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Reconciling Chemical Safety with Circular-Economy Targets: A Decision Framework for Post-Consumer Recycled (PCR) Polymers in Consumer-Goods Packaging Balancing REACH Compliance, Lifecycle GHG Footprint, and Regulatory Risk

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Abstract

Post-consumer recycled (PCR) polymers have transitioned from peripheral feedstock options to a structural pillar of consumer-goods packaging strategies, reflecting tightening circularity mandates, voluntary brand commitments, and shifting consumer expectations across both mature and emerging markets. Yet the recovery and reincorporation of secondary polymer streams reintroduces legacy chemical baggage—legacy flame retardants, plasticizers, heavy metals, and non-intentionally added substances—creating a persistent tension with the harmonized chemical-safety architecture of the European Union and analogous frameworks in adjacent jurisdictions. This paper develops an integrated decision framework that reconciles three frequently competing imperatives: harmonized chemical compliance, the lifecycle greenhouse-gas footprint of secondary polymer streams, and the cross-jurisdictional regulatory exposure that accompanies the circulation of recycle across global value chains. Drawing on a structured synthesis of peer-reviewed literature, regulatory texts, and case evidence from European, Asian, North American, and

African contexts, the framework articulates four sequential decision gates—source qualification, hazard screening, lifecycle benchmarking, and regulatory horizon scanning—each operationalized through measurable indicators and proportionate due diligence thresholds. The discussion is situated within the empirical realities of African secondary materials economies, where informal recovery dominates feedstock availability, and within the institutional landscape of mature recycling systems, where extended producer responsibility schemes shape feedstock economics. The findings suggest that achieving substantive convergence between chemical-safety obligations and circularity targets requires multi-criteria governance instruments, transparent supply-chain traceability, and adaptive thresholds that accommodate jurisdictional heterogeneity without diluting protective intent. The framework offers a structured pathway for brand owners, converters, regulators, and waste-system operators navigating operational ambiguity in recycle selection for packaging design.

Keywords: Post-consumer recycled polymers, Chemical safety governance, Circular economy, Lifecycle assessment, REACH compliance, Regulatory harmonization

1. Introduction

The transformation of plastics into the dominant material substrate of contemporary consumer-goods packaging over the past seven decades represents one of the most consequential shifts in industrial materials history, with cumulative production estimates and end-of-life trajectories now well documented in the global material-flow literature (Geyer, Jambeck & Law, 2017). The packaging segment alone consistently accounts for the largest single end-use of virgin polymer resin while generating the shortest in-use residence time and, accordingly, the largest tonnage of post-consumer plastic waste entering recovery and disposal systems each year. This structural asymmetry between production volume and end-of-life duration has rendered the management of plastic packaging waste a defining challenge of contemporary environmental governance, motivating an extensive body of regulatory, scientific, and industrial work directed at recovering hydrocarbon value through closed-loop circulation rather than dispersing it through incineration or landfill, with consumer-goods packaging occupying a particularly visible position within the broader debate owing to its consumer-facing character and short service-life economics.

Where mechanical and feedstock recycling preserve hydrocarbon value within the technosphere, however, the residue of historical formulation choices—plasticising additives, brominated flame retardants, antioxidant stabilisers, pigments, and a long tail of non-intentionally added substances—travels with the polymer matrix into secondary applications, raising chemical-safety questions that virgin-resin specifications had previously bracketed away from packaging designers (Hahladakis *et al.*, 2018). African material-flow studies have brought this dynamic into particularly sharp focus, demonstrating that imported plastic articles, often containing additive chemistries no longer permitted in their jurisdictions of origin, increasingly constitute the secondary feedstock pool feeding regional recycling sectors (Babayemi *et al.*, 2019). Recyclate streams entering converter operations cannot, therefore, be presumed compositionally equivalent to virgin-resin grades even when they meet conventional optical, melt-flow, or rheological screening criteria. This compositional inheritance becomes consequential precisely when packaging functions as a contact surface for foodstuffs, cosmetics, or pharmaceutical formulations, where migration potential is non-trivial, exposure pathways are direct, and regulatory thresholds calibrated against virgin-resin baselines may not adequately capture the cumulative chemical complexity of repeatedly recycled feedstock.

The contemporary policy momentum behind circular-economy adoption has elevated post-consumer recyclate from a discretionary input into a regulated and increasingly mandatory packaging component, generating obligations whose technical satisfaction sits in productive tension with the chemical-safety legacy outlined above. The conceptual foundation for this momentum rests on the reinterpretation of resource flows as closed loops rather than linear trajectories from extraction to disposal, an analytical pivot that has reshaped both academic scholarship and industrial strategy over the past decade (Geissdoerfer *et al.*, 2017). Within the European institutional environment, the translation of circularity from concept to enforceable target has accelerated through directives prescribing minimum recycled content in particular packaging formats, extended producer responsibility obligations, and design-for-recyclability requirements applied across the consumer-goods value chain (Mhatre *et al.*, 2020). Brand owners operating across multiple jurisdictions, therefore, confront a concurrent obligation to incorporate recyclate at specified percentages while satisfying chemical-safety thresholds whose underlying assumptions were calibrated against virgin-resin baselines. This pressure is further reinforced by voluntary commitments under industry coalitions and global plastics pacts, which extend beyond statutory minima and shape investor and consumer perceptions of corporate environmental performance, generating reputational stakes that frequently outweigh the direct compliance cost. New-product-development processes have been reorganised around circularity criteria in response, embedding end-of-life considerations into the earliest stages of packaging concept generation (Pinheiro *et al.*, 2019).

Despite its rhetorical ascendancy, the circular-economy paradigm has attracted a substantial body of theoretical critique that warrants close attention when designing technical reconciliation frameworks. Conceptual analysis has identified the limitations of treating circularity as an unqualified environmental good, noting that thermodynamic

constraints, rebound effects, and the persistence of contamination across recovery cycles can compromise the assumed benefits of closed-loop systems (Korhonen, Honkasalo & Seppälä, 2018). The narrative construction of expectations around circular transitions further reveals how stakeholder coalitions have invested differently in the concept, with policy-makers, recyclers, and brand owners articulating divergent visions of what successful circularity looks like in practice (Lazarevic & Valve, 2017). The theoretical landscape becomes more textured when situated within sustainable-development scholarship rooted in African and other Global South contexts, where the intersections among renewable-energy transitions, environmental-justice obligations, and material recovery are emphasised as inseparable dimensions of any credible sustainability claim (Adejo and Osinibi, 2016). Such scholarship cautions against the implicit transposition of European regulatory templates onto jurisdictions with substantially different waste-management infrastructure, informal-sector dynamics, and chemical-management capacities.

Against this backdrop, the present study develops a coherent decision framework enabling packaging designers, brand owners, recyclers, and regulators to navigate the tension between harmonised chemical-safety obligations, lifecycle greenhouse-gas performance, and cross-jurisdictional regulatory exposure when post-consumer recycled polymers are incorporated into consumer-goods packaging. The framework translates dispersed regulatory, scientific, and industrial knowledge into a structured set of decision gates applicable across product portfolios and market geographies. Four specific objectives organise the analysis: characterising the chemical-safety profile of post-consumer recycled polymer streams; quantifying the lifecycle greenhouse-gas implications of recyclate substitution at varying inclusion rates; mapping the regulatory architecture governing recyclate use across European, North American, Asian, and African jurisdictions; and integrating these strands into a sequential, indicator-based decision framework. The analytical scope encompasses food, beverage, personal-care, household-chemical, and toy packaging applications, with explicit treatment of feedstock heterogeneity, additive migration potential, and traceability infrastructure. The remainder of the article elaborates on the conceptual, empirical, and procedural foundations of the framework and presents the implementation pathways through which its outputs can be operationalised in commercial governance and regulatory enforcement practice across diverse market geographies.

1.1. Background and Material Context

The trajectory of polymer production over the past seven decades has rendered plastics the principal material substrate of contemporary consumer-goods packaging, with cumulative production estimates now well established in the global material-flow literature (Geyer, Jambeck & Law, 2017). The packaging segment alone consistently accounts for the largest single end-use of virgin polymer resin while generating the shortest in-use residence time and, consequently, the largest tonnage of post-consumer plastic waste entering recovery and disposal systems each year. Where mechanical and feedstock recycling can preserve hydrocarbon value within the technosphere, the residue of historical formulation choices—plasticizing additives,

brominated flame retardants, antioxidant stabilizers, and pigments—travels with the polymer matrix into secondary applications, raising chemical-safety questions that virgin resin specifications had previously bracketed away from packaging designers (Hahladakis *et al.*, 2018). African material-flow studies have brought this dynamic into sharper focus, demonstrating that imported plastic articles, often containing additive chemistries no longer permitted in their jurisdictions of origin, increasingly constitute the secondary feedstock pool feeding regional recycling sectors (Babayemi *et al.*, 2019). Recyclate streams entering converter operations cannot, therefore, be presumed compositionally equivalent to virgin resin grades even when they meet conventional optical, melt-flow, or rheological screening criteria. Packaging design that incorporates post-consumer recycled content thus inherits a distinct material-history profile that must be evaluated against the food-contact, toy-safety, and general consumer-product chemical thresholds operative in target markets. Such inheritance becomes consequential precisely when packaging functions as a contact surface for foodstuffs, cosmetics, or pharmaceutical formulations, where migration potential is non-trivial, and exposure pathways are direct. This compositional inheritance constitutes the central material rationale for the structured reconciliation that the present analysis develops, justifying the integration of chemical-safety data with circularity metrics throughout the decision logic that follows.

1.2. Drivers of the Reconciliation Imperative

The contemporary policy momentum behind circular economy adoption has elevated post-consumer recyclate from a discretionary input into a regulated and increasingly mandatory packaging component, generating obligations whose technical satisfaction sits in productive tension with the chemical-safety legacy described above. The conceptual foundation for this momentum rests on the reinterpretation of resource flows as closed loops rather than linear trajectories from extraction to disposal, an analytical pivot that has reshaped both academic scholarship and industrial strategy over the past decade (Geissdoerfer *et al.*, 2017). Within the European institutional environment, the translation of circularity from concept to enforceable target has accelerated through directives that prescribe minimum recycled content in particular packaging formats, extended producer responsibility obligations, and design-for-recyclability requirements applied across the consumer-goods value chain (Mhatre *et al.*, 2020). Brand owners operating across multiple jurisdictions, therefore, confront a concurrent obligation to incorporate recyclate at specified percentages while satisfying chemical-safety thresholds whose underlying assumptions were calibrated against virgin resin baselines. The pressure is reinforced by voluntary commitments under industry coalitions and global plastics pacts, which extend beyond statutory minima and shape investor and consumer perceptions of corporate environmental performance. New-product-development processes, in turn, have been reorganized around circularity criteria, embedding end-of-life considerations into the earliest stages of packaging concept generation (Pinheiro *et al.*, 2019). The reconciliation imperative thus arises from a confluence of statutory, voluntary, and reputational pressures that collectively render recyclate adoption non-negotiable, while leaving the chemical-safety dimension to be resolved at the level of the converter, the brand owner, or the recycler. This dispersion

of accountability is precisely what generates the operational ambiguity addressed by the present analysis, and it points to the necessity of an integrative decision architecture that aligns these dispersed obligations under a single procedural logic.

1.3. Theoretical and Policy Foundations

Despite its rhetorical ascendancy, the circular-economy paradigm has attracted a significant body of theoretical critique that warrants close attention when designing technical reconciliation frameworks. Conceptual analysis has identified the limitations of treating circularity as an unqualified environmental good, noting that thermodynamic constraints, rebound effects, and the persistence of contamination across recovery cycles can compromise the assumed benefits of closed-loop systems (Korhonen, Honkasalo & Seppälä, 2018). The narrative construction of expectations around circular transitions further reveals how stakeholder coalitions have invested differently in the concept, with policy-makers, recyclers, and brand owners articulating divergent visions of what successful circularity looks like in practice (Lazarevic & Valve, 2017). These divergent investments materialize in disagreements over acceptable contamination thresholds, mandatory recycled content quotas, and the appropriate locus of due diligence within multi-tier supply chains. The theoretical landscape becomes more textured when situated within sustainable development scholarship rooted in African and other Global South contexts, where the intersections among renewable energy transitions, environmental justice obligations, and material recovery are emphasized as inseparable dimensions of any credible sustainability claim (Adejo & Osinibi, 2016). Such scholarship cautions against the implicit transposition of European regulatory templates onto jurisdictions with substantially different waste-management infrastructure, informal-sector dynamics, and chemical-management capacities. The conceptual scaffolding for the present framework, therefore, acknowledges that technical reconciliation cannot be insulated from these broader normative debates: any decision rule about whether a recyclate stream meets the chemical-safety bar simultaneously expresses positions about distributive justice, the legitimate scope of precaution, and the acceptable burden of proof on actors with markedly different epistemic resources. These foundations inform the methodological orientation of the framework described below and shape the indicator architecture through which its decision gates are operationalized in practice.

1.4. Aim, Objectives, and Scope

This study aims to develop a coherent decision framework enabling packaging designers, brand owners, recyclers, and regulators to navigate the tension between harmonized chemical-safety obligations, lifecycle greenhouse-gas performance, and cross-jurisdictional regulatory exposure when post-consumer recycled polymers are incorporated into consumer-goods packaging. The framework translates dispersed regulatory, scientific, and industrial knowledge into a structured set of decision gates applicable across product portfolios and market geographies. Four specific objectives organize the analysis. The first is to characterize the chemical-safety profile of post-consumer recycled polymer streams by identifying the principal classes of legacy substances, contamination pathways, and analytical detection

challenges that govern hazard assessment. The second is to articulate the lifecycle greenhouse-gas implications of substituting virgin resin with recycle at varying inclusion rates, accounting for collection, sorting, washing, and reprocessing energy demands. The third is to map the regulatory architecture governing recycle use across European, North American, Asian, and African jurisdictions, with attention to substances of very great concern, food-contact authorizations, and import-export disciplines. The fourth is to integrate these analytical strands into a sequential decision framework supported by indicators that practitioners and regulators can apply at scale. The scope is restricted to consumer-goods packaging applications in food, beverage, personal-care, household-chemical, and toy categories, with explicit treatment of feedstock heterogeneity, additive migration potential, and traceability infrastructure. Industrial bulk packaging, electronic equipment housings, and structural building applications fall outside the scope, though their material flows are referenced where they generate cross-contamination risks for the targeted application categories. The analytical method is a structured synthesis of peer-reviewed and policy literature, complemented by case evidence drawn from European, North American, Asian, and African jurisdictions.

2. Conceptual and Material Foundations of Post-Consumer Recycle Streams

The technical foundations of post-consumer recycle production rest on a combination of mechanical reprocessing, solvent-based purification, and increasingly diversified chemical depolymerization routes that together generate a heterogeneous secondary resin landscape. Mechanical recycling remains the workhorse of the consumer-goods packaging recycle supply chain, capturing the majority of bottle-grade poly(ethylene terephthalate), high-density polyethylene, and polypropylene flows worldwide (Ragaert, Delva & Van Geem, 2017). The process sequence—collection, sorting, washing, size reduction, melt extrusion, and pelletization—appears straightforward in flowchart representation, but each stage introduces compositional variability that compounds across the chain. Polymer identification errors during sorting, even at single-digit percentage rates, generate cross-contamination effects whose downstream consequences for processability, optical clarity, and chemical compliance can be disproportionate to their numerical share of the input stream (Hopewell, Dvorak & Kosior, 2009).

The historical evolution of mechanical recycling provides an instructive context for the contemporary chemical-safety challenge. Two decades of industrial experience with bottle-to-bottle recycling of poly(ethylene terephthalate) have demonstrated that food-contact-grade output can be reliably produced when input streams are tightly controlled, washing and decontamination steps are validated against migration models, and downstream end-use specifications are aligned with input quality (Welle, 2011). The same conclusions cannot be straightforwardly transferred to polyolefins, whose lower glass-transition temperatures, more permeable matrices, and additive-rich formulation histories complicate decontamination performance and place greater diagnostic burdens on hazard assessment. Recent reviews of mechanical recycling performance for packaging-grade plastics have catalogued the principal sources of quality loss—oxidation during reprocessing, additive depletion, contamination from

labels and adhesives, and chain scission—and have outlined the operational interventions, including tighter sorting, dedicated wash circuits, and stabilizer dosing, required to preserve material performance across cycles (Schyns & Shaver, 2020).

The valorization of plastic solid waste extends beyond mechanical recycling to encompass primary, secondary, tertiary, and quaternary recovery routes, each with distinct chemical-safety, energy, and material-quality implications (Al-Salem, Lettieri & Baeyens, 2010). Primary recycling, characterized by closed-loop reuse of post-industrial scrap, generally retains the original specification profile; secondary or mechanical recycling, dominated by post-consumer streams, introduces the contamination pathways noted above; tertiary recycling, encompassing depolymerization, pyrolysis, gasification, and solvolysis, breaks down polymers to monomer or syngas precursors that can in principle reset the chemical profile but require considerable energy and capital investment; quaternary recovery via energy capture sits outside the circularity boundary and is generally excluded from the recycle accounting that consumer-goods brands rely upon. The hierarchy among these routes has consequences for which fraction of the post-consumer stream ultimately enters packaging applications versus lower-grade markets such as construction, pipe, or fibre.

Empirical characterization of plastic waste arriving at material recovery facilities has consistently demonstrated that recyclability is a property not just of the polymer but of its packaging architecture, additive history, and labelling regime (Faraca & Astrup, 2019). Multilayer films, opaque or pigmented containers, and articles with adhesive-attached labels routinely fall to lower-quality outputs even when their base polymers are nominally recyclable. The implication for consumer-goods packaging is that design decisions taken at the brand-owner stage—pigmentation choices, label substrate selection, sleeve-removability features—directly determine whether the resulting recycle fraction is suitable for food-contact closure or relegated to non-contact bulk applications. The polymer-specific dimensions of the closing-the-loop challenge have been mapped in detail for poly(ethylene terephthalate), polyethylene, and polypropylene streams from household collection systems (Eriksen *et al.*, 2019). Poly(ethylene terephthalate) shows the strongest empirical case for closed-loop bottle-to-bottle recycling owing to its monomer-recovery viability, established food-contact authorizations, and relatively narrow additive palette; polyethylene streams are more typically downcycled given pigment heterogeneity and additive complexity; polypropylene, the most additive-laden of the three, presents the steepest barriers to food-contact-grade recovery without advanced decontamination.

These polymer-specific gradients structure the realistic boundaries of what a circularity target can achieve in any given consumer-goods category and necessarily inform the design of any decision framework that purports to reconcile circularity with chemical safety. Beyond the polymer matrix itself, comprehensive reviews of the recycling field have catalogued the technical and economic determinants of plastic-solid-waste valorization, including emerging applications of secondary resin in composite formulations, infrastructure components, and lower-tier consumer goods (Singh *et al.*, 2017). These reviews underscore that the same recycle stream can occupy radically different value tiers depending on the chemical-safety and performance

specifications of the receiving market. Such heterogeneity is precisely what makes a structured decision framework operationally necessary: without explicit gating against compositional, performance, and regulatory thresholds, the routing of recyclate to its highest-value compatible application proceeds by ad hoc judgment, with predictable consequences for both safety outcomes and circularity claims. Taken together, the eight bodies of scholarship engaged in this section establish that the material foundations of the recyclate problem are simultaneously chemical, infrastructural, and institutional, and that none of these dimensions can be addressed independently of the others without producing distorted policy or commercial conclusions.

The implications of this material-foundation analysis extend beyond the question of whether a given recyclate stream meets the technical requirements of a specific packaging application. They reach into the design philosophy of the consumer-goods sector itself, since the willingness of brand owners to specify recyclate at non-trivial inclusion rates depends on confidence that the material foundation can be characterized, monitored, and corrected when deviations are detected. Achieving such confidence requires investment in feedstock-pedigree documentation, sortation analytics, and ongoing characterization of compositional variability across batches and across seasons. Without such investments, the operational risk of recyclate incorporation remains sufficiently large that brand owners default to inclusion rates well below the levels that the underlying material flows would, in principle, support. The decision framework developed in subsequent sections is designed to lower this operational risk by making the material-foundation evidence base explicit, traceable, and proportionate to the chemical-safety stakes of the receiving application, with the polymer-specific evidence catalogued in this section providing the empirical anchor against which the framework's source-qualification gate is calibrated.

3. Chemical Safety Profile and Hazard Pathways in Recyclate Streams

The chemical profile of post-consumer recycled polymers reflects the cumulative history of intentional formulation decisions, unintentional contamination events, and the partial efficacy of decontamination processes operating across the recovery chain. A foundational mapping of plastic-packaging-associated chemicals identified well over four hundred substances of toxicological concern across commonly used polymers, with significant data gaps regarding migration behaviour, toxicological properties, and regulatory status across major jurisdictions (Groh *et al.*, 2019). The diversity of this chemical inventory means that a single recyclate stream may simultaneously raise concerns under food-contact regulations, toy-safety standards, and chemicals legislation, even when each constituent falls below conventional analytical detection thresholds.

The hazard ranking literature provides a useful entry point for identifying the substance classes that warrant priority attention within recyclate streams. Comprehensive hazard assessments of polymers and their associated monomers, additives, and processing aids have established a graduated risk profile in which polyvinyl chloride, polyurethanes, and styrenic polymers occupy the upper tier, while polyolefins and poly(ethylene terephthalate) present comparatively lower intrinsic concern—although their additive packages can

substantially alter that baseline (Lithner, Larsson & Dave, 2011). For consumer-goods packaging applications, the practical implication is that polymer identity alone is an insufficient indicator of safety, and that the additive profile inherited from the original use context must be empirically characterized rather than inferred from the polymer label.

Plasticizer migration constitutes one of the most empirically documented chemical-safety pathways in recyclate streams. Phthalate esters, historically used as plasticizers in flexible polyvinyl chloride and present at lower but measurable levels in other polymers through cross-contamination, have been detected in household and industrial plastic waste streams at concentrations sufficient to challenge regulatory thresholds in food-contact applications (Pivnenko *et al.*, 2016). The persistence of phthalates in recyclate flows is reinforced by their use across multiple product categories and by the difficulty of separating contaminated articles during sorting. Their behaviour exemplifies a broader pattern in which substances banned or restricted in new applications continue to circulate through the secondary resin pool for years or decades after the regulatory action.

Heavy-metal contamination of reprocessed plastic represents a parallel hazard pathway with distinct mechanistic origins. Empirical investigations of the influence of metal contaminants on the quality of mechanically recycled plastic have shown that pigment residues, stabilizer residues, and adventitious contamination from collection and sorting infrastructure can introduce lead, cadmium, chromium, and antimony at concentrations that exceed thresholds for sensitive applications (Eriksen *et al.*, 2018). The challenge is compounded by the fact that even compliant metal concentrations in input streams can concentrate in particular fractions during separation processes, generating localized hot-spots that escape composite sampling regimes and complicating the assurance of compliance through end-product testing alone.

Brominated flame retardants, particularly polybrominated diphenyl ethers listed under the Stockholm Convention, illustrate the trans-jurisdictional dimension of legacy contamination. Substance-flow analyses for Nigerian electrical and electronic equipment polymer streams have demonstrated that decabrominated and other polybrominated diphenyl ether congeners persist in the secondary plastic pool at concentrations and tonnages that pose recycling-related safety challenges, particularly when polymer fractions from electrical and electronic equipment cross-contaminate consumer-goods recyclate streams (Babayemi *et al.*, 2015). Parallel investigations of e-waste polymer fractions in the same regional context have catalogued not only polybrominated diphenyl ethers but also other brominated flame retardants and heavy metals, underscoring the magnitude of the legacy chemical burden that the secondary resin pool must accommodate (Sindiku *et al.*, 2015). The implication for packaging recyclate flows is that even rigorous polymer-type segregation may be insufficient if the upstream collection system permits cross-stream contamination from electronic equipment housings.

Bisphenol A and structurally related bisphenols continue to attract regulatory attention owing to their endocrine-active properties and their documented presence in the food-contact polymer environment. Studies of bisphenol A occurrence in foods sampled in southwestern Nigeria have demonstrated that exposure pathways through plastic packaging remain relevant in jurisdictions with limited routine surveillance,

with implications for the human health risk associated with both virgin and recycled polymer streams (Adeyi & Babalola, 2019). Where bisphenol A enters the recyclate pool through historical food-contact applications, downstream uses in non-food packaging or in food-contact applications below a migration threshold demand specific verification rather than assumed compliance.

The food-packaging dimension of the chemical-safety challenge has been mapped in detail through structured reviews of the substances commonly encountered in materials intended for direct or indirect food contact (Geeke, Groh & Muncke, 2018). These reviews have catalogued non-intentionally added substances arising from impurities, degradation products, and contamination as a category whose toxicological data are particularly sparse, complicating the migration-modelling exercises on which food-contact authorizations rely. Recyclate streams elevate the relative weight of this category because each cycle of mechanical reprocessing introduces additional opportunities for non-intentionally added substance formation, and the cumulative analytical task becomes correspondingly more complex with each generation of recovery.

The literature on chemical additives in plastics has identified migration, leaching, and partitioning as the principal physical mechanisms through which chemical-safety risks manifest in service-life and end-of-life contexts (Hahladakis *et al.*, 2018). Migration coefficients depend on polymer matrix permeability, additive molecular weight, contact medium polarity, and temperature, and are typically more difficult to model accurately for recyclate matrices whose precise additive content is unknown. The combined effect of these uncertainties is that the conventional migration-modelling toolkit, designed around well-characterized virgin resin formulations, must be adapted with conservative safety factors when applied to post-consumer recycled streams.

The systemic challenge of legacy additives in a circular economy has been articulated through policy-oriented analyses identifying substantive policy gaps, the absence of harmonized recyclate-specific chemical standards, and the emerging countermeasures—including separation of legacy streams, substance-specific recyclate purification, and gate-out mechanisms—proposed to address them (Wagner & Schlummer, 2020). These analyses converge on the recognition that a credible reconciliation between chemical safety and circularity targets requires both upstream prevention and downstream gating, with the present framework drawing extensively on the categorization that this body of work has established and integrating its policy proposals into the indicator architecture developed in later sections of this study.

4. Circular Economy Targets and the Role of Consumer-Goods Packaging

The circular economy as applied to consumer-goods packaging has acquired a particular institutional density over the past decade, with statutory targets, voluntary pacts, and design protocols converging on quantitative thresholds for recycled content, recyclability, and recovery rates. The operationalization of circularity targets at the packaging level requires careful articulation of what is being closed, by whom, and with what indicator system, since superficially similar metrics can conceal substantively different policy intents (Niero & Hauschild, 2017). Frameworks that distinguish between technical, biological, and hybrid loops

have proven especially useful for packaging applications, where multilayer constructions, food-contact demands, and post-consumer collection logistics complicate the simple binary between recyclable and non-recyclable.

Prevention-oriented packaging policies have emerged as a distinct strand within the circular economy debate, focusing on reduction of packaging mass and elimination of problem materials rather than maximization of recycling rates alone. Comparative analyses of packaging waste prevention policies across European jurisdictions have demonstrated significant variation in the design of producer responsibility schemes, fee modulation criteria, and deposit-return systems, with implications for the price signals received by brand owners considering recyclate incorporation (Tencati *et al.*, 2016). The interaction between recycled-content mandates and prevention obligations creates non-trivial design tensions: a brand owner can simultaneously be required to reduce packaging mass, increase recyclate share, and ensure recyclability, and may face constraints in satisfying all three simultaneously without compromising functional or chemical-safety requirements.

The concept of quality, both for the recyclate itself and for the resulting packaging article, has emerged as a central organizing principle for translating circular economy aspirations into actionable specifications. Conceptual frameworks for analyzing the quality of post-consumer plastic packaging materials have established that polymer purity, additive content, molecular weight distribution, and colour uniformity each contribute to the functional grade of recyclate, and that downstream end-uses imply different quality thresholds (Hahladakis & Iacovidou, 2018). The implication for circularity targets is that aggregate recycling-rate statistics may overstate the genuine circularity achievement when much of the recovered material is downcycled into applications that would otherwise have used different feedstocks entirely.

Building on the quality framing, typological work on resource quality has further refined the analytical apparatus by distinguishing between resource attributes that affect environmental performance, economic value, and social acceptability of recovered materials (Iacovidou, Velenturf & Purnell, 2019). For single-use plastic bottles and similar packaging articles, this typology highlights how the same recyclate stream can perform differently along these dimensions depending on the institutional arrangements governing its collection, sorting, and reprocessing. The framework's analytical contribution is to discipline the conversation about circularity beyond the single-axis mass-balance metric that often dominates regulatory discourse, opening space for indicator systems that better capture the multidimensional character of resource performance.

Lessons from the broader resource-recovery literature underscore that the upcoming circular economy faces significant conceptual and operational hurdles when applied to post-consumer packaging streams. Comparative studies of resource recovery practices across jurisdictions have argued that the absence of standardized end-of-waste criteria, persistent informal-sector dynamics, and the dispersed nature of consumer-goods waste generation each impose practical limits on the achievable circularity rate (Singh & Ordoñez, 2016). The relevance of these constraints varies markedly between mature recycling systems and emerging-market contexts, where infrastructure deficits compound the chemical-safety challenges identified in earlier sections.

National-scale policy ambitions have acquired increasing prominence as governments seek to position themselves on the circular-economy spectrum. Calls for advanced economies to move toward zero plastic waste through reductions in single-use packaging and intensified recycling have generated specific roadmaps with measurable interim milestones (Walker & Xanthos, 2018). The design of such roadmaps reveals the political-economy considerations at play, including the relative weight assigned to producer responsibility, consumer behaviour change, and infrastructure investment. For consumer-goods brand owners, the heterogeneity of national roadmaps generates a planning environment in which recyclate-sourcing decisions must accommodate divergent regulatory trajectories rather than converge on a single global standard.

Regulatory case studies focused on specific packaging article categories illustrate the granular dynamics of circular-economy implementation. Analysis of the regulatory life cycle of plastic carrier bags within the European Union has documented the progression from voluntary measures, through information disclosure and price-based instruments, to outright prohibitions in selected applications (Steensgaard *et al.*, 2017). The same trajectory pattern—voluntary, then informational, then market-based, then prohibitive—appears recurrently in the regulation of single-use packaging more broadly, providing a template against which brand-owner planning horizons can be calibrated. Taken together, the seven bodies of scholarship engaged in this section converge on a recognition that packaging-level circularity targets cannot be evaluated in isolation from the chemical-safety, economic, and infrastructural conditions under which they are pursued. This recognition has direct consequences for the architecture of the decision framework developed below: any sequential gate that purports to evaluate recyclate suitability for a given consumer-goods packaging application must integrate circular-economy performance metrics with chemical-safety verification, lifecycle environmental indicators, and traceability data, treating these as simultaneously binding rather than serially negotiable.

The trajectory traced by these seven scholarly engagements illustrates that the discourse on packaging-related circularity has matured from aspirational rhetoric into an applied governance domain in which specific indicators, thresholds, and policy instruments now occupy the operational foreground. The maturation has been uneven across geographies, with European jurisdictions accumulating the densest body of statutory targets and African jurisdictions still negotiating the institutional architecture within which comparable targets might eventually be set. For consumer-goods brand owners with multi-region exposure, this gradient implies that recyclate-incorporation strategies cannot rely on a single global set of design assumptions but must be calibrated against the regulatory tempo of each market, with provisions for the differentiated tempo at which prevention, recyclability, and recycled-content obligations crystallize across jurisdictions. The decision framework's circularity-target gate is therefore designed to admit jurisdiction-specific parameter values rather than presume a single global threshold, allowing the same architectural logic to support coherent decision-making across markedly different regulatory environments without diluting the protective intent embodied in the underlying chemical-safety, lifecycle, and regulatory-risk evaluations.

5. Lifecycle Greenhouse-Gas Footprint of Post-Consumer Recyclate

Lifecycle assessment has become the principal analytical instrument through which the greenhouse-gas implications of recyclate substitution are quantified, and its outputs increasingly underwrite both regulatory and corporate decision-making. Comparative life-cycle assessments of plastic carrier bags have demonstrated that the greenhouse-gas balance of recyclate-containing articles depends sensitively on collection and sorting efficiency, transport distances, energy mix at the reprocessing facility, and assumed end-of-life routes for the resulting article (Civancik-Uslu *et al.*, 2019). The headline finding that recyclate generally outperforms virgin resin on a per-tonne greenhouse-gas basis must be qualified by these system-boundary considerations, particularly when recyclate streams travel long distances or pass through energy-intensive decontamination processes.

The greenhouse-gas advantages of recycling are not, however, independent of the environmental quality of the resulting recyclate. Recent analyses have documented that European plastic recycling, while delivering meaningful greenhouse-gas savings on a mass-balance accounting, also represents a pathway through which a fraction of plastic material is exported, mismanaged, or lost to the environment, generating offsetting environmental burdens that complicate the headline narrative (Bishop, Styles & Lens, 2020). The implication is that greenhouse-gas accounting frameworks that fail to capture leakage and contamination effects may systematically overstate the climate benefits of recycling, particularly where the recyclate is destined for export to jurisdictions with weaker downstream waste-management infrastructure.

Material-flow characterization at the national scale provides essential context for lifecycle-assessment practitioners seeking to attach plausible boundary conditions to their greenhouse-gas accounting. Comprehensive characterization of plastic flows in the United States has revealed substantial discrepancies between reported recycling rates and the actual fate of recovered material, with implications for the credibility of recyclate-based greenhouse-gas claims (Heller, Mazor & Keoleian, 2020). The same analytical approach, applied to other jurisdictions, would generate similarly granular pictures whose comparison would clarify the international heterogeneity in lifecycle outcomes from nominally similar recyclate flows.

Country-specific predictive modelling complements the retrospective material-flow studies by generating forward-looking scenarios for the greenhouse-gas performance of post-consumer plastic packaging recycling systems. The Dutch system has been modelled in detail, capturing the interaction between collection coverage, sorting technology investment, downstream demand for specific polymer grades, and the resulting greenhouse-gas savings achievable under different policy and investment trajectories (Brouwer *et al.*, 2018). The transferable methodological insight is that greenhouse-gas accounting for recyclate use in packaging cannot be detached from the institutional and infrastructural specificities of the system in which the recyclate is produced and consumed.

The European lifecycle-assessment literature has long engaged with the comparative greenhouse-gas performance of mechanical recycling, energy recovery, and landfilling for

plastic packaging waste, generating generally consistent findings regarding the climate primacy of recycling but flagging significant uncertainty in the underlying parameters (Lazarevic *et al.*, 2010). The persistence of this uncertainty over time reflects both the genuine variability of empirical recycling system performance and the methodological choices regarding allocation rules, system expansion, and end-of-life modelling. For consumer-goods brand owners, the implication is that confident greenhouse-gas claims associated with recyclate incorporation must be supported by transparent documentation of the lifecycle-assessment methodology adopted and the parameter values used.

International trade in plastic waste has emerged as an important and underappreciated determinant of the realized greenhouse-gas performance of national recyclate systems. The implementation of the Chinese import restrictions on plastic waste in the late 2010s reconfigured global plastic-waste flows substantially, exposing the dependence of European and North American recycling claims on downstream processing in lower-cost jurisdictions (Brooks, Wang & Jambeck, 2018). The post-restriction realignment of waste flows has had measurable consequences for the realized greenhouse-gas performance of recyclate streams, both because some material has been redirected to less greenhouse-gas-favourable disposal routes and because investment in domestic processing capacity has accelerated in response.

The Latin American and Global South dimensions of recyclate greenhouse-gas performance are illuminated by case studies of urban recycling systems with significant informal-sector participation. Analysis of plastic recycling in Rio de Janeiro has documented the carbon and energy implications of a recycling system characterized by informal collection, decentralized sorting, and close integration with the secondary-resin export market (Pereira de Pacheco, Ronchetti & Masanet, 2012). The greenhouse-gas performance of such systems can be unexpectedly favourable on a per-tonne basis owing to low-energy collection logistics, but is constrained by quality limitations that restrict the resulting recyclate to lower-tier applications. The methodological lesson is that greenhouse-gas accounting for recyclate must accommodate institutional heterogeneity rather than presume the technology profile of a Northern European mechanical recycling facility.

The broader question of how the energy carrier mix interacts with the recyclate greenhouse-gas performance also warrants attention. Modelling work on the integration of hydrogen as a secondary energy carrier in national grids has highlighted the potential for clean-energy transitions to alter the greenhouse-gas balance of energy-intensive industrial processes, including plastic reprocessing (Shittu *et al.*, 2019). To the extent that recyclate production becomes progressively decoupled from fossil-fuel-based electricity, the comparative greenhouse-gas advantage over virgin resin is likely to grow, although the rate at which this decoupling is realized varies markedly across jurisdictions. This dynamic component of the greenhouse-gas comparison must be reflected in any decision framework that aspires to remain credible across a multi-decade investment horizon. Taken together, the lifecycle literature converges on the conclusion that recyclate substitution generally delivers climate benefits, but that these benefits are conditional on system design, governance quality, and energy-system characteristics, all of which the present framework treats as adjustable parameters

rather than fixed assumptions.

The eight strands of lifecycle scholarship engaged in this section accordingly converge on a methodological caution that any greenhouse-gas claim associated with recyclate incorporation in consumer-goods packaging must be both context-specific and dynamically updated, with parameter values reflecting the realized rather than assumed performance of the underlying recovery system, and with explicit treatment of leakage, energy-mix evolution, and downstream-quality dependencies whose neglect can convert apparent climate benefits into illusory accounting outcomes.

6. REACH Compliance Architecture and Substances of Concern

The European Regulation on the Registration, Evaluation, Authorisation and Restriction of Chemicals constitutes the institutional core against which post-consumer recycled polymers destined for the European market must be evaluated, with knock-on effects for export-oriented producers in non-European jurisdictions whose recyclate is destined for European-bound consumer goods. The conceptual orientation of this regulatory framework toward the precautionary principle has been the subject of sustained scholarly analysis, with foundational contributions clarifying that the regulation incorporates precaution in both substantive and procedural dimensions while leaving residual ambiguity in the operationalization of those commitments (Hansen, Carlsen & Tickner, 2007). The implications for recyclate handlers are that the absence of complete chemical-composition information for a secondary resin stream cannot be assumed to default to permissive treatment, and that proactive screening obligations may attach even where formal restrictions have not yet crystallized for specific recyclate applications.

The regulatory salience of microplastics has reinforced this precautionary orientation in recent years, with mounting scientific evidence regarding the human-health and ecological implications of microplastic contamination informing the regulatory agenda. Analyses of marine microplastic burdens have argued that the implications for future generations are substantial and warrant precautionary regulatory action, with packaging applications of plastic identified as a primary contributor to the microplastic loading of marine and terrestrial environments (Galloway & Lewis, 2016). The relevance to the present analysis is that recyclate streams sourced from packaging fractions exposed to environmental degradation, including beach-cleanup recovery and ocean-bound waste interception, may carry microplastic and additive contamination profiles that complicate compliance assessment and require purpose-designed verification procedures.

The wastewater-treatment dimension of microplastic management has emerged as a related compliance frontier, with critical reviews demonstrating that conventional wastewater treatment plants achieve variable but typically incomplete removal of microplastic particles, generating effluent and biosolid streams that distribute microplastics into receiving environments (Iyare, Ouki & Bond, 2020). For brand owners assessing the regulatory exposure of their recyclate sourcing decisions, the implication is that the cumulative regulatory environment for plastic-derived contaminants is broader than narrow substance lists alone, encompassing water-quality, biosolid-application, and microplastic-specific instruments whose interaction with

packaging recyclate use will become more salient over time. The substance-of-very-high-concern designation under the European chemicals framework constitutes the most direct compliance touch-point for recyclate handlers. Listed substances, whether subject to authorization, restriction, or candidate-list designation, must be tracked through the recyclate supply chain to enable downstream users to satisfy their own due diligence obligations. The general pollution-control literature has catalogued the broader plastic-pollutant landscape into which these specific listed substances fit, demonstrating that effective waste management for pollution control and abatement requires integration of substance-level controls with system-level interventions (Rajmohan *et al.*, 2019). The applied implication for the present framework is that compliance at the substance level, while necessary, is not sufficient: the recyclate decision must integrate the substance-list information with broader pollution-control obligations operative in the target market and source jurisdiction.

The European policy perspective on the environmental impacts of plastics, including microplastics, has been articulated through structured analyses prepared for European Parliament committees and similar institutional venues, surveying both Union-level and Member-State-level measures and identifying gaps that future regulatory cycles are likely to address (da Costa, Rocha-Santos & Duarte, 2020). The directional thrust of this body of work suggests that the regulatory perimeter applicable to recyclate-containing packaging will continue to expand, encompassing not only substance restrictions but also product-level requirements relating to recycled content traceability, design-for-recyclability, and end-of-life communication. Brand owners engaged in long-cycle packaging investments must anticipate this expanding perimeter rather than calibrate their decisions to the present-moment regulatory snapshot.

The international trade dimension of compliance is illustrated by the global plastics-waste market, whose configuration was profoundly altered by the Chinese import restrictions and whose subsequent evolution has tested the assumptions of European recyclate sourcing strategies. Analyses of global recycling markets, with particular attention to the historic role of China as the dominant downstream processor, have clarified how the pre-restriction architecture privileged exports of insufficiently sorted material that would not have satisfied chemical-safety due diligence regimes had it been processed within the European boundary (Velis, 2014). The post-restriction shift toward domestic processing has increased the visibility of these chemical-safety questions, since material that previously left the regulatory perimeter is now processed within it. The convergence of these regulatory currents implies that compliance for post-consumer recyclate-containing packaging cannot be treated as a discrete event-based determination but must be integrated into ongoing supply-chain governance, with substance-of-very-high-concern lists updated regularly, restrictions on specific substance-application combinations added through formal regulatory procedures, and interpretive guidance issued by the European Chemicals Agency periodically tightening the operational expectations placed on registrants and downstream users. Recyclate-sourcing decisions taken based on compliance with the regulatory snapshot at the moment of formulation can become non-compliant within a short time horizon if the upstream supply chain does not incorporate horizon-scanning capacity.

The implication for the decision framework developed in subsequent sections is that compliance must be operationalized as a continuous indicator with periodic refresh cycles, rather than as a static checkpoint, and must include explicit provision for the migration of substances onto candidate lists before formal restriction. Brand owners and recyclate handlers operating across multiple jurisdictions must additionally track the procedural pathways through which substance restrictions develop, since the practical lead time between candidate-list inclusion and full authorization or restriction can be sufficient to permit anticipatory reformulation, but only if the relevant supply-chain actors maintain horizon-scanning capacity adequate to the task. The cumulative regulatory architecture surveyed in this section, therefore, exerts a structuring effect on the decision framework, requiring that compliance verification be embedded in ongoing supply-chain governance rather than treated as a discrete event-based determination at the point of formulation, and informing the indicator design through which the framework's regulatory-horizon-scanning gate is operationalized.

7. Regulatory Risk and Cross-Jurisdictional Heterogeneity

The cross-jurisdictional dimension of regulatory risk for post-consumer recycled polymers in consumer-goods packaging is shaped by markedly divergent waste-management infrastructures, chemical-management capacities, and policy-trajectory expectations across jurisdictions. West African policy responses to single-use plastic marine pollution provide a useful entry point for understanding this heterogeneity, with comparative analyses documenting the range of bans, levies, voluntary programmes, and infrastructural investments adopted across the sub-region (Adam *et al.*, 2020). The relevance for brand owners with sub-Saharan African packaging exposure is that recyclate-sourcing decisions taken in compliance with European regulations may not translate directly into compliance, market acceptance, or reputational sustainability in the West African operational context, where the upstream collection and downstream waste-management dynamics differ fundamentally.

Continental-level diagnostics for the African plastic-waste challenge have framed the policy and infrastructural environment in which sub-regional differences become tractable. Cross-country surveys of the land-based plastic-waste issue in Africa have catalogued the principal drivers, the emerging solution architectures, and the institutional weaknesses that constrain progress, with implications for the achievable circular-economy trajectory in jurisdictions that lack mature collection and sorting infrastructure (Jambeck *et al.*, 2018). The cross-jurisdictional reality for consumer-goods brand owners is that any decision framework must accommodate scenarios in which the collection system on which recyclate sourcing depends is dominated by informal-sector actors operating outside the formal chemical-management envelope.

Sub-national perception studies further refine the picture by documenting how communities that constitute the upstream supply chain for recyclate streams understand and engage with solid-waste-management practices. Survey work in Ogun State, Nigeria, has demonstrated significant variation in public perception of solid-waste-management performance, willingness to participate in source-segregation

programmes, and trust in formal collection institutions (Olukanni, Pius-Imue & Joseph, 2020). The implication for regulatory-risk assessment is that recycle availability in volume and quality is partially determined by community-level dynamics that lie outside the direct control of brand owners or regulators, and that strategies presupposing high source-segregation rates may overestimate the realistic recycle flow available for high-value packaging applications.

Scholarship on the implementation of circular-economy principles in industrial solid-waste management within developing economies has provided structured case-study evidence of the operational realities under which African recycle streams emerge. Case studies from Nigeria have documented both the constraints and the latent opportunities, with industrial clustering, supply-chain coordination, and policy alignment identified as recurring success factors (Ezeudu & Ezeudu, 2019). For decision-framework design, the takeaway is that recycle-sourcing decisions must be calibrated against the institutional density of the source jurisdiction rather than presumed against an idealized European reference.

University-scale and institutional-scale studies of solid-waste generation provide finer-grained empirical input to the regulatory-risk assessment. Solid-waste generation and characterization research at the University of Lagos, for example, has produced detailed compositional data for one of the largest tertiary institutions in West Africa, with implications for the recycle fractions that could plausibly be sourced from such institutional flows under appropriate collection arrangements (Adeniran, Nubi & Adelopo, 2017). The methodological transferability of this research to consumer-goods brand owners considering institutional-scale recycle sourcing is significant, as comparable compositional studies in other jurisdictions can inform the qualification of source streams.

The historical literature on solid-waste management in Nigerian urban centres, including foundational analyses of informal-sector recycling dynamics, has documented the role of the informal sector as the de facto recycle-collection backbone (Nzeadibe, 2009). For consumer-goods brand owners committed to traceable recycle supply chains, the persistence of informal-sector participation generates both an opportunity—in the form of substantial latent collection capacity—and a challenge—in the form of limited documentation, occupational-health risks, and difficulty in verifying source-stream provenance for chemical-safety purposes. Municipal solid-waste characterization in Nigeria has further demonstrated the heterogeneity of waste-stream composition across urban centres, with implications for the achievable recycle yield from any given collection system (Ogwueleka, 2009). The variability of waste composition across cities reflects differences in income levels, consumption patterns, and historical infrastructure investment, and means that recycle-sourcing strategies must be calibrated at the city or regional scale rather than treated as nationally uniform.

Globally comparative datasets place the African experience within the wider distribution of waste-management performance and infrastructure investment. The most comprehensive global snapshot of solid-waste management has documented the wide divergence in per-capita waste generation, recovery infrastructure, and policy investment across countries and income groups, with projections of the

trajectory through which these differentials may evolve over the coming decades (World Bank, 2018). For the present framework, the global dataset provides a calibration backdrop against which jurisdiction-specific decision rules can be set, recognizing that regulatory-risk assessment must accommodate not only present-state conditions but also the trajectory of institutional development. Taken together, the eight bodies of scholarship engaged in this section converge on a recognition that regulatory risk for post-consumer recycled polymers in consumer-goods packaging is irreducibly cross-jurisdictional, that the institutional realities of African and other emerging-market jurisdictions diverge meaningfully from European templates, and that any decision framework purporting to operate at scale must therefore accommodate jurisdictional heterogeneity at the indicator level rather than presume a single global compliance baseline.

The framework's regulatory-risk gate is consequently designed to admit jurisdiction-specific scoring rather than to apply a single global threshold, recognizing that the operational reality of recycle sourcing in West Africa differs substantively from that in Northern Europe in ways that cannot be wished away through harmonized terminology. The gate accommodates differences in the maturity of waste-management infrastructure, the institutional density of chemical-management capacity, the trajectory of policy ambition, and the realistic enforcement reach of regulatory agencies. Brand owners applying the framework in cross-jurisdictional contexts thus generate scoring outputs that reflect the actual rather than the formally stated regulatory environment, with explicit provisions for documenting the assumptions on which jurisdiction-specific parameters are set. This documentation requirement performs an additional governance function: it renders the decision-maker's regulatory-risk assumptions visible and auditable, opening them to challenge by external stakeholders where their internal calibration warrants critical review.

8. Architecture of an Integrated Decision Framework

The integration of the analytical strands developed in the preceding sections into an operationalizable decision framework requires a structured architecture that accommodates the multi-objective nature of the reconciliation problem. Multi-objective optimization methodologies, particularly those drawing on evolutionary algorithms, offer a methodological precedent: portfolio-level decision problems involving simultaneous balancing of risk, return, and sustainability metrics have been addressed through evolutionary computation techniques that systematically explore the Pareto frontier between competing objectives (Oshoba *et al.*, 2020). The transferable insight for recycle-sourcing decisions is that no single dominant solution exists across the chemical-safety, greenhouse-gas, and regulatory-risk axes simultaneously, and that decision support must therefore present trade-offs rather than prescribe singular optima.

The framework adopts a four-gate sequential architecture. The first gate, source qualification, establishes minimum thresholds for the institutional pedigree of the recycle supply chain, including documentation of the collection system, sorting facility certification, and recycle-grade declaration. The second gate, hazard screening, applies substance-of-very-high-concern testing protocols and migration modelling to verify compliance with chemical-

safety thresholds for the intended end-use category. The third gate, lifecycle benchmarking, computes the comparative greenhouse-gas performance of the proposed recycle-containing article against virgin-resin and alternative-material baselines, with sensitivity analysis on the principal lifecycle-assessment parameters. The fourth gate, regulatory horizon scanning, evaluates the proposed sourcing decision against announced and anticipated regulatory developments in target markets over a three-to-five-year planning horizon. Each gate is operationalized through specific indicators rather than narrative judgments, and the gates are sequenced to enable early elimination of unsuitable options before more analytically demanding evaluations are undertaken.

Digital infrastructure plays an increasingly significant role in the operational tractability of such frameworks. The deployment of artificial-intelligence-based interfaces for knowledge transfer in remote and underserved regions has demonstrated that decision-support tools can be made accessible to actors operating outside well-resourced institutional environments, broadening the population of stakeholders capable of engaging with structured frameworks of this type (Frempong, Ifenatuora & Ofori, 2020). For the present application, the implication is that the framework's gates can be implemented through digital platforms that lower the barrier to participation by smaller converters, recycling cooperatives, and institutional procurement units operating in jurisdictions with limited technical-services infrastructure. This accessibility consideration is particularly salient for African applications, where the latent pool of recycle suppliers extends well beyond the formally certified facilities visible in European-style supply-chain registers.

The recycle-sourcing decision depends on the realistic availability of chemical-safety-conformant feedstock, which in turn depends on the maturity of mechanical and advanced recycling capacities in the relevant geography. Recent reviews of advanced recycling technologies have outlined the suite of options beyond mechanical reprocessing, including solvolysis, pyrolysis, and depolymerization, that can, in principle, reset the chemical profile of contaminated polymer streams (Vollmer *et al.*, 2020). The framework treats these advanced routes as feedstock-quality enhancers within the source-qualification gate rather than as substitutes for it: a recycle stream upgraded through depolymerization and repolymerization can, in principle, achieve a chemical-safety profile equivalent to virgin resin, but the greenhouse-gas and economic implications must be jointly evaluated.

The sub-domain of chemical recycling, encompassing the production of monomer or other chemical building blocks from waste plastics, has matured substantially in the last decade. Foundational reviews have catalogued the principal chemical-recycling pathways, the polymer types for which each is most applicable, and the economic and energy implications of their adoption (Rahimi & García, 2017). For the present framework, chemical recycling represents an option that brand owners may invoke when mechanical recycle cannot satisfy the chemical-safety threshold, but where the greenhouse-gas and economic implications of the more energy-intensive route are tolerable. The strategic-direction literature on the future of plastics recycling has converged on the recognition that incremental improvements to existing mechanical-recycling chains are likely to be insufficient to meet long-term circularity ambitions, and that systemic redesign of polymer choice, additive selection, and end-of-life infrastructure is needed (Garcia & Robertson,

2017). The framework accommodates this directional thrust through its regulatory-horizon-scanning gate, which incorporates indicators relating to announced design-for-recyclability requirements and anticipated additive-restriction trajectories.

Sensor and monitoring infrastructure underpins the operational feasibility of continuous chemical-safety verification within the recycle supply chain. Engineering work on monitoring devices, including those incorporating security features for asset tracking and tamper-evidence functionality, illustrates the broader trajectory of low-cost monitoring instrumentation that can support recycle traceability and chain-of-custody verification at points along the recovery chain (Adeniji, 2019). For the framework, the implication is that source qualification need not depend exclusively on documentary attestations from upstream actors but can be supplemented by data streams generated through embedded monitoring infrastructure, enabling a hybrid governance regime in which paper-based documentation is increasingly complemented or replaced by sensor-derived evidence.

The framework's intellectual provenance also draws on the African research-conference platform within which interdisciplinary engagement on materials, energy, and sustainability has matured over the past decade. The proceedings record of regional scientific gatherings has documented the breadth of African scientific engagement with materials-related sustainability questions, providing a knowledge base on which decision-support frameworks for African operating contexts can be constructed (Adamah *et al.*, 2016). The framework explicitly references this regional knowledge base in its operating assumptions, recognizing that the credibility of decision-support tools in African applications depends on visible engagement with regionally generated scholarship rather than reliance on externally imported templates. The seven sources engaged in this section thus combine to articulate an architecture that is both methodologically rigorous and contextually adaptable, structured to absorb continuing empirical refinement and capable of supporting recycle-sourcing decisions across the full range of consumer-goods packaging applications encompassed by the scope of the present analysis.

The four-gate sequencing thus emerges not as an arbitrary procedural ordering but as a logically structured progression in which the analytically least demanding screens precede the most demanding, enabling early elimination of unsuitable options and concentration of evaluative effort on candidates capable of clearing the preceding gates. This sequencing logic produces both efficiency gains in the decision process and clearer audit trails when subsequent governance review is required.

9. Implementation Pathways, Trade-offs, and Strategic Outlook

The implementation of the integrated decision framework articulated above must reckon with the structural realities of the contexts in which recycle-containing consumer-goods packaging is produced, distributed, and consumed. The COVID-19 pandemic generated a particularly instructive natural experiment in this regard, as the disruption of solid-waste-management systems in developing countries during the lockdown period highlighted how thin the resilience margins of recovery infrastructure can be (Nzediegwu & Chang, 2020). For the framework, the implication is that

implementation pathways must include explicit provisions for resilience under exogenous shocks, recognizing that recycle availability and quality can shift abruptly in response to disruptions in collection logistics, sorting-facility operation, or downstream demand. Resilience indicators, therefore, deserve a place within the source-qualification gate, alongside the more conventional pedigree and certification metrics.

The pandemic also catalysed broader reconfigurations of service-delivery infrastructures, including the rapid expansion of digital health platforms in post-COVID healthcare systems, with associated lessons regarding the velocity at which technology-mediated supply-chain transformations can occur when underlying institutional incentives align (Omotayo & Kuponiyi, 2020). The transferable lesson for recycle sourcing is that digital traceability infrastructure, including blockchain-based chain-of-custody systems and remote-audit platforms, can be deployed at scale within compressed timeframes when regulatory and commercial incentives jointly support the transition. The framework's source-qualification gate is structured to accommodate accelerated adoption of digital infrastructure, with indicator definitions that accommodate progressively richer data streams as upstream digitalization matures.

Infrastructure design parallels from adjacent domains further illuminate the implementation pathway. Engineering design optimization for grounding systems in medium-voltage distribution networks in emerging power markets has demonstrated that infrastructure investments calibrated specifically for emerging-market conditions can outperform externally imported templates in both cost and performance (Adeniji, Shittu & Opara, 2020). For recycle-management infrastructure, the analogous insight is that purpose-built collection, sorting, and decontamination systems calibrated for the institutional and infrastructural realities of emerging markets can outperform replicated European templates and should be prioritized in implementation pathways for African and similar contexts. The framework's implementation guidance, therefore, favours locally adapted infrastructure investment over wholesale technology transfer, recognizing that the marginal cost of incremental adaptation is typically lower than the cost of subsequent reconfiguration.

The barriers and success factors for sustainable solid-waste-management adoption in Nigeria have been the subject of structured empirical research that identifies the institutional determinants of progress beyond simple infrastructural investment levels (Ezeah & Roberts, 2012). The findings, broadly applicable to the West African context, identify policy coherence, enforcement capacity, public participation, and economic incentives as the principal levers for transforming waste-management performance. The framework integrates these levers into its implementation guidance, recognizing that the technical sophistication of recycle-sourcing decisions cannot compensate for institutional weakness in the source jurisdiction. Brand owners and regulators applying the framework in such contexts must therefore invest concurrently in institutional capacity-building rather than presume that the technical decision can be insulated from the surrounding governance environment.

The empirical literature on solid-waste generation in developing-country urban contexts provides the quantitative grounding for realistic implementation planning.

Comparative evaluation of solid-waste generation, categorization, and disposal options in Nigeria, situated in the broader developing-country context, has produced reference data on per-capita generation, compositional shares, and disposal-route allocations that establish the baseline against which intervention scenarios can be evaluated (Babayemi & Dauda, 2009). For brand owners and regulators considering recycle sourcing in such jurisdictions, this baseline is essential to calibrating realistic flow expectations and avoiding over-commitment to recycle-share targets that exceed the available high-quality feedstock pool.

The role of the informal sector in plastic-waste recovery merits explicit articulation within any realistic implementation pathway. Comparative analysis of emerging trends in informal-sector recycling across developing and transition countries has documented the social, economic, and operational complexity of informal waste-recovery networks, including the interaction between informal collection systems and formal recycling enterprises (Ezeah, Fazakerley & Roberts, 2013). The framework treats informal-sector engagement as a normal element of source qualification rather than as an exception to be eliminated, with appropriate provisions for the integration of informal recyclers into formal chemical-safety verification regimes through capacity-building, certification, and market-access mechanisms. Strategic outlook considerations impose a longer time horizon on implementation planning than the immediate compliance cycle. The trajectory of consumer-goods packaging chemistry over the next decade is likely to be shaped by a combination of substance-by-substance regulatory action, design-for-circularity standards, and technology-driven changes in feedstock options, including the emergence of bio-based and chemically-recycled polymer streams. The decision framework anticipates these trajectories through its regulatory-horizon-scanning gate, but its strategic value depends on the willingness of brand owners and regulators to invest in monitoring capacity that goes beyond current-snapshot compliance. The trade-offs articulated by the framework do not resolve to single dominant solutions, and this is a feature rather than a limitation: the genuine reconciliation between chemical safety, greenhouse-gas performance, and regulatory risk is contingent on context-specific judgments about acceptable trade-off thresholds, and the framework's contribution is to render those judgments explicit and traceable rather than to adjudicate them prescriptively.

Looking forward, the convergence of advanced recycling technologies, digital traceability infrastructure, and harmonizing regulatory expectations is likely to compress the operational ambiguity that currently characterizes recycle-sourcing decisions. The strategic outlook is therefore one of progressive narrowing of the trade-off space rather than its abolition, with implementation pathways calibrated to the realistic pace at which infrastructural and regulatory conditions evolve. For African and other emerging-market jurisdictions, the trajectory may diverge from European templates in ways that warrant locally adapted implementation pathways, drawing on regional research capacity and indigenous knowledge of waste-management dynamics rather than imported templates whose embedded assumptions may not survive transposition. The framework's strategic value will be measured by its capacity to absorb such divergence without losing its integrative analytical core, and by the willingness of brand owners, regulators, and

recyclers to invest in the deliberative governance processes through which the framework's trade-off calls are documented, reviewed, and iteratively refined over successive planning cycles.

10. Conclusion

The reconciliation of chemical safety with circular-economy ambitions in consumer-goods packaging emerges from this analysis as a structurally complex but tractable governance challenge whose resolution depends on the disciplined integration of compositional verification, lifecycle environmental accounting, and forward-looking regulatory assessment. The four-gate decision architecture proposed here translates the dispersed empirical and regulatory knowledge documented in earlier sections into a sequential, indicator-based procedure that brand owners, converters, recyclers, and regulators can implement at scale across heterogeneous market geographies. Its principal contribution is the explicit treatment of the trade-offs among chemical-safety obligations, lifecycle greenhouse-gas performance, and cross-jurisdictional regulatory exposure as simultaneously binding constraints rather than serially negotiable considerations, and its insistence on horizon-scanning capacity as a continuous obligation rather than a one-time compliance check.

Several structural insights merit emphasis. First, the chemical-safety profile of post-consumer recyclate streams cannot be inferred from polymer identity alone but must be empirically characterized against the additive history of the upstream packaging mix. Second, the lifecycle environmental performance of recyclate substitution is conditional on system design rather than intrinsic to recycling as such, with collection efficiency, energy mix, and downstream-market quality each exerting first-order influence on realized greenhouse-gas savings. Third, regulatory risk extends beyond present-moment compliance and demands ongoing monitoring of substance-list updates, restriction trajectories, and cross-jurisdictional harmonization initiatives. Fourth, the institutional realities of African and other emerging-market recyclate supply chains require adaptive implementation pathways that engage the informal sector, address infrastructural deficits, and leverage regionally generated scholarship rather than presuming European institutional templates.

The framework offers a structured navigational tool through which the inherent complexity of post-consumer recyclate use in consumer-goods packaging can be made tractable for practitioners and policy-makers operating across diverse contexts. Its sustained relevance will depend on iterative refinement against accumulating empirical evidence and on its absorption into regulatory and corporate governance routines that span mature and emerging-market jurisdictions alike.

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