Wissen PUBLICATION GROUP

Journal of
Engineering Research and Innovations

Review Article

Volume: 1 | Issue: 1 | November 2026 | Pages 01–13

From Palm Triglycerides to Circular Polyurethane Engineering: Reaction Chemistry, Performance, Fire Safety and Industrial Readiness-A Critical Review

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Submitted: 24 October 2026 **Accepted:** 02 November 2026 **Published:** 13 November 2026

Citation: Judijanto, L. (2026). From Palm Triglycerides to Circular Polyurethane Engineering: Reaction Chemistry, Performance, Fire Safety and Industrial Readiness-A Critical Review. Journal of Engineering Research and Innovations, 1(1), 1-13.

Abstract

Palm-derived polyols offer a renewable route to polyurethane materials, yet their sustainability and industrial performance cannot be inferred from biogenic carbon content alone. This critical qualitative literature review synthesises 2020–2026 evidence across triglyceride modification, polyol functionality, urethane reaction chemistry, rigid and flexible foams, elastomers, coatings, composite applications, fire safety, ageing, end-of-life recovery and industrial scale-up. A mechanism-informed thematic method distinguishes palm-specific findings from transferable studies of other vegetable oils and conventional polyurethanes. The synthesis shows that epoxidation–ring opening, transesterification, selective addition and residue liquefaction generate different hydroxyl distributions, viscosities and reactive architectures. These differences interact with the isocyanate index, gel–blow balance, phase morphology and filler interfaces, making product-specific optimization indispensable. Flame retardancy, smoke reduction and occupational safety require independent substantiation; renewable feedstocks do not make polymer networks inherently non-combustible or recyclable. Recent advances in acidolysis, glycolysis, adaptive networks and enzymatic treatments create options but do not yet establish a universal closed loop. The paper proposes a seven-gate molecule-to-product framework and a staged industrial decision matrix connecting feedstock traceability, analytical control, service requirements, fire testing, recycled-output quality and functional-unit life-cycle assessment. Commercial translation should prioritize reproducibility and comparative evidence over nominal bio-based substitution percentages.

Keywords: Palm Oil, Bio-Based Polyols, Polyurethane, Epoxidation, Rigid Foam, Flexible Foam, Flame Retardancy, Chemical Recycling, Life-Cycle Assessment, Industrial Scale-Up.

Introduction

Background, Urgency and the Engineering Challenge

Polyurethanes occupy a broad materials landscape because isocyanate reactions with polyfunctional compounds can generate flexible segmented elastomers, highly crosslinked rigid foams, viscoelastic cushioning, waterborne coatings and specialised adhesives. These materials are not interchangeable: a seating cushion must recover shape after repeated loading, an insulation panel must retain thermal resistance and dimensional stability, and a coating must adhere under moisture, ultraviolet radiation and abrasion. The chemical architecture and processing window therefore depend on the intended service environment. A renewable-polyol strategy must satisfy the same end-use criteria as its incumbent petrochemical system rather than treating the percentage of renewable feedstock as a substitute for product qualification [1-3]. Vegetable oils offer preassembled carbon chains that may reduce reliance on fossil-derived polyol carbon. Palm oil is especially relevant because fractionation and established oleochemical operations provide triglycerides and fatty-acid fractions with varied chain distributions. However, common palm triglycerides do not contain the ready hydroxyl functionality of castor oil; the hydroxyl groups needed for standard urethane formation must be deliberately installed or generated through chemical transformations. Feedstock iodine value, fatty-acid composition, free acidity and oxidation history then influence achievable hydroxyl number, molecular architecture, color and viscosity. Treating crude palm oil, refined palm olein, palm-kernel oil, used cooking oil and liquefied palm-biomass residue as one homogeneous category conceals important differences [4-7].

The literature increasingly reports palm-modified flexible or rigid foams, but an engineering material is only as credible as the weakest stage in its production and use. A high hydroxyl value can increase potential crosslinking yet also elevate viscosity and processing sensitivity. Improving compressive strength may reduce flexibility, change cell opening or compromise impact behavior. A polyurethane with high renewable carbon remains susceptible to thermal degradation and smoke formation, and a cured crosslinked network remains difficult to remelt. Furthermore, the climatic benefit of a bio-based ingredient depends on sourcing, land-use changes, manufacturing inputs, service life and recovery pathways rather than the feedstock label alone [8-11].

Research Gap and Contribution

Existing reviews offer strong treatment of vegetable-oil polyurethane preparation, specialized non-isocyanate chemistries, polyurethane foam behavior, thermoset recycling and life-cycle assessment. The gap is not a complete absence of scientific work, but rather the fragmentation of evidence between these fields. Synthesis studies frequently conclude at the material characterization stage; fire-retardant studies optimize heat-release metrics without tracking feedstock-specific processing; recycling studies use conventional foam streams that may differ substantially from palm-based formulations. Consequently, direct evidence for a commercially qualified, fire-safe, aged and meaningfully recyclable palm-derived polyurethane product remains much narrower than the collection of individual laboratory successes may suggest [1,4,12,13,10].

This article offers an integrated, product-specific decision framework. It connects palm feedstock identity to conversion chemistry; chemical route to polyol descriptors; descriptors to gelling, blowing and network formation; morphology to service behavior; service behavior to fire and smoke requirements; and material composition to realistic end-of-life treatment. A final commercial readiness layer asks whether these relationships are repeatable under manufacturing constraints, and whether comparative life-cycle assessment supports a net environmental benefit. The analysis deliberately separates palm-specific experimental evidence from analogous vegetable-oil research and broad polyurethane chemistry, making the scope of each inference visible [5,14-16].

Research Purpose and Guiding Questions

The central purpose is to determine under what chemical, formulation, product-performance, safety, end-of-life and industrial conditions palm-derived polyols can become credible renewable inputs to engineering-grade polyurethanes. Eight questions guide the synthesis: which feedstocks and functionalization routes are fit for purpose; how polyol characteristics govern reaction and microstructure; how application classes demand different properties; how fire performance and ageing can be verified; which recycling pathways are compatible with the resulting networks; what functional-unit environmental boundaries are adequate; and which demonstrations justify investment in pilot and commercial implementation. The article does not assume that one preferred polyol route or replacement percentage will be optimal for all polyurethane applications [8,15,17,18].

Literature Review: Conceptual and Theoretical Foundations

Palm Feedstock Chemistry, Quality and Product Identity

Palm triglycerides comprise glycerol esterified with fatty acids that differ in chain length, degree of unsaturation and molecular geometry. Carbon–carbon double bonds furnish potential sites for epoxidation, radical addition or carbonyl-forming transformations, while ester linkages support transesterification and related alcoholysis routes. The balance of saturated and unsaturated moieties therefore affects maximum achievable functionality and the distribution of pendant versus terminal groups. Palm fractions and used cooking oils may offer attractive costs but introduce additional analytical variability. Oil-palm biomass liquefaction, by contrast, starts with polymeric lignocellulosic residues rather than the triglyceride feedstock itself, producing a chemically distinct polyol mixture [5,6,19,20]. For synthesis and incoming quality control, an iodine value helps estimate double-bond availability; acid value indicates titratable acidity that can interfere with polyurethane stoichiometry or catalyst behavior; hydroxyl value estimates hydroxyl-equivalent concentration; and viscosity influences metering, mixing and foam expansion. Molecular-weight distribution, water content, epoxide conversion and residual reagent content complement these conventional values. None should be used in isolation. Two polyols with similar hydroxyl numbers can possess different distributions of primary and secondary hydroxyl groups, different steric accessibility and different levels of functionality, leading to unequal cure rates and network structures even at the same nominal index [4,7,19,21].

Epoxidation and Epoxide Ring Opening

Epoxidation converts unsaturated double bonds into oxirane groups using an oxidant, often through a peracid-based chemistry. Subsequent reaction with alcohols, glycols, water or other nucleophiles opens the epoxide to introduce hydroxyl-containing structures. This two-step sequence is readily adapted to palm fractions, but selectivity is central: incomplete epoxidation, competing ester reactions or uncontrolled ring opening broaden the product distribution and raise acid number or viscosity. Opening agents influence hydroxyl value and compatibility because they change the number, accessibility and polarity of newly installed hydroxyls. A stronger claim of "green processing" requires scrutiny of oxidant efficiency, solvent and catalyst use, separation burdens and remaining residues [4,7,19,21].

Neswati and colleagues studied epoxidized palm oil with different opening agents and observed that the formulation could be tuned toward the lower hydroxyl values considered suitable for a flexible-foam precursor. More recent palm research introduced polysorbate-assisted opening and described flexible-to-semi-rigid foams prepared using palm-derived polyol. These studies are useful demonstrations of route flexibility, but different testing conditions, reactant ratios and product architectures prevent the results from establishing a universal hierarchy of ring openers. What can be transferred is the mechanistic principle that hydroxyl availability, side reactions and residual acidity jointly determine both polyol specifications and downstream process stability [4,7,19]. An experimentally relevant intermediate route is the use of methyl oleate as a chemically defined unsaturated fatty-acid ester rather than a mixed triglyceride fraction. Rigid-foam work on methyl-oleate-derived polyols illustrates how functionalisation and precursor purity can be linked to cellular morphology and insulation-oriented performance; however, its outcomes should not be extrapolated to crude palm oil without documenting equivalent functionality and feedstock differences [22].

Alternative Modification Routes and their Boundaries

Transesterification, glycerolysis and related alcoholysis reactions redistribute ester groups, introduce alcohol-derived fragments and may supply more accessible hydroxyl termini. These routes can be useful where lower viscosity and controlled equivalent weight are prioritized, yet incomplete conversion or catalyst residues can compromise storage stability and downstream reaction consistency. Hydroformylation followed by reduction theoretically introduces hydroxyl-bearing side chains by converting olefinic groups into aldehydes and then alcohols; ozonolysis and subsequent transformations cleave unsaturated sites to create shorter reactive fragments. Their presence in the broader vegetable-oil chemistry repertoire does not mean every route has been demonstrated industrially for palm-derived polyurethane polyols. Capital intensity, pressure systems, oxidation safety and separation requirements must be assessed per route [2,4,12,20].

Thiolene chemistry provides a complementary strategy because a functional thiol can react across an unsaturated bond, offering positional and functional control without relying on epoxide hydrolysis. Palm-derived polyols prepared using thiol–ene addition have been explored in cationic waterborne coating chemistry, establishing a specific application pathway rather than proving universally improved foam properties. For surface coatings, particle dispersion stability, cure completeness, water uptake, ultraviolet durability and adhesion may be more important than maximizing molecular branching. Meanwhile, castor, soybean and other vegetable-oil studies can illuminate chemical options but should be treated as mechanistic analogues whenever their fatty-acid composition differs significantly from palm oil [14,15,23,24].

An adjacent innovation pathway involves non-isocyanate polyurethanes formed through reactions such as cyclic carbonate with amines. Such materials can reduce or remove selected hazards of conventional isocyanate processing, yet they may introduce different reaction times, temperature requirements and network properties. They should be reported as an alternative polyurethane chemistry family rather than silently placed on the same performance scale as conventional MDI- or TDI-cured systems. Current reviews stress the potential of vegetable-oil non-isocyanate routes, but industrial suitability continues to depend on synthesis selectivity, hardening behavior, emission profiles and application-specific durability [2,3,12].

Stoichiometry, Reaction Kinetics and Network Architecture

Conventional polyurethane formation proceeds predominantly through the reaction of hydroxyl and isocyanate groups to generate urethane linkages. Water can react with isocyanate and generate carbon dioxide, followed by urea formation; consequently, water content and deliberate water blowing both affect the isocyanate requirement. The isocyanate index is conventionally 100 times the ratio of available NCO equivalents to the total relevant active-hydrogen demand (including the demand associated with water-blowing reactions and other reactive components). Because palm-derived polyols may be highly diverse in hydroxyl number and acidity, replacing a fossil polyol by mass without correcting the equivalent balance does not create a controlled experiment. Meaningful performance comparisons require matched or deliberately varied stoichiometry [1,6,8]. The component-level hydroxyl and isocyanate balances can be calculated from measured hydroxyl number and the isocyanate supplier's NCO mass fraction. Equations (1)–(4) provide an illustrative equivalent-balance convention in which m denotes component mass (g), OH is hydroxyl number (mg KOH g^{-1}), w(NCO) is NCO mass fraction, and $n(H_2O)$ is the amount of reactive water (mol). The constant 56,100 converts hydroxyl number to equivalents, while 42.02 g eq^{-1} is the molar mass per NCO group; these relationships are bookkeeping tools rather than kinetic or performance predictors [1,8].

$$E(OH,j) = m(j) \times OH(j) / 56{,}100 \quad (1)$$

$$E(NCO,i) = m(i) \times w(NCO,i) / 42.02 \quad (2)$$

$$E(NCO,water) \approx 2 \times n(H_2O) = 2 \times m(H_2O) / 18.015 \quad (3)$$

$$NCO\ index = 100 \times \Sigma E(NCO,i) / [\Sigma E(OH,j) + E(NCO,water) + E(other)] \quad (4)$$

In Equation (4), E(other) represents any additional active-hydrogen equivalents specified for the formulation; it must not be omitted where relevant. Water typically consumes two NCO equivalents per mole in the net formation of urea and carbon dioxide, whereas acidic impurities, catalysts and side reactions may require additional formulation-specific corrections. Experimental optimisation must still establish cream, gel, rise and tack-free times and the final foam morphology independently. Competition between the gelling reaction and blowing gas evolution determines whether an expanding foam forms stable cells, collapses, shrinks or develops excessive closed-cell content. Catalysts, surfactants, temperature, water, physical blowing agents, mixing energy and polyol molecular structure all alter this competition. Greater average functionality often promotes faster network development and higher crosslink density; however, hydroxyl type, mobility, intermolecular hydrogen bonding and local phase separation mediate whether this translates into strength, resilience or brittleness. A simple “more bio-polyol gives better properties” conclusion is therefore physically underdetermined without data on cell size, density, open-cell fraction and comparable cure histories [1,3,8,9].

Applications, Safety, Circularity and Sustainability as Different Theories of Value

Rigid insulation foam seeks low thermal conductivity, structural integrity, low water uptake and stable dimensions; flexible upholstery foam seeks air permeability, recovery, tear strength and comfort under cyclic compression. Elastomers prioritize tensile response, fatigue and often abrasion, whereas coatings and adhesives depend on interface chemistry, wetting, substrate compatibility, cure kinetics and weathering. Composite matrices introduce additional filler dispersion and interfacial stress-transfer questions. Consequently, comparable renewable-polyol percentages can produce different optimal formulations and divergent performance outcomes. The correct unit of engineering comparison is a product providing the same function for the same period, not an equal-mass pellet or unaged test coupon [1,3,14,15].

Fire risk adds a separate performance domain. Polyurethane decomposition generates combustible volatiles and, under some conditions, hazardous gaseous products and smoke. Phosphorus-containing reactive components, nitrogen-rich systems, mineral fillers and surface coatings may suppress heat release, catalyze protective char formation or modify gas-phase radical chemistry. However, adding a bio-based flame retardant does not itself prove low toxicity, adequate smoke performance or compliance with a building or transport test method. Fire tests vary substantially in heat flux, ventilation and specimen geometry. Performance claims should distinguish limited oxygen index, vertical burning, cone-calorimeter heat release, smoke density and application-specific classifications [25-29].

Circularity is similarly multidimensional. Rebonding and shredding divert some waste but generally do not regenerate the original molecular feedstock. Glycolysis and acidolysis may recover polyol-rich streams, yet amines, residual glycol, catalysts, color bodies and changed hydroxyl functionality complicate direct reuse. Selective hydrogenolysis, ammonolysis, chemoenzymatic processing and reversible bond networks broaden the opportunity space but vary widely in scale and energy burden. Finally, life-cycle assessment requires functional comparability and explicit sourcing; bio-based carbon may lower some burdens while worsening others. These concepts establish why “renewable,” “non-toxic,” “recyclable” and “climate-beneficial” must be demonstrated separately [10,13,30,31].

Method: Critical Qualitative Literature Review

Qualitative Design and Review Stance

The study employs a critical qualitative literature review rather than a systematic literature review. Its objective is to interpret material mechanisms, explain why apparently conflicting findings arise, and organize diverse peer-reviewed evidence into defensible technological propositions. It does not claim an exhaustive database census, registered protocol, PRISMA flow diagram, quantitative meta-analysis or pooled effect estimate. Conceptual transfer is assessed transparently: palm-oil-specific experiments carry direct relevance for feedstock modification, while other vegetable oils and generic polyurethane studies contribute mechanisms, safety insights and recycling concepts with explicitly stated scope limitations [2,4,10,12].

Literature Identification and Purposive Selection

A purposive corpus of reputable journal publications from 2020 through October 2026 was assembled around six major evidence streams: palm and vegetable-oil polyol chemistry, polyurethane network and foam performance, fire and smoke mitigation, chemical and mechanical recycling, newer catalytic or enzymatic recovery, and life-cycle or industrial-transition analysis. Search phrases included "palm oil polyol polyurethane", "palm olein foam isocyanate index", "vegetable oil epoxidation ring opening polyurethane", "bio-based rigid foam flame retardant smoke", "polyurethane glycolysis acidolysis recycling" and "polyurethane foam life cycle assessment". Publisher records, DOI pages, bibliographies and citation chaining were used to test relevance and trace original findings [5,8,10,11].

Selection emphasized sources with identifiable methods, defined ingredients or processing conditions, material characterization and interpretable product or process outcomes. Reviews were used to locate debate and methodological limitations, while primary studies were prioritized when a claim concerned particular foam properties or a chemical recovery yield. Publications on other biomass-derived polyols were retained only where a generalizable reaction or fire-safety mechanism could be explained. Conference summaries without adequate characterization, promotional product claims and papers with incomplete bibliographic verification were not relied upon as central evidence. The resulting corpus supports qualitative synthesis, not statistical estimates of what proportion of the total literature reports success [1,6,32,33].

Coding, Comparison and Inferential Safeguards

Deductive thematic codes covered feedstock specification, functionalization selectivity, polyol functionality, curing and foaming, service properties, fire behavior, recyclability, environmental boundaries and manufacturing readiness. Inductive coding identified repeated sources of disagreement, including the use of mass-based rather than equivalent-based substitution, different cell densities, contamination in recycled polyols, and inconsistent functional units. Each claim was classified as directly demonstrated for palm-derived chemistry, mechanistically transferable from an analogous system, or a forward-looking research proposition. Contradictory findings were not averaged; they were interpreted through differences in material structure, processing and test conditions [7,8,10,34].

This methodological distinction is important for industrial decision-making. A source may demonstrate a high-performing specimen yet provide no information on batch-to-batch reproducibility or aging. Likewise, a recycling paper may isolate a high-purity polyol under a particular solvent and catalyst system without establishing economics for mixed commercial waste. The review therefore uses explicit evidence tiers: mechanistic proof, laboratory product demonstration, realistic durability and fire qualification, pilot-process validation, and verified commercial/closed-loop deployment. Where publication records do not establish a higher tier, the synthesis does not award one by inference. The study generates no original measurements or new comparative numerical dataset [10,31,35,18].

Results: Thematic Findings

Palm Functionalization Produces a Portfolio of Polyols, not a Single Drop-in Ingredient

The first recurring result is the diversity of products obtainable from the same palm-origin label. Epoxidation and ring opening can tailor hydroxyl numbers, but the location and accessibility of the groups vary with the opening agent. Thiol–ene chemistry modifies double bonds through a different mechanism, while ester transposition changes chain and functionality distributions. Residue liquefaction produces yet another set of reactive mixtures. These routes create opportunities to choose polyols for flexible cushioning, high-functionality rigid foams or polar coating systems. They do not yield interchangeable ingredients merely because all contain palm carbon, nor can performance from a liquefied biomass foam be attributed to a refined-triglyceride polyol [5,6,14,19,20]. Palm-specific studies show that both chemical conversion choices and substitution levels affect the resulting foam morphology and mechanical response. Polaczek and colleagues compared low-density open-cell systems incorporating polyols obtained from palm oils of different origins, including used cooking oil. Separate rigid-foam work incorporated a renewable palm-olein polyol into insulation foam formulations, while studies of palm-olein viscoelastic foam evaluated variation in the methylene diphenyl diisocyanate index. These observations directly contradict a simplification in which the source oil determines the properties independently of polyol conversion and curing conditions. They instead support a more controlled chemistry-to-morphology interpretation [5,6,8]. Figure 1 summarises the principal synthesis emerging from this evidence: seven connected decisions must be made between palm feedstock procurement and validated circular engineering materials. The figure is a conceptual framework, not an experimentally established causal model or a quantitative prediction [1,10,11].

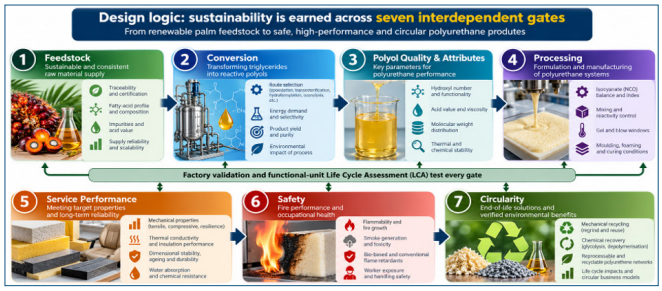


Figure 1: A Seven-Gate Interpretation of the Molecule-to-Engineered-Product Pathway; Author-Developed Conceptual Synthesis.

The sequence makes a crucial point visible. A formulation may pass early gates by achieving the desired hydroxyl number and promising initial strength but fail later because it produces excessive smoke, shows unstable aged conductivity, generates impure recycled polyol or cannot be manufactured reproducibly. Environmental performance is a cross-cutting test at each stage

rather than an assumed terminal reward. Feedback from fire qualification, product failures and recovered-material analysis should therefore inform polyol design and feedstock specifications from the outset [1,10,11].

Reaction-Structure Relationships Vary by Formulation Family

The second finding concerns the difference between polymer chemistry and measured bulk properties. The isocyanate index influences effective network formation, urea content and the relative balance of hard and soft domains; however, changing it also changes foaming and often final density. Palm-olein viscoelastic foams exhibited measurable shifts in compression force deflection, strength, resilience and cell dimensions as the index changed. Related studies using palm biomass-derived rigid foam likewise show the need to specify reactive equivalent ratios. These findings warn against attributing property differences solely to bio-polyol content when the isocyanate calculation, blowing behaviour, or cellular architecture have changed simultaneously [1,6,8].

For flexible foams, air permeability, cell interconnection, resilience and compression set are essential performance dimensions. A high density or highly crosslinked result may increase measured strength while reducing the comfort or elastic recovery that defines the application. Conversely, in rigid foam, a well-formed closed-cell morphology can improve initial insulation but also influence gas diffusion, dimensional change and fragility under humidity or temperature cycling. Foam density itself should be measured, not treated as an accidental byproduct of formulation. Comparisons based on equal test coupon thickness without equivalent densities, moisture conditioning and aging cannot unambiguously isolate the influence of a palm-derived polyol [5,7,9]. The non-foam evidence reinforces this application-specific interpretation. Palm-modified waterborne polyurethane has been studied for plywood protective coatings, where film dispersion, cure conditions and accelerated ultraviolet exposure matter. Other vegetable-oil polyurethane coating research demonstrates that corrosion behaviour and film properties depend on ester modification and network composition. Palm-based controlled-release coating work examines fertiliser release profiles, demonstrating that low permeability and extended service performance may be desirable even when these would be irrelevant in seating foam. Such evidence supports the proposition that a credible palm-derived polyol specification must be written backward from target product requirements [14,21,23,24].

Figure 2 displays a route-to-application map intended to prevent the common category error of comparing palm-derived polymers without reference to their functionalization chemistry. The pathways represent known chemical possibilities or demonstrated precursor strategies, but not a ranking of commercial readiness [4,7,14,20].

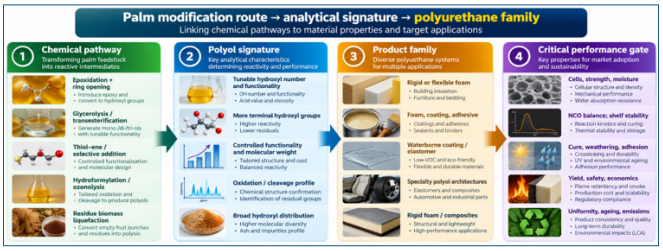


Figure 2: Conceptual Mapping of Functionalization Pathways, Polyol Descriptors and Application-Specific Verification Requirements; Author-Developed Synthesis.

The map shows how the decision shifts downstream: the correct question is not simply which reaction yields the highest hydroxyl value, but which route supplies the necessary equivalent weight, manageable viscosity and reproducible functionality for a target architecture. Hydroformylation and ozonolysis are included as mechanistic options requiring additional palm-specific and industrial validation; their presence is not evidence that they outperform better-documented epoxidation and ring-opening routes. Similar caution applies when general vegetable-oil studies are transferred to palm compositions [4,7,14,20].

Rigid Foams: Thermal and Mechanical Performance Cannot be Optimized Separately

A major attraction of palm-based rigid polyurethane foam is insulation, but thermal conductivity cannot be inferred reliably from polyol origin or compressive strength. It is jointly influenced by cell size, cell wall conduction, radiation, gas composition and changes in gas composition during service. Palm-olein-derived polyols have been tested as partial replacements in low-density rigid foams, providing useful proof of formulation feasibility. The real qualification question extends to long-term dimensional stability, water sorption, creep, adhesion to facings and aged conductivity after the blowing-agent gas has diffused. Separate polyisocyanurate ageing studies demonstrate how blowing-agent depletion can degrade thermal properties even when the foam initially performs well [9,34,36].

For structural or semi-structural uses, a compressive-test improvement at one strain or density is insufficient to establish broad mechanical competitiveness. The amount and type of crosslinking, the cell morphology and filler dispersion can alter initial stiffness and failure mode. The broader review evidence and direct bio-based foam-composite investigations suggest that natural fibers, inorganic fillers and reactive flame-retardants can reinforce some properties yet create processing challenges, including elevated viscosity, agglomeration and irregular cells. Because these changes often occur together, formulation studies should report density-normalized performance and include a petrochemical control prepared under the same cure and environmental conditions [2,25,27,32].

Flexible Foam, Elastomers, Coatings and Composites Occupy Different Design Spaces

Flexible and viscoelastic polyurethane systems reveal a distinctive property tension. Incorporating palm polyol can alter the balance between soft-segment mobility and hard-domain association, producing changes in recovery, compression hardness and tensile response that are not reducible to renewable fraction alone. Cell morphology and index interact to determine the measured response; for transport seating, long-term compression set, fatigue and emission constraints may ultimately dominate short-duration laboratory strength measurements. The literature on foam preparation and energy harvesting further emphasizes how pore structure, resilience and deformation behavior can become functional assets in one field even while being limitations in another [1,5,8]. Elastomer research using other bio-derived diols indicates that covalently integrated aromatic, phosphorus or dynamic motifs can simultaneously influence stiffness, thermal behavior, flame resistance and reprocessability. That result is relevant as a molecular-design principle, not proof that a palm-based elastomer with matching behavior has already been commercialized. Coatings and adhesives have still different service functions. Vegetable-oil-derived polyurethane adhesives

are assessed by bond strength and weathering, and palm-derived coating systems by dispersion and film resistance. Thus, any synthesis claiming "engineering-material performance" should identify the product family, test method, benchmark, exposure duration and acceptable failure threshold [14,15,23,37].

Composites add a network of interfaces rather than merely a higher filler loading. Oil-palm fibers or biochar-like reinforcing particles may offer biomass valorization routes, but fillers can carry moisture, ash or polar functionality that changes isocyanate consumption or weakens adhesion to hydrophobic soft segments. Particle size, treatment, dispersion sequence and foam expansion conditions determine whether reinforcement improves stiffness or introduces stress concentrations. Evidence from bio-based foam composites supports careful interface engineering; it does not justify assuming that every palm-residue filler is compatible with every palm-derived polyol. Repeated moisture-conditioned tests and interfacial micrographs are especially valuable where field exposure is humid [2,3,6,25].

Fire Resistance, Smoke and Thermal Decomposition as Non-Negotiable Performance Tests

Fire-safety studies demonstrate several technically distinct strategies. Reactive flame retardants integrate phosphorus- or nitrogen-containing functional groups into a polymer backbone, whereas additive strategies disperse minerals, char promoters or other suppressants. Surface coatings form another intervention by changing oxygen access, heat transfer or condensed-phase protective residues. These mechanisms operate at different stages of heating and combustion, and each can alter foam processing, moisture behavior, toxicity, mechanical resilience or recyclability. For palm-based formulations, the central translational issue is not whether a flame-retardant additive works in an abstract polyurethane system, but whether the full formulation meets its intended fire standard without losing target functional performance [25,26,27,32,]. Selected experimental studies illustrate the opportunities and boundaries. Bio-derived phosphorus–nitrogen systems and modified framework or mineral structures have reduced indicators of burning in flexible or rigid polyurethane specimens. Alginate-based coatings and structured biomimetic layers have likewise been explored as approaches to restrict heat or smoke release. The studies vary in baseline foam density, loading, preparation procedure and fire method; thus their percentage reductions cannot be ranked as if they were obtained in a common trial. Moreover, a reduced peak heat release rate does not guarantee low smoke toxicity or acceptable flame spread under the final product's jurisdiction-specific requirements [26-29].

Intrinsic flame-retardant chemistry provides a different design logic: attach the protective group to a reactive polyol or diol so that it is less likely to migrate than a physically dispersed small molecule. Recent polyurethane elastomer and advanced energy-harvesting material studies demonstrate that this approach can combine multiple functions. Yet these favorable specimens still require durability, fatigue and failure analysis, and an intrinsic chemical modification may complicate subsequent depolymerization or recovered-monomer quality. These trade-offs are acute for thin coatings, electronics or vehicle interiors, where fire behavior must be assessed alongside abrasion, prolonged exposure and component assembly [27,32,37].

Fire-safety evidence also underlines the need to measure toxic products directly instead of relying on ignition or heat-release indicators alone. Głowacki combined calorimetric and smoke-density techniques with evolved-gas analysis when examining fire-retardant flexible polyurethane foams, illustrating that formulations require parallel evaluation of heat, smoke and combustion-product chemistry [38]. Transferring those findings to palm-based foams requires matched density, additive loading and test conditions rather than assuming chemical origin determines toxicity. Smoke should be treated as its own design objective rather than a secondary footnote to flame inhibition. A condensed-phase barrier may lower volatile release and so suppress some smoke metrics, but additives can also change decomposition products, including aromatic and nitrogen-containing species. Research reporting smoke density or total smoke release is valuable, yet the selection of instruments, oxygen availability and experimental scale affects interpretation. Industrial assessments should consider ignition resistance, heat release, effective heat of combustion, smoke quantity and chemical composition, plus product-specific pass/fail standards. The carbon origin of the polyol cannot establish fire-safety compliance [25-28]. An additional difficulty arises when the flame-retardant system is evaluated only on freshly produced foam. Additives may migrate, coatings may abrade or crack, and moisture cycling may change cell walls or adhesion. A composition that satisfies short laboratory tests may therefore be exposed to years of elevated humidity, cyclic loading or ultraviolet irradiation before an actual fire event. Design qualification should integrate fire tests after accelerated ageing and physical damage as appropriate to the intended product. Pairing heat-release and smoke tests with mechanical and thermal performance is more informative than pursuing a single maximum limited oxygen index [2,28,29,36].

End-of-Life Routes are Composition-Sensitive and Unequal in Readiness

Mechanical recycling is the easiest route conceptually for many foam streams: clean offcuts can be cut, ground, bonded or blended into secondary products. However, rebonding typically does not restore the original polyol and can generate a material with different density, durability, fire behavior or market value. Separation of clean industrial scrap from post-consumer foam contaminated by adhesives, fabric, fire retardants and dirt substantially changes the economic proposition. A life-cycle assessment of mechanical recovery can show benefits under suitable assumptions, but avoided virgin production, transport burdens and achievable product quality must be specified before the pathway is labelled circular. Glycolysis is among the most developed chemical recovery strategies, using glycols and catalysts to cleave susceptible urethane networks and recover polyol-rich components. Reviews show that rigid and flexible foams require different formulations and processing conditions because their molecular structures and crosslink densities vary. Microwave-assisted glycolysis has been reported to accelerate processing for selected rigid waste foams, and formulations with recovered polyol have been used to make new rigid products. This does not mean recycled material is universally interchangeable with virgin feedstock. Recovered streams may contain free amines, glycol, urea fragments, catalysts and broad molecular-weight distributions that alter cure kinetics and emissions [11,30,33,34]. A particularly significant quality issue is aromatic diamine formation in some conventional isocyanate-derived recycling streams. Research on deamination of glycolysate shows that unwanted methylenedianiline must be addressed and that different deamination treatments affect new-foam properties differently. Such findings are directly relevant to circular palm-polyurethane design: adding renewable polyol

carbon at the front end does not remove the need to manage isocyanate-derived chemistry at the back end. Recovered-polyol qualification therefore requires an amine value, residual-glycol determination, acidity, molecular-weight distribution, viscosity, hydroxyl value and contaminant analysis in addition to routine foam performance testing [11,13,39].

Acidolysis presents an alternative chemical pathway and increasingly strong demonstrations. Fast maleic-acid acidolysis of a selected flexible-foam stream recovered a polyol-rich fraction under comparatively mild conditions, while separate work optimized acidolysis for polyurethane adhesive waste. Reviews emphasize that acid choice, polymer composition, reagent ratio and separation strategy strongly influence the recovered product. These results provide credible proof of chemical recoverability, but quality claims should be tied to the actual polymer stream and downstream polyurethane specification. Acid recovery, reagent use and waste-water treatment are also indispensable when comparing acidolysis with glycolysis on environmental or economic grounds [13,16,40]. Beyond glycolysis and acidolysis, catalytic cleavage approaches seek different products and selectivities. Iridium-catalyzed hydrogenolysis of urethane linkages has illustrated the possibility of selectively generating alcohols and formamides, even in the presence of other carbonyl functionality. Ammonolysis has been investigated for recovery of polyol and aromatic amines from rigid polyurethane. Such discoveries enlarge the chemical recycling toolbox but can impose catalyst supply, separation, pressure, reagent or regulatory costs that are invisible in small conversion-yield tables. Successful transformation of a model substrate cannot be equated with operation on a heterogeneous foam mattress, composite panel or coated automotive part [11,40,41].

Dynamic networks and triggered degradation represent an alternative approach that changes the original polymer design. Vitrimers use bond-exchange mechanisms to enable stress relaxation and selected reprocessing behavior, while specially engineered cleavable motifs can facilitate degradation and upcycling under controlled conditions. Recycled polyurethane glycolysate has also been investigated as a feedstock for vitrimer materials. These studies provide useful principles for creating recoverable engineering networks, but their chemistry may be incompatible with the foaming profiles, fire additives or high crosslink density of a given palm-based rigid foam. It would therefore be premature to describe standard thermoset palm-polyurethane products as mechanically reprocessable merely because dynamic covalent polyurethane systems exist [13,35,37,42,43].

A complementary chemical-recycling option is to regenerate isocyanate functionality rather than recover only a polyol-rich fraction. O'Dea demonstrated organoboron-assisted cleavage and reuse of recovered isocyanates in selected polyurethane systems, extending the conceptual routes to closed-loop material recovery [44]. Nevertheless, Rossignolo emphasised that separation, waste heterogeneity and process-specific resource requirements remain important constraints, so laboratory regeneration cannot by itself establish safe, economical recycling for palm-based composite foams [45]. Enzymatic research is evolving rapidly but warrants a readiness distinction. Early urethanase studies used enzymes to cleave relevant carbamates or to complement chemical glycolysis, while later molecular modelling and structure-guided engineering investigated catalytic mechanisms and more robust biocatalysts. A 2025 report demonstrated glycolysis-compatible urethanases with kilogram-scale polyurethane depolymerization under a specified chemoenzymatic environment. More recent 2026 work expanded the enzyme repertoire and used computational redesign to improve activity. These are meaningful advances, yet enzymatic accessibility, pretreatment, aromatic-amine separation, actual composite contaminants and scalable product recovery remain formidable constraints; evidence on enzymes does not prove biodegradation of intact cured polyurethane in the environment [46-51].

The newest comparative evidence suggests that end-of-life design must start with the anticipated collection stream and desired recovered product. Material recovery might be appropriate for clean industrial offcuts, glycolysis for certain segregated foam waste, acidolysis for selected network types, and selective chemoenzymatic treatment for particular depolymerization intermediates. Recent closed-loop and techno-economic analyses demonstrate that some regenerated formulations can replace part of virgin polyol under defined conditions, not that mixed global polyurethane waste has a single established optimum. Thus, end-of-life compatibility is a constraint on monomer, catalyst, flame-retardant and additive selection at the start of materials development [11,18,52-54].

Environmental Outcomes Depend on the Functional Unit and Sourcing

The life-cycle assessment literature is explicit about the danger of comparing renewable and fossil polyurethane formulations on incomparable bases. Differences in density, insulating life, blowing-agent choice, isocyanate fraction and allocation procedures can reverse or obscure results. A kilogram of polyol is not an adequate functional unit for an insulation product that must provide thermal resistance for decades. Nor is a kilogram of flexible foam sufficient for a cushioning system with a specified compression set, mass and service lifetime. Functional-unit comparisons must account for all major ingredients, processing energy, rejected material, transport, replacement frequency and end-of-life treatment [10,36,55]. Sourcing is especially consequential for palm oil because plantations occupy land with potentially high biodiversity and carbon value. The relevant claim is not that a particular palm-derived molecule has an intrinsically fixed climate burden; rather, the burden depends on origin, land history, agricultural practices, extraction and fractionation, allocation among oil and coproducts, and supply-chain verification. Waste cooking palm oil may avoid some upstream allocations but introduces collection and contamination issues. Existing polyurethane LCA studies also identify the continued relevance of isocyanates, which may dominate important impact categories even when the polyol carbon has been replaced. Supplier declarations should therefore separate bio-based content from measured life-cycle environmental outcomes [2,5,10].

Recent palm-sector studies also show why upstream sustainability declarations should be differentiated from material-level life-cycle evidence. Analyzed life-cycle carbon footprint of Indonesian refined palm oil and its embodied trade emissions, while identified efficiency trade-offs associated with certification in Malaysian palm production. These studies do not determine the footprint of a particular polyurethane formulation, but they strengthen the case for country- and supplier-specific sourcing scenarios, transparent allocation and sensitivity analysis before making comparative environmental claims. Chemical modification and

recycling can create their own impact hotspots. Epoxidation requires oxidants and may require catalysts, water or solvents; high-pressure conversion routes require sophisticated energy and safety controls; glycolysis and acidolysis consume heat and chemical reagents. Environmental performance must incorporate process yields, unused reagents, catalyst management, wash streams and purification. Recycled polyol earns a climate benefit only when it actually displaces virgin feedstock and satisfies the target function without unacceptable performance loss. Sensitivity analysis is essential where electricity sources, land-use factors, recovered-product yields or assumed lifetimes are uncertain [10,13,20,52].

A robust prospective LCA for palm-derived polyurethane should thus present separate results for fossil resource depletion, climate impact, land-related impacts, toxicity-relevant inventory, water consumption and end-of-life outcomes. The analysis should use comparative controls of equal function, transparent system boundaries and multiple sourcing scenarios rather than one aggregated green score. Because recycled and bio-based labels address different lifecycle stages, dual circularity claims require both traceable renewable feedstock and operationally demonstrated recovery of material into a useful next product. This review treats unresolved feedstock sourcing and market-level displacement effects as uncertainty, not as evidence of either automatic superiority or inevitable inferiority [10,17,52,55].

Industrial Scale-Up and the Difference Between Demonstrator and Product

Manufacturing polyurethane requires continuous control of raw-material specifications, pumping behavior, storage stability, mixing energy, exotherm, timing and product variability. A bench specimen cured in a beaker or small mold may appear satisfactory even when its polyol cannot be reliably dosed on an industrial line. A palm-derived polyol with seasonally variable free acidity or viscosity may demand changes in catalysts, surfactants and isocyanate equivalent ratios, leading to inconsistent cells or adhesion. Conversely, an overly conservative formulation may sacrifice the performance advantages of a bio-based ingredient. Pilot trials should therefore document incoming-batch distributions and establish acceptable control limits for water, hydroxyl number, acid value, viscosity and stability [3,8,9,14].

Palm-derived fatty-acid ester research provides a useful intermediate between broad vegetable-oil reviews and direct industrial foam recipes. For example, Kamairudin et al. (2023) linked methyl-oleate-based polyol synthesis to rigid-foam characteristics, underscoring the need to document conversion specifications and control formulations alongside application performance. It remains important to distinguish a model ester precursor from industrially fractionated palm oil when evaluating processing variability and raw-material procurement. Scale-up evaluation should begin with a clearly specified product and reference formulation. For rigid construction foam, the reference should include density, closed-cell content, initial and aged thermal conductivity, dimensional stability, moisture absorption and the relevant fire classification. For flexible seating, it should include density, indentation hardness, rebound, tear, cyclic compression and volatile emissions. For coatings and adhesives, it should cover adhesion, cure, weathering, abrasion and chemical resistance. Industrial transfer further requires raw-material traceability, a hazard review, equipment compatibility, reliable collection of processing data and cost modelling. A laboratory improvement in one property is an input to product development, not an independent market-entry decision [1,14,15,36].

Costing requires a transparent accounting of polyol feedstock, chemical conversion, oxidants or alternative reagents, catalysts, purification, energy, shipping and waste handling, alongside the cost of qualifying an unfamiliar ingredient. Alternative modification routes may produce excellent molecules but require high-pressure hydrogen or elaborate separation, making their economics less attractive than simpler routes for commodity foams. Recovered polyols offer a potential second source of value, but only where waste collection, contaminant control and regenerated foam properties satisfy product demand. Published techno-economic and process-optimization research should be used as context-specific evidence rather than copied as a universal cost threshold [18,20,40,52].

The qualitative result is therefore a shift from maximum renewable-content research toward minimum total-system risk at a viable renewable fraction. A moderate palm-polyol substitution may be superior to a nominally 100% bio-polyol approach if it offers reliable processing, longer life, safe combustion behavior and actual recovery infrastructure. Conversely, a chemically tailored high-renewable-content system can be valuable where its equivalent chemistry and application requirements are well matched. The appropriate outcome measure is an independently tested product meeting target service and environmental criteria, not the most impressive isolated substitution percentage published for a laboratory formulation [3,5,7,10].

Discussion and Analysis

Answering RQ1 and RQ2: Route Selection is an Application-Specific Chemical Problem

The first two questions ask which feedstocks and chemical modifications are most appropriate. The evidence favors neither one universally superior palm fraction nor one synthesis route for all applications. Palm olein and other triglyceride feedstocks can support epoxidation and hydroxylation; thiol–ene chemistry can be useful for specialized waterborne products; and liquefied biomass-derived mixtures address a different residue-valorization objective. The correct starting decision combines feedstock analytical variability, target equivalent weight, functionality and route-specific waste generation. For commodity foam, robust scale-up and inexpensive reagents may dominate; for protective coatings, controlled chemistry and film properties may justify more specialized reactions. The trade-off is functional and economic rather than merely chemical [5,6,14,19,20].

A practical decision rule follows. Define the end-use product and its required polymer architecture first, calculate its hydroxyl-equivalent and viscosity window second, and select the cheapest verifiable chemical transformation capable of meeting both. Report actual renewable carbon, not merely the percentage of a branded polyol charged into the mixing vessel. Maintain explicit feedstock categories because oil-palm biomass liquefaction cannot be interpreted as an experiment on palm triglyceride epoxidation. These design principles turn an often feedstock-led research program into a problem-led materials engineering program, increasing the chance that synthesis discoveries meet tangible manufacturer specifications [4,7,10].

Answering RQ3 and RQ4: Property Trade-Offs Must be Interpreted Mechanistically

The third and fourth questions concern formulation response and the distinction between product classes. The causal chain proposed by this review is polyol functionalization → hydroxyl type and equivalent weight → isocyanate demand and cure kinetics → hard/soft segment organization or cell architecture → service behavior. Each step is affected by additives and processing. Thus, a property change attributed to polyol substitution becomes more convincing when the experiment controls density, index, curing schedule and cell morphology. An apparent compressive improvement may result from a higher density rather than better polymer strength; a superior initial conductivity may arise from blowing-agent differences that disappear during ageing [6,8,9,36]. Products need distinct multi-criteria optimization. Rigid foam should be evaluated for thermal resistance, compressive behavior, moisture, durability and fire response simultaneously. Flexible foam should favor a balanced set of resilience, low compression set, tear, comfort and emissions. Elastomers require fatigue and toughness, coatings demand adhesion and weathering, and composite matrices depend heavily on reinforcement interaction. This analysis suggests that papers claiming broad "improved performance" should identify what deteriorated as well as what improved. A credible technology readiness judgment is not possible unless the failed or marginal properties are reported beside successful ones [1,3,14,37].

Answering RQ5: Fire-Safe Sustainability is a Two-Sided Design Condition

The fifth question can be answered clearly: palm-derived polyol content does not confer inherent fire safety. Fire mitigation must be engineered, verified and maintained through ageing. Phosphorus–nitrogen reactive systems, mineral additives and functional surface coatings offer a toolbox, but can change cure, flexibility, char formation, smoke or recycling chemistry. For construction and automotive applications, fire performance is a threshold condition rather than a cosmetic improvement. Laboratory reductions in heat release must be interpreted alongside smoke metrics, emission chemistry and the standard relevant to the assembled product rather than a small isolated foam block [9,26-29]. This conclusion creates a research priority that is easily overlooked: test flame-retardant strategies on palm-based reference foams under controlled equivalent ratios, identical density targets and comparable conditioning, then repeat critical tests after accelerated ageing. Investigations should also measure additive migration or coating durability where appropriate, and determine whether a fire-protective motif complicates chemical recovery. An apparently desirable fire additive that prevents the recovered polyol from meeting specifications can shift environmental burden rather than eliminate it. Multi-objective testing, not a single combustion number, is essential for the sustainable engineering label [10,27,37,40].

Answering RQ6: Circularity Must Be Designed and Demonstrated

The sixth question exposes a structural paradox. Conventional polyurethane foams are valued partly because stable covalent networks resist deformation, hydrolysis and ordinary heat-driven reprocessing. These very features complicate mechanical recycling. Chemical cleavage routes offer the prospect of returning material to feedstock but incur separation, process-control and contaminant burdens. New dynamic polymers shift the initial design to permit later reprocessing, whereas enzymes and selective catalysts may complement chemical decomposition. No available evidence justifies describing all palm-derived conventional polyurethane as biodegradable, recyclable in ordinary municipal systems or compatible with a particular closed-loop process [13,16,43,49,53].

The preferred circularity approach should be selected against a collection and product scenario. Factory offcuts are often cleaner and more suitable for rebonding or targeted glycolysis than composite post-consumer waste. A commercial foam containing pigments, flame retardants, facings or adhesives may require substantial pretreatment before producing qualified recycled polyol. Recovery yield alone is not the entire metric: purity, hazardous amines, stable re-formulation, repeat cycles and avoided virgin material production determine whether the process approaches a credible loop. For an engineering-grade bio-polyurethane, demonstrable high-value second use is a more rigorous target than a laboratory mass balance showing chemical conversion [10,11,13,43,52].

Answering RQ7: Sustainability Depends on Avoided Function-Specific Burdens

The seventh question is ultimately comparative. A palm-based foam with a lower fossil-derived polyol fraction can still be environmentally unfavorable if land-use history, poor durability, high reagent intensity, inefficient blowing agents or large scrap rates outweigh its feedstock advantage. Conversely, a traceable palm-derived formulation that lasts as long as its fossil alternative and displaces virgin production may offer meaningful benefits. Life-cycle assessment should maintain the same end-use service output, identify regional electricity and feedstock scenarios, and disclose uncertainty in land-use and allocation. The analysis must not quietly assume that biogenic carbon renders all chemical processing or end-of-life emissions neutral [5,10,17,55]. Environmental claims should be expressed by category, not compressed into an unqualified "eco-friendly" designation. Renewable content is a compositional statement; reduced climate impact is a modelling or measured-system finding; toxicity and fire safety concern other evidence; recycling concerns actual post-use pathways. Procurement can require batch certification and chain-of-custody evidence, yet these remain only inputs to functional LCA. Industry and researchers should publish sensitivity ranges and make explicit whether their calculations count carbon storage, end-of-life incineration, avoided fossil production or chemical-recycling credits. These choices can materially influence comparisons and should be intelligible to readers outside the LCA discipline [10,52,55].

Answering RQ8: The Factory-Readiness Sequence and Unresolved Evidence

The eighth question concerns translation from laboratory opportunity to reproducible materials. The proposed program begins with chemical specification and representative feedstock sampling; moves to bench-scale stoichiometric optimization with matched petrochemical controls; proceeds to pilot processing across multiple raw-material batches; then requires application-specific durability, ageing, fire qualification, cost and environmental assessment. No single stage should be passed merely because renewable carbon content increased. Failures should trigger formulation or feedstock changes before equipment scale is increased. Such a stage-gated approach aligns investment decisions with realistic product and regulatory constraints [1,3,10,18]. Figure 3 translates the foregoing analysis into a proposed industrial readiness sequence. The requirements are intentionally qualitative and should be adapted to the laws, product standards, production

equipment and customer specifications governing a particular polyurethane product [10,13,18,].



Figure 3: Illustrative Stage-Gated Industrial Readiness Architecture; Criteria are Proposed by this Review and are not a Validated Standard.

The figure emphasizes the distinction between evidence of synthesis and evidence of reliable manufacture. It also shows why circularity should not be postponed to the disposal stage: retained additives, cured-network structure and collection arrangements can make the selected route ineffective or expensive. The key managerial question is whether every critical gate has a documented result and a responsible owner, not whether a laboratory article has reported the largest percentage of palm-based polyol substitution [10,13,18].

Proposed Minimum Reporting Standard and Research Priorities

Future experimental studies should document palm fraction and provenance, relevant fatty-acid composition, iodine value, oxidation history and moisture; the complete polyol synthesis process; hydroxyl and acid values, viscosity and molecular-weight indicators; exact polyol substitution on both mass and equivalent bases; isocyanate index and correction for water; catalysts, surfactants, blowing agents and other additives; processing temperatures and times; and at least one genuine same-function petrochemical reference. Foam results should include density, cell structure and key mechanical metrics. The precise test battery should reflect product purpose, but every study should report negative or conflicting results rather than selectively showcasing improvements [5,7,8].

For rigid insulation, stronger evidence will require thermal-conductivity ageing, dimensional stability, moisture sorption, creep and post-ageing fire testing. For flexible products, repeated compression, tear and fatigue must be included. For coatings, weathering, adhesion retention and hydrolytic or chemical exposure are necessary. Researchers should include traceable test standards and statistical dispersion for independently prepared batches, not merely repeated measurements on one specimen. Reporting such information would allow later comparative syntheses to separate chemistry-driven phenomena from processing noise and density effects. The most useful next-generation dataset may be a rigorously controlled multi-batch process study rather than another high-substitution single-formulation demonstration [1,9,14,36].

Circularity trials should begin with the exact formulated polyurethane, including flame retardants and fillers, rather than a chemically convenient surrogate. They should report waste-source composition, preprocessing demand, reaction yield, mass balance, recovered-product purity, amine hazards, regenerated formulation performance and repeat-cycle behavior. Pilot work should compare environmental impacts of the selected recycling route with competing end-of-life scenarios using a functional unit. Current evidence from acidolysis, glycolysis and enzymatic treatment provides a promising starting point, but comparative cost, energy and product-quality results under common commercial conditions remain limited [13,16,33,50,52,54]. An emerging materials-engineering research question is whether inherently reprocessable urethane networks can be designed from palm polyols while retaining the moisture resistance, foam kinetics and fire properties required for service. Equally important is whether recovered palm-based polyol fractions can be purified to consistent specifications without excessive additional energy or hazardous reagents. Studies of bio-based dynamic networks, enzymatic bond cleavage and advanced catalytic recycling should be linked to actual palm-derived target formulations to address this question. Such integration offers a more substantive advance than treating bio-based origin and end-of-life recoverability as unrelated fields [35,37,43,49,51].

Integrated Decision Matrix and Contribution to Engineering Practice

A synthesis of the reviewed evidence supports a hierarchy of decisions. Chemical feasibility is necessary but does not justify commercial investment on its own. Product performance has to be demonstrated under matched formulation conditions; fire and smoke requirements must be satisfied independently; ageing must show that value persists; and recycling must generate acceptable material under a credible collection scenario. Environmental assessment should then compare the same delivered function against a fossil-based incumbent and plausible recovery options. Table 1 condenses these tests into practical stop/go questions for project qualification. The combined framework provides a reasoned method for prioritizing projects, tracking uncertainties and avoiding a green label unsupported by service or circularity performance [3,10,11,13].

Table 1: Minimum Evidence and Stop/Go Questions for Industrial Qualification of Palm-Derived Polyurethane Materials (Author-Developed Synthesis).

Decision Dimension	Necessary Evidence	Key Stop/Go Question
Feedstock/ chemistry	Traceability; iodine, OH, acid, water, viscosity; route yield	Is reactive polyol quality stable across batches?
Foam or coating	Controlled equiva-lents; morphology; matched incum-bent; service tests	Does the product perform the same function reliably?
Safety and durability	Product-relevant fire/smoke tests; emissions; aged property retention	Does it remain safe and effective after ageing?
Circular recovery	Documented waste stream; recovery purity; repeat product quality	Does collection and recovery produce useful material?
Manufacture and LCA	Pilot run; cost; supply; functional unit; uncertainty analysis	Is the product technically and environmentally viable?

As Table 1 illustrates, the decision matrix is a synthesis tool rather than an asserted certification standard. It locates the most significant uncertainty at the point where a project could fail commercially or environmentally. A palm-polyol project targeting insulation, for example, should stop or reformulate if fire classification or aged conductivity is inadequate, even when the polymerization chemistry and renewable fraction appear excellent. A flexible-foam project should similarly resist scaling if compression set, odor or surface cracking fails after cyclic use. The framework thus connects laboratory formulation decisions with product assurance and process governance, making engineering relevance explicit [1,10,27,36].

Conclusion and Recommendations

Palm-derived polyols provide a credible renewable chemical platform for engineering-grade polyurethane research, but neither palm origin nor bio-based substitution is sufficient to establish product sustainability. The decisive variable is the alignment of molecular modification, hydroxyl functionality, formulation stoichiometry and network architecture with a specific application. Rigid foams, flexible cushioning, elastomers, coatings and composite matrices require different balances of mechanical properties, porosity, adhesion, insulation and longevity. Chemistry should therefore be selected backward from service specifications, verified with matched reference formulations and tested across representative feedstock batches. Broad claims that higher hydroxyl number or greater renewable content always improve polyurethane performance are not supported by the diverse mechanisms and trade-offs considered here. Safety and circularity are independent obligations. Fire-retardant systems must be assessed through ignition, heat release, smoke and product-specific standards after appropriate conditioning, while chemical recovery must demonstrate actual recovered-polyol quality and repeated value retention. Mechanical recovery, glycolysis, acidolysis, catalytic cleavage, enzymatic processing and adaptable networks provide distinct opportunities but cannot be conflated into a universal recycling solution. Recovered materials may carry contaminants, hazardous amines, altered functionality or additional environmental burdens. Designing the network with the anticipated end-of-life pathway in mind is preferable to assuming that any cured bio-based polyurethane will become recyclable merely by virtue of its raw-material origin. For research institutions, priorities are mechanism-informed polyol characterization, equivalent-based comparisons, multi-batch reproducibility, ageing, smoke analysis and studies that couple palm-derived networks with actual recycling streams. For manufacturers, priorities are incoming feedstock specifications, processing-window control, hazard analysis, application-specific product certification, traceable sourcing and commercially credible waste collection. For policymakers and buyers, the strongest requirements are transparent renewable-content accounting, independent fire and durability tests, functional-unit life-cycle comparisons and verifiable supply chains. A stage-gated pathway from chemistry through product assurance and circularity offers the most defensible route for translating promising palm oleochemical experiments into responsible industrial materials [56-59].

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