absent in many petrochemical benchmark monomers. Formulators should report iodine value or fatty-acid distribution before modification, measured epoxide equivalent weight, carbonate equivalent weight, residual unsaturation, hydroxyl number, acid value and thermal stability. Composition-based predictions can guide the first experiments, but chemical analysis must confirm every synthesis stage. Comparisons should specify whether carbonation targets a purified epoxidized triglyceride, a fatty-acid monoester, or a mixed ester stream; the different chain lengths, polarities and numbers of reactive sites may shift everything from mixing energy to network strength [5,22,23,26,31].

Network Architecture and Hydroxyurethane Interphases

Polyhydroxyurethane properties arise from coupled chemical and physical networks. Urethane carbonyls and hydroxyl groups form hydrogen-bonded associations, which may raise cohesive strength while introducing temperature- and humidity-dependent relaxations. A greater molecular functionality can increase gel fraction and stiffness, but excessive conversion to a highly crosslinked state can reduce toughness or produce cure stress. Diamine backbone flexibility, aromaticity, molecular weight and functionality further regulate glass transition, phase mobility and potential crystallinity. Directly comparing tensile strengths measured at different humidity, specimen thickness or cure histories is accordingly unreliable. A meaningful structure-property analysis specifies the monomer architecture and the test environment together [18,25,32,33].

The interface is chemically and mechanically distinct from the network interior. A coating can demonstrate strong dry adhesion because pendant hydroxyls hydrogen-bond with oxides, cellulose or other polar substrate groups. The same polarity can facilitate water uptake, weaken interfacial hydrogen bonds, plasticize the nearby polymer and assist the transport of corrosive species to a metallic surface. Thus, the valuable hydroxyl functionality of PHUs creates a conditional, not universal, adhesion benefit. Substrate preparation, contamination, surface energy, oxide chemistry and wetting during the application window interact with polymer chemistry to determine how much of the theoretical binding potential becomes durable adhesion [2,19,34-36].

One route to overcome network compromises is hybrid chemistry. Epoxy-PHU combinations, thiol-epoxy accelerated systems, crosslinkable acrylics, nanocellulose additions and selected inorganic fillers may modify cure rate, modulus, transport paths and surface interactions. Hybridization, however, changes the meaning of the isocyanate-free claim and the renewable-content calculation: the NIPU fraction may be only one part of a multi-component formulation. Such approaches should be evaluated on their actual

component inventories, processing hazards and end-use advantage rather than promoted as chemically pure alternatives. Coatings researchers have already illustrated that curing acceleration and particle-containing formulations can deliver benefits, but the contribution of each component requires controlled formulation comparisons [14,19,37-39].

An experimentally informative complement to this mechanistic account is supplied by Yuk et al. [40], who prepared vegetable-oil-derived polyhydroxyurethanes with controlled viscoelastic adhesion and assessed the role of pendant hydroxyl groups through chemical blocking and modeling. Their results support hydrogen bonding as an important contributor to cohesion and pressure-sensitive adhesion, but they do not remove the need to characterize water uptake and long-duration assembly performance. The lesson for palm-derived networks is to measure polar-site contributions independently of backbone mobility and molecular weight, since an apparent initial adhesion gain can arise from several coupled variables [40,41].

Reprocessability introduces another apparent tension. Permanent thermosetting networks often provide solvent resistance and dimensional retention but resist melt reshaping. Dynamic covalent chemistries, exchangeable linkages and carefully designed polyhydroxyurethane associations can allow materials to be reshaped or repaired under controlled conditions. However, recovery of a network after heating is not proof of recovery of adhesion, corrosion performance or foam-cell architecture. Dynamic rearrangement may also change creep resistance under sustained load or elevated service temperatures. The relevant design objective is therefore not maximum reprocessing speed but useful recovery without loss of properties that govern the target product's service life [20,42-45].

Carbon Dioxide Utilization and Lifecycle Interpretation

Using carbon dioxide as a reactant changes the carbon inventory of a chemical process, but the term carbon capture must be used with precision. Stoichiometric incorporation into a cyclic carbonate establishes that carbon from a feed gas appears in a chemical structure; it does not demonstrate permanent geological storage, negative process emissions or a climate-neutral polymer. Manufacturing may require heat, pressure, purified carbon dioxide, catalysts, oxidants, feedstock processing and transport. The carbon held in a product may be released later through incineration, degradation or chemical treatment. A scientifically defensible comparison separates the amount of CO_2 chemically incorporated from avoided cradle-to-grave greenhouse-gas emissions relative to a functionally equivalent incumbent [4,15,16,46].

Functional equivalence is crucial for environmental accounting. A kilogram-to-kilogram comparison can be misleading when formulations have different density, coating coverage, cure loss, maintenance interval or lifetime. A protective-film analysis should specify surface area, coating thickness, substrate and corrosion category, service duration and replacement schedule. For adhesives, bond geometry and maintained mechanical load should be normalized. For thermal-insulation foams, thermal resistance over the use period is more meaningful than equal polymer mass. Life-cycle and techno-economic studies of biomass-derived hydroxyurethanes emphasize that synthesis route, solvent demand, recovery and recycling assumptions can materially shift the apparent advantage [3,15,47,48].

A circularity claim likewise requires a credible pathway. The words recyclable, reprocessable, degradable and renewable refer to different properties: thermomechanical reshaping, chemical depolymerization, biological disintegration and biomass-derived origin need not coexist. Recoverable morphology and mechanical strength following multiple cycles are measurable outcomes, while the scale-up of collection, sorting and contaminant removal may present larger bottlenecks than laboratory chemistry. For a palm-derived NIPU, the complete question is whether an industrial article can be manufactured, used, repaired or reprocessed, and safely recovered with lower cumulative material and energy demand than the incumbent, over an explicit system boundary and exposure schedule [7,42-44,48].

Method: Critical Qualitative Literature Review

Source Selection and Narrative Strategy

This article uses a critical qualitative literature review, not a systematic literature review, PRISMA-based synthesis or quantitative meta-analysis. The objective is to interpret mechanistic explanations, identify contradictions, compare material families and construct a model that connects chemical preparation with credible

industrial applications. The literature window is 2020 through October 2026, with particular attention to peer-reviewed materials chemistry, coatings, adhesion, catalysis, polymer engineering, renewable feedstocks and life-cycle studies. Core concepts guiding source discovery include epoxidized vegetable oils, cyclic-carbonate conversion, carbon dioxide cycloaddition, polyhydroxyurethanes, non-isocyanate polyurethane foams, protective coatings, adhesives, reprocessable thermosets and palm oleochemicals. Review articles orient the conceptual landscape; primary studies supply the most specific property and process claims [1,2,3,16,47].

Papers were selected purposively for topical relevance, mechanistic specificity and the ability to test competing interpretations, with secondary citation tracing used to locate enabling or contrasting studies. The emphasis is on recent journal evidence rather than patent promotion, distributor datasheets or unsupported performance claims. Records are interpreted in four evidentiary classes: direct palm-oil or palm-residue reports; vegetable-oil NIPUs from non-palm feedstocks; broader hydroxyurethane, cyclic-carbonate or hybrid polymer studies; and cross-cutting carbon-accounting and economic research. This hierarchy prevents apparently persuasive properties measured in linseed- or soybean-based networks from being asserted as established palm-oil outcomes. Where reports use different temperature, humidity, cure state or specimen design, we interpret direction and mechanism rather than calculating a pooled material-property ranking [5,14,15,32,49].

Recent application-specific studies were additionally checked against publisher metadata before inclusion in the synthesis. Particular attention was given to experiments that report actual corrosion testing, environmental conditioning or direct perturbations of the hydroxyurethane hydrogen-bond network, because they constrain broader mechanistic interpretations. Publications were not assigned synthetic quality scores, and bibliographic coverage is not claimed to be exhaustive; thematic coverage and evidentiary relevance, rather than PRISMA selection frequencies, define the review [40,41,50].

Thematic Coding and Critical Appraisal

An interpretive coding matrix was organized around the four FCNP nodes. Feedstock codes cover origin, fraction identity, unsaturation, functional-group distribution and traceability; carbonation codes include catalyst, conversion, temperature, pressure, solvents and processing losses. Network codes identify amine type, carbonate functionality, mixing and curing conditions, gelation, glass transition, dynamic bonds and hybrid phases. Performance codes record adhesion, thermal and chemical resistance, water sensitivity, fatigue, protection mechanism, reprocessing and environmental functional unit. Studies relevant to more than one node are cross-linked so that a proposed improvement can be assessed for downstream compromises. For example, elevated crosslink density may improve solvent resistance while increasing brittle fracture or compromising repairability [18,21,35,42,43].

The analysis gives particular weight to negative space in published data. A study reporting strong dry lap shear but no immersed lap shear answers a narrower question than one demonstrating wet-substrate durability. A carbonate synthesis study without catalyst recovery does not establish pilot economics. A recyclable film study that omits aged electrical or corrosion performance cannot verify that recycling retains its protective function. Such omissions are not proof of poor materials, but they constrain how strongly a reviewer can recommend industrial deployment. This interpretive posture intentionally avoids fabricated pass percentages, invented comparative performance values and misleading statistical precision. The framework is hypothesis-generating and designed to guide practical experiments rather than to substitute for experimental validation [2,5,15,19,36].

Review Boundaries and Limitations

The scope centers on isocyanate-free polyhydroxyurethane production from cyclic carbonate and amine precursors, while acknowledging alternative hybrid or related NIPU pathways where they clarify application performance. It does not classify every carbonate-containing polymer as PHU, or every palm-derived polyol as a validated precursor for cyclic-carbonate aminolysis. The recent literature is heterogeneous in raw materials, chemical routes and reporting standards; studies often optimize synthetic conversions rather than directly comparable service tests. The corpus therefore supports a structured set of conditional conclusions but cannot support a universal

claim of superiority over petrochemical polyurethane. Future experimental benchmarking and independent, application-specific life-cycle inventory remain necessary to test the resulting hypotheses [1,3,13,31].

Results: Thematic Synthesis of the Literature

Feedstock Architecture and the Scope of Palm Evidence

The first finding is that vegetable-oil NIPU properties depend on functionality distributions more than feedstock labels. Research on linseed-oil-based thermosets demonstrates that multifunctional triglyceride cyclic carbonates can support mechanically robust networks, while soybean-based systems illustrate how oil architecture, additional carbonate components and formulation change curing and mechanical behavior. These findings identify design levers that plausibly apply to palm precursors: reactive-site availability, backbone flexibility, unsaturation conversion and the balance between mono- and multifunctional constituents. They do not establish equal performance for palm oil, because commercial palm fractions generally exhibit different distributions of fatty-acid unsaturation and thus different likely carbonate functionality at equivalent conversion conditions [31-33,51].

Second, palm-derived research should be divided by chemical route. The palm-olein polyurethane-acrylate literature offers evidence that functional palm precursors can participate in novel non-isocyanate polymer formulations. Oil-palm empty fruit bunch biomass can also yield aromatic lignin-rich derivatives and biopolyol components, creating a separate family of potential hybrid hard-segment modifiers. Yet both routes require careful attention to whether the final network forms through carbonate-amine addition, acrylate photopolymerization, epoxy chemistry or another mechanism. A manuscript that merges these outcomes without distinguishing reactive pathways risks an inflated claim of evidence density. Chemically explicit route diagrams and functional-group analyses would substantially strengthen this young palm-specific literature [11-14].

Third, the desirable identity of a palm raw material depends on the product. A relatively flexible and less densely functionalized precursor may be advantageous in conformable films, sealants or flexible elastomers where low-temperature deformability matters. A demanding solvent-resistant coating could instead require higher reactive-site density, a multifunctional aromatic co-monomer or a hybrid cure. Using a highly modified fraction simply to increase the renewable-content percentage can therefore be counterproductive if extensive catalyst loading, purification, co-monomer consumption or extra cure energy offsets the molecular advantage. The FCNP approach consequently begins with performance specifications and selects fractions backward, rather than assuming a single palm-olein chemistry should cover every application [5,18,19,52].

The evidence also shows value in looking beyond edible triglycerides. Lignin-based NIPUs and lignin-epoxy hybrids offer alternative rigidity, aromatic content and chemical diversity, and studies of lignocellulosic fractionation suggest possible uses for residues from agro-industrial processing. When palm empty fruit bunches are considered, their lignin chemistry cannot be treated as a molecular substitute for epoxidized palm oil; purity, molecular-weight distribution and functional-group quantification may create new variability. An attractive research strategy is therefore to distinguish palm lipid-derived flexible segments from lignin-derived rigid or functional modifiers and test their effects separately before combining them into multifunctional networks [6,12,37,53,54].

Carbonation Efficiency Versus Process Practicality

Carbonation is a compelling use of carbon dioxide because cyclic carbonates are directly relevant to later amine reaction. Studies of homogeneous, heterogeneous and alternative catalytic systems show that carbon dioxide and epoxy groups can be coupled across diverse substrates. However, conversion efficiency in small-molecule chemistry cannot be assumed for vegetable-oil mixtures. Viscosity increases, diffusion paths broaden and sterically buried sites become harder to access as the molecular feedstock becomes more multifunctional. Consequently, an industrially meaningful carbonation report should present more than a final conversion percentage: rate data, viscosity trajectory, catalyst removal, recoverable solvent, pressure envelope, energy input and chemical-quality variance across batches matter to downstream processing [21-23,27,30].

A second issue is the relation between carbonate equivalent weight and the network design space. Under-

carbonated intermediates may leave less reactive molecules that act as plasticizers or non-functional diluents, causing poor gelation or extractables. Conversely, forcing higher carbonation conversion by prolonged heating can increase energy use and create unwanted changes to acid value, color or molecular integrity. Careful stoichiometry between carbonate groups and amine functionalities is particularly important because nominal mass-based ratios can mask the uncertainty of mixed oil precursors. The key process target is not necessarily maximum conversion at any cost, but a reproducible carbonate equivalent weight and impurity profile sufficient to deliver specified cure and application properties [5,22,26,31].

Alternative catalyst studies offer valuable research directions. Deep eutectic solvents are attractive as potentially tunable reaction media, while heterogeneous catalysts are investigated for separation and reuse, and halide-free catalytic pathways can reduce particular impurity concerns. None is automatically sustainable: catalyst synthesis, replacement frequency, solvent regeneration and downstream compatibility need assessment. For anticorrosion coatings, trace halides or ionic residues may be a disqualifying outcome even where the chemistry is highly effective in the reactor. A rational screening study should examine carbon dioxide conversion and final coating salt-spray or electrochemical durability together, revealing whether catalyst optimization in the first chemical unit operation undermines performance in the last [21-29,30].

Low-temperature, low-pressure and solvent-free manufacturing remain important goals, but their feasibility depends on the entire synthesis-and-cure chain. Atmospheric-pressure cycloaddition to a model epoxide does not establish ambient-temperature curing of a multifunctional palm carbonate with an industrially acceptable pot life. Likewise, solvent-free formulation may increase viscosity, impede mixing or reduce wetting of a porous substrate. Specific reporting should distinguish carbonation temperature from subsequent aminolysis cure temperature, and pot life from time-to-handle and ultimate network-property development. Commercial readiness demands compatible process windows rather than optimizing each laboratory reaction independently of the rest of the manufacturing sequence [5,9,10,28].

Polymerization Kinetics, Cure Control and Network Tuning

The hydroxyurethane formation step is frequently constrained by slower aminolysis kinetics than familiar isocyanate-polyol reactions. Amine nucleophilicity, carbonate ring structure, steric environment, functional-group concentration and processing temperature collectively shape reaction rates. Studies on sequence control, bis-cyclic-carbonate monomers and new high-molecular-weight PHU preparation illustrate that deliberate monomer and amine architecture can address these limitations. A more reactive amine, however, can reduce useful mixing time, whereas a high-viscosity prepolymer may create coating defects before cure. Cure design therefore must distinguish molecular reaction speed from the operational process window required for mixing, application, leveling and adhesion to the chosen substrate [8,24,25].

Hybrid reactions have emerged as one practical way to decouple application time from ultimate network strength. Thiol-epoxy acceleration, epoxy-PHU combinations, acrylic functionality and selected multifunctional co-reactants can build additional networks or induce faster mechanical setting. Comparative adhesive and coating research indicates that such strategies may be competitive where pure cyclic-carbonate aminolysis is too slow. The trade-off is that accelerated curing can produce shrinkage, incomplete wetting or heterogeneous crosslink domains. A formulation study should accordingly report both early-time handling and final properties after a defined cure, using an unchanged substrate and thickness to establish whether the hybrid route gives a true application advantage [19,37-39].

High glass-transition and high-modulus formulations solve only some industrial problems. Reactive extrusion and batch-foaming studies suggest that process-intensified chemistry and stronger networks are possible, while aromatic and lignin-derived monomers can modify rigidity. Nevertheless, a high-Tg foam or thermoset may not provide the flexibility required of a thin coating on a thermally expanding steel or polymer substrate. Raising Tg also changes stress-relaxation behavior and can make low-temperature impact damage more likely. Industrial performance thus demands target ranges, not unidirectional maximization, of modulus, elongation, Tg, gel fraction, solvent resistance and time-

dependent creep [10,32,52,53].

Adhesion, Coatings and Durability: The Hydroxyurethane Paradox

An important thematic result is the growing evidence base for hydroxyurethane adhesives and coatings, including waterborne hybrids, bio-based textile coatings and purpose-built high-strength adhesive systems. These studies demonstrate useful design pathways but cover different adherends, surfaces, test geometries and environmental exposures. Dry lap-shear strength or peel adhesion after a short cure cannot establish resistance to prolonged humidity, salt immersion, ultraviolet radiation or thermal cycling. For protective surfaces, failure may occur through interfacial debonding long before a bulk tensile specimen loses strength. Reports should therefore document substrate composition and pretreatment, coating thickness, cure schedule, conditioning and observed cohesive-versus-adhesive failure modes [2,19,20,34-36].

The pendant hydroxyl produced by cyclic-carbonate aminolysis is a molecular advantage with a countervailing liability. It can foster favorable hydrogen-bonding interactions with polar substrates and increase cohesion in dry conditions. Yet water competes for hydrogen-bond sites and may permeate the polymer, increasing local free volume or plasticization and changing stress transfer across the interface. Higher hydroxyl content does not automatically mean greater moisture sensitivity in every formulation; hydrophobic segments, domain segregation and fillers can moderate water transport. Nevertheless, claims of adhesion improvement require test pairs before and after conditioning, preferably at more than one temperature and exposure duration, to quantify the balance [18,34-36].

Recent experimental evidence sharpens the distinction between promising surface chemistry and proven wet durability[50]. demonstrated corrosion-resistant coatings using crosslinked succinic-acid-derived NIPU compositions, showing that network design can address water-resistance concerns without implying equivalence for every feedstock[55]. reported that the level of tetraethyl orthosilicate in NIPU-polysiloxane hybrids altered corrosion resistance non-monotonically, with excessive loading associated with phase separation. Taken together, these studies show why filler content, microstructure, and adhesion after electrolyte exposure must be investigated jointly rather than optimized as independent variables [50,55].

For metallic corrosion protection, the testing logic must extend beyond adhesion. A competent coating is a transport barrier against oxygen, water, chloride and other reactive species while surviving mechanical damage and substrate movement. Electrochemical impedance can detect evolving barrier integrity; adhesion pull-off after exposure can indicate interfacial deterioration; salt-fog or cyclic corrosion tests challenge specific failure pathways. None of these alone captures all industrial environments. Studies of anti-corrosion and anti-fouling NIPU formulations indicate feasibility, yet a direct comparison with commercial polyurethanes or epoxies should control dry-film thickness, surface preparation and cure state. Only then can researchers distinguish chemical superiority from an advantageous but confounded test design [17,19,39,56].

Wet-bond performance is also composition dependent. Huang et al [57] investigated hyperbranched-siloxane modification of a bio-based thermosetting NIPU adhesive for wood-panel bonding, directly addressing the vulnerability of wet adhesion. Because wood bonding and metallic corrosion protection impose different interfaces and ageing modes, the result supports a hydrophobic-network design hypothesis rather than a transferable protection rating. Systematic paired measurements of dry and conditioned strengths remain necessary to establish the improvement attributable to a palm-specific formulation [57,58].

Chemical and thermal durability present another set of interacting mechanisms. Ester-rich vegetable-oil segments may introduce hydrolytic vulnerabilities under particular aqueous conditions, whereas dense or hydrophobic networks may slow access of water and reagents to susceptible groups. Elevated temperature can accelerate diffusion and molecular relaxation, and ultraviolet light can alter surface chemistry, color, chalking or crack development. A thermogravimetric decomposition onset is not an indicator of multi-year weathering resistance. The informative design is a multi-stressor programme with both accelerated and naturally exposed specimens, chemical identification of degradation products, and a clear distinction between

polymer bulk retention and the more commercially consequential integrity of the coated or bonded assembly [1,17,18,34].

Foams, Elastomers, Composite Reinforcement and Reprocessing

Foaming adds a formidable process constraint because gas formation, viscosity increase, gelation and cell stabilization must occur in compatible time windows. Traditional isocyanate-based polyurethane formulations have refined such interactions through decades of industrial practice. NIPU foams made using carbon dioxide or other suitable blowing strategies demonstrate growing feasibility, and room-temperature formulations using cascade reactions and controlled exotherms illustrate approaches to accelerate structure development. However, foam density, cell openness, compressive behavior and dimensional stability depend on the actual processing trajectory. An attractive laboratory specimen produced in a small mold does not establish continuous production, thermal insulation consistency, fire performance or ageing resistance under service conditions [9,10,46-48].

A major development is the demonstration of reprocessable composite NIPU foams from renewable cyclic-carbonate systems. This 2026 work is particularly significant because it moves circularity from molecular theory toward materials that can be physically reprocessed. Its feedstock basis should, however, be kept separate from palm-specific evidence: soybean- or other oil-derived carbonate chemistry has different composition and may generate a different distribution of network functionality. Transferable lessons include the need to coordinate cyclic-carbonate architecture, dynamic or recoverable networks and foam-processing windows. Non-transferable outcomes include any precise mechanical or processing performance measured for a particular non-palm formulation until a corresponding palm precursor is synthesized and tested under comparable conditions [7,42,47,49].

For elastomers and flexible functional systems, controlled segment mobility is often more useful than maximum crosslink density. Vegetable-oil-derived NIPU chemistry has been explored in flexible sensors, recyclable coatings and self-healing systems that seek to retain functional behavior over deformation and temperature variation. Such work suggests opportunities for palm-derived sealants, conformable layers and flexible molded products. Yet repeated strain can expose interphase delamination, slow physical relaxation, creep and changes in electrical or barrier function that do not appear in one-time tensile tests. Recovery after a cut or heating step should be tested in an assembly context, and the energy and downtime required for healing should be included in the proposed benefit [14,33,42,45,56].

Natural-fiber composites offer another perspective because PHU interfacial hydroxyls can potentially interact with cellulose-rich reinforcements. Composite studies report encouraging mechanical and circular features, but they also demonstrate why substrate moisture and heterogeneous fiber surfaces deserve rigorous conditioning. A fiber-polymer interface that develops strong bonding in dry specimens may admit water along capillary pathways or weaken under cyclic humidity. For a palm supply-chain concept, empty-fruit-bunch fibers and palm-derived NIPU binders could form a compelling circular design hypothesis, yet the two feedstocks' processing variability and interfacial compatibility must be experimentally characterized. It would be inappropriate to infer a proven fiber-composite formulation from separate achievements in cellulose composites and palm oleochemical synthesis [12,37,44].

Discussion and Critical Analysis

FCNP as a Conditional Causal Framework

The synthesis of recent research indicates that palm-derived NIPUs should be judged through causal links rather than by isolated laboratory milestones. The FCNP framework treats feedstock identity and batch consistency as upstream determinants of epoxide and carbonate functionality; carbonate concentration and processing conditions then shape network formation, while network mobility and interfacial chemistry govern product performance. These relationships are not linear guarantees. Greater functionality can raise cohesive strength and still worsen brittleness; high carbonate conversion can simplify stoichiometry but demand excess heat; stronger dry interfacial interactions can coincide with moisture-driven damage. A rigorous design framework must retain these conflicts and identify the application conditions under which a particular formulation is attractive [1,5,18,21,30].

Figure 1 illustrates the directional structure of the

proposed FCNP framework and the reverse movement of design requirements from service performance back to raw material selection. The diagram is a conceptual synthesis, not an experimentally estimated predictive model, and its arrows indicate testable relationships rather than proven causal coefficients [5,15,18,19].

It also shows how application failure should trigger earlier changes to feedstock characterization or reaction chemistry rather than being concealed in an averaged materials score.

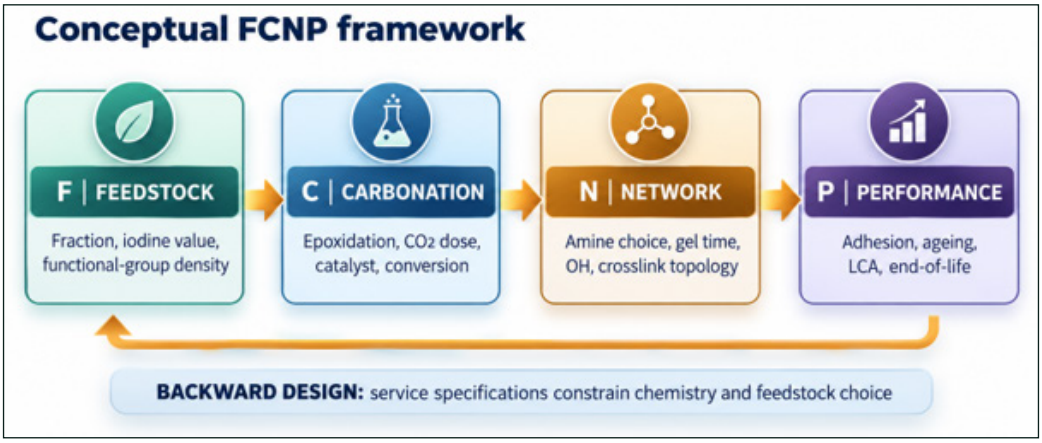


Figure 1: Feedstock-Carbonation-Network-Performance (FCNP) Framework, with Backward Design from Industrial Requirements. Original Conceptual Synthesis.

As Figure 1 emphasizes, feedstock optimization has little meaning without a target industrial function. For example, corrosion-protection requirements define acceptable wet adhesion and ionic contamination, which constrain catalyst choice, crosslink structure and eventually the precursor fraction. A flexible adhesive may prioritize peel toughness and low-temperature curing instead. The framework therefore provides a disciplined way to avoid selecting palm raw material solely because it achieves a high renewable-carbon percentage in the finished resin [5,15,18,19].

One implication is that reporting standards should follow the framework's causal structure. A chemically oriented study should measure precursor iodine or epoxy value, carbonate conversion, catalyst content and cure conditions rather than offering only spectroscopy and an unconditioned strength value. An application-oriented study should preserve this chemistry information even while adding service performance, so independent researchers can distinguish structural effects from processing artifacts. A carbon-oriented study must include the same process energy and reaction-yield data to calculate realistic material inventories. Making these elements part of one dataset enables future comparative analyses without pretending that the current field already possesses a large set of standardized performance measurements [8,15,23,26].

Interpreting CO2 Incorporation without Climate Overclaim

A favorable carbon claim requires explicit interpretation of physical carbon flow and counterfactual production. Incorporating CO_2 into a five-membered cyclic carbonate provides a useful carbon-based reagent instead of discarding the molecule as emissions, but it does not determine the electricity emissions, compression energy, oxidant footprint or disposal burden. Nor is the carbon in the final product necessarily permanently stored. A rigorous account specifies the source and treatment of CO_2, raw-material origins, reactor energy, catalyst preparation, purification losses and the destination of polymer carbon after use. Attributional and consequential life-cycle approaches may yield different results, especially when agricultural coproduct allocation and competing feedstock markets matter [4,15,16,46].

For transparent comparison, Equation (1) defines avoided greenhouse-gas emissions per identical functional unit as the reference system burden minus the evaluated NIPU system burden. Both terms must encompass the same service duration, maintenance and end-of-life boundary, with consistent treatment of energy sources

and feedstock coproducts. Positive avoided emissions therefore express a lower assessed footprint than the comparator, not an automatically negative absolute footprint [15,46].

$$E_{avoided,FU} = E_{comparator,FU} - E_{NIPU,FU} \quad (1)$$

In Equation (1), each E represents a greenhouse-gas burden expressed in kilograms of CO_2-equivalent per functional unit (FU). The reference and NIPU functional units must be defined using equivalent protected area, bond performance or insulation delivered, as applicable. The physical amount of CO_2 reacted into cyclic carbonates is reported as a separate inventory indicator rather than subtracted again from the cradle-to-grave burden, avoiding double counting. Figure 2 clarifies the relationship between the chemical event of CO_2 fixation and the larger comparative environmental decision. The conversion reaction is nested inside a system that also includes raw-material supply, catalysis, energy, service duration, maintenance and disposal or recycling [3,15,46]. The full inventory explicitly includes the comparator system so that chemically fixed carbon cannot be confused with net avoided greenhouse-gas emissions.

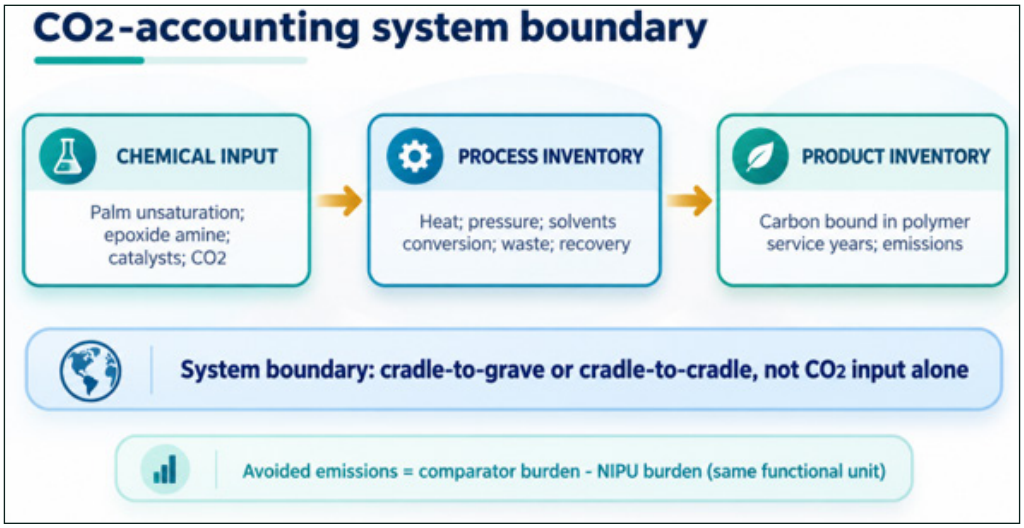


Figure 2: Carbon-Dioxide Incorporation, Life-Cycle Inventory and Functionally Equivalent Comparison Boundary. Original Conceptual Synthesis.

The upper pathway in Figure 2 must therefore be interpreted alongside the baseline product performing exactly the same function. Avoided emissions arise only where the NIPU system's cradle-to-grave burden is lower than that of the equivalent incumbent under transparent assumptions. Reporting kilograms of chemically bound CO_2 is informative but is not a sufficient metric for sustainability, particularly when an alternative material has lower application losses or a longer replacement interval [3,15,46].

These considerations also change the meaning of the word bio-based. The renewable carbon percentage depends on the accounting convention and the inclusion of diamines, catalysts, curing additives, blowing agents and inorganic fillers. If a coating is marketed as palm-derived but requires a large petrochemical co-reactant fraction to reach acceptable cure speed or corrosion resistance, the claim should state the fraction clearly. Conversely, hybrid formulations should not be rejected solely because they contain nonrenewable components; if they substantially extend service life or eliminate more hazardous inputs, they may be more favorable per application. The decisive comparison is full-system impact at equivalent functionality, not a ranking based on a single material-origin attribute [3,15,47,52].

Product-Specific Qualification: Coatings, Adhesives, Foams and Elastomers

Figure 3 summarizes this double-edged interfacial chemistry. The relevant comparison is not between a hydroxyl-containing and a hydroxyl-free ideal molecule in the abstract, but between complete formulations that exhibit potentially different wetting, hydrogen bonding, network relaxation, diffusion coefficients and

interfacial fracture behavior [19,34,35,39]. The figure also identifies material-design interventions that should be evaluated alongside changes in moisture transport and deformation under load.

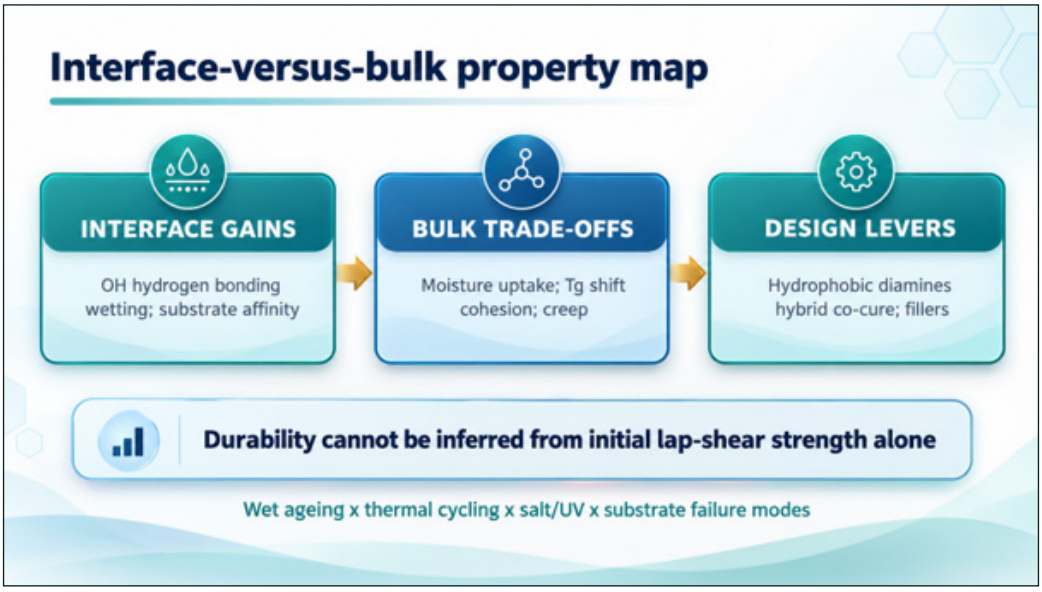


Figure 3: Hydroxyl-Mediated Interfacial Opportunities and Bulk Durability Trade-Offs. Original Conceptual Synthesis.

As Figure 3 illustrates, increasing the number of polar sites may initially improve dry adhesion while simultaneously increasing the importance of moisture uptake, temperature-dependent mobility and repeated swelling. The design levers include flexible hydrophobic segments, co-curing, controlled network density and fillers, all to be validated with wet-strength retention and barrier measurements rather than with dry adhesion alone [19,34,35,39].

For protective coatings, the most immediate qualification priority is durability of the film-substrate system. A reasonable experimental matrix measures application viscosity, pot life, cure at relevant ambient temperature and humidity, dry-film thickness, pinhole frequency and initial wetting. It then subjects matched specimens to aqueous immersion, thermal cycling, salt-related stress and relevant ultraviolet exposure, with periodic adhesion and barrier analyses. Failure modes should be recorded independently of a headline strength number: blistering, underfilm corrosion, interfacial delamination, cohesive cracking and discoloration are not interchangeable. This programme would permit palm-derived PHUs to be compared with incumbent coatings on the functional basis of protection maintained over time [17,19,34,56].

To make wet durability comparisons reproducible, Equation (2) expresses percentage adhesion retention after conditioning as the ratio of measured wet-aged to initial dry strength. The same joint configuration, cure history and statistical reporting convention must be retained for both values. Retention alone is not sufficient because a weak initial joint can exhibit a deceptively high percentage while remaining industrially unfit.

$$R_{adhesion}\,(\%) = 100 \times S_{aged} / S_{initial} \qquad (2)$$

Here, S represents the same specified adhesion or bond-strength measure on matched specimens, and the aged condition must report temperature, time and exposure chemistry. The percentage should be accompanied by absolute strength and observed adhesive or cohesive failure modes. Equation (2) is proposed as a reporting metric, not as evidence that a specific palm-derived NIPU has already passed a durability standard.

A useful response variable for coatings is the fraction of adhesion retained after a predeclared exposure schedule

rather than the maximum dry adhesion obtained immediately after curing. Modern comparative literature suggests that siloxane modification and controlled crosslinking can improve selected failure pathways, but the direction and magnitude depend on the complete resin and the test geometry. Relative retention, electrochemical resistance and visible failure modes should therefore be reported together before claims of industrial durability are made [41,50,55].

For adhesives, stiffness and initial shear strength should be balanced against peel behavior, strain-rate sensitivity, creep and wet-interface retention. More hydrogen bonding can strengthen a dry joint but also make performance depend on moisture and temperature. Standardized adherends and surface preparation would be especially valuable because improved adhesion can be confounded by differences in grit blasting, oxidation or moisture contamination. Cure temperature and fixture time determine whether the polymer is viable in a production line, regardless of excellent final thermomechanical properties. Recent studies of reusable, ultra-strong or high-adhesion hydroxyurethanes establish promising design principles, but no palm-specific universal performance equivalence can be inferred without matched joint testing [2,20,35,36,52].

A recent assessment of vegetable-oil-based polyurethane adhesives also highlights the broader opportunity to engineer renewable bonding systems, while cautioning against treating all vegetable-oil chemistries as directly comparable. In particular, hydroxyl-rich NIPUs can deliver useful interfacial interactions but should be qualified after wet exposure, not just by room-temperature dry bonding. Evidence from siloxane-modified thermosetting NIPU and vegetable-oil-based adhesive reviews indicates that formulation architecture, conditioning protocol and adherend selection must remain visible in every performance comparison [40,57,58].

For foams, qualification must capture the kinetics of foaming and crosslinking together. Relevant metrics include foam rise and tack-free times, cell-size distribution, open-cell fraction, density variation, thermal conductivity, compression set, flame response and dimensional stability after humidity-temperature conditioning. Reprocessing is an additional design objective that should be scored after the recovered foam is tested as an insulation or cushioning product, not simply after material recombination. The 2026 studies of reprocessable foams and recent developments in CO_2-blown NIPUs provide a credible comparator literature, but reproducing those properties in palm-derived systems will require measurement of carbonate equivalent weight and the effect of saturated chain content on gelation, gas entrapment and relaxation [7,9,46-49].

For flexible films and elastomers, the most practical qualification might involve low-temperature flexibility, fatigue life, crack growth, environmental stress exposure and retention of barrier or functional properties after repeated deformation. Bio-derived polysiloxane-containing NIPU sensors and elastic NIPU systems suggest multiple routes to tuned segment mobility. Yet a technology positioned as self-healing should be evaluated by the amount of recovered functional performance per repair cycle, the energy required for repair and any decline in adhesion to real substrates. An apparently attractive self-healing network may be commercially unattractive when recovery requires prolonged high-temperature treatment incompatible with installed components. Product design must therefore align polymer dynamics with realistic service and maintenance constraints [33,42,45,56].

Material Selection and Evidence-Weighted Industrial Decision Gates

The proposed translation pathway has five gates. At Gate 0, feedstock and precursor screening establishes reproducible composition and traceability. Gate 1 measures carbonate conversion, functional-group balance, cure kinetics and basic network properties. Gate 2 demonstrates pilot-relevant mixing, pot life, coating or foam processing, batch repeatability and quality control. Gate 3 subjects end-use articles to agreed multi-stressor qualification against commercial controls, including ageing and failure-mode analysis. Gate 4 assesses cradle-to-grave impacts, actual industrial cost and availability of credible collection or reprocessing pathways. Each gate must set pass criteria before testing so an unexpectedly successful isolated result cannot substitute for the more complete evidence required by the next gate [5,10,15,49].

Figure 4 translates FCNP into a staged industrial

research programme. The stage-gate structure is deliberately stricter than the usual laboratory progression from precursor synthesis to a single tensile test because industrial defects can arise during mixing, cure, application, ageing or end-of-life handling [10,15,19,48]. Each gate links a characterization result to a pre-specified acceptance criterion before the programme advances to a more costly industrial trial.

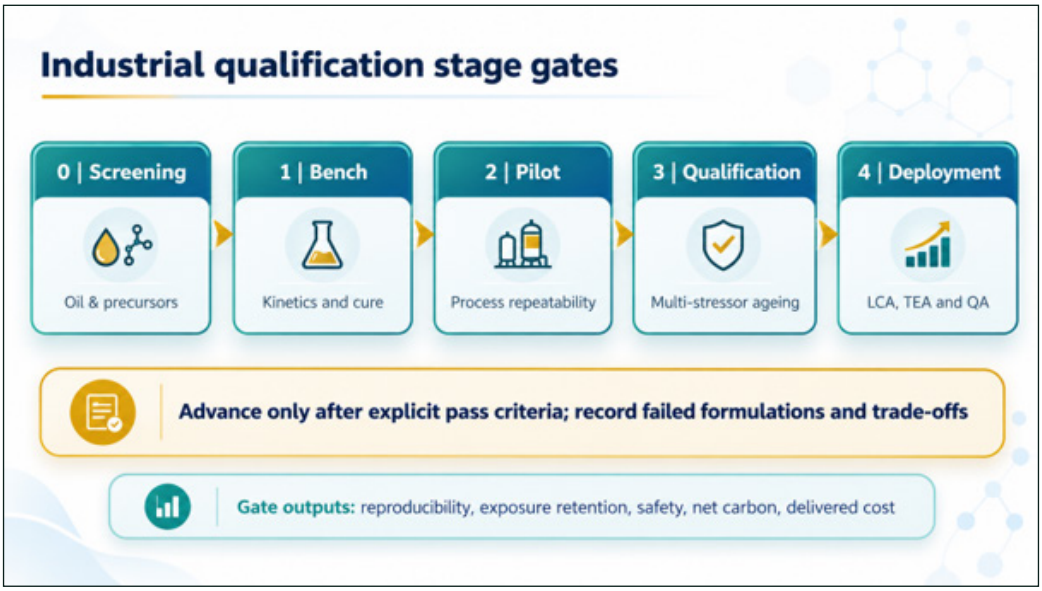


Figure 4: Five Decision Gates from Feedstock Screening to Industrial Deployment of Palm-Derived NIPUs. Original Conceptual Roadmap.

In Figure 4, failure at a downstream gate triggers reformulation or selection of an alternative palm fraction rather than an unqualified sustainability claim. For example, a formulation that reaches a target network modulus but leaves ionic catalyst residues would return to carbonation chemistry before any anticorrosion marketing claim. A foam that recovers its structure after recycling but fails the thermal-resistance benchmark would return to network and cell-morphology design rather than advance on circularity alone [10,15,19,48].

Pilot-scale economics should not be reduced to the price of palm feedstock or the apparently low nominal cost of carbon dioxide. Expenses arise from epoxidation reagents, carbonate synthesis time, compression and purification, equipment utilization, storage stability, catalyst recovery, hazardous waste handling and the final thermal curing cycle. Formulation costs also include scrap rates caused by variable precursor functionality. The techno-economic literature indicates that reprocessing pathways and process architecture can change both cost and emissions, but field-specific numbers cannot be assigned to an untested palm process without transparent inventory data. Sensitivity analyses should vary carbonate yield, product lifetime, electricity source, process scale and recycled-content substitution simultaneously [5,12,15,23].

A Research Agenda Addressing the Strongest Evidence Gaps

The highest-priority experimental programme should compare deliberately characterized palm feedstocks under otherwise matched conditions. Palm olein, selected fatty-acid derivatives and suitable modified fractions should be epoxidized and carbonated with measurement of equivalent weight and residual impurities, then combined with a defined set of flexible, rigid and multifunctional amines. This design would permit direct attribution of changes in cure kinetics, glass transition, adhesion and water uptake to feedstock functionality rather than to many simultaneous formulation differences. At least one conventional polyurethane or high-performance commercial adhesive or coating must serve as a functional benchmark. Source traceability and replicated batches are essential to separating naturally variable palm composition from random processing variability [11,14,18,31].

A second priority is to test hybridization strategies through factor-separated experiments. A promising study might compare neat palm carbonate-amine PHU, the same network with one carefully defined epoxy co-cure, and a third formulation containing a selected functional filler. Keeping the dry-film thickness, cure, adherend and exposure identical would reveal whether apparent improvements result from true chemical synergy. Similar controlled studies are needed for lignin modifiers and photoreactive functional groups: their contribution to strength or post-modification should be separated from changes in renewable carbon content and manufacturing complexity. Current advances in tunable and photo-modifiable PHUs expand the possible design space, but their reported performance should not be transplanted to palm networks without molecular compatibility and durability experiments [37,38,43,53,54,59].

The third priority is transparent comparative environmental research. Studies should inventory the specific palm feedstock and geographical cultivation context, conversion and purification yields, reactor duty, formulation additives, manufacturing scrap, service duration and end-of-life fate. For coated infrastructure, the functional unit should include the same substrate and protection interval, or should explicitly model repainting and maintenance. For a foam, thermal resistance or cushioning work delivered over a defined lifetime offers a defensible functional basis. Carbon accounting should report incorporation as a separate chemical indicator, with avoided emissions calculated only after full process comparison. A prospective study of different renewable-electricity scenarios could also identify whether energy-system improvements matter more than marginal changes in carbonate conversion [3,4,15,46].

The fourth priority is to translate reprocessability from proof-of-concept specimens into products. Multiple cycles should report mass retention, mechanical integrity, rheology, molecular changes and requalification of the service-specific property that originally justified adoption. For coatings this may mean repaired wet adhesion and renewed barrier performance; for foams, cell morphology and thermal properties after reshaping; for adhesives, repeated bond performance rather than polymer-film tensile recovery. Dynamic-network chemistry and innovative postsynthetic modification offer powerful tools, yet researchers must test whether environmental and economic savings exceed the heat, solvent and handling burden of the recovery operation. A circular material is only industrially circular when the physical collection and manufacturing loop can operate at practical scale [7,24,42-44].

Table 1 distills the proposed minimum reporting package into measurable items and an explicit limitation that must be resolved before industrial claims are made. Such a package would allow meaningful comparisons between palm fractions and non-palm controls across the same functional endpoints, while preserving information about formulation architecture and process burden [5,15,18]. The table also separates precursor reproducibility, product qualification and life-cycle credibility so that progress in one dimension cannot be used to infer success in another.

Table 1: Proposed Minimum Evidence Package for FCNP-Guided Palm NIPU Qualification.

FCNP stage	Required observations	Decision-relevant unresolved issue
Feedstock	Composition, epoxy/carbonate equivalents, batch variation	Can the same specification be procured repeatedly?
Carbonation	Yield, catalyst residue, energy, purification and viscosity	Does carbon conversion remain economical at scale?
Network	Pot life, gel time, cure, Tg, toughness, residual amine	Can processing and network targets coexist?
Coatings/adhesives	Wet adhesion, barrier, creep, failure mode after ageing	Does the assembly retain its intended function?

Foams/elastomers	Cell stability, cyclic deformation, conditioning response	Does a pilot formulation survive realistic service?
Lifecycle	Functional-unit footprint, maintenance, recovery cost	Is the entire product system preferable?

The evidence package in Table 1 is deliberately application neutral at the first three stages and application specific at the performance stage. Its underlying principle is reproducibility: a result should be tied to defined chemical equivalent weights, ambient conditions and an independently comparable test. A manufacturer would then be able to assess whether the material provides a real reduction in hazardous process inputs or life-cycle burden without accepting an undocumented compromise in manufacturing throughput or service durability [5,15,35].

Conclusions and Recommendations

Palm-derived non-isocyanate polyurethanes offer a credible research platform connecting renewable oleochemistry, carbon dioxide-derived cyclic carbonates and adaptable polymer materials. The evidence supports the chemical plausibility of palm precursor modification and identifies diverse complementary technologies in the broader hydroxyurethane field. It does not yet establish that palm-based formulations routinely meet industrial specifications for curing speed, wet adhesion, thermal and chemical durability, foam stability or validated circularity. The most consequential research gap is therefore not another demonstration of an isolated functional group, but the production of reproducible palm-specific formulations whose properties survive full-assembly qualification under realistic exposure.

The FCNP framework clarifies why performance depends on connected decisions. Fatty-acid composition influences accessible functionality; carbonation conditions govern reactive precursor quality; amine selection and network architecture determine curing and interfacial behavior; and industrial service determines whether those chemical choices were appropriate. Hydroxyl functionality can assist adhesion while introducing moisture-sensitive behavior, and more robust crosslinking can limit reprocessing. Similarly, chemical incorporation of carbon dioxide must be distinguished from avoided life-cycle emissions. Renewable origin, technical durability and circular recovery are distinct objectives that may reinforce one another in well-designed products but cannot be treated as interchangeable evidence of sustainability.

Future work should prioritize matched feedstock-composition studies; low-temperature and solvent-minimized synthesis with catalyst accountability; pilot-scale cure and viscosity windows; long-term wet, thermal, ultraviolet and chemical ageing; and functional-unit life-cycle assessment incorporating feedstock traceability, repair and recovery. Industrial collaborators should define pass criteria before formulation screening and maintain a consistent commercial benchmark throughout testing. The most credible near-term applications are likely to be selected use cases in which a specific hazard reduction, renewable feedstock advantage or reprocessable architecture outweighs demonstrable trade-offs. The appropriate scientific conclusion is conditional optimism grounded in measurement, not a blanket claim that palm-derived NIPUs have already displaced conventional polyurethane systems.

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