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Toothpaste Tube Waste in the Circular Economy: Sustainable Packaging Innovation, Industry Challenges, and Pathways Toward Circular Oral Care

Abstract
Toothpaste tubes constitute a significant yet under-recognized contributor to global plastic waste, with billions of units discarded annually. Their multi-layered composition, typically combining polyethylene and aluminium, renders them incompatible with conventional recycling systems, thereby posing persistent environmental challenges. This narrative review examines current waste management practices, recent material innovations, and emerging sustainable alternatives within the oral care packaging sector.
Major focus is shift toward mono-material high-density polyethylene (HDPE) tubes, advancements in specialized recycling technologies, and alternative product formats such as toothpaste tablets, refill systems, and biodegradable materials. Although these approaches show promising potential for reducing environmental impact, their scalability is constrained by economic limitations, insufficient recycling infrastructure, and inconsistent consumer behaviour.
The review identifies a critical gap between technological innovation and real-world implementation, emphasizing the need for integrated system-level interventions. Policy mechanisms, particularly extended producer responsibility, alongside targeted infrastructure development and consumer education, are essential to enable a transition toward circular economy models in oral care packaging. Further research is needed to better understand lifecycle performance, clinical efficacy of alternative formats, and region-specific implementation strategies to ensure both environmental sustainability and public health outcomes.

INTRODUCTION

Packaging waste from the global oral care market has become a growing concern, with toothpaste tubes representing a particularly problematic waste stream. Estimates suggest that 1.5 to 20 billion toothpaste tubes are manufactured and discarded annually worldwide (1,2), with approximately 300 million tubes disposed of in the United Kingdom alone each year. (3) Americans generate an estimated 32 million pounds of waste from dental products annually, with only about 5% currently recycled. (4)

A major change in toothpaste packaging has been the shift in toothpaste packaging from metal tubes to laminate structures composed of polyethylene and aluminium foil. This transition, driven by functional advantages such as improved shelf life and product stability, has directly influenced the material composition of contemporary toothpaste tubes and underpins many of the recycling challenges observed today. (5)

As a result, traditional toothpaste tubes now consist of multiple laminated layers, including high-density and low-density polyethylene bonded with an aluminium foil barrier to provide essential product preservation. (6)

While this multi-material design effectively maintains product integrity and extends shelf life, it renders conventional tubes virtually non-recyclable through standard municipal recycling programs. Consequently, discarded toothpaste tubes can persist in landfills for 400–1,000 years before fully decomposing. (7)

With increasing regulatory pressure and rising consumer demand more sustainable options, the oral care industry faces mounting pressure to develop innovative packaging solutions. Leading oral healthcare brands including Haleon, Colgate-Palmolive, Unilever, and Procter & Gamble have transitioned to recyclable mono-material toothpaste tubes in recent years. (8,9) This review examines the current state of toothpaste tube waste management, evaluates emerging recycling technologies and alternative packaging formats, and identifies barriers to adoption and policy interventions that could facilitate the transition toward sustainable oral care packaging.

While existing studies have explored various aspects of toothpaste tube recycling and sustainable packaging, the current literature remains fragmented and largely descriptive. Limited attention has been given to integrating material innovations, real-world recycling performance, and consumer behaviour within a single analytical framework. Furthermore, industry-driven advancements, particularly the transition to mono-material tubes, have not been sufficiently evaluated in terms of their practical effectiveness across different waste management systems.

Therefore, a comprehensive and critical synthesis of these dimensions is required to better understand the feasibility and impact of current solutions. This review aims to address this gap by providing an integrated evaluation of technological developments, environmental implications, and implementation challenges in toothpaste tube waste management.

1.1 Literature Search and Review Approach

This narrative review synthesizes peer-reviewed literature, policy documents, and industry reports published between 2010 and 2026 to provide a comprehensive evaluation of developments in sustainable oral care packaging, Peer-reviewed studies were identified through systematic searches of Scopus, Web of Science, and Google Scholar using targeted keywords such as ‘toothpaste tube recycling,’ ‘mono-material tubes,’ and ‘circular economy’, ‘Sustainable packaging,’ ‘Waste management’. Given that technical advancements in packaging design often emerge through industrial innovation prior to formal academic publication, this review incorporates grey literature to capture real-world implementation and recycling performance. To ensure high research transparency and academic rigor, strict inclusion and exclusion criteria were applied to these non-scholarly sources.

Inclusion criteria

- Peer-reviewed journal articles, systematic reviews, and relevant reports
- Studies addressing toothpaste tube packaging, recycling technologies, or sustainable oral care alternatives
- Publications focusing on environmental impact, material innovation, consumer behaviour, or policy frameworks
- Articles published in English between 2010 and 2026

Exclusion criteria

- Non-English publications
- Opinion pieces, editorials, and non-referenced sources
- Studies unrelated to oral care packaging or waste management
- Duplicate publications

These curated sources provide essential insights into consumer-use outcomes and operational outcomes for Material Recovery Facilities (MRFs) not yet fully represented in academic journals

2. Composition and Environmental Impact of Traditional Toothpaste Tubes

2.1 Multi-Material Complexity

Most conventional toothpaste tubes are made using multi-layer laminates as combining distinct materials, each serving specific functional purposes. A standard tube structure consists of an outer polyethylene layer that provides mechanical strength and allows for printing, an aluminium barrier layer that limits oxygen ingress, and an inner polyethylene or polypropylene layer to ensure compatibility with the toothpaste formulation. Tube caps are most commonly produced from polypropylene or, less frequently, polystyrene. (8,10)

The aluminium barrier layer in toothpaste tubes helps prevent oxygen entry, helping to preserve the active ingredients and maintain product quality. However, this design feature simultaneously presents a major drawback from a waste-management perspective. Multi-layer tubes are difficult and costly to separate using conventional municipal recycling methods. As a result, these tubes can contaminate both plastic and aluminium recycling streams, reducing the quality and efficiency of recovered materials. (6,11)

Toothpaste tubes have historically been one of the most mis-cycled items in UK households, with approximately 30% of households disposing of them incorrectly. Even when tubes reach recycling facilities, they are often rejected during optical sorting due to their multi-material composition. (3)

Multilayer packaging structures are widely used because the combination of different polymers and non-polymeric barrier materials provides complementary functional properties, including mechanical strength, barrier performance and product stability. However, the same structural complexity creates substantial challenges at the end-of-life stage. Differences in polymer composition and processing behaviour, together with the presence of adhesives, coatings, inks and metallic layers, complicate sorting, separation and subsequent recycling. Consequently, the development of packaging that balances barrier performance with end-of-life recyclability has become an important objective in sustainable packaging design.(12)

2.2 Environmental Impact

The environmental burden of toothpaste tubes extends beyond end-of-life disposal challenges. According to sustainability reports and industry analyses, the production phase involves petroleum extraction for plastic components and bauxite mining for aluminium layers, processes that are associated with increased energy use, greenhouse gas emissions, and ecological disturbance. (13)

The environmental burden begins at the production phase, involving energy-intensive petroleum extraction for plastics and bauxite mining for aluminium. (13) Manufacturing steps such as polymer synthesis and aluminium smelting contribute significantly to the carbon footprint. (14) At the end of life, these non-recyclable materials fragment into microplastics that leach into soil and groundwater. (7)

3. Current Recycling Initiatives and Technological Innovations

3.1 Mechanical Processing of Multi-Material Waste

In the absence of widespread municipal infrastructure for laminates, specialized circularity models have been pioneered by organizations like TerraCycle, which operates across 20 countries (15,16)

Their mechanical recovery process is a multi-stage sequence designed to overcome the "sticky" challenge of residual product:

- Mechanical Shredding: Packaging is first shredded to expose the internal surface area and residual toothpaste. (15)
- Aqueous Washing Cycles: High-intensity washing removes chemical contaminants and product residue that typically cause rejection in standard systems. (15)
- Advanced Separation: Eddy current separation is utilized to isolate the thin aluminium foil layers, while density-based sorting (typically sink-float tanks) categorizes the remaining polyethylene and polypropylene fraction. (15)
- Upcycling: These isolated polymers are then pelletized for conversion into durable secondary goods, a model adopted by brands such as Crest, Oral-B, and ARM & HAMMER. (15,17)

3.2 Advanced Chemical and Delamination-Based Recycling

When mechanical recycling is limited by the incompatibility of different layers, advanced separation and chemical recycling approaches have been investigated. These include solvent-based separation, delamination, hydrolysis, glycolysis, aminolysis and catalytic depolymerization. Such approaches aim to separate or convert individual components of multilayer structures into reusable materials or chemical feedstocks. However, their broader implementation remains constrained by process complexity, economic considerations, energy requirements and the need for further scale-up and infrastructure development.(18,19)

3.3 Material Science Breakthrough: Mono-Material HDPE (#2)

A notable development in improving circularity has been the introduction of mono-material HDPE tubes in the 2019, designated as #2 plastic. Standard HDPE lacks the gas barrier properties necessary to prevent oxygen ingress, which would otherwise degrade fluoride stability and flavour profiles. (2,20,21)

Proprietary Modification: The technical solution involved creating a proprietary modified HDPE formulation that matches the barrier performance of traditional aluminium laminates without utilizing secondary materials. (20,21)

Industry Standardization: To ensure this wasn't a "walled garden" technology, Colgate-Palmolive shared this innovation through initiatives led by WRAP, enabling competitors-including Haleon (Sensodyne), Unilever, and Procter & Gamble-to adopt the standard. This collaborative approach has resulted in the technology covering over 91% of the UK toothpaste market. (8,9)

3.4 Operational Streamlining and Infrastructure Integration

Mono-material HDPE tubes are intended to align with existing recycling systems, making their processing more feasible at scale with standard Material Recovery Facility (MRF) operations:

Optical Sorting Compatibility: Unlike multi-material laminates, which are often rejected during optical sorting, mono-material tubes are identified as high-value HDPE #2, allowing for automated recovery.

Elimination of Manual Intervention: Standardization removes the need for costly manual separation of aluminium-layered components from plastic streams. (8)

Legislative Scaling: While currently limited to approximately 37 UK local authorities, this infrastructure is mandated to expand under the Simpler Recycling legislation, which requires all English local authorities to collect these tubes by March 2026. (8,9)

4. Sustainable Alternative Packaging and Product Formats

The transition toward a circular economy in oral care necessitates a paradigm shift away from traditional single-use tube-based packaging. Current alternatives range from solid formulations that eliminate the need for plastic tubes to the use of bio-based materials designed for industrial composting. However, the successful adoption of these formats is contingent upon balancing clinical efficacy, consumer hygiene perceptions, and infrastructure readiness.

4.1 Solid Formulations: Tablets and Powders

Toothpaste tablets and powders represent a significant departure from conventional paste, gaining traction due to their potential to reduce plastic waste through the use of glass jars, aluminium tins, or compostable pouches. (13,22) While these products contain standard dentifrice ingredients like sodium bicarbonate and fluoride, their clinical performance remains a point of academic debate. Variability in fluoride bioavailability and abrasivity poses a challenge for high-caries-risk populations, as robust clinical data evaluating their long-term effectiveness in caries prevention is currently limited. (13)

From an environmental perspective, Life Cycle Assessment (LCA) data provides critical quantitative insights. A study by Suppipat et al. (2022) revealed that 65% of the total environmental impact of toothpaste tablets is concentrated in the use phase, while 20% is attributed to ingredient production. (23) Notably, the study found that dosage control is a primary driver of environmental performance; when standardized to a 0.4 g dose, the environmental burden of tablets dropped significantly to 154 millipoints. Furthermore, the integration of glass packaging can offer an additional 10% positive impact across the product life cycle, provided that effective municipal recycling is achieved. (23)

4.2 Jar-Based and Refillable Systems

Modern jar-based formulations utilize glass or recyclable plastic (HDPE or PET) and are designed for integration with standard municipal recycling programs. (23) Despite the presence of antimicrobial ingredients to mitigate hygiene concerns regarding direct brush-to-jar bacterial transfer, these formats have struggled to achieve market penetration, currently capturing less than 2% of the global market. Similarly, refill and reuse systems, such as cartridge or concentrate models, face significant adoption barriers including higher initial costs, limited retail availability, and consumer unfamiliarity with the format within the oral care category. (24)

4.3 Biodegradable and Compostable Material Limitations

The industry has also explored bio-based materials, such as polylactic acid (PLA), polyhydroxyalkanoates (PHA), and sugarcane-derived polyethylene. (24) However, these materials present a significant infrastructure-readiness gap:

- Thermal Requirements: Most certified compostable plastics require industrial facilities operating at 55–60°C to degrade effectively; home composting systems rarely achieve the temperatures necessary for timely decomposition. (17)
- Accessibility Gaps: In the United States, only approximately 5% of the population currently has access to municipal composting programs that accept these specialized materials. (13)

Consequently, while bio-based materials offer a theoretical path to circularity, their real-world impact is currently limited by the fragmented nature of global composting infrastructure. Achieving a system-level transition will require coordinated investment in both material innovation and the downstream waste management systems necessary to process them.

Table 1: Comparative Analysis of Toothpaste Packaging Formats and Their Environmental Implications

Packaging Type	Material composition	Recyclability	Environmental Impact	Advantages	Limitations
Conventional Multilayer Tubes	Plastic (PE) + Aluminium laminate	Not recyclable in standard systems	High (landfill persistence, microplastics)	Excellent barrier properties, long shelf life	Difficult to recycle, material separation challenges
Mono-material HDPE Tubes	High-density polyethylene (HDPE)	Recyclable (where facilities exist)	Moderate (dependent on collection efficiency)	compatible with existing recycling streams, industry adoption	Requires proper cleaning, limited infrastructure in some regions
Toothpaste Tablets	Solid formulation (no tube)	Packaging recyclable/low waste	Low–Moderate (depends on packaging type)	Eliminates plastic tubes, reduced waste	Limited clinical evidence, user acceptance issues
Toothpaste Powders	Powder in glass/metal containers	Highly recyclable packaging	low	Reusable containers, minimal plastic use	Less convenient, niche adoption
Jar-based Toothpaste	Glass or recyclable plastic containers	Recyclable	Moderate	Easy recyclability, reusable options	Hygiene concerns, low market acceptance

Biodegradable Tubes	PLA, PHA, bio-based plastics	Industrial composting required	Potentially low (if properly processed)	Renewable materials, reduced fossil fuel use	Limited composting infrastructure, performance concerns
Refill Systems	Reusable containers + refill packs	Reduced waste generation	Low	Supports circular economy, less single-use packaging	Higher cost, low consumer adoption

5.Socio-Behavioral Barriers and the Value-Action Gap in Sustainable Oral Care Adoption

The transition toward a circular economy in oral care is not merely a technical or infrastructural challenge but is deeply rooted in complex socio-behavioural dynamics. Despite increasing environmental awareness, a significant "value-action gap" persists, where consumer stated preferences for sustainable products do not consistently translate into actual purchasing behaviour or correct disposal practices. (25,26)

5.1 Psychological and Practical Adoption Barriers

Consumer behaviour research identifies a stark discrepancy between environmental concern and market reality within the oral care sector. While large segments of the population express a desire to reduce plastic waste, the adoption of sustainable alternatives-particularly novel formats-remains low (23)

- Sensory-Motor Friction: Toothpaste tablets represent a significant departure from established sensory-motor habits. The requirement to chew a dry tablet to create a paste is often perceived as unfamiliar, unpleasant, or awkward, creating a psychological barrier to adoption that conventional cream-based formulations do not face. (9)
- Perceived Utility vs. Effort: For many consumers, the marginal environmental benefit of switching to a tablet format is outweighed by the perceived effort required to alter decades of ingrained brushing behaviour. (27)

5.2 Disposal Literacy and the "Recyclability Paradox"

A critical barrier to achieving high recovery rates is the lack of disposal literacy among the general public.

- Misinformation Bottlenecks: A significant proportion of consumers incorrectly believe that conventional multi-material laminate tubes are recyclable through standard kerbside programs. This misplaced confidence reduces the motivation to seek out sustainable alternatives or participate in specialized collection programs.
- Preparation Impact on Recovery: The success of mono-material HDPE tubes is uniquely sensitive to consumer preparation. (8) Industry trials demonstrate a stark recovery discrepancy: tubes that are properly emptied and capped achieve a 60% recovery rate, whereas tubes containing residual product in mixed waste streams see recovery plummet to below 17%. This data highlights that without effective consumer preparation, technical recyclability fails to translate into actual environmental gains. (3,9)

6. Regulatory Frameworks, Policy Interventions, and Industry Commitments

The shift toward sustainable packaging is increasingly mediated by top-down regulatory pressures and coordinated industry action, designed to internalize environmental costs and incentivize circular design. (8,9)

6.1 Extended Producer Responsibility (EPR) and Eco-Modulation

EPR policies, such as the EU Packaging and Packaging Waste Directive, shift the financial burden of end-of-life management from municipalities to manufacturers.

- Economic Incentives: These frameworks utilize eco-modulation, where producers pay reduced fees for packaging that is demonstrably recyclable. (9)
- Design Catalysts: Under new EPR frameworks, mono-material HDPE tubes avoid the financial penalties associated with hard-to-recycle laminates, creating a direct economic incentive for material standardization. (11)

6.2 Legislative Mandates: The UK "Simpler Recycling" Model

National-level policies are evolving to bridge the infrastructure gap. In the United Kingdom, the Simpler Recycling legislation represents a pivotal intervention.

- Standardized Collection: This policy mandates that all English local authorities must collect redesigned toothpaste tubes alongside other common plastics by March 31, 2026. (11)
- Systemic Scaling: This mandate is expected to significantly increase the current infrastructure, which presently only covers approximately 37 local authorities. (11)

6.3 Corporate Pledges and Multi-Stakeholder Collaboration

Voluntary industry commitments serve as critical benchmarks for the sector's transition toward circularity.

- Target Dates: Major stakeholders have established aggressive sustainability timelines: Corporate disclosures and industry reporting indicate that Colgate-Palmolive aims for 100% recyclable, reusable, or compostable packaging by 2025, while Procter & Gamble has committed to 100% recyclability by 2030. (2,8)
- Global Initiatives: Collective action is further supported by the Ellen MacArthur Foundation's New Plastics Economy Global Commitment, which brings together over 500 organizations to promote circular economy

principles and facilitate the diffusion of sustainable practices across the value chain. (7,8)

7. Discussion

7.1 Strategic Future Directions and Recommendations for Systemic Circularity

The realization of a truly circular economy in oral care requires moving beyond isolated material innovations toward integrated, system-level transformations. Circularity should be considered across the entire packaging value chain, encompassing material selection and packaging design, manufacturing, product use, collection, recycling, waste management and system-level interventions. A systems-based approach is particularly important because interventions focused exclusively on end-of-life recycling may overlook opportunities for waste prevention, improved packaging design, reuse and more sustainable production and consumption practices. (28).

7.2 Infrastructure Scaling and Standardized Labeling

The environmental efficacy of recyclable mono-material tubes is currently tethered to the availability of specialized sorting and recycling facilities. Future efforts must prioritize substantial investment in municipal Material Recovery Facilities (MRFs) to ensure that the technical compatibility of HDPE #2 tubes is matched by regional collection capacity. (8) Furthermore, to mitigate the "Recyclability Paradox," there is an urgent need for clear, standardized disposal labeling. Providing consumers with unambiguous visual cues to "empty completely and keep the cap on" is essential to transition recovery rates from the current sub-17% failure rate toward the 60% potential observed in controlled trials. (9,18,29)

7.3 Advanced R&D: Renewable Barriers and Natural Biodegradation

While modified HDPE has solved the immediate oxygen-barrier challenge, the next frontier in material science involves decoupling packaging from petroleum-based feedstocks. Research should prioritize:

- Renewable Barrier Materials: Developing oxygen-barrier layers derived from renewable sources that maintain recyclability while reducing the carbon footprint of the production phase. (14)
- Natural Biodegradation: Exploring materials capable of safe biodegradation under natural environmental conditions, thereby bypassing the current 5% accessibility limitation of industrial composting infrastructure. (14)

7.4 Value-Chain Coordination and Accessibility

Achieving meaningful sustainability gains requires coordinated action across the entire value chain, aligning manufacturer investment with public policy and consumer behaviour. Policy measures, such as targeted incentives and EPR frameworks, must be leveraged to increase the affordability and retail accessibility of sustainable alternatives like tablets and refill systems, which currently occupy less than 2% of the market. (8) This system-level approach ensures that innovations are not just technically viable but are economically and socially integrated. (30)

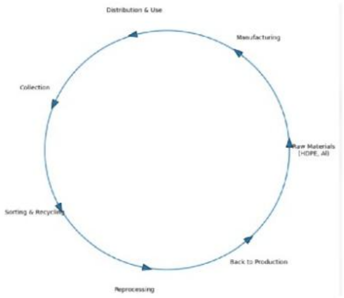

Figure 1: Proposed Circular Economy Framework for Global Oral Care Packaging Systems.

Figure 1: Proposed Circular Economy Framework for Global Oral Care Packaging Systems.

8. Conclusion

Toothpaste tube waste remains a formidable environmental challenge, yet the industry has reached a critical inflection point where practical, scalable solutions are within reach. The transition to mono-material HDPE packaging
represents a landmark achievement in sustainable design, establishing a technical foundation that allows toothpaste

packaging to finally integrate with standard recycling infrastructure.

However, the "Recyclability Paradox" underscores that technical innovation alone is insufficient. The stark discrepancy between 60% recovery for properly prepared tubes and less than 17% for contaminated units highlights the indispensable role of consumer education and disposal literacy. Furthermore, the persistent gaps in municipal infrastructure continue to limit the geographical reach of these advancements.

In summary, the oral care sector possesses the technical and business models necessary to deliver meaningful environmental benefits. The success of this transition now depends on scaling these innovations through legislative support, infrastructure investment, and a fundamental shift in consumer engagement. By aligning material science with systemic policy interventions, the industry can move beyond the "take-make-waste" model toward a sustainable, circular paradigm.

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